Assessing the Impacts of Solar Power and Battery Storage System Integration in Thailand Using the LEAP-NEMO Framework

Supakorn Ukumphan
Faculty of Engineering, Mahasarakham University, Mahasarakham, Thailand
67010353012@msu.ac.th

Yao Xiao
Hunan Mechanical and Electrical Polytechnic, Changsha, China
65010363003@msu.ac.th

Caixia Yang
Hunan Mechanical and Electrical Polytechnic, Changsha, China
65010363002@msu.ac.th

Buncha Wattana
Faculty of Engineering, Mahasarakham University, Mahasarakham, Thailand
buncha.w@msu.ac.th

Supannika Wattana
Faculty of Engineering, Mahasarakham University, Mahasarakham, Thailand
supannika.w@msu.ac.th (corresponding author)

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ABSTRACT

Driven by energy security and climate change concerns, the Thai government has prioritized the deployment of high-potential solar power integrated with battery energy storage. This paper aims to assess the impacts of integrating solar and Battery Energy Storage Systems (BESS) in Thailand, with a particular emphasis on its potential to enhance energy security and reduce CO_2 emissions. For this purpose, three scenarios were developed for the assessment: the Reference Scenario (REF), the Solar Power Only Scenario (PVOnly), and the Solar Power with Battery Energy Storage System Scenario (PVBESS). An integrated Low Emissions Analysis Platform (LEAP) – Next Energy Modeling (NEMO) framework was developed and employed to assess the optimal integration of solar power and BESS in Thailand for the period of 2024-2037. The assessment revealed that promoting solar and BESS integration offers significant benefits, for example, enhanced energy supply diversification, decreased reliance on natural gas imports, and a transition toward a decarbonized power sector. However, integrating solar power and BESS could raise several emerging challenges including the high cost of batteries, end-of-life management issues, and regulatory barriers. To address these challenges, this paper proposes several strategies, including leveraging ongoing price reductions together with the provision of tax incentives, developing comprehensive recycling infrastructure, and implementing streamlined procedures to simplify the installation application process. The coordinated implementation of these strategies offers a robust pathway to integrate renewable energy and storage systems into sustainable development.

Keywords-energy security; carbon reduction potential; electricity sector; strategic pathway; carbon neutrality

I. INTRODUCTION

Global warming and climate change challenges are primarily caused by the continuous increase in Greenhouse Gas (GHG) emissions. Many countries, including Thailand, have implemented numerous measures and strategies to reduce GHG emissions across various economic sectors. Thailand has relied heavily on fossil fuels as a main energy source over the past 50 years. In 2024, fossil fuels accounted for 79.2% of the country's total primary energy consumption, reaching 104,709 Kilotonnes of Oil Equivalent (KTOE) [1]. Approximately 30% of the total fossil fuel consumption was used for electricity generation, with natural gas accounting for about 78% of this share, followed by lignite and imported coal [2]. Such a high dependence on fossil fuels poses substantial energy security risks and barriers to achieving sustainability commitments.

In response to the energy security and sustainability challenges, the Thai government has developed a national energy plan aimed at increasing the proportion of renewable energy and other alternative fuels to systematically reduce both fossil fuel reliance and the associated GHG emissions. One of the government's key strategies is to boost solar power's contribution to the country's power production. This is because Thailand has a substantial solar energy potential, with average solar radiation levels higher than in many countries. Peak solar radiation typically occurs from April to May, reaching 20–23 MJ/m²/day in most regions [3]. Given this potential, solar energy has been prioritized in Thailand's national energy plan as a primary renewable source. The Power Development Plan 2018 (PDP2018) (2018–2037) was implemented in 2018 and further updated in 2020 as PDP2018 revision 1 [4]. The main objective of this plan is to increase the share of renewable energy in electricity generation to 33% in 2037 – about double the share compared to 2024. Under this plan, the installed capacity of solar power would rise significantly from 3,313 MW in 2024, to 15,574 MW in 2037. In addition, the latest PDP (PDP2024) was drafted in 2022 and has been planned for implementation since 2024 [5]. According to the draft of PDP2024, the solar capacity target is set even higher, reaching 33,269 MW by 2037. However, as of April 2025, the implementation of the long-delayed PDP2024 may need to be further postponed, allowing for a more thorough revision aimed at reducing long-term power supply. To mitigate reliability challenges in the Thai power system, the PDP2024 has integrated Battery BESS as a grid modernization component.

Previous research has examined the technical aspects of renewable energy and BESS [6-8], has analyzed the economic impacts of renewable energy penetration [9-12], and has assessed the environmental impacts of solar waste management [13, 14]. While existing studies have contributed valuable insights into renewable energy impacts in Thailand, the ongoing transition shaped by rapid technological advancements and shifting policy priorities highlights the need for new research to offer relevant recommendations. This study, therefore, assesses the integration of solar power and BESS in Thailand for the period 2024-2037. It evaluates the development and application of an integrated LEAP – NEMO framework for the optimal integration of solar power and BESS to balance technical and environmental objectives within the Thai power system.

II. METHOD

A. *Research Tools and Scope of Study*

This study employs a combined framework of scenario analysis and energy system modeling to assess the impacts of integrating solar and BESS in the power sector. This approach has been widely adopted to evaluate the implications of renewable energy deployment in various countries. Authors in [15] analyzed the impact of alternative electricity development pathways on electricity generation in Vietnam. Similar analyses have been applied to assess scenario impacts in Kenya [16]. In addition, the long-term electricity pathways to achieve carbon neutrality in China have been examined [17]. To assess the energy and environment implications, several modeling tools are available, such as MAED, MESSAGE, SIMPACTS, TIMES, EnergyPLAN, and LEAP. Authors in [18] conducted a review of 37 computer tools, including LEAP, TIMES, and MESSAGE for analyzing the energy and environmental impacts of renewable energy. Authors in [19] provided a review of 19 software tools for analyzing, designing, and optimizing hybrid renewable energy systems. The LEAP framework was also employed in [20-22] to assess the impacts of renewable energy deployment.

In this study, the integrated LEAP-NEMO modeling framework is employed to assess the implications of solar and BESS integration. LEAP is an energy planning and GHG emission modeling tool developed by the Stockholm Environment Institute (SEI) [23]. Its primary purpose is to support energy and environmental policy planning at national and regional levels. LEAP–NEMO is designed to support long-term energy planning and optimization, especially in developing countries, and provides flexibility in creating energy system models. This capability enables the inclusion of energy storage capacity, such as BESS, into the simulation framework [24]. LEAP is deployed for Monitoring, Reporting, and Verification (MRV) of GHG mitigation strategies and features a Graphical User Interface (GUI) suitable for climate change planning and sustainable development. The integrated LEAP-NEMO framework combines strong capabilities in optimization and capacity expansion modeling with a user-friendly GUI that is accessible to both researchers and policymakers. Consequently, the integrated LEAP-NEMO framework has been extensively deployed to analyze energy and environmental issues [25-27].

Figure 1 illustrates the integrated LEAP-NEMO framework developed for this study, which provides an integrated platform for energy planning by combining demand forecasting, optimal supply expansion, and environmental assessment. The workflow initiates with LEAP projecting sectoral electricity demand based on historical load profiles and growth assumptions. This demand is then passed to the NEMO model, which determines the optimal dispatch and capacity expansion while considering critical engineering and reliability constraints. The output from NEMO is utilized by LEAP to quantify the resulting primary energy consumption and associated CO_2 emissions. The development of energy system modeling is mainly based on government plans including the PDP and the Alternative Energy Development Plan (AEDP). This model incorporates key parameters, such as projected electricity demand, generation capacity expansion, fuel mix assumptions, and other sector-specific variables to estimate future electricity scenarios. The estimation provides the projected power production, energy mix for power production, primary energy requirements, and associated carbon emissions. In this research, the analysis covers a projection period from

2025 to 2037, aligning with the timeframe of Thailand's latest PDP (PDP2018 revision 1).

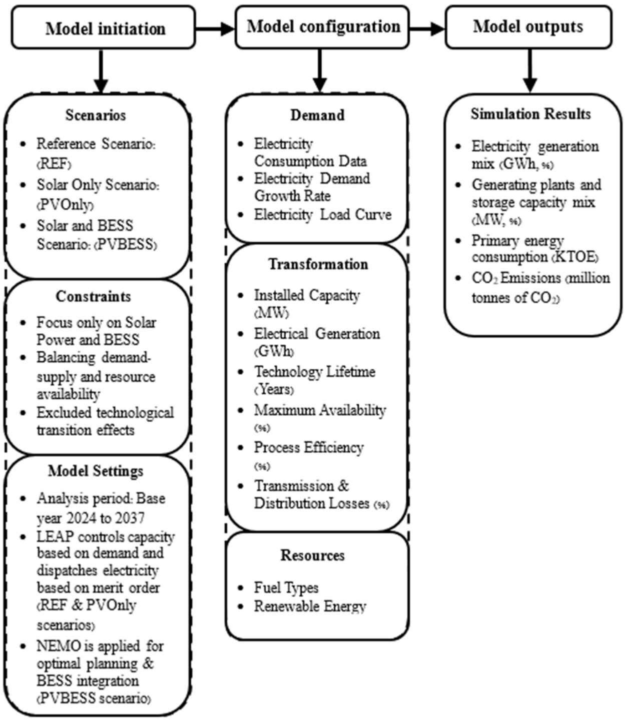

Fig. 1. Framework of the LEAP-NEMO Model.

B. The Algorithm of the LEAP Model

The LEAP model calculates energy consumption, transformation, and carbon emissions, based on user-defined input data. It supports flexible methodologies, from simple accounting to complex simulations, and is designed for long-term scenario analysis with low initial data requirements.

1) Energy Consumption

The total energy consumption based on the energy demand sector is calculated by:

$$EC_n = \sum_i \sum_j AL_{n,j,i} \times EI_{n,j,i} \quad (1)$$

where *EC* refers to the total energy consumption of a given sector within an energy demand sector, *AL* refers to the activity level in a specific sector and to a given energy type, *EI* refers to the energy intensity of the sector, which is the energy consumed per unit of activity level, *n* refers to the fuel type, *j* refers to the device, and *i* refers to the sector.

The net energy consumption for transformation, which represents the additional energy input required due to conversion inefficiencies, is calculated by:

$$ET_S = \sum_m \sum_t ETP_{t,m} \times \left(\frac{1}{f_{t,m,s}} - 1 \right) \quad (2)$$

where *ET* refers to the net energy consumption for transformation, *ETP* refers to the energy consumption transformation products and can be electricity in the case of power plants products, *f* refers to the energy transformation efficiency, *s* refers to the type of primary energy, *m* refers to the equipment, and *t* refers to the type of secondary energy.

2) Transformation

The transmission and distribution module maps domestic fuel requirements to input fuels and adjusts total requirements based on module outputs and inputs. The fuel calculations for each process are:

$$INPUT_p = \frac{OUTPUT_p}{EFFICIENCY_p} \quad (3)$$

For the Transmission and Distribution module:

$$EFFICIENCY_p = 1 - LOSSES_p \quad (4)$$

where *INPUT* refers to fuel or feedstock, *OUTPUT* refers to electricity generation, *EFFICIENCY* refers to the conversion efficiency of the power plants, *LOSSES* refer to the energy losses during the conversion process, and p refers to each process in the system.

3) Carbon Emission

The carbon emissions from final energy consumption can be assessed and calculated using:

$$CEC = \sum_i \sum_j \sum_n AL_{n,j,i} \times EI_{n,j,i} \times EF_{n,j,i} \quad (5)$$

where *CEC* refers to the carbon emission factor, *AL* refers to the activity level, *EI* refers to the energy intensity, which is used as a factor of carbon emissions by fuel type, *n* refers to the fuel type, *j* refers to the equipment type, and *i* refers to the economic sector.

The carbon emission from the energy transformation can be calculated by:

$$CET = \sum_s \sum_m \sum_t ETP_{t,m} \times \frac{1}{f_{t,m,s}} \times EF_{t,m,s} \quad (6)$$

where *CET* refers to the carbon emission, *ETP* refers to the energy transformation products, *EF* refers to the emission factors from one unit of the primary fuel types consumed, *f* refers to the energy transformation efficiency, *t* refers to the type of secondary fuel or energy output, *m* refers to the equipment used in energy transformation, and *s* refers to the type of the primary fuel consumed.

C. Scenario Development

Three scenarios (REF, PVOnly, and PVBESS) were developed to assess the impacts of increasing solar energy and integrating BESS into the electricity generation system. The REF scenario represents a continuation of 2024. Under this scenario, the power generation mix continues to develop in line with existing technological advancements and energy resource trends. This scenario serves as a reference case for assessing the impacts of alternative policy interventions. The PVOnly scenario reflects the PDP 2018 revision 1. In the former, the share of solar energy in total generating capacity is projected to have substantially increased to 21.1% by 2037. The PVBESS scenario builds on the PVOnly scenario by integrating BESS into the electricity supply. An overview of the key scenario features and assumptions is presented in Table I.

TABLE I. KEY SCENARIO FEATURES AND ASSUMPTIONS

Scenarios	Key Scenario Features and assumptions
Reference: (REF scenario)	• Represents the current trends of the existing energy and technology mix for power generation. • Maintains the Combined Cycle Gas Turbine (CCGT) power plants as the dominant technology, with 59% of the total generating capacity. • Assumes a steady 6.5% share of solar energy in the technology mix throughout the entire study period. • Assumes a constant share in the technology mix: thermal (22%), biomass (9.6%), hydro (7.4%), wind (2.8%), gas turbine (0.6%) for the whole period.
Solar Only: (PVOnly scenario)	• Reflects the PDP 2018 revision 1. • Decreased the share of CCGT and thermal in generating capacity to 36% and 10%, respectively, by 2037. • Substantial increase of solar power in technology mix (6.5% in 2024, 21.1% in 2037). • Greater proportion in the technology mix: hydro (14%), gas turbine (5%), and wind (4%) in 2037.
Solar with BESS: (PVBESS scenario)	• Assumes generating capacity of all technologies, consistent with the PVOnly scenario. • Incorporates BESS into the electricity system.

III. DATA CONSIDERATIONS

To assess and analyze the impacts of each scenario, this research necessitates comprehensive data across multiple dimensions, such as electricity, energy, and environment. The data on electricity demand, disaggregated by the economic sector, can be collected from the Thailand Energy Situation 2024 published by the Energy Policy and Planning Office (EPPO), and the Thailand Energy Balance 2024 published by the Department of Alternative Energy Development and Efficiency (DEDE) [1, 2]. The projected demand growth for electricity can be sourced from the draft PDP 2024 [28]. Data on the installed capacity by technology are available from the Electricity Generating Authority of Thailand (EGAT) and the Energy Regulatory Commission (ERC) [29, 30]. The information on power production by plant type, as well as the transmission and distribution losses, can be obtained from the Thailand Energy Balance by DEDE [1]. The electricity load profile for Thailand (yearly load curves) is available from EGAT and ERC [31, 32]. In order to develop scenarios, information on the capacity mix (thermal, combined-cycle, solar, wind, hydro, and other technologies) for the years 2024–2037 can be collected from the PDP2018 (first revision) and research studies relevant to Thailand [4, 33]. Information on specific technologies, including power plant lifetimes, maximum availability factors, capacity credits, electricity reserve margins, and generation efficiencies can be obtained from EGAT and supplemented by relevant literature [22, 33-35]. For BESS, the technical features assumed a 15-year service life, with performance parameters set at 80% for maximum availability, 90% for round-trip efficiency, and 90% for capacity credit.

IV. RESULTS AND DISCUSSION

This study examines how the expansion of solar power and the integration of BESS affect the electricity sector, with their impacts analyzed in terms of the generation capacity mix, projected output, primary energy demand, supply diversification, and CO_2 emissions from 2024 to 2037.

A. *Capacity Mix*

Thailand's existing power generating capacity reached 55,387 MW in 2024 (Figure 2). The largest share was contributed by CCGT, which accounted for 60%, followed by thermal power (11%), biomass (10%), hydro (7%), solar (6%), and other technologies including gas turbine, wind, biogas and Municipal Solid Waste (MSW) (6%). A high proportion of CCGT in the capacity mix could be attributed to natural gas discoveries in the Gulf of Thailand over the past fifty years. Additionally, natural gas is considered a more environmentally friendly alternative to other fossil fuels. To supply sufficient demand for electricity, the generating capacity would have increased from 55,387 MW in 2024 to 77,210 MW by 2037 under the REF and PVOnly scenarios. The integration of BESS in the PVBESS scenario would, however, have resulted in a higher projected capacity of 88,939 MW by 2037. In the PVBESS scenario, BESS would have been introduced starting from 2031 at 61.5 MW, with a continuous growth projected to have reached 11,729 MW by 2037. The BESS capacity in the PVBESS scenario represents the optimal capacity determined by the NEMO optimization model. Figure 2 also shows that CCGT continues to play a major role in the capacity mix in the REF scenario. A high reliance on natural gas would contribute to worsening the country's energy security in terms of a less diversified energy supply and more natural gas imports. In fact, Thailand began importing natural gas in 2000, with initial imports of 1,971 KTOE, which grew substantially to 16,588 KTOE by 2024 [1]. In the PVOnly and PVBESS scenarios, the share of CCGT in the capacity mix would decrease to 34% and 30%, respectively. This trend follows Thailand's energy policy, which aims to diminish the share of natural gas in the power generation fuel mix while promoting renewable energy integration, particularly through solar power and the deployment of BESS. Regarding solar power, its capacity under the REF scenario is expected to have grown modestly from 3,585 MW in 2024 to 4,998 MW in 2037. In contrast, the PVOnly and PVBESS scenarios show a substantial expansion, with the capacity rising to 16,311 MW by 2037.

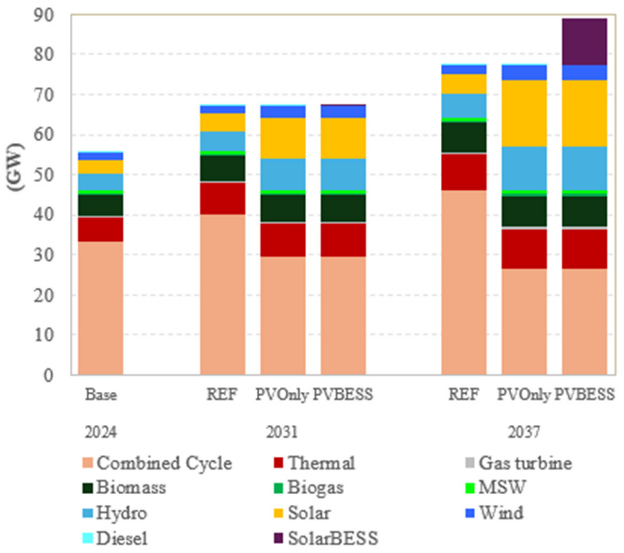

Fig. 2. Electricity generating capacity by technology.

B. Power Generation

Figure 3 illustrates the projected electricity generation and generation mix for various scenarios. To supply sufficient electricity needs, power generation is projected to have risen from 210 TWh in 2024 to nearly 400 TWh in 2037 across all three scenarios. The electricity generation mix in 2024 was dominated by natural gas, which accounted for about 72% of the whole share. The proportions of biomass, coal, solar, hydro, and other sources in the generation mix were 12%, 6%, 3%, 3%, and 4%, respectively. To meet the rising electricity demand, the share of natural gas in the REF scenario would have increased further to 77% by 2037. However, this share is lower in the scenarios with renewable integration, falling to 61% in the PVOnly scenario and 57% in the PVBESS scenario. This indicates that electricity generation in the REF scenario relies on a less diversified energy supply. The continued growth in natural gas demand would necessitate higher imports, thereby posing significant risks in terms of energy insecurity and import dependency, as discussed above.

Figure 3 shows that the decline in natural gas share would be primarily substituted by a greater reliance on renewable sources. For example, the share of hydropower is projected to increase to 8% in the PVOnly scenario and 9% in the PVBESS scenario. This increase is attributed to a combination of domestic hydropower generation and, more significantly, to the imports from neighboring countries. Regarding solar energy, electricity generation in the REF scenario exhibits a slight increase of only 1.4%, reaching 5,499 GWh in 2037. Conversely, solar power generation would increase compared to its generation in 2024, by about 4 times in the PVOnly scenario and 4.6 times in the PVBESS scenario. The highest solar generation observed in the PVBESS scenario, is likely because part of the solar output is stored in the BESS, enhancing system flexibility. It is further observed that the BESS is systematically charged during off-peak periods of high solar generation and discharged during peak demand hours. This strategy reduces solar curtailment and lessens reliance on inefficient fossil-fueled peaking plants.

In terms of biomass, electricity generation in the REF scenario is projected to have increased by 60% over 2024–2037. In comparison, the PVOnly scenario shows a 100% increase, while the PVBESS scenario exhibits the highest growth at 125%. Such an increase in power production would enhance the proportion of biomass in generation mix, indicating both a more diversified energy mix and an effective utilization of agricultural waste – highlighting Thailand's advantage as an agricultural-based economy. The share of coal would rise marginally from 6% in 2024 to 8% in both the PVOnly and PVBESS scenarios. Despite its environmental drawbacks, coal will continue to play a role in Thailand's electricity mix for the next 15 years. As the share of renewable energy increases, policymakers must retain coal as a backup resource to ensure system stability and improve overall reliability.

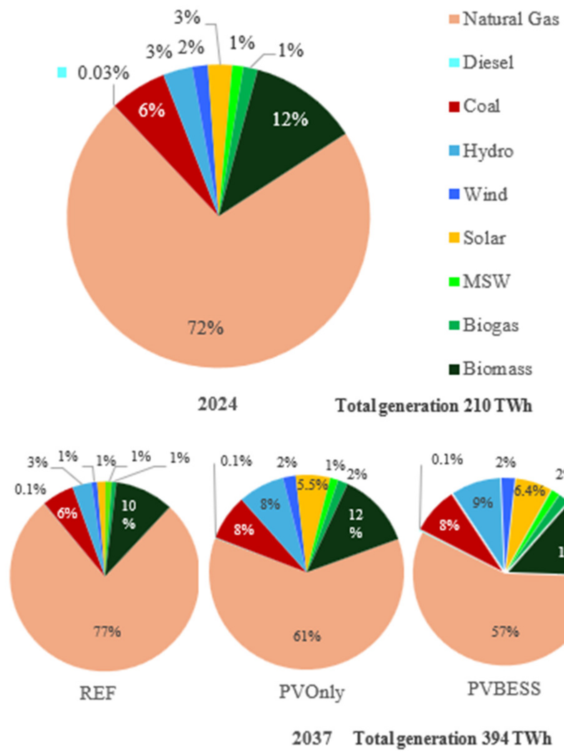

Fig. 3. Electricity generation shared by energy sources.

C. Primary Energy Supply and Energy Diversity

The primary energy supply for electricity generation and energy diversity for the REF, PVOnly, and PVBESS scenarios are presented in Table II. In the REF scenario, the former would grow from 34,448 KTOE in 2024 to 64,098 KTOE in 2037. The PVOnly scenario would yield a marginal reduction of only 0.8% (63,561 KTOE) relative to the REF scenario. This slight decrease is partly due to reduced natural gas use, which is offset by the substantial increases in renewable energy requirements (Table II). In contrast, the PVBESS scenario would result in a 4.5% increase (67,016 KTOE) relative to the REF scenario. This growth is attributed to a larger share of renewable energy in electricity generation and additional supply from BESS, despite a significant decline in fossil fuel requirements.

Table II also shows that the projected increase in fossil energy requirements for the REF scenario is 25,741 KTOE, from 26,953 KTOE in 2024 to 52,694 KTOE in 2037. In comparison, the PVOnly and PVBESS scenarios would reduce fossil fuel requirements by 13% and 17%, respectively, relative to the REF scenario. In terms of natural gas requirements, the PVOnly and PVBESS scenarios are projected to be 17% and 23% lower, respectively, than the REF scenario. The reduction in fossil requirements could offer significant benefits including enhanced energy security through lower import dependency and a substantial reduction in CO_2 emissions.

In contrast to the REF scenario, where primary energy is dominated by imported fossil fuels with volatile prices and high GHG emissions, the solar energy in the PVBESS scenario incurs no fuel costs, generates zero operational emissions, and enhances national energy security. Therefore, this 'increase' in primary energy represents a strategic shift from a fossil-dependent system toward a self-reliant and sustainable energy structure. Furthermore, the integration of BESS ensures that this renewable contribution enhances, rather than compromises, system reliability and contributes to a more diversified and resilient power supply. The effective integration of solar power with BESS is essential for achieving the ambitious renewable energy goals specified in the draft of PDP2024.

In terms of energy diversity, the Herfindahl-Hirschman Index (HHI) is employed in this study as an indicator to examine the energy diversification. The HHI is derived from the sum of the squared shares of each energy source in a country's energy mix [36]. The HHI decreases with greater diversification and increases with greater concentration of energy sources. According to Table II, the natural gas share in the REF scenario is projected to have increased from 71% in 2024 to 75% in 2037. Conversely, the biomass share is forecasted to have dropped by 2% in the same period. As a result of these changes, the HHI is projected to have increased from 0.53 (2024) to 0.59 (2037). The energy supply in the REF scenario, therefore, becomes less diversified. Under the PVOnly scenario, the share of natural gas would decline, while those of renewable energy and coal would increase. This shift in energy input shares would lead to a lower HHI of 0.43 in 2037. This value signifies a greater improvement in energy diversity compared to the REF scenario. The PVBESS scenario achieves the greatest energy diversity, with an HHI of 0.33 in 2037 – lower than that of both the REF and PVOnly scenarios. This improvement is attributed to the integration of BESS, which contributes 4.8% of the total primary energy requirement. The additional share from BESS, thereby, enhances the diversification of the energy supply.

D. Carbon Dioxide Emissions

The impacts of expanding solar power and integrating BESS on the electricity sectors in terms of CO_2 emissions are presented in Table III. The values in brackets in Table III show percentage differences from the REF scenario. Under the REF scenario, CO_2 emissions are projected to have increased from 67 million tons in 2024, to 130 million tons in 2037, representing a net rise of 63 million tons. In 2037, CO_2 emissions under the PVOnly and PVBESS scenarios would be 13,225 (10.2%) and 17,001 (13.1%) thousand tons lower, respectively, than under the REF scenario. These results demonstrate that increasing the share of solar energy helps mitigate the carbon emissions effectively, while the integration of BESS further deepens these reductions. However, this transition towards greater solar and BESS integration could raise challenges for the Thai electricity grid, requiring new strategies to manage the complex interactions between renewable generation and storage systems. In addition, higher levels of solar and BESS integration also raise significant sustainability challenges, particularly concerning the management of end-of-life solar panels and batteries. Addressing the issues of recycling, waste reduction, and resource recovery is essential to ensuring that the transition remains environmentally responsible and economically sustainable.

TABLE II. PRIMARY ENERGY REQUIREMENTS AND ENERGY DIVERSITY

	2024	2037		
		REF	PVOnly	PVBESS
Total primary energy requirement (KTOE)	**34,448**	**64,098**	**63,561**	**67,016**
Fossil energy (KTOE)	**26,953**	**52,694**	**45,908**	**43,981**
Natural Gas	70.6%	75.2%	62.5%	55.7%
Coal	7.6%	6.9%	9.6%	9.8%
Diesel	0.04%	0.08%	0.13%	0.14%
Renewable energy (KTOE)	**7,495**	**11,404**	**17,653**	**19,841**
Biomass	14.6%	12.6%	15.9%	16.9%
Hydro	1.6%	1.7%	4.1%	4.4%
Solar	1.4%	0.7%	3.0%	3.2%
Biogas	1.8%	0.9%	2.0%	2.1%
MSW	1.5%	1.3%	1.7%	1.8%
Wind	0.9%	0.5%	1.1%	1.2%
Electricity (KTOE)	**-**	**-**	**-**	**3,193**
BESS	-	-	-	4.8%
HHI	**0.53**	**0.59**	**0.43**	**0.33**

V. POLICY IMPLICATIONS

To develop strategies for the long-term sustainability of the country's electricity generation, this study evaluates the impacts of integrating solar and BESS in Thailand for the period 2024-2037. The specific impacts are analyzed in terms of electricity generating capacity mix, projected electricity generation, primary energy requirements, diversification of energy supply, and carbon dioxide emissions. Table IV summarizes the key findings. Values in brackets show percentage differences from the REF scenario.

TABLE III. CO_2 EMISSIONS IN THE ELECTRICITY SECTOR

Years	REF	PVOnly		PVBESS	
		Changes from REF scenario		Changes from REF scenario	
	(thousand tons)	(thousand tons)	(%)	(thousand tons)	(%)
2024	67,018	-	-	-	-
2031	103,829	-5,932	(-5.7)	-11,014	(-10.6)
2037	129,934	-13,225	(-10.2)	-17,001	(-13.1)

TABLE IV. SUMMARY OF THE SCENARIO IMPACTS ON VARIOUS ASPECTS FOR THE YEAR 2037

	REF	PVOnly		PVBESS	
Energy impacts					
Fossil requirements (KTOE)	52,694	45,908	(-12.9)	43,981	(-16.5)
Natural gas requirements (KTOE)	48,213	39,712	(-17.6)	37,309	(-22.6)
Natural gas saving (KTOE)		8,501		10,904	
Energy diversity index	0.59	0.43		0.33	
Environmental impacts					
CO_2 emissions (thousand tons)	129,934	116,709	(-10.2)	112,933	(-13.1)
CO_2 saving (thousand tons)		13,225		17,001	

Table IV demonstrates that the integration of BESS with expanded solar generation capacity would yield a 16.5% reduction in fossil fuel consumption (PVBESS scenario), a significant improvement over the 12.9% reduction achieved through solar expansion alone (PVOnly), relative to the REF scenario. This indicates that combining energy storage with solar power is more effective than relying solely on expanding the solar energy capacity. Furthermore, natural gas requirements would decline significantly, by 17.6% in PVOnly and 22.6% in PVBESS, compared with the REF scenario. As discussed above, natural gas consumption would rely more on imports to meet future demand. Therefore, the synergistic integration of energy storage with solar power generation would help reduce natural gas imports by 10,904 KTOE in the PVBESS scenario, a significantly larger reduction than the 8,501 KTOE achieved by solar alone (PVOnly). In terms of fuel diversification, integrating energy storage with solar power would achieve greater energy diversity. The HHI is reduced from 0.59 in the REF scenario, to 0.43 in the PVOnly scenario and further down to 0.33 in the PVBESS scenario. Regarding CO_2 emissions, the integration of BESS with solar energy expansion would substantially reduce them, fostering a more sustainable and environmentally friendly power sector. In short, the integration of energy storage systems delivers greater benefits than relying on solar or renewable energy alone.

Although solar power promotion and BESS integration are beneficial for the power sector of Thailand, the following challenges may emerge:

- High battery costs have been a major barrier to the widespread integration of energy storage systems in Thailand. This financial barrier makes solar-only installations a more attractive option for customers whose energy demand is primarily during daylight hours. However, battery prices have dropped significantly from 1,014 $/kWh in 2010, to 234 $/kWh in 2020 [37]. Moreover, the prices have currently dropped below $100/kWh and continue to decline. This decline is driven by the battery market expansion, growing manufacturing capacity, declining material costs, technological innovation, and intense competition. For Thailand, ongoing price reductions represent an important opportunity to accelerate the adoption of energy storage within its electricity infrastructure. In addition to falling prices, the provision of tax incentives would further expedite the widespread deployment of energy storage.
- Managing the end-of-life of solar panels and battery storage could be another challenge. While solar energy and BESS are efficient solutions for the clean energy transition, their end-of-life management poses significant environmental challenges. The operational lifespan of solar panels is typically 20–30 years and that of lithium-ion batteries is even shorter, about 8–20 years, depending on their application [22, 34]. Decommissioned solar panels and batteries represent a significant source of electronic waste, posing serious environmental and management challenges. The challenges associated with integrating solar power and battery storage extend beyond national boundaries. From a regional perspective, countries such as Bangladesh and India are facing similar issues related to the environmental management of solar panels and battery storage [38, 39]. To address these challenges, effective strategies should focus on the development of comprehensive recycling infrastructure, aiming to achieve both cost reduction and enhanced value recovery from materials. Regulatory challenges are also important. In Thailand, complex and time-consuming permitting and grid connection processes pose significant regulatory barriers. Complex permitting and application processes for solar rooftop installations, which involve multiple agencies, cause significant delays, and hinder the utilization of Thailand's high-potential solar energy. Additionally, overlapping responsibilities and a lack of coordination among authorities create administrative inefficiencies. To meet the solar target, the government should simplify application processes by implementing streamlined procedures such as one-stop services. This would expedite permits for solar projects and better support prosumers.

To sum up, the policy promoting solar power and BESS integration offers significant benefits and is essential to achieving the renewable energy targets outlined in the draft of PDP2024 as well as realizing long-term energy security and environmental sustainability. However, in order to effectively utilize this potential, a comprehensive analytical framework is needed as a crucial step toward informed decision-making. Such a framework should incorporate detailed data on capital and operational expenditures, fuel price fluctuations, and environmental externalities to accurately assess net benefits and optimize deployment strategies. This comprehensive, cost-inclusive approach is vital for advancing from conceptual policy support to evidence-based planning and investment, ultimately guiding the development of a resilient, efficient, and sustainable electricity system.

VI. CONCLUSIONS

This study assesses the impacts of integrating solar power and BESS in Thailand by employing the integrated LEAP-NEMO modeling framework to analyze three scenarios (REF, PVOnly, and PVBESS) from 2024 to 2037. This assessment provides the optimal integration of solar power and BESS to balance technical and environmental objectives within the Thai power system. The findings revealed that a transition toward solar energy and BESS offers a beneficial solution to the energy and environmental issues of the country. The integration of solar with BESS may significantly enhance Thailand's energy security by diversifying the energy supply mix and reducing the existing heavy reliance on imported natural gas. This transition could effectively drive the power sector's decarbonization. However, several challenges may emerge, including the high capital cost of batteries, the urgent need for end-of-life management of BESS and solar panels, and existing regulatory complexities that could hinder rapid deployment. In order to overcome these challenges and accelerate the integration of solar and BESS technologies, this study proposes three strategies, including economic incentives, circular economy planning, and regulatory reform. This includes the provision of economic incentives, such as tax incentives, to attract more customers during the continuing price reductions in battery technology. Implementing circular economy planning—through comprehensive recycling infrastructure and regulations for BESS—is essential to address end-of-life environmental concerns. Furthermore, regulatory reform is needed to streamline and simplify the permitting and installation process for renewable projects. The coordinated implementation of these strategies is not only beneficial but also essential in establishing a practical and resilient roadmap for Thailand to achieve a sustainable, secure, and low-carbon energy future. In addition to the coordinated implementation of recommended strategies, a comprehensive analytical framework that integrates detailed cost structures, fuel price dynamics, and environmental impacts is further needed to optimize deployment pathways. Accordingly, such a framework is currently being developed as part of an ongoing research program at this university.

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