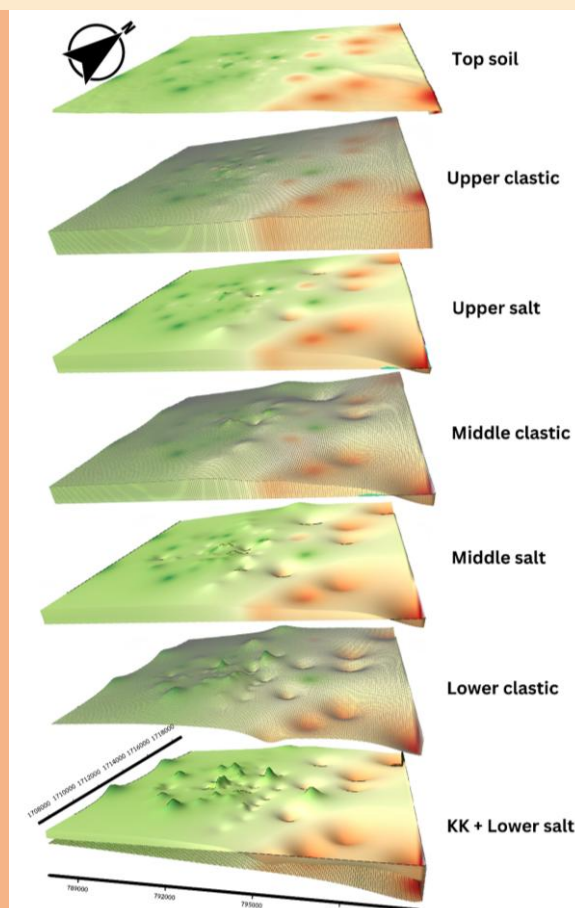
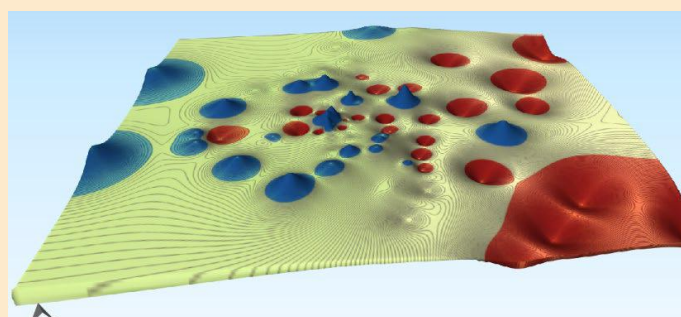
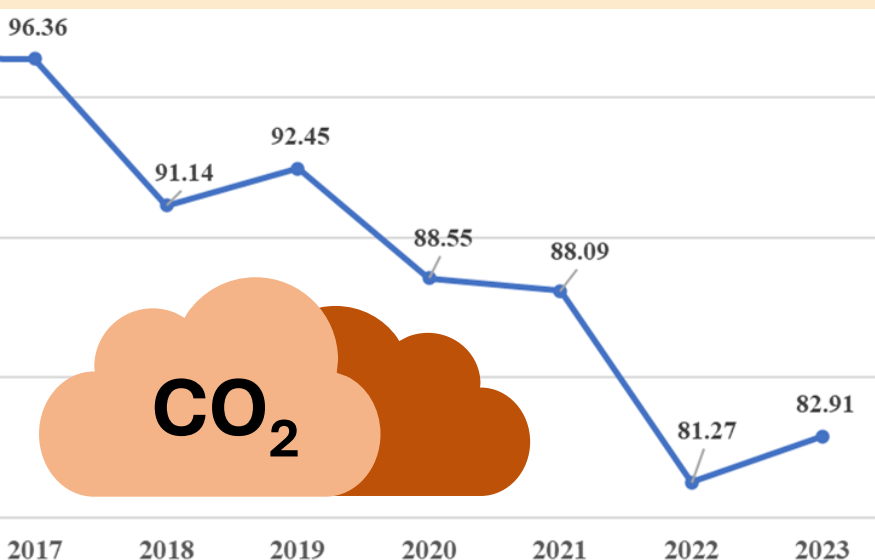


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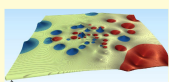
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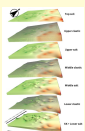
On the cover



1) Thailand's CO₂ Emissions from Electricity Generation Sector (Mt CO₂) (*Jitkla, W. & Noh, D.-W., p.10, fig. 3*)



2) Areas overlying salt structures on a 3D model, where red indicates subsidence (negative values) in the salt basin, blue indicates uplift (positive values) in the salt dome, and yellow indicates stable areas. (*Suphakdee, P. & Chanket, U., p.43, fig. 12b*)



3) Visualization of salt layers and individual sedimentary layers using a 3D model with the Qgis2threejs plugin. (*Suphakdee, P. & Chanket, U., p.39, fig. 9*)



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ข้อคิดเห็นของบทความทุกเรื่องที่ดีพิมพ์ลงในวารสารฯ ฉบับนี้ถือว่าเป็นความคิดอิสระของผู้เขียน กองบรรณาธิการไม่มีส่วนรับผิดชอบ หรือไม่จำเป็นต้องเห็นด้วยกับข้อคิดเห็นนั้น ๆ แต่อย่างใด

LMDI Decomposition of CO₂ Emissions from Thailand's Electricity Generation Sector (2014–2023)

Wanchanok Jitkla^{1,2*} and Dong-Woon Noh^{1*}

¹ Global Energy Technology Policy Professional Program, Department of Global Climate Environmental Studies,
Hanyang University, Seoul 04763, South Korea

² Department of Mineral Resources, Ministry of Natural Resources and Environment, Bangkok 10400, Thailand

*Corresponding author: wanchanok.jitkla@gmail.com, dwroh@hanyang.ac.kr

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Abstract

This study analyzes the driving forces of carbon dioxide (CO₂) emissions from Thailand's electricity generation sector during 2014–2023 using the additive Logarithmic Mean Divisia Index (LMDI) method. Electricity generation accounts for the largest share of Thailand's energy-related CO₂ emissions and is central to achieving national climate targets under the Nationally Determined Contributions (NDC) and long-term carbon neutrality and net-zero goals. An additive LMDI framework based on an extended Kaya identity decomposes changes in total CO₂ emissions into five components: activity, structural, fuel mix, thermal efficiency, and emission factor effects. The analysis uses annual electricity generation data from the Global Change Data Lab, energy consumption data from Thailand's Energy Balance compiled by the Department of Alternative Energy Development and Efficiency (DEDE), and default emission factors from the 2006 IPCC Guidelines. In addition, scenario-based projections are developed to assess emission pathways consistent with Thailand's 2030 NDC target, 2050 carbon neutrality, and a 2065 net-zero greenhouse gas emissions goal. The results show that total CO₂ emissions from the electricity sector declined by approximately 10.02 Mt CO₂ during 2014–2023. Improvements in thermal efficiency and structural changes in the generation mix were the main drivers of emission reductions, while shifts in fuel mix from coal toward natural gas and renewable energy provided additional mitigation effects. However, rising electricity demand, captured by the activity effect, partially offset these gains. Scenario analysis suggests that pathways featuring accelerated renewable energy deployment and earlier coal phase-out are more consistent with Thailand's higher-ambition NDC targets and long-term decarbonization goals. The findings provide quantitative evidence on the relative importance of demand growth, efficiency improvement, and structural change, offering policy-relevant insights for electricity-sector decarbonization in Thailand.

Keywords: CO₂ emissions; electricity generation; energy transition; fuel mix; LMDI decomposition; Thailand

1. Introduction

Electricity generation plays a central role in modern economic systems by supporting industrial activity, urban development, and household welfare. In many emerging economies, growth in electricity demand is closely linked to economic expansion, resulting in increased energy consumption and greenhouse gas emissions. Thailand is no exception. Despite recent progress in energy-efficiency improvements and renewable

energy deployment, the electricity generation sector remains the largest single source of carbon dioxide (CO₂) emissions within the national energy system, largely due to continued reliance on fossil fuels, particularly natural gas and coal.

Over the past decade, Thailand's electricity demand has grown steadily in response to economic development, urbanization, and rising living standards. Although the share of renewable electricity has increased, fossil-fuel-based

generation continues to dominate the power mix. Natural gas remains the primary generation fuel, while coal and lignite still contribute a substantial share, particularly in baseload generation. As a result, the electricity sector occupies a critical position in Thailand's national climate strategy, representing both a major challenge and a key opportunity for achieving carbon neutrality and long-term decarbonization goals.

Thailand's climate and energy policies are framed by its international commitments under the Paris Agreement and domestic planning instruments. The country's Second Updated Nationally Determined Contribution (NDC) sets a target to reduce greenhouse gas emissions by 30 percent below business-as-usual levels by 2030, or up to 40 percent with international support, alongside long-term goals of achieving carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065¹. These objectives are operationalized through the Power Development Plan (PDP), the Alternative Energy Development Plan (AEDP), and the Energy Efficiency Plan (EEP), which collectively emphasize renewable energy expansion, energy-efficiency improvement, gradual coal phase-down, and modernization of the electricity system. However, translating these policy ambitions into effective emission reductions requires a clear understanding of the underlying drivers of changes in CO₂ emissions in the electricity sector.

Decomposition analysis provides a systematic approach for identifying the factors that drive changes in energy-related CO₂ emissions. Among available methods, the Logarithmic Mean Divisia Index (LMDI) approach is widely applied due to its theoretical consistency, perfect decomposition without residual terms, and flexibility in incorporating structural and technological variables. Previous LMDI-based studies on Thailand's power and energy sectors have demonstrated that economic activity and electricity demand growth

are major contributors to increases in emissions, while improvements in efficiency and gradual shifts in fuel structure have partially offset these effects. Nevertheless, most existing research relies on long historical periods, aggregate sectoral data, and standard decomposition frameworks, offering limited insight into recent structural changes and their policy relevance under Thailand's current decarbonization agenda.

This study addresses these limitations by applying an extended additive LMDI framework to analyze changes in CO₂ emissions in Thailand's electricity generation sector over the period 2014–2023. This period is deliberately selected as it represents a critical phase of policy and structural transition in the Thai power sector, characterized by successive revisions of the Power Development Plan, accelerated renewable energy deployment, gradual coal phase-down, and the formulation of key national climate commitments, including the Second Updated Nationally Determined Contribution and the Long-Term Low Greenhouse Gas Emission Development Strategy. By decomposing total emission changes into activity, structural, fuel mix, thermal efficiency, and emission factor effects, the analysis provides a detailed assessment of how technological progress, fuel substitution, and changes in electricity generation structure have influenced emission trends during this period. In addition, scenario-based analysis aligned with Thailand's national climate targets is developed to examine possible implications of alternative electricity demand trajectories and decarbonization pathways for the 2030 NDC target, 2050 carbon neutrality, and the 2065 net-zero greenhouse gas emissions goal.

2. Literature Review

The Logarithmic Mean Divisia Index (LMDI) is a widely used index decomposition method for analyzing changes in energy consumption and

¹ According to Thailand's Second Updated Nationally Determined Contribution (NDC), the projected business-as-usual (BAU) greenhouse gas emissions in 2030 are approximately 555 Mt CO₂eq (economy-wide, excluding LULUCF). Thailand commits to reducing emissions by 30% below the BAU level by 2030, or up to 40% with international support. Building on this near-term mitigation target, Thailand's Revised Long-Term Low Greenhouse Gas Emission Development Strategy (LT-LEDS) defines carbon neutrality by 2050 as achieving net-zero carbon dioxide (CO₂) emissions through balancing residual CO₂ emissions with removals or offsets, while net-zero greenhouse gas emissions by 2065 refer to minimizing anthropogenic emissions of all greenhouse gases and fully balancing remaining emissions with removals (UNFCCC, 2022).

CO₂ emissions. It enables total emission changes to be systematically attributed to multiple driving factors—including activity, structural change, energy/thermal efficiency, fuel mix, and emission factors—without residual terms. Owing to its theoretical consistency, path independence, and flexibility in incorporating technological and structural variables, LMDI has been extensively applied to the power sector, where electricity demand, generation structure, and technology evolve simultaneously (Chontanawat *et al.*, 2020; Mai *et al.*, 2020).

Previous LMDI-based studies in the energy and industrial sectors consistently identify activity or output growth as the dominant driver of emission increases, while improvements in efficiency, fuel switching, and renewable energy deployment partially offset this effect. High-resolution decomposition analyses further emphasize the importance of accounting for technology-specific efficiency and structural change when assessing emission dynamics, particularly in emerging economies undergoing energy transitions (Shrestha *et al.*, 2009).

In the context of Thailand, LMDI and related decomposition methods have been applied to analyze CO₂ emissions from the electricity and broader energy sectors. Existing studies consistently find that economic growth and rising electricity demand are primary drivers of emission increases, whereas improvements in efficiency and gradual changes in fuel structure provide limited mitigation, resulting mainly in relative rather than absolute decoupling between economic growth and emissions (Muangthai *et al.*, 2014; Chen *et al.*, 2025). However, most studies rely on long historical periods, aggregated sectoral data, and standard decomposition frameworks, offering limited insight into recent technology-driven structural changes under Thailand's current decarbonization agenda.

This study advances the literature by focusing on the recent period 2014–2023 and applying an expanded LMDI framework with higher-resolution, technology-level data disaggregated by generation technology, fuel type, and producer category. This approach enables a more detailed assessment of how efficiency improvements, structural changes, and fuel substitution have

shaped recent CO₂ emission trends in Thailand's electricity sector.

3. Methodology and Data

3.1 Logarithmic Mean Divisia Index (LMDI) Method

The additive Logarithmic Mean Divisia Index (LMDI) is employed in this study as the principal method for decomposing changes in CO₂ emissions within Thailand's electricity sector. LMDI is widely recognized for its ability to provide perfect decomposition, ensuring that all changes in emissions are fully attributed to defined contributing factors without residual terms. This mathematical robustness allows researchers and policymakers to precisely quantify the influence of diverse drivers such as emission factors, energy efficiency, fuel mix, structural shifts, and overall activity levels across multiple time periods.

The decomposition in this study is based on an extended Kaya-type identity, articulated as:

$$C = \sum_i C_i = \sum_i G_{tot} \times \frac{G_{th}}{G_{tot}} \times \frac{G_i}{G_{th}} \times \frac{F_i}{G_i} \times \frac{C_i}{F_i} \dots (1)$$

Where:

G_{tot} : total electricity generation from all sources;
 G_{th} : total electricity generation from all thermal (fossil-based) fuels;
 G_i : total electricity generation from fuel i ;
 F_i : fuel consumption of type i ; and
 C_i : CO₂ emissions from fuel i .

The LMDI method utilizes both multiplicative and additive decomposition formulas to capture the impact of each key factor. The total change in CO₂ emissions over any given period, such as from 2014 to 2023, can be expressed as:

$$\Delta C_{tot} = C^t - C^0 \dots \dots \dots (2)$$

$$\Delta C_{tot} = \Delta C_{act} + \Delta C_{str} + \Delta C_{mix} + \Delta C_{eff} + \Delta C_{ef} (3)$$

Table 1: Formulation of the LMDI Approach.

Identity	$C = \sum_i C_i = \sum_i G_{tot} \times \frac{G_{th}}{G_{tot}} \times \frac{G_i}{G_{th}} \times \frac{F_i}{G_i} \times \frac{C_i}{F_i}$	
Division	Multiplicative decomposition	Additive decomposition
	D	ΔC
Effect of each factor	$D_{act} = \exp \left(\sum_i \frac{(C_i^t - C_i^0) / (\ln C_i^t - \ln C_i^0)}{(C^t - C^0) / (\ln C^t - \ln C^0)} \ln \left(\frac{G_{tot}^t}{G_{tot}^0} \right) \right)$	$\Delta C_{act} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{G_{tot}^t}{G_{tot}^0} \right)$
	$D_{str} = \exp \left(\sum_i \frac{(C_i^t - C_i^0) / (\ln C_i^t - \ln C_i^0)}{(C^t - C^0) / (\ln C^t - \ln C^0)} \ln \left(\frac{G_{th}^t}{G_{th}^0} \times \frac{G_{tot}^0}{G_{tot}^t} \right) \right)$	$\Delta C_{str} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{G_{th}^t}{G_{th}^0} \times \frac{G_{tot}^0}{G_{tot}^t} \right)$
	$D_{mix} = \exp \left(\sum_i \frac{(C_i^t - C_i^0) / (\ln C_i^t - \ln C_i^0)}{(C^t - C^0) / (\ln C^t - \ln C^0)} \ln \left(\frac{G_i^t}{G_{th}^t} \times \frac{G_{th}^0}{G_i^0} \right) \right)$	$\Delta C_{mix} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{G_i^t}{G_{th}^t} \times \frac{G_{th}^0}{G_i^0} \right)$
	$D_{eff} = \exp \left(\sum_i \frac{(C_i^t - C_i^0) / (\ln C_i^t - \ln C_i^0)}{(C^t - C^0) / (\ln C^t - \ln C^0)} \ln \left(\frac{F_i^t}{G_i^t} \times \frac{G_i^0}{F_i^0} \right) \right)$	$\Delta C_{eff} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{F_i^t}{G_i^t} \times \frac{G_i^0}{F_i^0} \right)$
	$D_{ef} = \exp \left(\sum_i \frac{(C_i^t - C_i^0) / (\ln C_i^t - \ln C_i^0)}{(C^t - C^0) / (\ln C^t - \ln C^0)} \ln \left(\frac{C_i^t}{F_i^t} \times \frac{F_i^0}{C_i^0} \right) \right)$	$\Delta C_{ef} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{C_i^t}{F_i^t} \times \frac{F_i^0}{C_i^0} \right)$

Source: Formulation of the Logarithmic Mean Divisia Index (LMDI) method adapted from Ang *et al.* (1998) and Ang (2004, 2005).

Each component term represents a specific driving factor of CO₂ emission change, defined as:

$$\Delta C_{act} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{G_{tot}^t}{G_{tot}^0} \right) \dots \dots \dots (4)$$

$$\Delta C_{str} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{G_{th}^t}{G_{th}^0} \times \frac{G_{tot}^0}{G_{tot}^t} \right) \dots \dots \dots (5)$$

$$\Delta C_{mix} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{G_i^t}{G_{th}^t} \times \frac{G_{th}^0}{G_i^0} \right) \dots \dots \dots (6)$$

$$\Delta C_{eff} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{F_i^t}{G_i^t} \times \frac{G_i^0}{F_i^0} \right) \dots \dots \dots (7)$$

$$\Delta C_{ef} = \sum_i \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln \left(\frac{C_i^t}{F_i^t} \times \frac{F_i^0}{C_i^0} \right) \dots \dots \dots (8)$$

Definitions of Effects:

ΔC_{act} (Activity Effect) measures the effect of changes in total electricity generation (G_{tot}) between the two periods.

ΔC_{str} (Structural Effect) indicates the impact of changes in the proportion of total thermal generation within overall electricity generation (G_{th}/G_{tot}).

ΔC_{mix} (Fuel Mix Effect) reflects the impact of changes in the share of electricity generated from each fuel i in total thermal generation (G_i/G_{th}).

ΔC_{eff} (Thermal Efficiency Effect) captures the change in CO₂ emissions due to variations in the efficiency of converting fuel energy into electricity (F_i/G_i).

ΔC_{ef} (Emission Factor Effect) represents the change in CO₂ emissions resulting from variations in the emission factor of fuel (C_i/F_i).

In the context of Thailand's electricity sector, LMDI enables the clear separation of the effects of technology upgrades, shifts in energy mix—such as increased adoption of renewables or switching from coal to natural gas—changes in sector structure, and rising or falling electricity demand. Moreover, the additive form of LMDI permits direct quantification of each factor's contribution to total emission changes, enhancing transparency in scenario analysis and policy evaluation.

While LMDI offers mathematical precision and analytic clarity, some limitations should be acknowledged. Notably, incomplete or missing data may affect the accuracy of factor attribution, and impacts from unmeasured influences—such as abrupt policy changes or behavioral shifts—may not be captured fully. Appropriate zero-value handling techniques and sensitivity checks are recommended to strengthen confidence in results.

3.2 Data

This section describes and summarizes the key datasets, sources, and classification methods used for the LMDI decomposition analysis of CO₂ emissions within Thailand's electricity sector from 2014 to 2023.

3.2.1 Energy Consumption Data and Trends

Primary energy consumption data were obtained from Thailand's Energy Balance published by the Department of Alternative Energy Development and Efficiency (DEDE). The data are originally reported in thousand tons of oil equivalent (KTOE) and were converted to petajoules (PJ) using the standard conversion factor (1 KTOE = 0.041868 PJ) to ensure analytical consistency and compatibility with the default 2006 IPCC carbon emission factors expressed in tonnes of CO₂ per terajoule (t CO₂/TJ). All energy use variables employed in the LMDI calculations were therefore harmonized in PJ.

Thermal energy inputs to electricity generation include bituminous coal, briquettes and other coal, lignite (Mae Moh), high-speed diesel, fuel oil, and natural gas in various forms. Consistent

with the LMDI framework, these fuels were aggregated into three categories:

- (i) Coal Products: bituminous coal, briquettes/other coal, lignite (Mae Moh);
- (ii) Oil Products: high-speed diesel (HSD), fuel oil;
- (iii) Natural Gas: natural gas, methane, pipeline gas, LNG.

As summarized in **Fig. 1**, Thailand's energy consumption structure has changed substantially over the past decade. The share of coal declined from 22.42% in 2014 to 13.53% in 2023, indicating a gradual move away from coal as a primary energy source. Natural gas remained the dominant fuel throughout the period, accounting for approximately 55–67% of total energy consumption throughout the period and continuing to play a central role in thermal power generation. In contrast, the share of renewable energy increased markedly, rising from 11.93% in 2014 to 30.74% in 2023, reflecting sustained expansion of low-carbon energy sources. Correspondingly, the overall share of thermal (fossil-based) fuels decreased from 88.07% to 69.26% (**Fig. 1**), highlighting a gradual but steady rebalancing of Thailand's energy mix toward diversification and decarbonization.

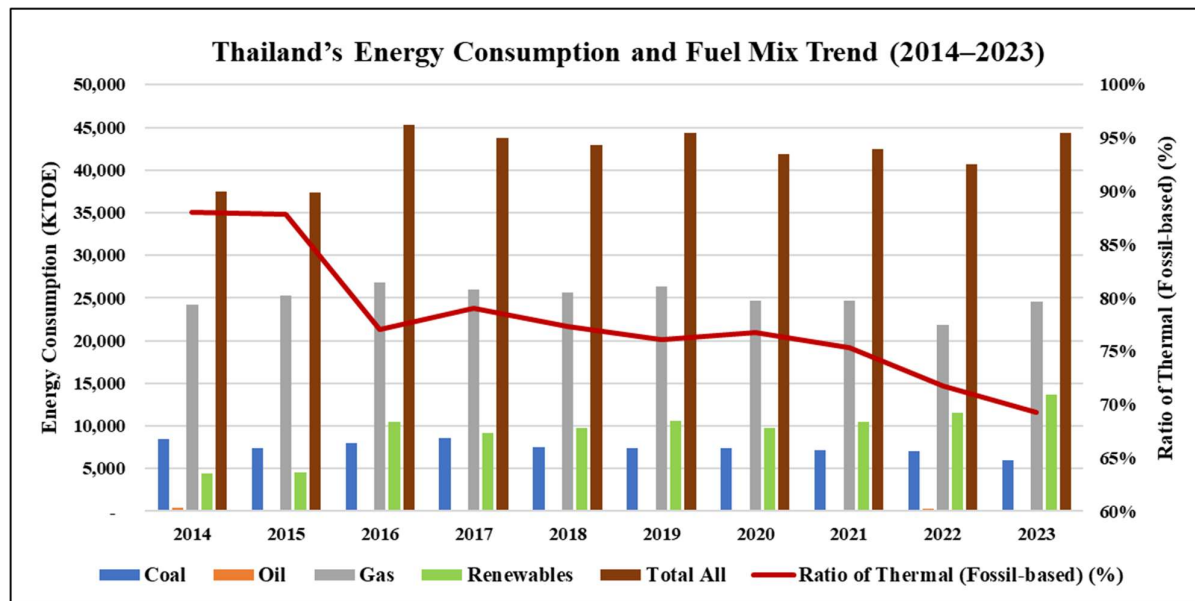


Fig. 1: Thailand's Energy Consumption and Fuel Mix Trend (2014–2023).

3.2.2 Electricity Generation and Fuel Mix Evolution

Electricity generation data were obtained from the Global Change Data Lab (GCDL), which reports national annual figures in terawatt-hours (TWh). For consistency in analysis and to ensure compatibility with the 2006 IPCC default carbon emission factors ($\text{t CO}_2/\text{TJ}$), all electricity generation values were converted to petajoules (PJ) using the conversion factor $1 \text{ TWh} = 3.6 \text{ PJ}$. This harmonization allows direct comparison with energy consumption data and enables coherent calculation of efficiency and fuel mix effects within the LMDI decomposition framework.

Consistent with the categorization of energy consumption, electricity generation from thermal power fuels is grouped into three main categories: coal products, oil products, and natural gas. This classification supports clear trend analysis of Thailand's evolving generation mix and facilitates sectoral CO_2 emission calculations.

As illustrated in **Fig. 2**, Thailand's electricity generation experienced notable shifts in fuel composition and volume over the period 2014–2023. Total electricity generation increased from approximately 173.76 TWh in 2014 to 190.49 TWh in 2023, reflecting steady growth in electricity demand. Fossil-fuel-based (thermal) generation—comprising coal, oil, and natural gas—remained

the backbone of the generation portfolio but exhibited a declining share, decreasing from 91.82% of total generation in 2014 to 84.37% in 2023.

Coal-fired generation declined from 37.57 TWh (21.62%) in 2014 to 30.43 TWh (15.97%) in 2023, indicating a gradual phase-down consistent with Thailand's decarbonization efforts. Oil-based generation accounted for a very small share of total output and declined further from 0.96% to 0.47% over the study period. Natural gas continued to serve as the dominant generation fuel, maintaining a share of approximately 63–72% throughout the period and increasing slightly to 67.93% in 2023.

Renewable electricity generation increased substantially, rising from 14.21 TWh (8.18%) in 2014 to 29.77 TWh (15.63%) in 2023. Among renewable sources, bioenergy consistently accounted for the largest share, followed by hydropower, solar, and wind. This expansion reflects Thailand's continued deployment of renewable energy capacity and the influence of national policy incentives.

Overall, the combination of steady growth in electricity generation and evolving fuel mix highlights a gradual transition toward a cleaner power generation structure. These trends are critical for modeling CO_2 emission trajectories and assessing the impacts of energy transition policies within the LMDI framework.

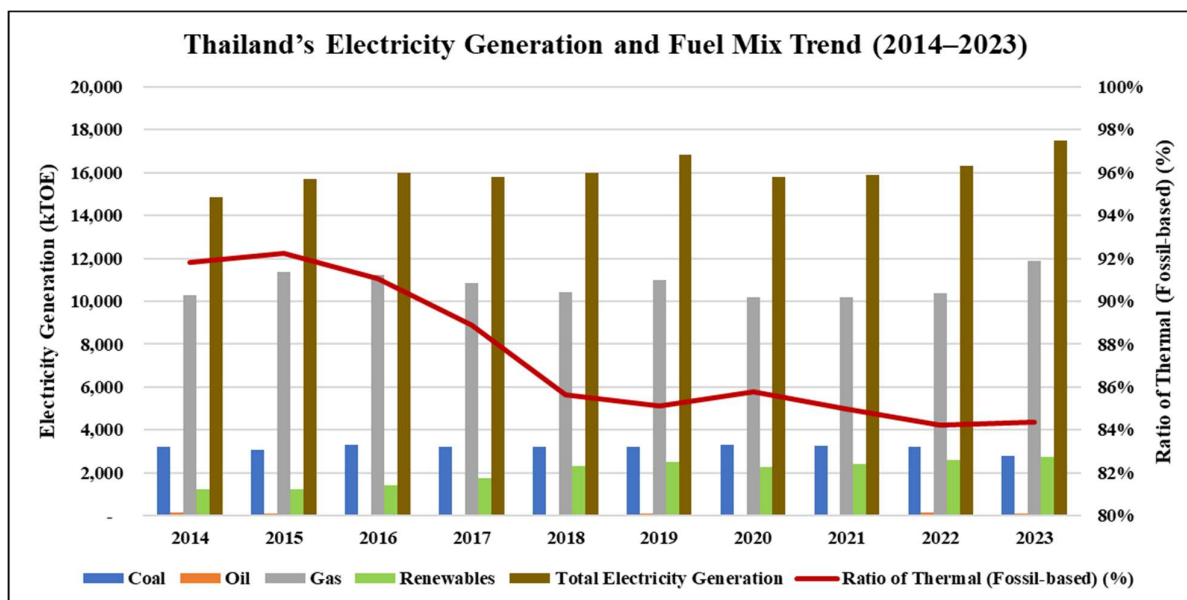


Fig. 2: Thailand's Electricity Generation and Fuel Mix Trend (2014–2023).

Electricity imports are excluded from the LMDI decomposition analysis and treated separately from domestic electricity generation. Although imported electricity is included in Thailand's national energy balance as part of total electricity supply, it does not generate direct CO₂ emissions within the domestic electricity generation sector and is predominantly sourced from hydropower in neighboring countries. This exclusion ensures that the decomposition results accurately reflect changes in Thailand's domestic fuel mix, thermal efficiency, and generation structure driven by national energy and climate policies.

3.2.3 Carbon Emission Factors

In this study, the effect of CO₂ emission factors was held constant over the entire period from 2014 to 2023. This approach is based on the adoption of default carbon emission factors from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 2: Energy, Table 2.2), as summarized in **Table 2**. These standardized values (t CO₂/TJ) are assigned to primary fuels used in stationary combustion—such as coal, oil, and natural gas—within the energy industry.

Table 2: Carbon Emission Factors.

Fuel	CO ₂ (Default Emission Factor)
	t CO ₂ / TJ
Coal	
Bituminous	96.1
Briquettes & other coal	97.5
Lignite	101.0
Oil	
High-Speed Diesel	74.1
Fuel Oil	77.4
Natural Gas	56.1

In the IPCC framework, *stationary combustion* refers to the burning of fuels in fixed installations—such as power plants, industrial boilers, and electricity generation facilities—that do not involve mobile sources. This category is therefore most relevant for analyzing emissions from Thailand's electricity sector.

According to the IPCC 2006 Guidelines, these emission factors are default fixed values and

remain constant over time. As a result, carbon intensity per unit of energy input does not vary throughout the study period. Consequently, the CO₂ emission factor effect does not contribute to changes in total CO₂ emissions from Thailand's electricity generation sector during 2014–2023. All observed changes in total CO₂ emissions in this analysis arise from other influencing factors—including the thermal efficiency effect, fuel mix effect, structural effect, and activity effect—rather than from variations in emission factors.

3.3 Scenario Design and Assumptions

This study develops a set of stylized scenarios to examine possible future CO₂ emission pathways in Thailand's electricity sector that are consistent with national mitigation milestones for 2030, 2050, and 2065. The scenarios are designed as policy-consistent but methodologically controlled experiments, allowing the effects of changes in electricity demand (activity), generation structure and fuel mix, and technology-related efficiency improvements to be assessed within the LMDI decomposition framework. Therefore, these scenarios should be interpreted as analytical scenarios rather than definitive forecasts or predictions of Thailand's future electricity system.

Scenario assumptions are primarily derived from Thailand's Second Updated Nationally Determined Contribution (NDC 2.0), the Long-Term Low Emission Development Strategy (LT-LEDS, 2022), and the draft Power Development Plan (PDP 2024–2037). Rather than forecasting outcomes, the scenarios represent alternative, internally consistent pathways constructed to isolate key emission drivers relevant to power-sector decarbonization.

3.3.1 Scenario Drivers and Analytical Link to LMDI

Across all scenarios, three core drivers are varied in line with the LMDI decomposition structure:

1) *Electricity demand growth (activity effect)*, reflecting alternative assumptions regarding economic growth, energy efficiency improvements, and demand-side management;

2) *Generation mixes and fuel composition (structural and fuel-mix effects)*, capturing shifts from coal and natural gas toward renewable and other low-carbon electricity generation technologies;

3) *Thermal efficiency and low-carbon technology deployment (thermal efficiency effect)*, including improvements in fossil-fuel power plant performance and the gradual introduction of CCUS, hydrogen, and other low-emission options in later periods.

Emission factors are held constant across all scenarios, consistent with the use of default emission factors from the IPCC (2006) Guidelines, thereby ensuring analytical consistency within the LMDI framework.

3.3.2 BAU Definition, NDC Targets, and Scenario Specifications

1) Business-as-Usual (BAU) Definition

Thailand's Second Updated Nationally Determined Contribution (NDC 2.0, 2022) specifies an economy-wide business-as-usual (BAU) greenhouse gas emission level of approximately 555 Mt CO_{2e} in 2030, but it does not provide sector-specific emission baselines or detailed annual emission trajectories. In this study, the BAU emissions pathway for the electricity generation sector is constructed based on projected electricity demand, generation mix assumptions, and fuel-specific emission factors consistent with the Draft Power Development Plan (PDP 2024–2037), the Alternative Energy Development Plan (AEDP), and observed historical electricity generation trends.

The resulting electricity-sector BAU represents a policy-consistent reference pathway, rather than a no-policy counterfactual. It serves as the baseline against which the 30% and 40% emission reduction targets under Thailand's NDC are operationalized in the scenario analysis.

2) NDC Targets and Policy Benchmarks

Under Thailand's NDC 2.0 (2022), the country commits to reducing greenhouse gas emissions by 30% below the BAU level by 2030 on an unconditional basis, achievable through domestic mitigation measures.

In addition, Thailand has announced an enhanced ambition to reduce emissions by 40% below BAU by 2030. This 40% target is operationalized as comprising two components: (i) a 33.3% reduction from BAU (unconditional), achievable through national policies and domestic resources; and (ii) a 6.7% reduction

from BAU (conditional), contingent upon enhanced international support in finance, technology, and capacity building. Accordingly, the overall 40% reduction target is driven primarily by domestic mitigation efforts, supplemented by a smaller conditional component dependent on international assistance.

In this study, the analysis focuses on two mitigation benchmarks: a 30% unconditional reduction target (hereafter referred to as NDC 30) and the domestic component of the 40% reduction target, corresponding to a 33.3% reduction from BAU (hereafter referred to as NDC 40 Unconditional). For consistency with Thailand's national implementation framework, the term NDC 40 (Unconditional) is used exclusively to denote the domestic mitigation component of the overall 40% ambition.

Based on the constructed BAU pathway, electricity-sector CO₂ emissions in 2030 are projected at 120.0 Mt CO₂, which serves as the reference level for operationalizing the mitigation targets. Accordingly, NDC 30 corresponds to an emission level of 84.0 Mt CO₂, while NDC 40 (Unconditional) corresponds to 67.7 Mt CO₂.

To ensure methodological consistency in the LMDI decomposition analysis, the BAU pathway is extended to 2050 and 2065. In 2050, BAU electricity-sector emissions are projected at 73.60 Mt CO₂, implying corresponding emission levels of 51.52 Mt CO₂ under NDC 30 and 41.52 Mt CO₂ under NDC 40 (Unconditional). By 2065, Thailand's net-zero greenhouse gas emissions objective implies near-zero electricity-sector emissions under deep decarbonization pathways.

Note: Thailand submitted its Third Updated Nationally Determined Contribution (NDC 3.0) on 4 November 2025, committing to reduce net greenhouse gas emissions to 152 Mt CO_{2e} by 2035 (a 47% reduction relative to 2019 levels). As the scenario framework and analytical design of this study were finalized prior to the release of NDC 3.0, all scenario benchmarks remain anchored to NDC 2.0 and contemporaneous energy planning assumptions in order to maintain analytical consistency.

3) Scenario Design and Specifications

▪ *Scenario 1 (PDP-aligned pathway):* Follows the electricity demand trajectory, efficiency improvements, and generation mix evolution

specified in the Draft Power Development Plan (PDP) 2024. It represents a moderate and policy-consistent decarbonization pathway under relatively high electricity demand assumptions.

▪ *Scenario 1A (Accelerated renewable deployment and coal phase-down)*: Adopts the same electricity demand and efficiency assumptions as Scenario 1 but assumes a more rapid reduction in coal-fired power generation and a higher penetration of renewable electricity from 2024 onward. This scenario isolates the effect of a more ambitious supply-side decarbonization strategy under high-demand conditions.

▪ *Scenario 2 (Lower-demand pathway)*: Assumes a reduced electricity demand growth rate based on historical trends observed during 2014–2023, with an estimated compound annual growth rate (CAGR) of approximately 1.8% per year. For the projection period, electricity demand growth is fixed at this rate, while the generation mix structure remains consistent with Scenario 1. This scenario isolates the role

of the activity effect in driving changes in electricity-sector CO₂ emissions.

▪ *Scenario 2A (Lower demand with enhanced renewable deployment)*: Combines the reduced demand growth assumption of Scenario 2 with moderately higher renewable energy shares and an accelerated coal phase-down. This scenario represents a conservative yet more mitigation-oriented decarbonization pathway that integrates both demand-side moderation and strengthened supply-side transformation.

4. Results and Discussion

4.1 Historical CO₂ Emissions from the Electricity Generation Sector (2014–2023)

As shown in **Table 3** and **Fig. 3**, total CO₂ emissions from Thailand's electricity generation sector exhibited a fluctuating but overall declining trend, decreasing from 92.93 Mt CO₂ in 2014 to 82.91 Mt CO₂ in 2023.

Table 3: Thailand's CO₂ Emissions from Electricity Generation Sector (Mt CO₂) (2014–2023).

CO ₂ emission (Mt CO ₂)	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Coal	34.72	30.61	33.11	35.17	30.82	30.26	30.28	29.52	29.11	24.80
Bituminous	16.42	10.75	13.65	15.46	13.39	12.84	13.27	11.80	11.88	9.19
Briquettes & other coal	0.48	4.68	2.27	3.06	2.59	3.01	3.16	2.81	2.92	2.26
Lignite (Mae Moh)	17.83	15.17	17.19	16.65	14.84	14.42	13.85	14.92	14.31	13.35
Oil	1.23	0.67	0.35	0.20	0.16	0.19	0.17	0.48	0.94	0.51
High-Speed Diesel	0.06	0.07	0.10	0.12	0.11	0.11	0.08	0.18	0.86	0.50
Fuel Oil	1.18	0.60	0.24	0.08	0.05	0.08	0.09	0.30	0.08	0.01
Gas	56.97	59.35	62.97	60.98	60.16	62.01	58.10	58.09	51.22	57.60
Total	92.93	90.62	96.42	96.36	91.14	92.45	88.55	88.09	81.27	82.91

The emission trajectory is broadly divided into three distinct phases. During the first phase (2014–2017), emissions increased and reached a peak of 96.42 Mt CO₂ in 2016, reflecting strong growth in electricity demand and continued reliance on fossil-fuel-based generation, particularly natural gas and coal. In the second phase (2017–2019), emissions declined gradually, coinciding with expanded renewable energy deployment and observable improvements in generation efficiency. The third phase (2019–2023) captures the combined effects of the COVID-19 pandemic and subsequent economic recovery, with emissions declining sharply during 2020–2022 before rebounding modestly in 2023.

Throughout the study period, natural gas remained the dominant contributor to CO₂ emissions from the electricity sector, accounting for approximately 61–69% of total emissions. In contrast, coal-related emissions declined both in absolute terms and as a share of total emissions. Oil-based emissions remained negligible, reflecting the limited role of oil in electricity generation. Overall, the historical trend suggests a gradual decoupling of electricity-sector emissions from electricity demand growth, although fossil fuels continue to dominate the generation mix, as illustrated by the fuel-specific emission shares in **Fig. 4**.

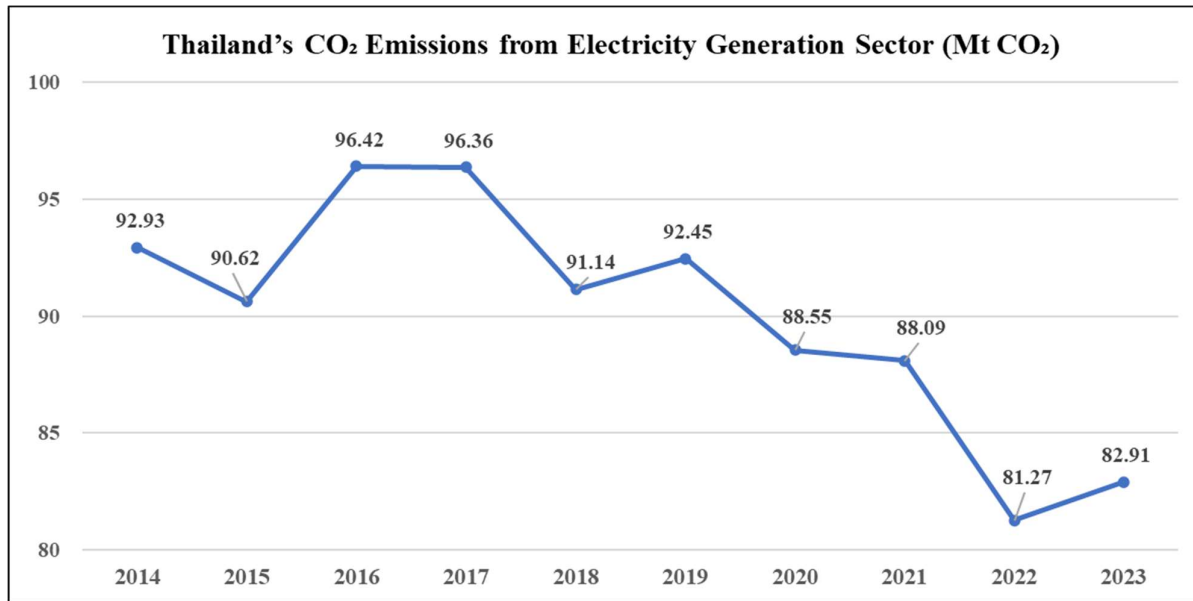


Fig. 3: Thailand's CO₂ Emissions from Electricity Generation Sector (Mt CO₂).

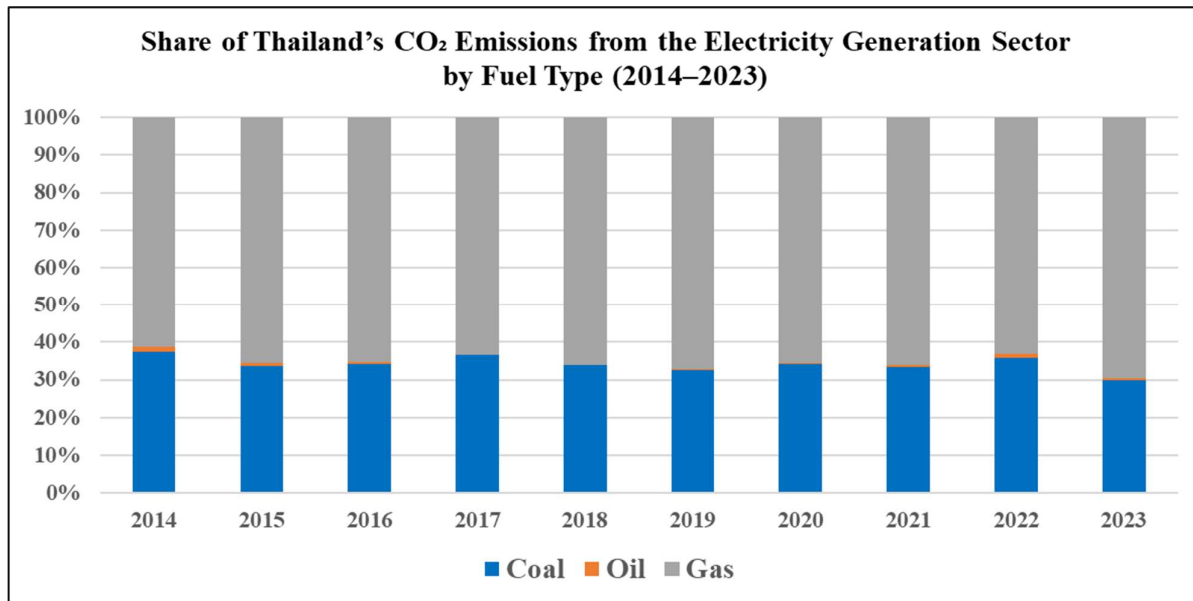


Fig. 4: Share of Thailand's CO₂ Emissions from the Electricity Generation Sector by Fuel Type (2014–2023).

4.2 LMDI Decomposition Results and Analysis

4.2.1 Historical Decomposition (2014–2023)

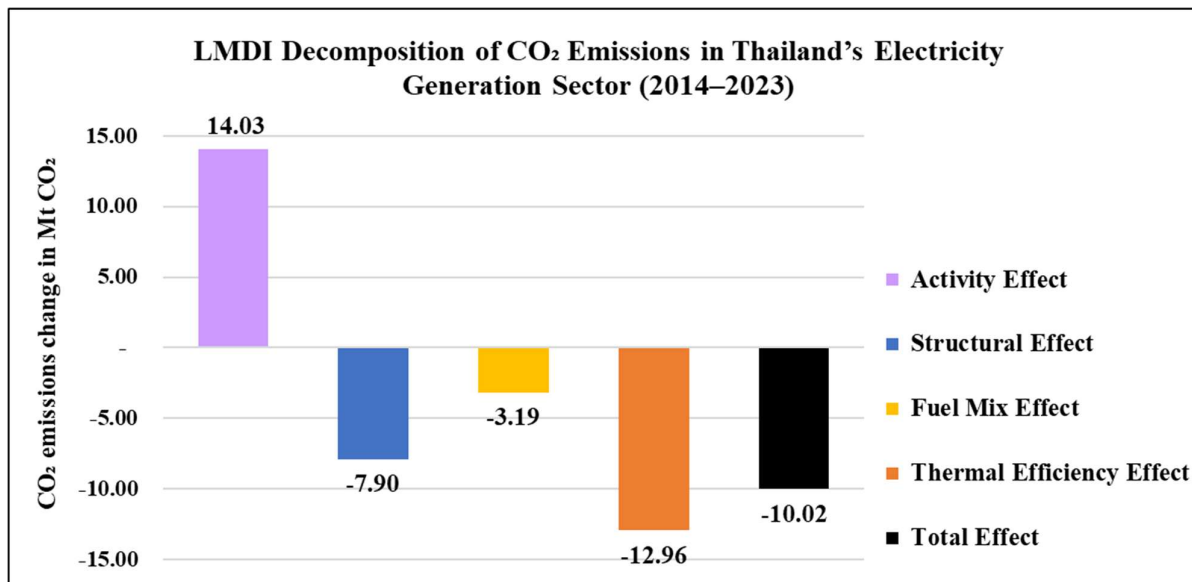
Table 4 and Fig. 5 present the additive LMDI decomposition results for changes in CO₂ emissions from Thailand's electricity generation sector over the period 2014–2023. Over this decade, total CO₂ emissions declined by approximately 10.02 Mt CO₂, indicating a net reduction despite continued growth in electricity generation.

The decomposition results indicate that this overall decline resulted from the interaction of opposing effects. The activity effect (ΔC_{act}) was the dominant positive driver, contributing a cumulative increase of +14.03 Mt CO₂. This reflects rising electricity demand associated with economic expansion, population growth, urbanization, and increasing electricity consumption across residential, commercial, and industrial sectors. As electricity generation expanded to meet this growing demand, upward pressure on emissions persisted throughout the study period.

Table 4: LMDI Decomposition of CO₂ Emissions Change in Mt CO₂ (2014–2023).

Period	ΔC_{act}	ΔC_{str}	ΔC_{mix}	ΔC_{eff}	ΔC_{ef}	ΔC_{tot}
2014-2015	5.00	0.41	-1.93	-5.78	-	-2.31
2015-2016	1.65	-1.19	0.95	4.39	-	5.80
2016-2017	-1.09	-2.32	-0.04	3.39	-	-0.06
2017-2018	0.93	-3.49	0.47	-3.12	-	-5.21
2018-2019	4.73	-0.54	-0.67	-2.21	-	1.31
2019-2020	-5.52	0.69	0.97	-0.04	-	-3.90
2020-2021	0.52	-0.82	-0.05	-0.11	-	-0.46
2021-2022	2.07	-0.78	-0.28	-7.83	-	-6.82
2022-2023	5.75	0.16	-2.62	-1.65	-	1.64
2014–2023	14.03	-7.90	-3.19	-12.96	-	-10.02

Note: Positive (negative) values indicate emission increases (reductions). ΔC_{tot} is decomposed into activity, structural, fuel-mix, efficiency, and emission-factor effects (Mt CO₂).

**Fig. 5:** LMDI Decomposition of CO₂ Emissions in Thailand's Electricity Generation Sector (2014–2023).

Note: Positive (negative) values indicate emission increases (reductions). ΔC_{tot} is decomposed into activity, structural, fuel-mix, efficiency, and emission-factor effects (Mt CO₂).

In contrast, several factors contributed substantially to emission reductions. The thermal efficiency effect (ΔC_{eff}) was the most significant mitigating factor, reducing emissions by -12.96 Mt CO₂, indicating improvements in power generation efficiency, particularly within thermal power plants. The structural effect (ΔC_{str}), amounting to -7.90 Mt CO₂, reflects gradual changes in the composition of the electricity supply system, including a declining share of high-carbon generation technologies and an increasing contribution from lower-carbon and non-fossil electricity sources. In addition,

the fuel-mix effect (ΔC_{mix}) contributed a reduction of -3.19 Mt CO₂, capturing shifts toward cleaner fossil fuels, such as greater reliance on natural gas relative to coal and oil.

The emission-factor effect (ΔC_{ef}) remained zero throughout the study period, as constant default emission factors from the IPCC Guidelines were applied. Overall, the results suggest that improvements in generation efficiency and structural changes played a key role in mitigating CO₂ emissions, although these gains were partially offset by sustained growth in electricity demand.

4.2.2 Relationship between Decomposition Effects and Key Variables

1) Activity Effect (ΔC_{act})

The activity effect (ΔC_{act}) captures the impact of changes in total electricity generation on CO₂ emissions. Over the period 2014–2023, ΔC_{act} was the dominant upward driver of emissions, contributing a cumulative increase of +14.03 Mt CO₂.

As illustrated in **Fig. 6**, ΔC_{act} closely tracks variations in total electricity generation. Periods of increasing electricity output—such as 2014–2015, 2018–2019, and 2022–2023—are associated with positive ΔC_{act} values, indicating emission increases driven by expanding electricity demand. In contrast, during the COVID-19 shock in 2019–2020, electricity generation declined sharply, resulting in a negative ΔC_{act} .

Overall, this relationship confirms that growth in electricity demand remains a key constraint on emission reduction. Higher levels of electricity generation continue to translate directly into higher CO₂ emissions in a power system that is still dominated by fossil fuels.

2) Structural Effect (ΔC_{str})

The structural effect (ΔC_{str}) captures changes in the composition of electricity generation between fossil-based and non-fossil sources. Over the period 2014–2023, ΔC_{str} contributed a cumulative reduction of -7.90 Mt CO₂, making it one of the most significant drivers of emission mitigation.

As illustrated in **Fig. 7**, a clear inverse relationship is observed between ΔC_{str} and the share of fossil-based electricity generation, which declined from 91.82% in 2014 to 84.37% in 2023. Years characterized by larger reductions in the fossil share correspond to more negative ΔC_{str} values, indicating that shifts toward non-fossil electricity generation directly reduced CO₂ emissions.

This relationship highlights structural decarbonization—driven by the gradual expansion of renewable energy and imported hydropower—as a central mechanism for emission mitigation in Thailand’s power sector.

3) Fuel Mix Effect (ΔC_{mix})

The fuel mix effect (ΔC_{mix}) reflects changes in the composition of fuels used within thermal electricity generation. Over the study period, ΔC_{mix} contributed to a cumulative emission reduction of -3.19 Mt CO₂.

As shown in **Fig. 8**, ΔC_{mix} is negatively associated with the share of coal-fired generation. The decline in coal’s share from 23.6% in 2014 to 18.9% in 2023, together with increased reliance on natural gas, reduced the average emission intensity of thermal power generation. In contrast, temporary increases in coal use—such as during 2015–2016 and 2019–2020—coincide with positive ΔC_{mix} values.

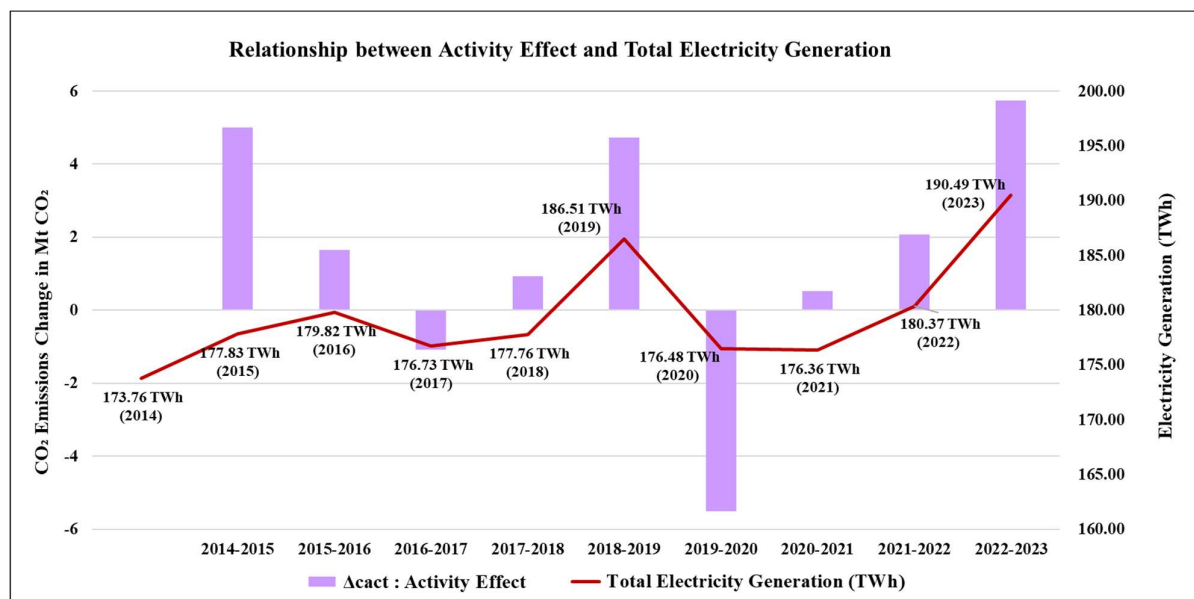


Fig. 6: Relationship between Activity Effect and Total Electricity Generation (2014–2023).

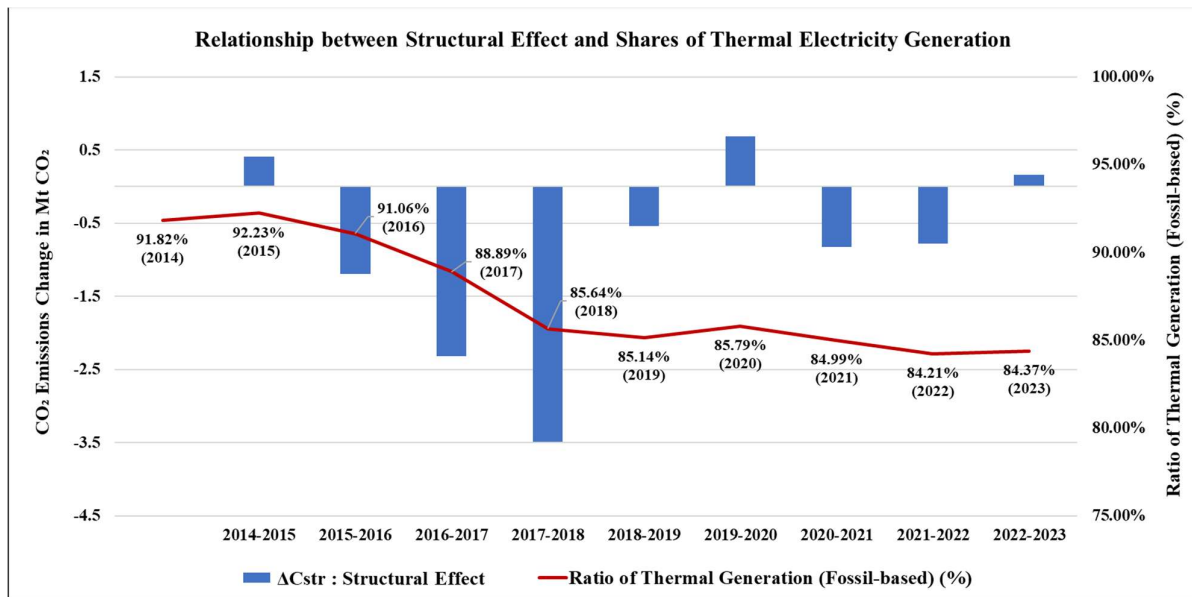


Fig. 7: Relationship between Structural Effect and Shares of Thermal (Fossil-based) Electricity Generation (2014–2023).

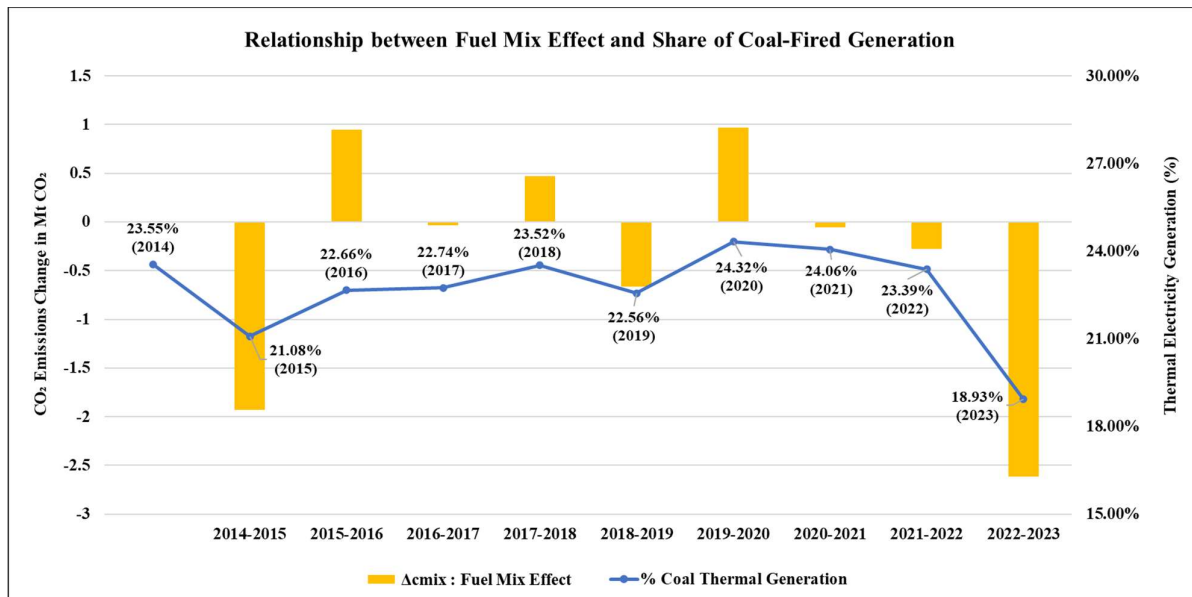


Fig. 8: Relationship between Fuel Mix Effect and Share of Coal-Fired Generation (2014–2023).

Overall, these results indicate that fuel substitution—particularly the shift from coal to natural gas—has played a meaningful, though secondary, role in reducing CO₂ emissions from Thailand's electricity sector.

4) Thermal Efficiency Effect (ΔC_{eff})

The thermal efficiency effect (ΔC_{eff}) reflects changes in fuel-to-electricity conversion efficiency and constitutes the largest emission mitigation driver in Thailand's electricity sector during 2014–2023, contributing a cumulative reduction of -12.96 Mt CO₂.

As shown in Fig. 9, the temporal pattern of ΔC_{eff} closely aligns with changes in fossil fuel generation efficiency. Periods in which the fuel-to-electricity ratio declines—indicating improvements in conversion efficiency—coincide with more negative ΔC_{eff} values, reflecting stronger efficiency-driven emission reductions. Conversely, years characterized by higher fuel-to-electricity ratios are associated with weaker or positive ΔC_{eff} values. This consistency indicates that variations in fossil fuel generation efficiency are a key determinant of the thermal efficiency effect observed over the study period.

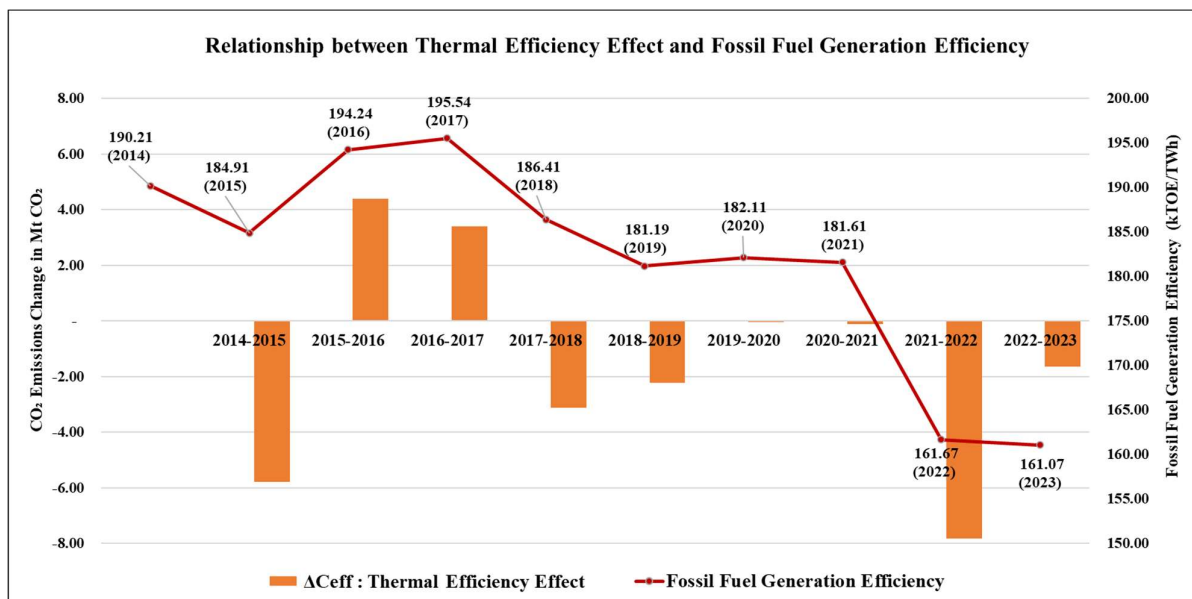


Fig. 9: Relationship between Thermal Efficiency Effect and Fossil Fuel Generation Efficiency (2014–2023).

These results highlight that improvements in fossil fuel generation efficiency play a central role in mitigating CO₂ emissions, while the effectiveness of efficiency gains remains sensitive to fluctuations in electricity demand and system-level dispatch conditions.

Overall, the decomposition results indicate that while electricity demand growth remains the primary upward pressure on emissions, structural decarbonization, fuel substitution, and sustained improvements in power plant efficiency—particularly through the retirement of aging, low-efficiency units and the increased deployment of combined-cycle gas turbine (CCGT) technology—have played critical roles in mitigating CO₂ emissions in Thailand's electricity sector.

4.2.3 Scenario-Based Decomposition Results for the 2030 NDC, 2050 Carbon Neutrality, and 2065 Net-Zero GHG Emission Pathways

This section presents scenario-based decomposition results for possible CO₂ emission pathways in Thailand's electricity generation sector under four mitigation scenarios (Scenarios 1, 1A, 2, and 2A), as defined in Section 3.3.2. The analysis is conducted relative to an electricity-sector Business-as-Usual (BAU) pathway, which serves as the reference baseline for evaluating emission reductions.

The BAU pathway is treated as a policy-consistent reference case and does not represent a mitigation scenario. Instead, it provides a counterfactual emission trajectory against which the effectiveness of NDC-aligned mitigation scenarios is assessed. Accordingly, emission reductions of 30% and 40% are interpreted as percentage reductions relative to the electricity-sector BAU level in the corresponding target years.

The analysis evaluates whether the four mitigation scenarios are consistent with Thailand's 2030 Nationally Determined Contribution (NDC) targets, as well as with the longer-term policy objectives of carbon neutrality by 2050 and net-zero greenhouse gas emissions by 2065. In addition, the results examine how alternative assumptions regarding electricity demand growth and supply-side transitions may lead to different possible long-term emission pathways.

Using a comparative scenario approach in combination with the Logarithmic Mean Divisia Index (LMDI) decomposition framework, this section identifies the relative contributions of activity, structural, fuel-mix, and thermal efficiency effects in shaping emission outcomes across scenarios.

1) Comparison of CO₂ Emissions Across Scenarios

Table 5 and Fig. 10 compare scenario-based estimated CO₂ emissions for Thailand's

electricity generation sector under the four mitigation scenarios over the period 2020–2065, with 2020 adopted as the base year. Although historical electricity-sector emission data are available through 2023, the year 2020 is selected to ensure consistency with Thailand’s national energy planning framework, particularly the Draft Power Development Plan (PDP 2024–

2037), which reports policy benchmarks at five-year intervals (2020, 2025, 2030, and beyond).

Using 2020 as the base year facilitates direct comparability between historical LMDI decomposition results for the period 2014–2023 and scenario-based analytical pathways aligned with national planning milestones.

Table 5: Scenario-Based Estimated CO₂ Emissions under Four Mitigation Scenarios (Mt CO₂).

Year	Scenario 1	Scenario 1A	Scenario 2	Scenario 2A	BAU Target	NDC 30 Target	NDC 40 (Unconditional)* Target
2020**	88.55	88.55	88.55	88.55	180.1	126.07	101.61
2025	96.47	94.76	86.65	86.54	178.8	125.16	100.93
2030	79.69	67.68	68.38	67.65	120.0	84.00	67.70
2035	69.23	63.17	55.51	55.28	112.0	78.40	63.19
2040	55.06	52.66	43.37	43.37	93.9	65.80	52.98
2045	40.29	38.96	32.24	32.24	84.0	58.80	47.39
2050	23.99	23.99	19.50	19.50	73.6	51.52	41.52
2065	-	-	-	-	-	-	-

Note: (1) *The NDC 40 (Unconditional) represents the 33.3% domestic reduction from the electricity-sector BAU and excludes the 6.7% conditional component dependent on international support.

(2) **The 2020 values reported for Scenarios 1, 1A, 2, and 2A represent historical electricity-sector CO₂ emissions estimated from the author’s LMDI decomposition analysis for the period 2014–2023.

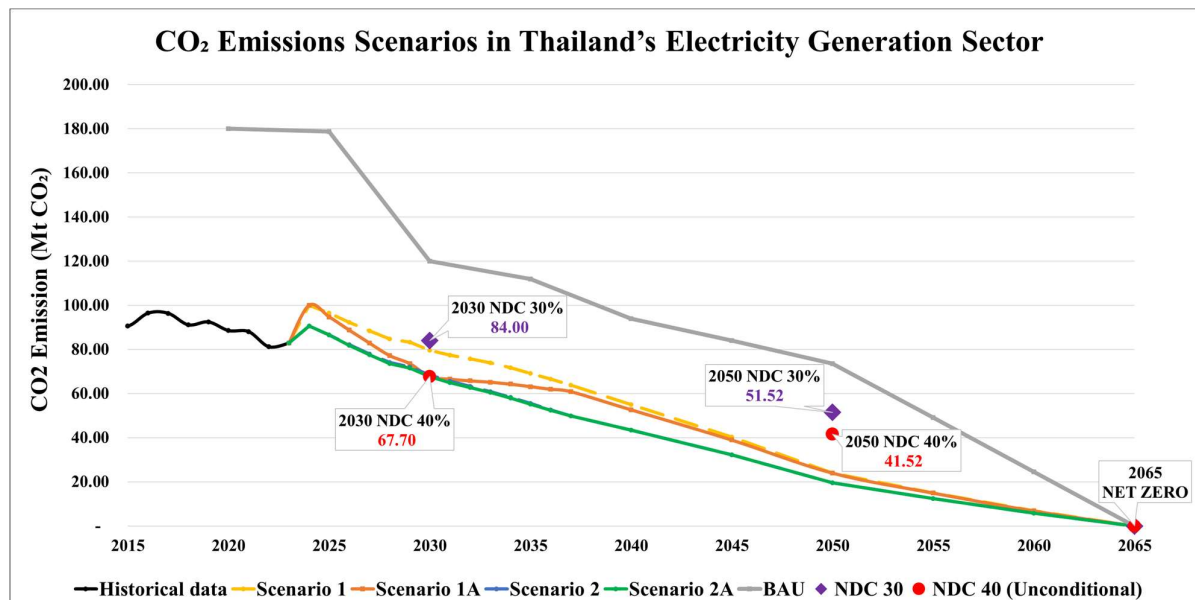


Fig. 10: Scenario-Based CO₂ Emission Pathways under Four Mitigation Scenarios in Thailand’s Electricity Generation Sector.

Note: The NDC 40 (Unconditional) represents the 33.3% domestic reduction from the electricity-sector BAU and excludes the 6.7% conditional component dependent on international support.

It should be noted that the 2020 values reported for Scenarios 1, 1A, 2, and 2A represent historical electricity-sector CO₂ emissions estimated from the author's LMDI decomposition analysis. In contrast, the BAU, NDC 30, and NDC 40 (Unconditional) values shown for 2020 are analytical reference levels derived from the constructed electricity-sector BAU pathway and corresponding percentage reduction targets. These values do not represent observed emissions but serve as benchmark levels for scenario comparison.

2) LMDI Decomposition Results by Scenario

Table 6 presents the additive LMDI decomposition of changes in total CO₂ emissions (ΔC) into five contributing effects: activity (ΔC_{act}), structural (ΔC_{str}), fuel-mix (ΔC_{mix}), thermal efficiency (ΔC_{eff}), and emission-factor (ΔC_{ef}) effects across the four mitigation scenarios. All emission changes are interpreted relative to the electricity-sector BAU pathway in order to isolate the net mitigation effects arising from alternative demand and supply-side assumptions.

▪ Scenario 1 (PDP-aligned pathway)

Under Scenario 1, CO₂ emissions are estimated under the scenario assumptions to decline from 88.55 Mt CO₂ in 2020 to 23.99 Mt CO₂ by 2050. The activity effect remains positive throughout the projection period, reflecting continued

electricity demand growth under PDP-aligned assumptions. However, increasingly negative structural and fuel-mix effects more than offset this upward pressure. Improvements in thermal efficiency contribute additional reductions, although their marginal impact diminishes toward mid-century.

As illustrated in **Fig. 11**, structural transformation and fuel substitution appear to be the dominant drivers of long-term decarbonization in this policy-consistent pathway.

▪ Scenario 1A (Accelerated renewable and coal phase-down)

Under the scenario assumptions, Scenario 1A shows deeper emission reductions through stronger negative structural and fuel-mix effects driven by faster renewable energy expansion and earlier coal retirement. The estimated emission level reaches 67.68 Mt CO₂ by 2030, broadly consistent with the NDC 40 (Unconditional) benchmark defined relative to the electricity-sector BAU.

Although the activity effect remains positive under high-demand conditions, it is fully offset by more aggressive supply-side transformation. As shown in **Fig. 12**, fuel substitution and structural change appear to dominate the emission pathway in this accelerated decarbonization scenario.

Table 6: LMDI Decomposition of CO₂ Emissions in Thailand's Electricity Sector Across 4 Mitigation Scenarios (Mt CO₂).

Scenarios	Year	ΔC_{act}	ΔC_{str}	ΔC_{mix}	ΔC_{eff}	ΔC_{ef}	ΔC_{tot}
Scenario 1	2020–2030	31.90	-24.81	-2.30	-13.65	-	-8.87
	2020–2050	31.46	-62.92	-17.85	-15.26	-	-64.57
	2020–2065	2.90	-58.56	-31.40	-1.49	-	-88.55
Scenario 1A	2020–2030	29.35	-29.82	-6.62	-13.79	-	-20.88
	2020–2050	31.46	-62.92	-17.85	-15.26	-	-64.57
	2020–2065	2.90	-58.56	-31.40	-1.49	-	-88.55
Scenario 2	2020–2030	17.68	-23.04	-2.14	-12.69	-	-20.18
	2020–2050	21.38	-57.82	-18.55	-14.06	-	-69.05
	2020–2065	2.44	-58.56	-30.95	-1.49	-	-88.55
Scenario 2A	2020–2030	17.59	-23.40	-2.41	-12.69	-	-20.91
	2020–2050	21.38	-57.82	-18.55	-14.06	-	-69.05
	2020–2065	2.44	-58.56	-30.95	-1.49	-	-88.55

Note: Positive values denote emission increases; negative values denote reductions. ΔC_{tot} is decomposed into ΔC_{act} , ΔC_{str} , ΔC_{mix} , ΔC_{eff} , and ΔC_{ef} (Mt CO₂).

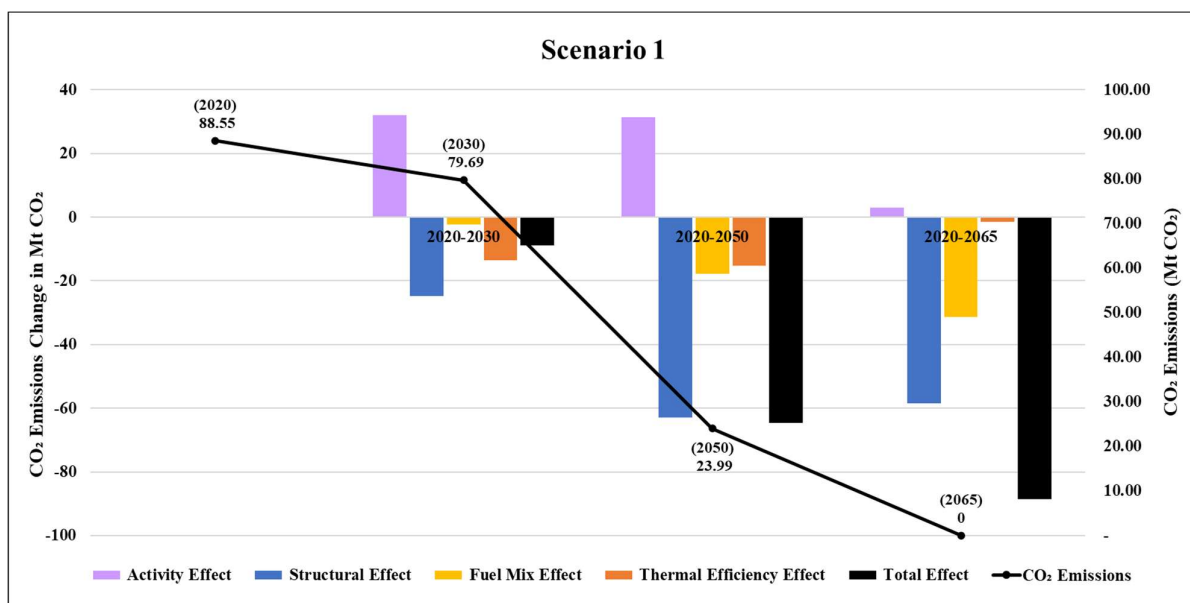


Fig. 11: LMDI Decomposition of CO₂ Emissions in Thailand's Electricity Sector under Scenario 1 (PDP-Aligned Pathway), 2020–2065.

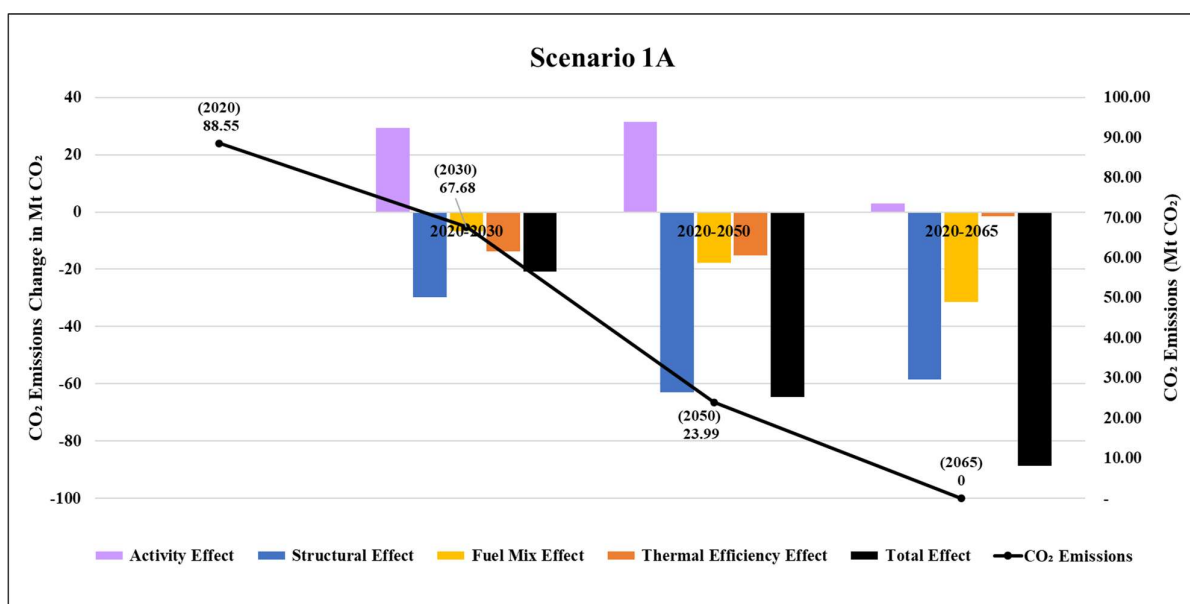


Fig. 12: LMDI Decomposition of CO₂ Emissions under Scenario 1A (Accelerated Renewable and Coal Phase-Down Pathway), 2020–2065.

▪ *Scenario 2 (Lower-demand pathway)*

Scenario 2 assumes moderated electricity demand growth, resulting in a smaller positive activity effect compared with Scenario 1. Emissions are estimated under the scenario assumptions to decline to 68.38 Mt CO₂ in 2030 and further to 19.50 Mt CO₂ by 2050.

While structural and efficiency effects remain important drivers of emission reductions, the reduced activity effect lowers upward emission pressure, enabling cumulative mitigation gains to accumulate more rapidly. **Fig. 13** demonstrates that demand moderation may significantly enhance the effectiveness of structural and efficiency improvements.

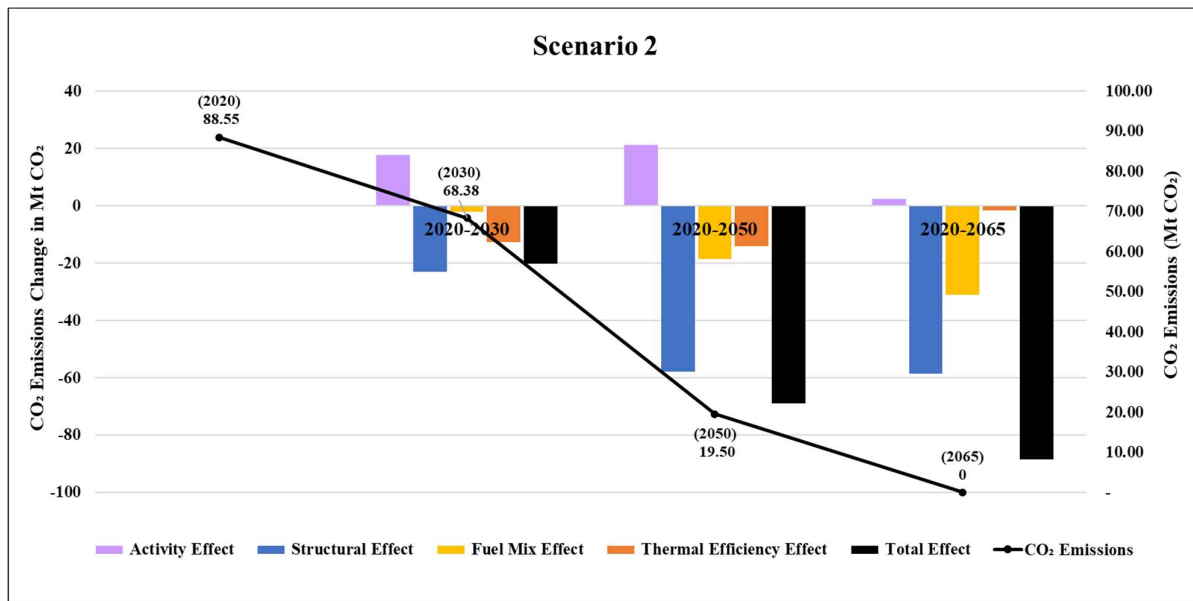


Fig. 13: LMDI Decomposition of CO₂ Emissions under Scenario 2 (Lower-Demand Pathway Based on Historical Trend), 2020–2065.

▪ *Scenario 2A (Lower demand with enhanced renewables)*

Scenario 2A combines moderated electricity demand growth with accelerated renewable deployment and faster coal phase-out. Under this integrated pathway, emissions are estimated to decline to 67.65 Mt CO₂ by 2030—which is broadly consistent with the NDC 40 (Unconditional)

benchmark—and continue falling toward near-zero levels by 2065.

Although the activity effect remains positive and comparable to Scenario 2, it is more than offset by strongly negative structural, fuel-mix, and efficiency effects. As illustrated in **Fig. 14**, Scenario 2A shows the deepest and most sustained decarbonization pathway among all scenarios.

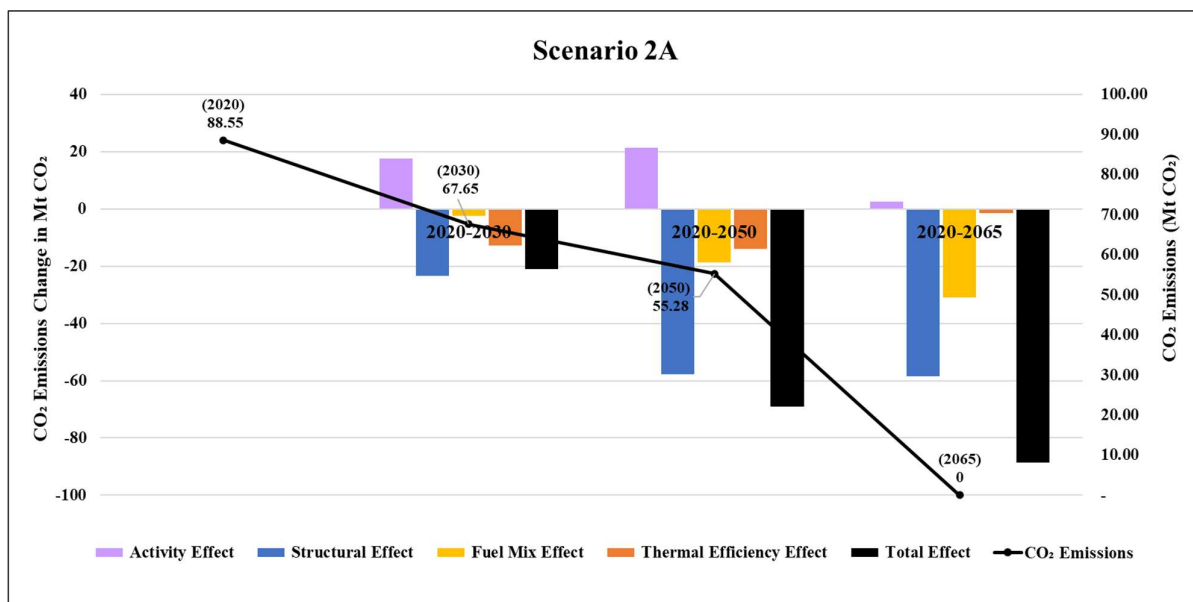


Fig. 14: LMDI Decomposition of CO₂ Emissions under Scenario 2A (Lower-Demand Pathway with Enhanced Renewables), 2020–2065.

Overall Comparative Insights

Across all scenarios, structural transformation and fuel substitution consistently appear to be the primary drivers of long-term emission reductions, while activity growth remains a persistent upward pressure. Scenarios that combine moderated demand growth with accelerated supply-side transition (particularly Scenario 2A) are associated with the most robust and durable decarbonization outcomes.

The decomposition results therefore highlight the importance of aligning demand-side moderation with aggressive structural and fuel-mix transformation if Thailand seeks to align the electricity sector with medium- and long-term climate objectives.

4.3 Policy Implications

The combined results from the LMDI decomposition and scenario analysis provide clear guidance for Thailand's power-sector decarbonization strategy. Although structural change, fuel substitution, and efficiency improvements have contributed significantly to emission reductions, electricity demand growth remains the dominant upward driver across all scenarios. Only the enhanced mitigation pathways (Scenarios 1A and 2A), which combine accelerated renewable deployment with earlier coal phase-down, are fully consistent with Thailand's -40% NDC target and long-term net-zero objectives.

1) Managing the activity effect (ΔC_{act})

Mitigating the activity effect requires strengthening nationwide energy-efficiency policies, demand-side management, and reductions in electricity intensity across the industrial, commercial, and residential sectors. Without moderating electricity demand growth, emission reductions achieved through structural transformation may be partially offset.

2) Strengthening the structural effect (ΔC_{str})

Deeper emission reductions from the structural effect depend on accelerating the transition toward a renewable-dominated generation mix. This transition must be supported by grid modernization, energy storage deployment, and regulatory reforms that enhance system flexibility and integration of variable renewable energy.

3) Enhancing the fuel-mix effect (ΔC_{mix})

Further improvements in the fuel-mix effect require decisive coal phase-down and rapid renewable energy expansion, as demonstrated in Scenarios 1A and 2A. These measures are essential for aligning Thailand's power sector with its NDC and Long-Term Low Emission Development Strategy (LT-LEDS) commitments.

4) Sustaining the thermal efficiency effect (ΔC_{eff})

Continued progress in the thermal efficiency effect will depend on upgrading existing thermal power assets and adopting high-efficiency generation technologies. However, the long-term mitigation potential of this effect is expected to decline gradually as fossil-based generation is phased out.

5) Utilizing the Emission Factor Effect (ΔC_{ef})

While the emission-factor effect remained constant in the historical analysis, future emission reductions beyond 2050 would require the deployment of carbon capture, utilization, and storage (CCUS) technologies, as well as the adoption of low-carbon fuels such as hydrogen and ammonia to address residual emissions.

Overall, achieving Thailand's climate targets for 2030, 2050, and 2065 would require coordinated and sustained action across all five decomposition drivers. The results indicate that accelerated renewable energy deployment, combined with effective electricity demand management, represents the most robust and resilient pathway for long-term decarbonization of the power sector.

5. Conclusion

5.1 Summary and Key Findings

This study applied the Logarithmic Mean Divisia Index (LMDI) method to examine the drivers of CO₂ emissions in Thailand's electricity generation sector during the period 2014–2023 and to evaluate future mitigation pathways aligned with national climate targets.

Three key findings emerge from the analysis.

First, although electricity-sector CO₂ emissions fluctuated over time, total emissions declined overall during 2014–2023. The observed trajectory

reflects periods of demand-driven growth, efficiency-led reduction, and pandemic-related contraction. Natural gas remained the dominant source of emissions, while coal's contribution declined steadily and oil played only a marginal role.

Second, the LMDI decomposition reveals that emission changes resulted from the interaction of opposing forces. Electricity demand growth (the activity effect) was the primary upward driver of emissions, whereas structural transformation, fuel substitution, and—most notably—improvements in thermal efficiency contributed to emission reductions. Overall mitigation during the historical period was therefore achieved through technological upgrading and gradual shifts toward cleaner electricity generation.

Third, the long-term scenario analysis suggests that Thailand's ability to align the electricity sector with national climate targets depends strongly on electricity demand growth and the pace of structural transformation in the power sector. Under the assumptions used in this study, moderate mitigation pathways appear sufficient to align with the -30% NDC benchmark, but they may be insufficient for deeper emission reductions. Accelerated mitigation pathways—characterized by faster renewable energy deployment and earlier coal phase-down—are more consistent with the -40% NDC benchmark and long-term carbon neutrality and net-zero emission objectives. Across all scenarios, structural and fuel-mix effects appear to become increasingly important over time, while the activity effect remains persistently positive.

Taken together, these findings suggest that Thailand's power-sector decarbonization strategy must simultaneously manage electricity demand growth and accelerate structural change toward low-carbon electricity generation.

5.2 Limitations

Several limitations of this study should be acknowledged.

First, the analysis relies on aggregated national-level data and fixed IPCC default emission factors, which do not capture plant-level heterogeneity or changes in fuel characteristics over time.

Second, the LMDI approach is deterministic and does not explicitly incorporate uncertainty or sensitivity analysis. As a result, scenario outcomes depend on assumptions derived from the PDP 2024 and the LT-LEDS.

Third, the study focuses exclusively on CO₂ emissions from electricity generation and does not consider other greenhouse gases, co-pollutants, economic costs, or distributional impacts.

Fourth, the scenario analysis does not incorporate detailed power-system dispatch, grid constraints, investment costs, electricity price effects, industrial competitiveness, or market dynamics. Therefore, the scenario results should be interpreted as indicative possible pathways rather than definitive predictions.

Finally, the scenario framework reflects policy assumptions developed prior to the adoption of Thailand's NDC 3.0; subsequent policy updates may alter future emission pathways and mitigation benchmarks.

5.3 Further Research

Future research should

- (i) incorporate plant-level and technology-specific data,
- (ii) extend decomposition analysis to other sectors and cross-sectoral interactions,
- (iii) integrate LMDI with energy-system or economy-wide models,
- (iv) update scenario design to reflect evolving NDC commitments and regional energy integration, and
- (v) include electricity price, industrial competitiveness, and economic cost considerations in future scenario assessment.

Such extensions would strengthen the analytical basis for Thailand's long-term energy and climate policy.

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Geo-Informatics Technology for Comparing Surface Deformation on Salt Dome and Salt Basin Structure in Chaiphum, Thailand

Patcharin Suphakdee^{1, 2*} and Urawan Chanket¹

¹ Geo-Informatics Program, College of Computing, Khon Kaen University, Khon Kaen 40002, Thailand

² Mineral Resources Regional Office 2, Department of Mineral Resources, Ministry of Natural Resources and Environment, Khon Kaen 40000, Thailand

*Corresponding author: patcharin.su@kkumail.com

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Abstract

The northeastern region of Thailand is characterized by a prominent topographic feature known as the Korat Plateau, which is composed of the Korat Basin and the Sakon Nakhon Basin. The general geology of the upper part of the Korat Basin is notably characterized by the Maha Sarakham Formation, which is primarily composed of evaporite minerals such as halite, potash, gypsum, and anhydrite. These evaporite deposits, particularly rock salt, exhibited plastic behavior and could flow under pressure, leading to deformation and displacement of their layers. This movement resulted in the formation of various halokinetic structures. Therefore, this study investigated rock salt deformation within different parts of the sedimentary basin and compared ground displacement across areas with distinct rock salt structures in Chaiphum Province. The objective was to gain insights into the natural mechanisms of rock salt deformation and their influence on topography, environmental impacts, and resource management. The research incorporated extensive subsurface datasets integrated with surface deformation rates derived from InSAR time-series analysis using Sentinel-1 imagery from 2015 to 2024. The results revealed a clear contrast in surface deformation rates between areas overlying salt domes and those over salt basins. Areas above salt dome structures exhibited deformation rates ranging from -4.18 to +7.05 mm/year. The maximum uplift was observed in Ban Chuan, Ban Chuan Subdistrict, in the northeastern part of Bamnet Narong District. On the other hand, areas overlying salt basin structures showed deformation rates between -6.43 and +5.13 mm/year, with the greatest subsidence occurring in the Ban Nong Yai But floodplain, Hua Thale Subdistrict, Bamnet Narong District. These deformation patterns were closely associated with variations in geological structure, sediment type, and topographic characteristics. This integrated analysis provided detailed insights into the relationship between subsurface salt structures and surface deformation, offering valuable information for spatial planning and sustainable environmental management.

Keywords: InSAR, rock salt, salt tectonic, geo-informatics, surface deformation, Thailand

1. Introduction

1.1 General significance

Evaporites are formed from the evaporation of saline water until the dissolved substances in the brine crystallize into mineral forms. These minerals typically precipitate in order of their solubility, from least to most soluble, which includes carbonates, sulfates, halides, and

potash minerals. Tectonic movements can alter the shape and position of these evaporite layers, especially halides, which tend to form thicker deposits than other evaporite types.

The movement of salt generally occurs due to the flow of mobile evaporites—evaporite sediments that can move under certain conditions. This mobility is driven by gravitational forces following salt deposition

and pressure from the overburden sediments, which vary in weight and density. These conditions are particularly dynamic along basin margins where density variations are more pronounced. Salt movement may also begin during the initial deposition phase in the sedimentary basin due to differences in density between the evaporite layers and the surrounding rocks. However, salt deformation and mobility can vary depending on the structural geology of each area and may be influenced by geomorphological forces (Warren, 2016). Salt movement results (Fig. 1) in the formation of

various geological structures, such as salt domes (salt diapirs), salt basins, salt pillows: early-stage structures formed by salt uplift that have not yet breached the overlying rock layers, salt rollers: typically found near basin margins in zones of tectonic faulting, salt walls: long, vertical salt intrusions along fractures, minibasins: small basins formed by subsidence of overlying rock layers into the underlying salt. These diverse forms reflect the dynamic nature of salt tectonics and its interactions with geological and environmental factors.

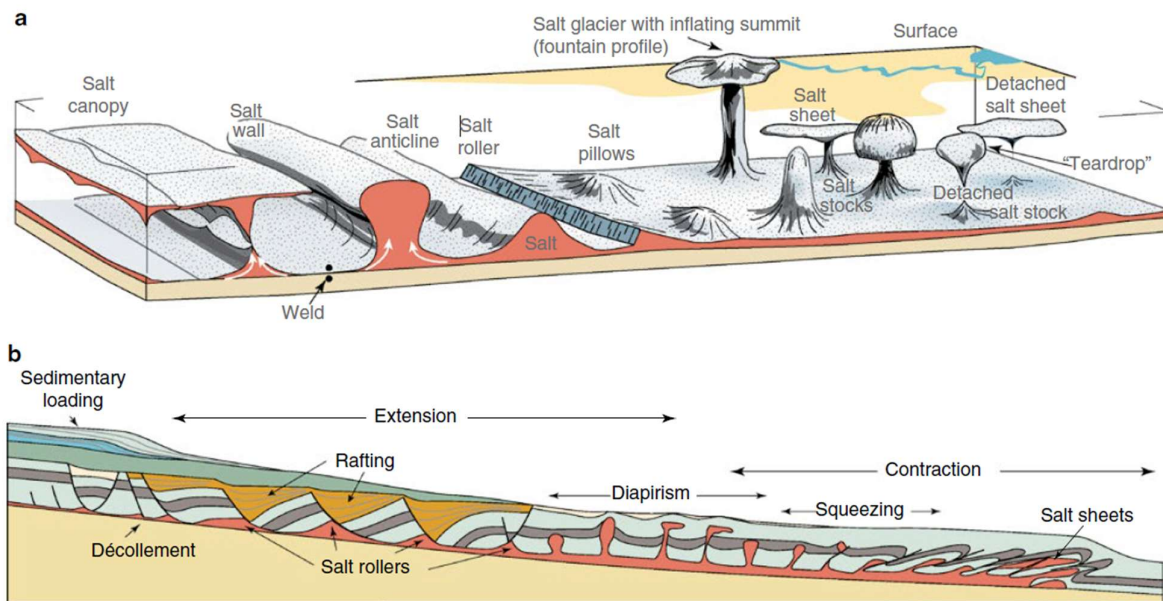


Fig. 1: Different salt structural models: (a) Morphological classification of external geometries and deformation styles that control salt distribution within salt-mobilized basins, showing linear structures (left) and vertical structures (right); (b) General evolutionary geometries of salt structures under extensional and compressional tectonic regimes, illustrating up-dip and down-dip salt movement, respectively (after Warren, 2016).

1.2 Geological setting of Khorat Plateau

The northeastern Thailand, also known as the Khorat Plateau, has undergone significant tectonic evolution driven by plate movements. During the Late Paleozoic to Early Mesozoic, the Shan–Thai (Sibumasu) and Indochina continental blocks converged through the eastward subduction of the Paleo-Tethys oceanic lithosphere beneath the Indochina block, culminating in continental collision during the Middle to Late Triassic (~250–200 Ma) as part of the Indosinian Orogeny (Metcalf, 2011, 2013; Searle & Morley, 2011; Sone & Metcalfe, 2008). Evidence of the closure of

the Paleo-Tethys Ocean is preserved along the Nan–Uttaradit and Sra Kaeo suture zones of Thailand. The associated arc magmatism and sedimentary sequences are represented by the Loei–Phetchabun Volcanic Belt, developed along the western margin of the Indochina Terrane (Barr & Charusiri, 2011; Burrett *et al.*, 2021).

The Indochina Terrane represents one of the principal continental tectonic units of mainland Southeast Asia, extending across eastern Thailand, Laos, Cambodia, and Vietnam (Fig. 2). Geological and paleogeographic evidence suggests that this terrane originated as a continental fragment along the northern margin of Gondwana before

being separated through Paleozoic rifting processes (Barber *et al.*, 2011). Subsequent tectonic interactions, including subduction, arc magmatism, and continental accretion, culminated in its amalgamation with magmatic belts related surrounding terranes during the Paleozoic–Mesozoic evolution of the Paleo-Tethys realm. The tectonic development of the Indochina Terrane has been a key factor in the construction of the Southeast Asian continental framework and has significantly influenced the distribution of mineral resources, basin evolution, and hydrocarbon systems throughout the region.

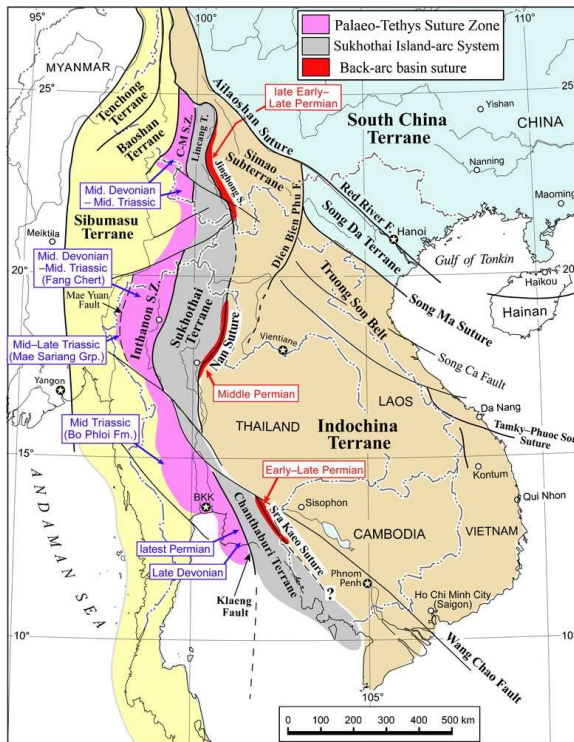


Fig. 2: Simplified tectonic map of mainland Southeast Asia showing the major continental blocks, suture zones, fault systems, and to the tectonic evolution of the Indochina and Sibumasu terranes (Sone & Metcalfe, 2008).

Following orogenic uplift and subsequent weathering processes, sedimentation occurred in response to global geological cycles. Continental deposits, including sand, silt, gravel, and mud, accumulated within the basin environment (Racey & Goodall, 2009). In addition, evaporitic minerals formed under arid conditions, leading to the development of sedimentary sequences known as the Khorat Group.

Subsequently, during the late Cenozoic (Aitchison, Ali & Davis, 2011; Meng *et al.*, 2012)

(approximately 50–55 million years ago), the collision between the Indian and Eurasian plates generated compressional forces that resulted in the uplift of the Khorat Group, forming the present-day Khorat Plateau (Bunopas, 1981; Charusiri, Pongsapich & Khantaprab, 1991; Charusiri *et al.*, 2000, 2007). This tectonic activity also led to the uplift of the Phu Phan Range (Morley, 2012; Veeravinantanakul *et al.*, 2018), which divides the region into two major basins: The Sakon Nakhon Basin to the north and the Khorat Basin to the south (**Fig. 3**).

During the Cenozoic era, continued convergence between the Indian and Eurasian plates caused deformation of pre-existing sedimentary strata, resulting in folding, faulting, and fracturing (Charusiri *et al.*, 2000). These tectonic forces also induced halokinetic processes within the evaporite-rich Maha Sarakham Formation, particularly in both the Sakon Nakhon and Khorat basins. This led to salt flow, fracturing, and uplift driven by internal pressure and ongoing tectonic stress.

Geologically, the basin margins are predominantly composed of sedimentary rocks such as sandstone, siltstone, conglomerate, shale, and mudstone. In the western margin, corresponding to the Loi–Phetchabun tectonic zone, limestone, volcanic rocks, and pyroclastic deposits are also present. The central part of the Khorat Plateau is characterized by extensive evaporite deposits, including rock salt and associated minerals.

In addition, basaltic rocks intruded and extruded during the Tertiary period of the Cenozoic era, particularly during the Miocene to Pliocene (approximately 23–2 million years ago), after the formation of the Khorat Group. These basalt flows, derived from low-viscosity magma, spread across the plateau surface and are widely distributed in provinces such as Nakhon Ratchasima, Buriram, Surin, Sisaket, and Ubon Ratchathani. Finally, recent fluvial and colluvial deposits overlie the older formations, especially along river systems and colluvial. Details of the geological map are presented in **Fig. 3**.

The evolution of salt basins and salt structures in the Khorat Plateau is associated with the dynamic deposition of alternating evaporite and clastic sediments, which occurred through

three distinct sedimentation cycles. As a result of the plastic properties of salt, the overlying sedimentary layers exert pressure and create density contrasts. Combined with the uplift of the Khorat Plateau and the Phu Phan mountain range, these processes cause the salt layers within the Khorat Basin to migrate. This movement follows the topographic gradient of the basin toward its center, resulting in the deformation of salt layers into structures such as salt domes (salt anticlines) and salt basins (salt synclines) (**Fig. 1**). These features are widely observed in both the Khorat Basin and the Sakon Nakhon Basin (Suwanich, n.d.).

Evaporite deposits within the Khorat Plateau consist predominantly of rock salt, potash, gypsum, and anhydrite, and are stratigraphically assigned to the Maha Sarakham Formation (**Fig. 4, 5**) of the Khorat Group. Dating back to the Late Cretaceous (approximately 93.9–100.5 Ma), this formation was deposited in an arid paleo-environment characterized by marine transgressions into inland basins, lagoons, or marshes (Meesook, 2000). The formation unconformably overlies the sandstones of the Khok Kruat Formation and is capped by the reddish-clastic sediments of the Phu Thok Formation. The formation is characterized by a cyclic deposition of evaporites and clastic sediments (Suwanich, 2007), typically divided into six distinct lithological units (from oldest to youngest):

- 1) *Basal Anhydrite*: The foundational layer in contact with the gray-green sandstones of the Khok Kruat Formation. It transitions from a carbonaceous, fissile upper part to a dense, indurated lower section.

- 2) *Lower Salt and Potash*: The primary evaporite unit, whose thickness varies significantly due to halokinesis (salt flow). It is economically vital as it hosts high-grade potash deposits and variegated salts, particularly within salt domes or central basin areas.

- 3) *Lower Clastic*: A semi-consolidated, reddish-purple to chocolate-brown claystone/siltstone. It often exhibits gypsum-filled fractures and may contain disseminated carnallite or other potash minerals.

- 4) *Middle Salt*: Composed of high-purity halite. The coloration grades from milky white at the top to honey or orange hues at the base. It frequently displays deformation textures (elongated salt grains) resulting from lithostatic pressure and flow.

- 5) *Middle Clastic*: A dense, highly plastic, dark reddish-brown claystone. It acts as a separating layer between the Middle and Upper salt units and contains interbedded gypsum veins.

- 6) *Upper Salt*: The uppermost evaporite layer, characterized by honey-colored halite with thin anhydrite laminations. This unit is often thin or absent in many localities due to post-depositional dissolution by groundwater.

1.3 Research gap

Several studies have investigated salt-related geological structures in Thailand, including salt domes and salt basins, with primary emphasis on geological mapping, stratigraphic interpretation, and resource assessment. For example, Fuangkhaichon (2015) examined the geomechanical properties of rock salt, including stress–strain behavior, permeability, elastic characteristics, and plastic deformation. Similarly, Malila (2001) employed remote sensing data, geophysical surveys, and field investigations to study rock salt occurrences in the Khorat Basin and to identify geological features associated with salt-bearing formations.

In recent years, Interferometric Synthetic Aperture Radar (InSAR) has been widely applied for monitoring and analyzing ground deformation in various geological settings. Luachapichatikul (2020) investigated land subsidence in Bangkok, where unconsolidated soft sediments constitute the dominant geological environment. Inpai (2023) compared surface deformation patterns between Chiang Mai and Bangkok, while Boonsuya *et al.* (2023) examined land subsidence in Nakhon Sawan Province associated with groundwater extraction in urban areas. These studies have demonstrated the effectiveness of InSAR techniques for detecting and monitoring ground deformation under diverse geological and environmental conditions.

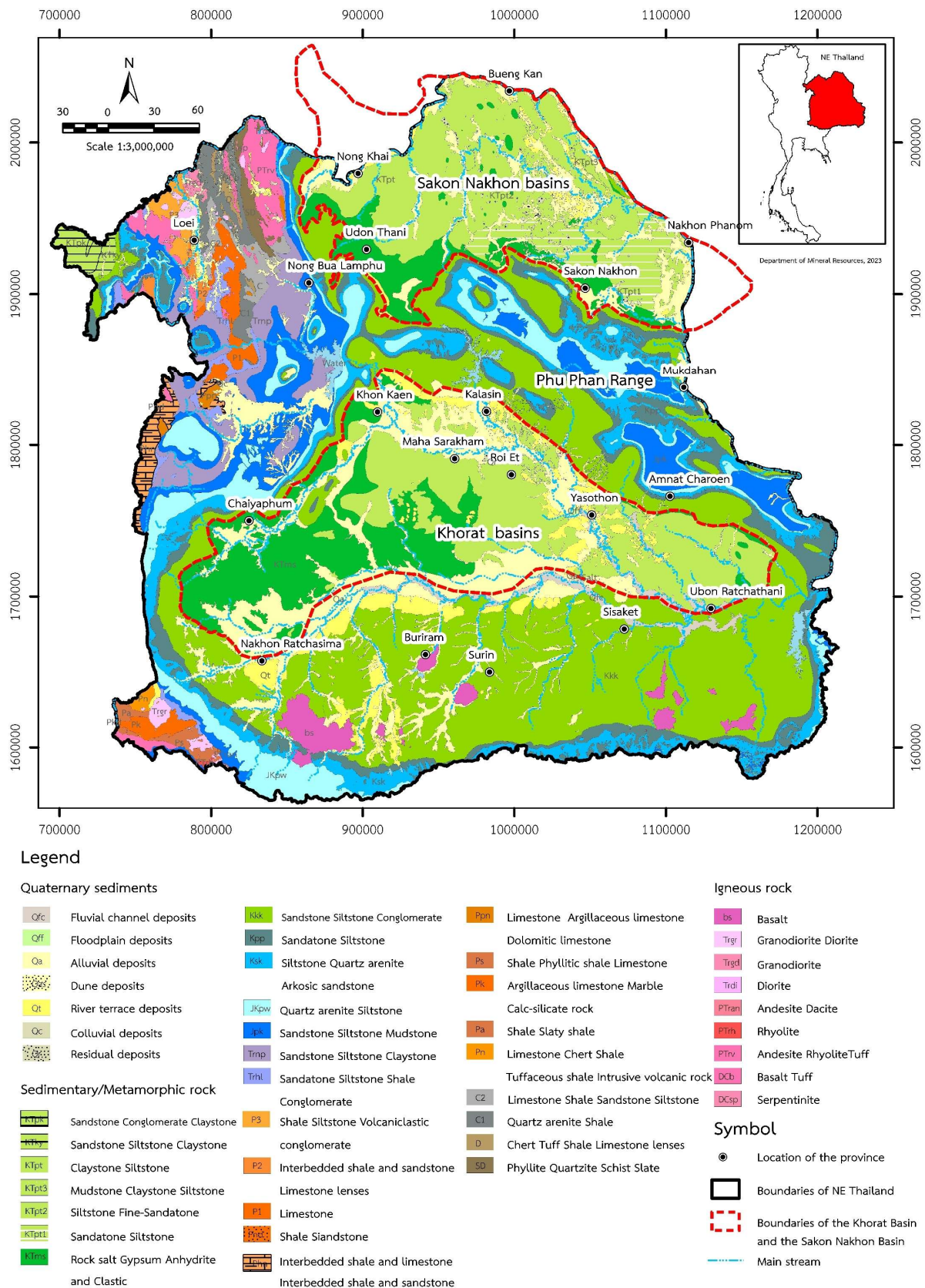


Fig. 3: Geological map illustrating the areal extent of the Sakon Nakhon Basin and the Khorat Basin (Modified from DMR, 2023).

Age	Formation	Lithology
Quaternary		Top soil or alluvium
Tertiary	Phu tok Formation	Upper Clastic Member
Late Cretaceous	Maha sarakham Formation	Upper anhydrite
		Upper Salt Member
		Middle Clastic Member
		Middle anhydrite
		Middle Salt Member
		Lower Clastic Member
		Lower anhydrite
		Potash layer
		Upper sylvite
		Upper carnallite
		Tachyhydrite
		Lower carnallite
		Lower sylvite
	Khok kraut Formation	Lower Salt Member
		Basal anhydrite
		Conglomerate and sandstone

Fig. 4: Stratigraphic succession of evaporite deposition in the Maha Sarakham Formation (Shen & Siritongkham, 2020).

Despite these advances, the application of advanced geo-informatics technologies, particularly the integration of Remote Sensing, InSAR, and Geographic Information System (GIS)-based spatial analysis, remains limited in studies of salt-related geological structures in Thailand. In particular, quantitative comparisons of ground deformation characteristics between salt dome and salt basin settings have received little attention. Consequently, the influence of salt tectonic geometries on the magnitude, spatial distribution, and temporal behavior of surface deformation remains insufficiently understood. Furthermore, the deformation characteristics of areas underlain by rock salt have not been systematically evaluated using integrated geospatial approaches.

1.4 Aim and objectives

The aim of this study is to investigate the influence of subsurface salt structures on ground surface deformation in northeastern Thailand through the integration of three-dimensional geological modeling and satellite-based InSAR analysis.

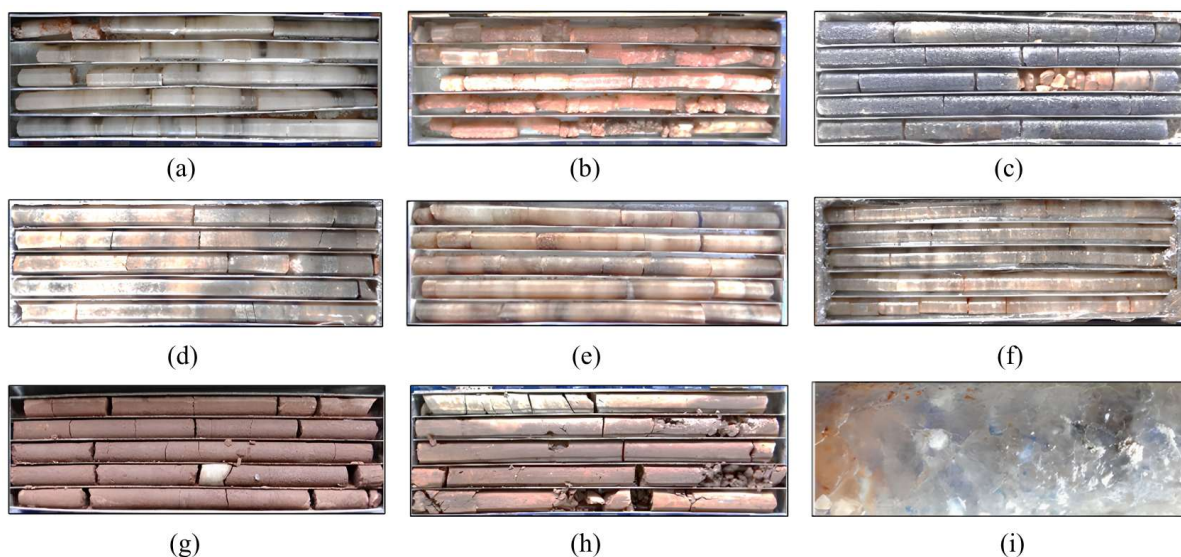


Fig. 5: (a) Colorless to white, transparent halite. (b) Carnallite (potash mineral) associated with halite. (c) Blue halite associated with sylvite (potash mineral). (d), (e), (f) Smoky-gray and milky-white halite. (g) Reddish-brown clastic sediments of the upper unit, corresponding to the Phu Thok Formation. (h) Reddish-brown sediments interbedded with gypsum-anhydrite layers. (i) Crystal characteristics of colorless transparent halite and blue halite (Nuchit Sirithongkham, personal communication, September 11, 2025).

The objectives of this study are:

- 1) To develop a three-dimensional (3D) geological model of salt dome and salt basin structures using borehole and spatial datasets within an open-source Geographic Information System (GIS) environment.
- 2) To characterize the geometry and spatial distribution of subsurface salt layers and their relationships with overlying sedimentary strata.
- 3) To quantify vertical ground deformation using Time-Series Interferometric Synthetic Aperture Radar (Time-Series InSAR) derived from satellite radar imagery.
- 4) To evaluate the relationships between subsurface salt structures and observed ground deformation patterns in study area.

2. Study area

2.1 Location

The study area covers Bamnet Narong District and parts of Chatturat District, Chaiyaphum Province, Northeastern Thailand, encompassing a total area of approximately 143 km². The area is bounded by the following corner coordinates: 787955E/1718491N, 800764E/1718509N, 800770E/1707312N, and 787976E/1707282N, referenced to the WGS 1984 UTM Zone 47N coordinate system. The study area is situated on the floodplain of the Chi River and lies at elevations ranging from approximately 190 to 251 m above mean sea level (**Fig. 6**).

2.2 Topography

The terrain is generally flat, with slope gradients ranging from 0–2%. River floodplains account for approximately 13% of the total area of Chaiyaphum Province. Geographically, the study area is located in the western part of the Khorat Basin.

2.3 Geological setting

The study area is largely dominated by lowland terrain, with a fluvial plain occupying the central part of the area. Quaternary deposits consist mainly

of alluvial sediments composed of sand, silt, and gravel. In certain poorly drained depressions, saline surface crusts are distinctly developed. These unconsolidated sediments overlie the evaporite-bearing units and associated sediments of the Maha Sarakham Formation (DMR, 2007).

2.4 Land use

Land use in Chaiyaphum Province can be classified into seven major categories, with agricultural land constituting the dominant type, accounting for 55.30% of the total area. Forest land represents 33.66%, followed by urban and built-up areas at 4.53%, while other land-use categories collectively account for 6.51% (Land Development Department, 2023).

Within the study area, agricultural land is the predominant land-use type, with scattered residential communities distributed throughout the surrounding area. To the west of the study area, dense built-up development occurs within the urban area of Bamnet Narong District, located approximately 5 km from the study site. The eastern, southern, and northern sectors are characterized by dispersed settlements, solar power generation facilities, and small villages distributed around the study area.

3. Data and Methodology

3.1 Data

3.1.1 Borehole Data

Borehole data were obtained from potash and rock salt exploration programs conducted by the Department of Mineral Resources (DMR), Thailand, between 1967 and 2018. A total of 82 boreholes were included in this study. The spatial distribution of borehole locations is shown in **Fig. 6**.

3.1.2 Seismic Data

Interpreted seismic data provided by ASEAN Potash Chaiyaphum Public Company Limited were used in this study. The dataset, acquired since

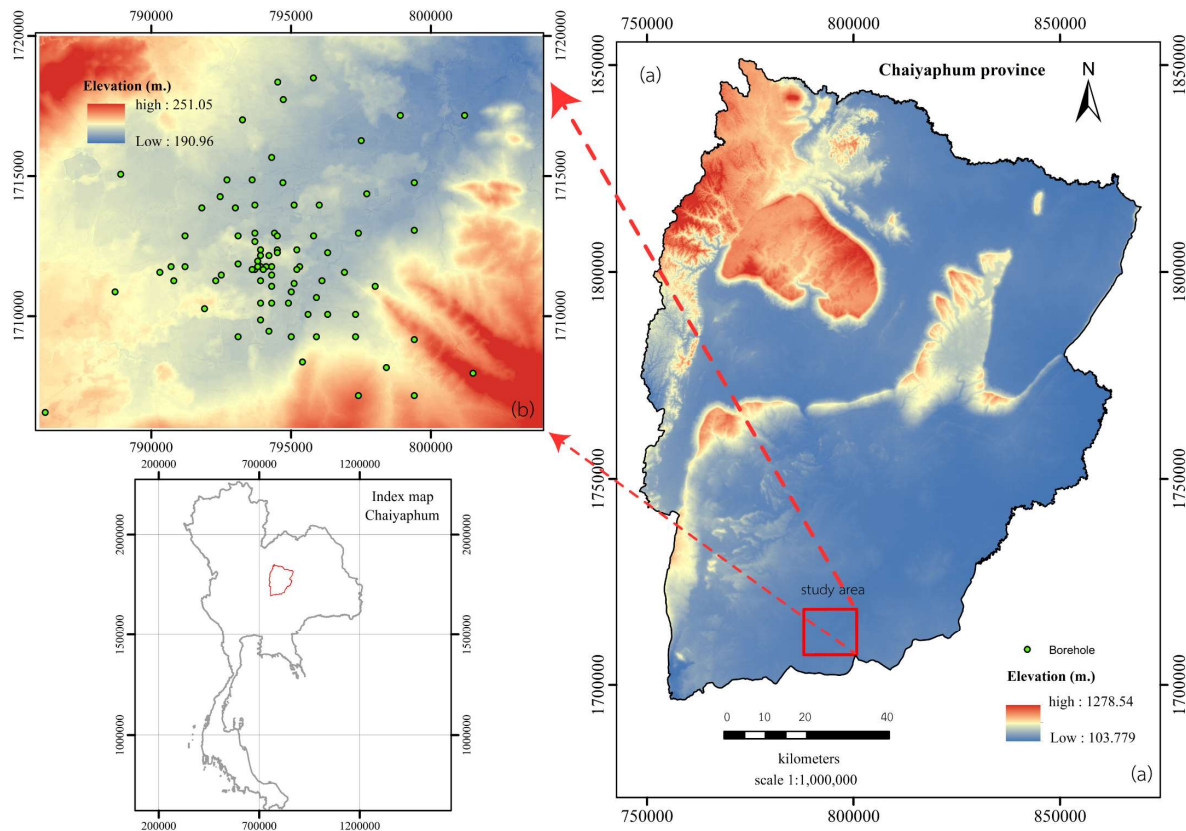


Fig. 6: Location map of the study area: (a) Borehole locations superimposed on an elevation map of Chaiyaphum Province derived from a Digital Elevation Model (DEM) with a spatial resolution of 30 m.; (b) Borehole location and elevation map of the study area derived from a DEM with a spatial resolution of 5 m.

1999, was analyzed to delineate the spatial distribution of salt dome and salt basin structures along both east–west and north–south profiles. These interpreted structural constraints were further used as reference points for validation and construction of the 3D geological model.

3.1.3 Digital Elevation Model (DEM)

Digital Elevation Model (DEM) data with spatial resolutions of 30 m and Shuttle Radar Topography Mission with resolution of 5 m (Land Development Department, Thailand) were used to characterize topographic variations and support geomorphological and spatial analyses.

3.1.4 Sentinel-1 Satellite Data

Sentinel-1 Synthetic Aperture Radar (SAR) data from the European Space Agency (ESA) were utilized in this study. The dataset consists

of Interferometric Wide Swath (IW) mode imagery acquired using the Terrain imagery acquired using the Terrain by Progressive Scans (TOPS) technique, providing a swath width of approximately 250 km with a pixel spacing of approximately 3×22 m.

Level-1 Single Look Complex (SLC) products, which contain both amplitude and phase information of the backscattered radar signal, were used for interferometric processing.

A total of 36 Sentinel-1 images acquired between April 2015 and March 2024 were selected to represent seasonal variations in Thailand, including summer (April), rainy season (July), and winter (November). This selection accounts for seasonal variations in groundwater and surface water conditions, which may influence deformation of salt structures.

For InSAR analysis, six images acquired in April (**Table 1**) during the period 2019–2024 were used to estimate annual displacement rates. Additionally, 24 ascending and 24 descending image pairs covering the period 2015–2024 (**Table 2, 3**) were processed using Differential InSAR (DInSAR) to analyze deformation trends under different seasonal conditions over a 10-year period.

Table 1: Details of Sentinel-1 SAR Data Used for PS-InSAR Analysis.

No.	Acquisition Date	Orbit Direction	Polarization
1	25-04-62	Ascending Orbit	VV+VH
2	19-04-63	Ascending Orbit	”
3	26-04-64	Ascending Orbit	”
4	21-04-65	Ascending Orbit	”
5	28-04-66	Ascending Orbit	”
6	22-04-67	Ascending Orbit	”

3.2 Methodology

The research workflow for applying geoinformatics technology to compare land

surface deformation associated with salt dome and salt basin structures is illustrated in **Fig. 7**. The methodology comprises main stages, as follows:

3.2.1 3D Geological modeling

The development of the three-dimensional (3D) geological structure model was based on the integration of subsurface geological datasets, including borehole data, seismic data, and Digital Elevation Models (DEM).

Borehole data were systematically prepared by classifying lithological units into eight stratigraphic layers: top sediments, upper clastic, upper salt, middle clastic, middle salt, lower clastic, lower salt, and the basement of the Khorat Formation. This classification facilitated interpolation and 3D modeling. A total of 82 boreholes were compiled and formatted into .xls and .csv files, of which 72 boreholes were selected as input datasets. Layer thicknesses were determined by measuring depth intervals from ground surface elevation (referenced to mean sea level) to lithological boundaries, enabling the identification of thickness and depth positions of both salt and clastic layers.

Table 2: Ascending-Orbit Sentinel-1 SAR Images Used for DInSAR Analysis.

Summer Season			Rainy Season			Winter Season		
Pair No.	Date	Polarization	Pair No.	Date	Polarization	Pair No.	Date	Polarization
1	10-04-58: 04-04-59	VV	1	15-07-58: 09-07-59	VV	1	12-11-58: 30-11-59	VV
2	11-04-60: 18-04-61	VV+VH	2	09-08-60: 23-07-61	VV+VH	2	13-11-60: 20-11-61	VV+VH
3	18-04-61: 13-04-62	VV+VH	3	23-07-61: 30-07-62	VV+VH	3	20-11-61: 27-11-62	VV+VH
4	13-04-62: 19-04-63	VV+VH	4	30-07-62: 24-07-63	VV+VH	4	27-11-62: 21-11-63	VV+VH
5	19-04-63: 14-04-64	VV+VH	5	24-07-63: 19-07-64	VV+VH	5	21-11-63: 28-11-64	VV+VH
6	14-04-64: 21-04-65	VV+VH	6	19-07-64: 14-07-65	VV+VH	6	28-11-64: 23-11-65	VV+VH
7	21-04-65: 28-04-66	VV+VH	7	14-07-65: 09-07-66	VV+VH	7	23-11-65: 30-11-66	VV+VH
8	28-04-66: 22-04-67	VV+VH	8	09-07-66: 15-07-67	VV+VH	8	30-11-65: 24-11-67	VV+VH

Table 3: Descending-Orbit Sentinel-1 SAR Images Used for DInSAR Analysis.

Summer Season			Rainy Season			Winter Season		
Pair No.	Date	Polarization	Pair No.	Date	Polarization	Pair No.	Date	Polarization
1	02-04-58: 08-04-59	VV+VH	1	07-07-58: 13-07-59	VV+VH	1	04-11-58: 10-11-59	VV+VH
2	03-04-60: 10-04-61	VV+VH	2	20-07-60: 27-07-61	VV+VH	2	17-11-60: 24-11-61	VV+VH
3	03-04-61: 10-04-62	VV+VH	3	27-07-61: 04-07-62	VV+VH	3	24-11-61: 19-11-62	VV+VH
4	10-04-62: 16-04-63	VV+VH	4	16-07-62: 22-07-63	VV+VH	4	19-11-62: 25-11-63	VV+VH
5	16-04-63: 05-04-64	VV+VH	5	22-07-63: 17-07-64	VV+VH	5	25-11-63: 26-11-64	VV+VH
6	05-04-64: 06-04-65	VV+VH	6	10-07-64: 23-07-65	VV+VH	6	13-11-64: 20-11-65	VV+VH
7	06-04-65: 13-04-66	VV+VH	7	23-07-65: 30-07-66	VV+VH	7	20-11-65: 27-11-66	VV+VH
8	13-04-66: 04-04-67	VV+VH	8	30-07-66: 24-07-67	VV+VH	8	27-11-65: 21-11-67	VV+VH

To ensure model validation, 10 boreholes located outside the concession area were selected as testing data points, spatially distributed across the study area. In addition, seismic profile (**Fig. 8**) interpretation within the concession area was conducted to identify the spatial locations of salt domes and salt basins. These were converted into *.xls* and *.csv* formats, generating 20 XYZ validation points, which were used to assess the accuracy of the interpolated model.

3.2.2 InSAR processing

▪ PS-InSAR Analysis

Synthetic Aperture Radar (SAR) data were acquired from Sentinel-1 Single Look Complex (SLC) Level-1 products in ascending orbit mode for the period 2015–2024, obtained from the Alaska Satellite Facility. A subset of six images acquired in April during 2019–2024 was selected for Interferometric Synthetic Aperture Radar (InSAR) processing using SNAP2StaMPS through a graphical user interface (GUI), with advanced parameter settings optimized for geological conditions and surface stability.

Subsequently, time-series processing was conducted using StaMPS within the MATLAB environment. Upon completion of processing,

displacement values were converted from the Line-of-Sight (LOS) direction to vertical displacement, and expressed as Persistent Scatterer (PS) points in units of millimeters per year (mm/yr).

For the PS-InSAR analysis, six Sentinel-1 scenes acquired during the same season (April) between 2019 and 2024 were selected. The objective was not to characterize short-term deformation dynamics but rather to evaluate long-term deformation trends associated with salt-related geological structures over a six-year period. Acquiring imagery from the same season minimized the influence of seasonal variations in soil moisture, vegetation cover, and surface conditions, thereby improving the consistency of interannual comparisons.

Given the relatively slow and gradual nature of deformation associated with subsurface salt structures, the selected image set was considered sufficient to identify broad deformation patterns and long-term surface displacement trends. Nevertheless, the limited number of scenes may reduce the density of persistent scatterers and increase uncertainty in comparison with conventional PS-InSAR studies based on dense image time

series. Therefore, the results should be interpreted primarily as indicators of long-term deformation trends rather than high-resolution temporal deformation measurements.

The results were presented in the form of time-series graphs illustrating surface displacement over different periods, as well as spatial maps depicting vertical deformation patterns, expressed in centimeters per year (cm/yr), to facilitate interpretation of temporal and seasonal variations in ground movement.

The LOS (Line-of-Sight) velocity measured by InSAR represents a combination of the three-dimensional displacement components and can be expressed as:

$$V_{LOS} = -\sin \theta \cos \alpha V_E + \sin \theta \sin \alpha V_N + \cos \theta V_U$$

Where V_{LOS} is the line-of-sight velocity, V_E , V_N , and V_U are the east–west, north–south, and vertical velocity components, respectively, (θ) is the radar incidence angle, and (α) is the satellite heading angle (Hanssen, 2001).

This study focuses exclusively on vertical ground deformation associated with salt-related geological structures. Such deformation is generally characterized by slow and gradual ground movement, and horizontal displacement is assumed to be negligible. Under this assumption ($(V_E = V_N = 0)$), the LOS velocity can be simplified to:

$$V_{LOS} = V_U \cos \theta$$

The InSAR-derived LOS velocity was converted to vertical velocity using the incidence angle of the radar sensor according to:

$$V_U = \frac{V_{LOS}}{\cos \theta}$$

where V_U is the vertical velocity, V_{LOS} is the line-of-sight velocity, and θ is the radar incidence angle. This conversion assumes that horizontal

displacement components are negligible and that surface deformation is dominated by vertical motion, as commonly applied in subsidence studies (Hanssen, 2001; ESA, 2007).

The conversion of LOS velocity to vertical velocity assumes negligible horizontal displacement. Therefore, the estimated vertical deformation may contain uncertainties in areas where horizontal motion is present. This limitation is particularly relevant in salt-related geological settings, where complex deformation processes may involve both vertical and lateral ground movements (Brouwer & Hanssen, 2023). The assumption of negligible horizontal displacement may introduce uncertainty into the estimated vertical velocity in areas affected by horizontal ground motion. Therefore, the derived vertical deformation values represent an approximation of the actual surface displacement field.

▪ SBAS-InSAR Analysis

For Differential InSAR (DInSAR) analysis, image pairs were selected from the ASF Vertex Data Search platform and processed using the Small Baseline Subset (SBAS) approach. Image pairs were selected based on consistent polarization, acquisition geometry (path and frame), and a high degree of spatial overlap to ensure interferometric coherence and reliable deformation measurements. A total of 24 interferometric pairs were analyzed, comprising eight pairs for each seasonal period. Processing was performed using the GAMMA InSAR software package with multilooking parameters of 20×4 and a phase filtering value of 0.6.

The SBAS technique minimizes spatial and temporal decorrelation by utilizing interferometric pairs characterized by small temporal and perpendicular baselines. The method generates a network of coherent interferograms that are subsequently combined through time-series inversion to estimate surface displacement over time. This approach is particularly suitable for monitoring slow and progressive ground deformation across

large areas, including agricultural and sparsely urbanized environments.

Surface displacement derived from the interferometric phase represents movement in the satellite Line-of-Sight (LOS) direction. To facilitate geological interpretation, LOS displacement was converted to vertical displacement under the assumption that horizontal ground motion was negligible. Accordingly, vertical displacement (V_U) was estimated from LOS velocity (V_{LOS}) using:

$$V_U = \frac{V_{LOS}}{\cos \theta}$$

where (θ) is the radar incidence angle. For Sentinel-1 imagery, the incidence angle typically ranges from approximately 33° to 43°. This conversion assumes that deformation is dominated by vertical motion, which is considered appropriate for the slow and gradual deformation associated with subsurface salt-related geological processes. Nevertheless, the estimated vertical displacement may contain uncertainties where horizontal motion is present and should therefore be interpreted as an approximation of actual ground deformation (Hanssen, 2001; ESA, 2007).

Finally, displacement trends derived from all interferometric pairs were integrated to determine the average annual deformation rates associated with salt dome and salt basin structures and to evaluate their spatial relationships with subsurface geological features.

3.2.3 Model validation

▪ Validation of the 3D Model

The accuracy of the 3D geological model was evaluated based on the estimated spatial distribution of various salt-related geological structures derived from interpolation and modeling techniques. Model validation was conducted using a set of 30 independent validation points. These validation points were derived from two

data sources: (1) borehole data, where 10 points were selected based on lithological interpretation indicating the presence and characteristics of salt structures, verified through comparison with nearby boreholes; and (2) seismic interpretation data, from which 20 points representing salt structural features were extracted. The positional accuracy of the model was assessed by comparing the modeled outputs with the observed validation points using the Root Mean Square Error (RMSE) statistic to quantify spatial discrepancies.

▪ Validation of InSAR Results Using ASF Data Search Vertex

The validation of land subsidence data derived from InSAR techniques is a crucial step to ensure the reliability and accuracy of the results. The deformation data are continuous quantitative variables obtained from remote sensing processing and are typically expressed as decimal values.

The objective of this validation is to evaluate the degree of consistency and correlation between subsidence datasets derived from different acquisition geometries, particularly between ascending and descending orbital observations. In principle, these two datasets are statistically independent due to their differing viewing geometries.

A statistical correlation analysis was therefore employed to quantify the relationship between the two datasets. The Pearson correlation coefficient was used to measure both the strength and direction of the relationship between subsidence values derived from the ascending and descending orbits. The coefficient can be computed using the following equation:

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}}$$

Where r represents the Pearson correlation coefficient; x denotes the land subsidence rate

derived from ascending orbit data; $\bar{x}$ represents the mean value of subsidence rates from the ascending orbit; y denotes the land subsidence rate derived from descending orbit data; and $\bar{y}$ represents the mean value of subsidence rates from the descending orbit.

The resulting correlation coefficient (r) ranges from -1 to +1 and is used to describe the direction and magnitude of the relationship between land subsidence datasets derived from ascending and descending orbital observations. A value of r approaching +1 indicates a strong positive correlation, meaning that both datasets vary in the same direction; when subsidence values increase in one dataset, they tend to increase correspondingly in the other. Conversely, a value of r approaching -1 indicates a strong negative correlation, representing an inverse relationship between the two datasets. A value of r near 0 suggests a weak or negligible relationship between the variables.

A high positive correlation coefficient indicates strong consistency between the deformation results obtained from both ascending and descending orbits, thereby supporting the reliability and validation of the InSAR-derived land subsidence measurements.

▪ *Validation of InSAR Results Using StaMPS*

The validation of InSAR-derived deformation results processed using the StaMPS (Stanford Method for Persistent Scatterers) technique is essential to ensure the reliability and robustness of the outputs. In this study, several quality control criteria were applied to assess the accuracy of Persistent Scatterer (PS) results.

First, the temporal coherence of each PS point was evaluated, and only points with values greater than 0.7 were considered reliable for further analysis. Second, the standard deviation

of the estimated deformation rate for each PS point was examined, with an acceptable threshold of less than 5 mm/year, indicating stable and low-noise deformation measurements.

In addition, the reliability of the results was assessed based on the spatial density of PS points. A sufficient number of PS points was required to ensure representative spatial coverage, particularly in rural areas where typical densities range from 5 to 50 points/km². Furthermore, the temporal coverage of the dataset was considered adequate when spanning at least 1–2 years, allowing for the detection of consistent deformation trends over time.

Finally, the validity of the InSAR results was further supported by qualitative consistency with local geomorphological features and anthropogenic activities. Agreement between deformation patterns and observed surface conditions provides additional confidence in the reliability of the StaMPS-derived results.

3.2.4 Structural zonation

The classification of salt structural patterns was divided into three categories, including salt dome areas, salt basin areas, and relatively flat terrain. This classification was conducted using contour lines with a 1-meter contour interval derived from the Digital Elevation Model (DEM) of the lower rock salt layer. The different structural zones were delineated based on the interpreted three-dimensional (3D) geological model of salt structures.

3.2.5 Comparative deformation analysis

The comparative analysis of ground surface deformation between salt dome and salt basin structures was conducted by integrating a three-dimensional (3D) geological structural model with surface displacement rate maps. This

approach enabled the assessment of spatial variations in ground deformation associated with different subsurface salt structures. Areas exhibiting the highest annual rates of subsidence and uplift were identified within zones underlain by salt dome and salt basin structures.

The integrated analysis provides insights into the spatial characteristics of ground deformation

related to different salt structural settings and improves the understanding of the interactions between subsurface geological structures and surface deformation. The results may contribute to land-use planning, geohazard assessment, and sustainable resource management in regions influenced by subsurface salt deposits.

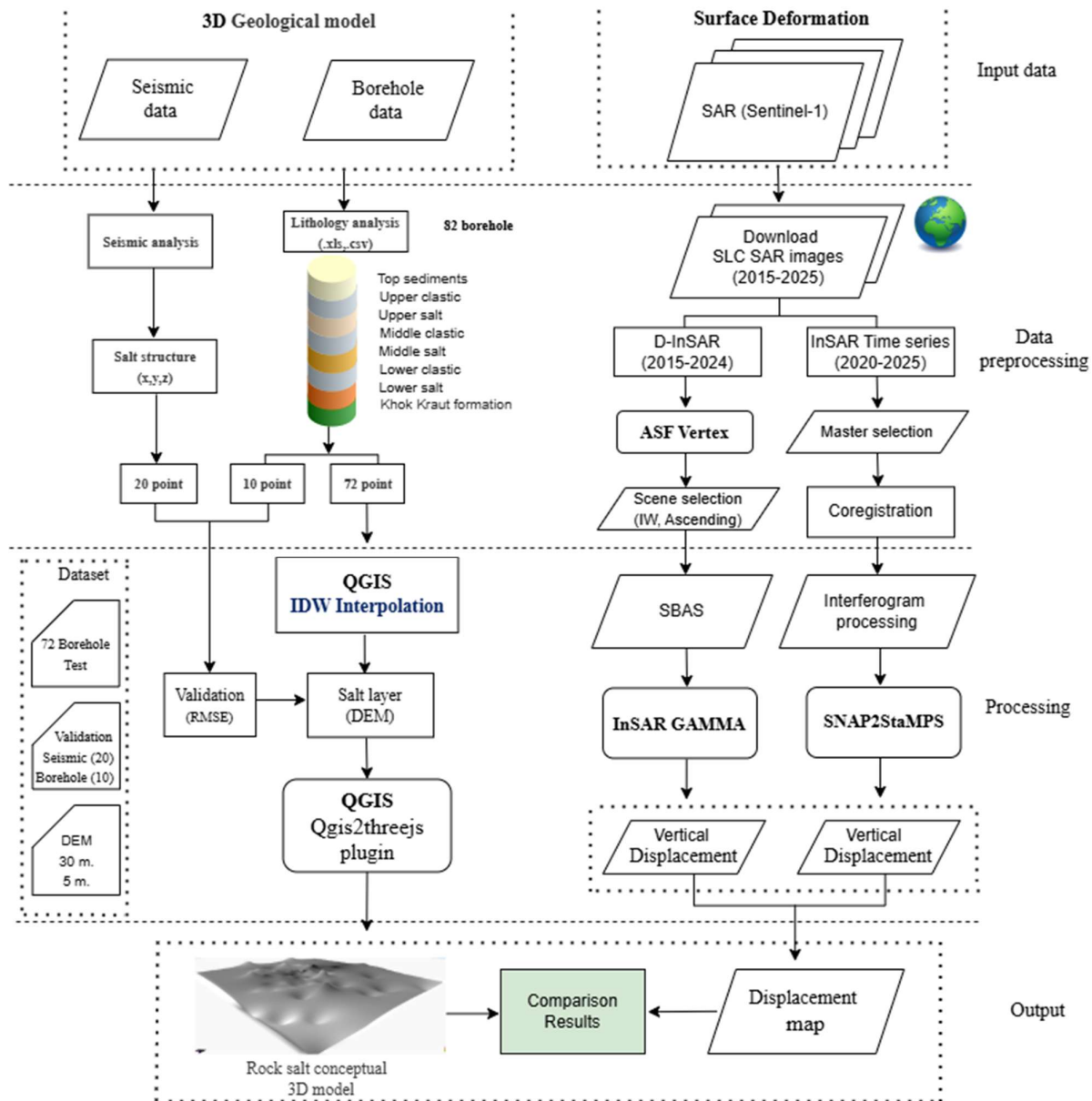


Fig. 7: Framework of the research methodology.

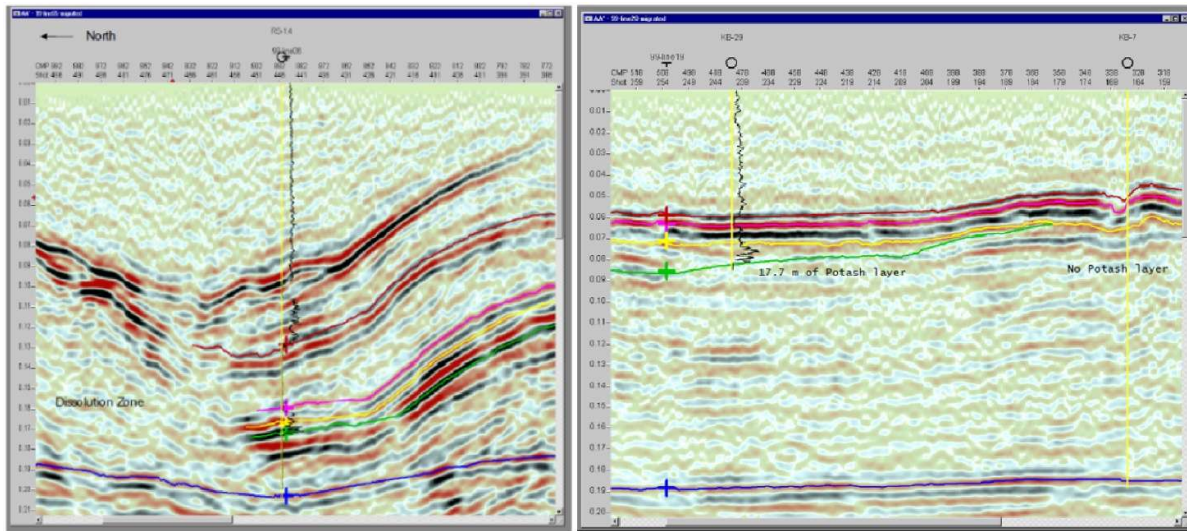


Fig. 8: Representative seismic and borehole data provided by ASEAN Potash Chaiphaphum Public Company Limited (personal communication, February 28, 2025).

4. Results

4.1 3D Geological Model

Data compiled from a total of 82 boreholes were systematically analyzed to differentiate and classify sedimentary and rock salt units into eight stratigraphic layers, namely: the uppermost overburden layer, upper sediment layer, upper rock salt layer, middle sediment layer, middle rock salt layer, lower sediment layer, lower rock salt layer, and the sandstone unit of the Khok Kruat Formation.

The occurrence of these layers varies among boreholes; some records indicate the presence of all eight stratigraphic units, whereas others reveal only a subset, depending on the local salt structural conditions. A comprehensive summary of the borehole data is presented in **Table 4**.

The modeling process was conducted by classifying the dataset into distinct groups based on the interpretation of borehole data. These groups were delineated according to geological characteristics and stratigraphic sequences, resulting in eight separate datasets. Each layer dataset, in .csv format, was imported into QGIS and

subsequently converted into shapefile format. Spatial interpolation was then performed using the Inverse Distance Weighting (IDW) method. The interpolation results for each layer were generated in raster format. The three-dimensional geological model was subsequently visualized using the Qgis2threejs plugin, as shown in **Fig. 9**. The detailed interpolation results for each layer, arranged from the lowermost to the uppermost units, are described as follows:

1) The Khok Kruat Formation was interpreted from borehole data based on its geological characteristics. A total of 24 boreholes penetrated the sandstone unit of this formation. Spatial interpolation using the IDW method yielded Z-values ranging from -243.03 to 69.15 meters. The interpolation results indicate that the sandstone layer exhibits a regional dip from west to east (KK+Lower salt layers in **Fig. 9**), consistent with the structural configuration of the Khorat Basin. The western margin of the basin is characterized by prominent sandstone escarpments of the Khorat Group, particularly in the Phang Hoei Range, from which the strata dip eastward toward the central part of the basin.

Table 4: Borehole geological data compilation results.

No.	Layer	Thickness (m.)	Average thickness (m.)	Number of holes
1	Top soil	1 – 40	14.23	64
2	Upper clastic	12.19 – 316.08	57.28	72
3	Upper salt	3.65 – 90.76	32.97	35
4	Middle clastic	2.44 – 46.18	25.06	26
5	Middle salt	2.14 – 159.64	45.32	53
6	Lower clastic	1.22 – 36.96	16.62	54
7	Lower salt	1.37 – 298.22	90.27	70
8	Khok Kruat fm.	0.65 – 5.67	2.44	24

2) The Lower salt unit was interpreted from borehole data based on its geological characteristics, with a total of 70 boreholes intersecting this layer. Spatial interpolation using the IDW method produced Z-values ranging from -199.12 to 169.15 meters. The interpolation results reveal that the western part of the study area is characterized by more pronounced salt dome structures, whereas the eastern part exhibits a relatively gentle salt basin morphology, consistent with the regional configuration of the Khorat Basin. The lower rock salt unit is generally thicker and exhibits the highest degree of deformation compared to other salt layers. This is primarily attributed to the overburden pressure exerted by the overlying sediments, which induces halokinetic movement. As a result, the lower salt layer undergoes upward deformation, forming salt domes that extend from the basement toward near-surface levels, with significant vertical thickness.

3) The Lower clastic unit was interpreted from borehole data based on its geological characteristics, with a total of 54 boreholes intersecting this layer. Spatial interpolation using the IDW method yielded Z-values ranging from -183.55 to 183.60 meters. The interpolation results indicate that, in the western part of the study area, the lower sedimentary unit overlies and drapes the margins of salt dome structures. In the northern sector, portions of this unit rest

relatively horizontally above the lower rock salt. In contrast, in the eastern part characterized by a salt basin setting the lower sedimentary unit predominantly overlies the margins of the basin, conforming to its geometry.

4) The Middle salt unit was interpreted from borehole data based on its geological characteristics, with a total of 53 boreholes intersecting this layer. Spatial interpolation using the IDW method yielded Z-values ranging from -135.01 to 158.13 meters. The interpolation results indicate that the middle rock salt unit conformably overlies the lower sedimentary unit. It is distributed along the flanks of structural features, occurring adjacent to both salt dome and salt basin geometries developed within the underlying lower sedimentary layer.

5) The Middle clastic unit was interpreted from borehole data based on its geological characteristics, with a total of 26 boreholes intersecting this layer. Spatial interpolation using the IDW method yielded Z-values ranging from -126.04 to 186.04 meters. The interpolation results indicate that the middle sedimentary unit conformably overlies the middle rock salt layer, occurring predominantly along the flanks of both salt dome and salt basin structures. This unit extensively drapes and nearly caps the crest of the salt domes, resulting in a relatively smoother

topography in the western part of the study area, while maintaining an overall eastward dip.

6) The Upper salt unit was interpreted from borehole data based on its geological characteristics, with a total of 35 boreholes intersecting this layer. Spatial interpolation using the IDW method yielded Z-values ranging from -100.64 to 184.69 meters. The interpolation results indicate that the upper rock salt unit is predominantly distributed in the central part of the study area, where it accumulates above the middle sedimentary unit. This accumulation results in a broadly convex geometry associated with salt dome development in the central region. Additionally, a localized small-scale salt basin is observed near the central zone of the area. The unit exhibits an increase in thickness, while the overall structural configuration maintains a gentle basin ward inclination toward the west.

7) The Upper clastic unit was interpreted from borehole data based on its geological characteristics, with a total of 72 boreholes intersecting this layer. Spatial interpolation using the IDW method yielded Z-values ranging from 164.34 to 218.99 meters. The interpolation results indicate that the upper sedimentary unit is predominantly characterized by a basin-like morphology in the central part of the study area, surrounded by gently elevated terrains forming low-relief ridges.

8) The overburden layer was derived from the interpretation of a Digital Elevation Model (DEM) with a spatial resolution of 5 meters, yielding Z-values ranging from 190.96 to 251.05 meters. The results indicate that the Qgis2threejs plugin. Overburden surface exhibits a gentle slope from the northwestern and southeastern margins toward the central part of the study area. Additionally, the surface shows a northeastward inclination, consistent with the drainage direction of Lam Khan Chu, which flows toward the Chi River.

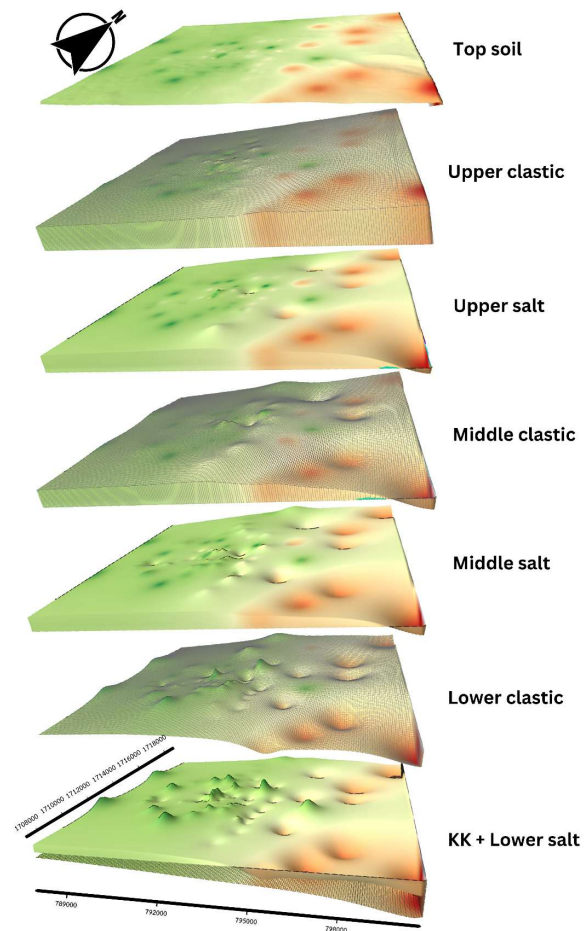


Fig. 9: Visualization of salt layers and individual sedimentary layers using a 3D model with the Qgis2threejs plugin.

4.2 InSAR-derived deformation map

The InSAR processing, based on six satellite images using the SNAP2STAMPS program, yielded a total of 1,242 Permanent Scatterer Interferometry (PSI) points. The resulting map (**Fig. 10**) illustrates ground subsidence and uplift within Bamnet Narong and Chatturat districts, Chaiyaphum Province, presenting vertical displacement rates in millimeters per year. Areas indicated in dark red represent the highest subsidence rates, ranging from -6.43 to -4.51 mm/year. In contrast, dark orange and orange colors indicate slightly to moderate subsidence, with values between -4.50 and -1.00 mm/year. Meanwhile, yellow areas are relatively stable, exhibiting displacement rates ranging from -0.99 to 0 mm/year. Furthermore,

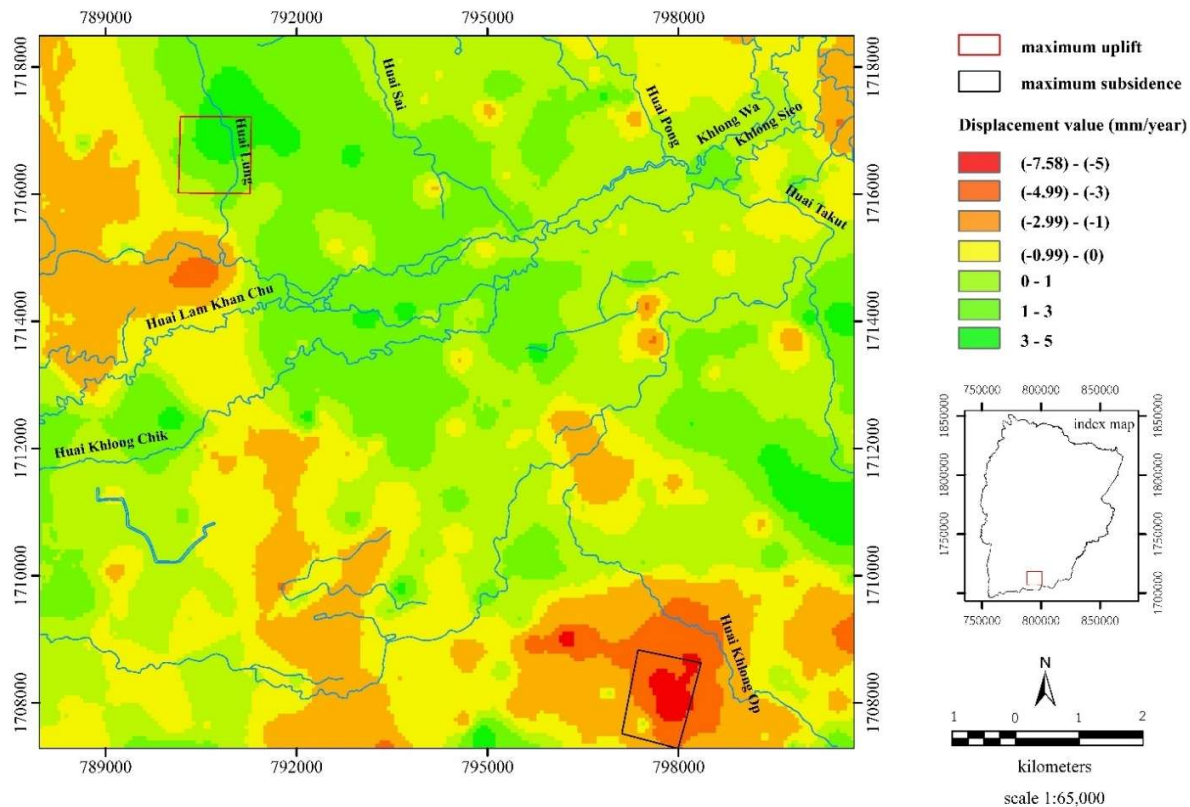


Fig. 10: Map showing the distribution of InSAR-derived PSI points interpolated using IDW.

light green areas indicate a slight uplift trend (0 to +1 mm/year), whereas dark green represents significant uplift, ranging from +3 to +7.05 mm/year.

The analysis of vertical ground displacement using the InSAR technique in the study area reveals spatially variable changes in ground elevation over an annual period. The displacement values range from approximately -6.43 to +7.05 mm/year, indicating heterogeneous ground movement across the area. Spatially, the northwestern and southern parts of the study area exhibit moderate to severe subsidence, as indicated by orange to red color bands. These subsiding zones are predominantly concentrated in areas with a high density of built-up structures and urban settlements. In contrast, the central and eastern parts of the study area generally show stable to slightly uplifting conditions,

represented by light green to dark green colors, suggesting relatively stable ground conditions during the observation period.

Furthermore, selected areas of interest reveal localized subsidence signals in certain zones. These localized deformations are presumed to be associated with land-use activities, such as large-scale construction, soil layer modification, or groundwater extraction. In addition, the spatial alignment of some subsiding areas follows a northwest–southeast trend, which may be related to underlying geological structures, representing the dominant structural orientation of the region.

Overall, the results indicate that ground deformation in the study area occurs in a non-uniform manner, reflecting the combined influence of natural geological controls and anthropogenic activities.

4.3 Model Validation results

The validation of the model was conducted by integrating seismic data with borehole information. Most exploration boreholes within the concession area were recorded with gamma logs, which were utilized to correlate seismic reflections with geological stratigraphic boundaries. These boreholes served as control points for converting seismic time surfaces into depth domains. The top of the potash-bearing layer, as interpreted from the seismic data, is located within the uppermost part of the lower rock salt unit. The depth values of this horizon were used as Z-values to validate the accuracy of the geological model generated using IDW interpolation.

Model validation is essential in geoinformatics-based modeling due to the integration of datasets with varying coordinate systems, spatial resolutions, and acquisition periods, which may introduce uncertainties and cumulative errors during processing. Therefore, accuracy assessment was conducted to ensure that the model reliably represents spatial characteristics and geological relationships.

In this study, validation was performed using borehole data from the Department of Mineral Resources, comprising 72 modeling points and 10 independent validation points, (**Fig. 11**) together with 20 additional validation points derived from integrated seismic interpretation and borehole data. The accuracy of the model generated using IDW interpolation was first evaluated using the Root Mean Square Error (RMSE) between interpolated Z-values and borehole-derived depths. The RMSE value of 54.22 indicates relatively high uncertainty, primarily due to uneven borehole distribution, with dense clustering in the central area and sparse coverage elsewhere, leading to increased interpolation error in poorly constrained zones.

The IDW interpolation method was selected in this study due to its compatibility with the open-source QGIS platform and the Qgis2threejs plugin, which enabled preliminary visualization of the spatial distribution and morphology of the salt structure in a cost-effective and accessible manner. Although the interpolation results exhibited certain uncertainties, the modeled salt structure showed reasonable agreement with previously reported geological interpretations within the study area, indicating that the generated model is acceptable for preliminary analysis and regional-scale assessment. Nevertheless, for detailed investigations and economic evaluation purposes, more advanced geostatistical and three-dimensional modeling techniques, supported by higher-density subsurface data, would be required to improve model accuracy and reliability.

To address this limitation, an indirect validation approach was applied by comparing the predicted spatial trends of the lower rock salt structure with geological expectations based on borehole data and regional salt basin models. The comparison of 30 validation points showed that 25 points (83%) were consistent with the expected structural positions, while 5 points (17%) exhibited a generally reliable representation of the regional salt structure.

4.4 Deformation by structural zone

The classification of salt structures was categorized into three types: salt dome areas, salt basin areas, and relatively flat areas. This classification was conducted using contour lines with a contour interval of 1 meter, derived from the DEM of the lower rock salt layer. Subsequently, different spatial zones were delineated based on the 3D structural model (**Fig. 12**). Accordingly, three types of ground deformation patterns associated with salt structures were identified as follows:

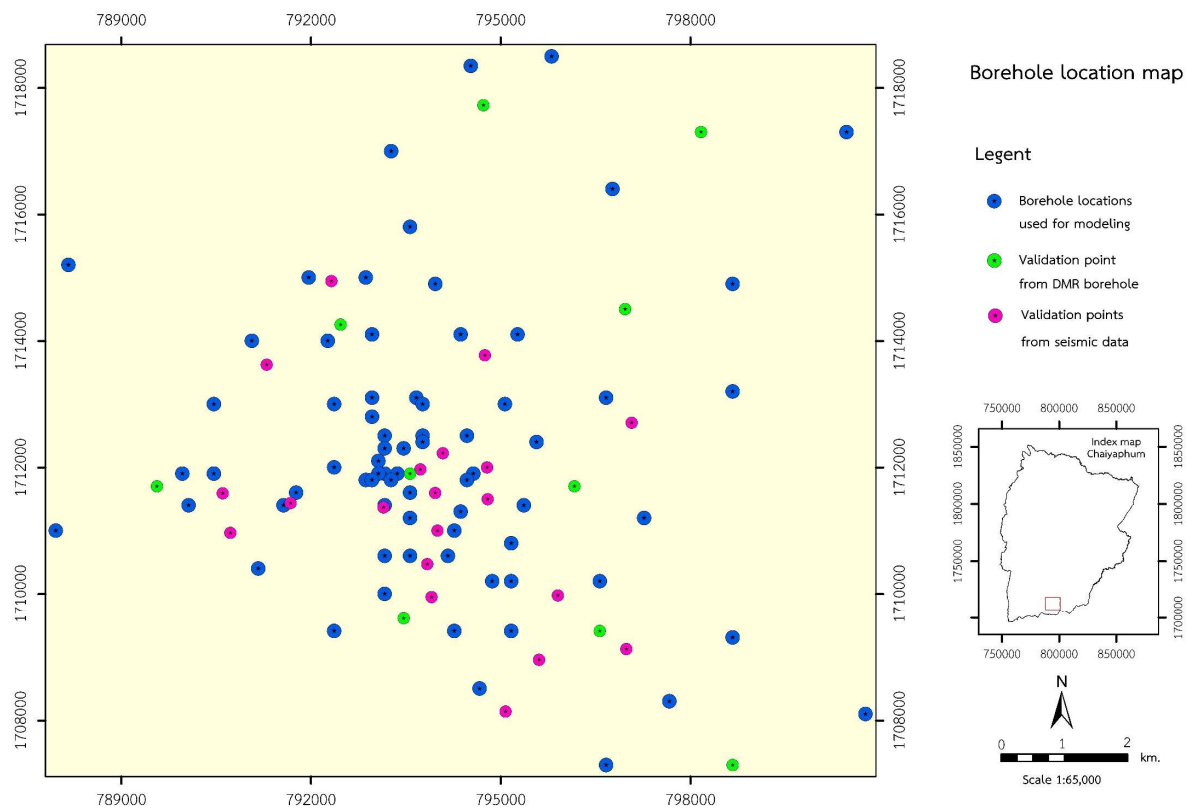


Fig. 11: Borehole and validation point location map.

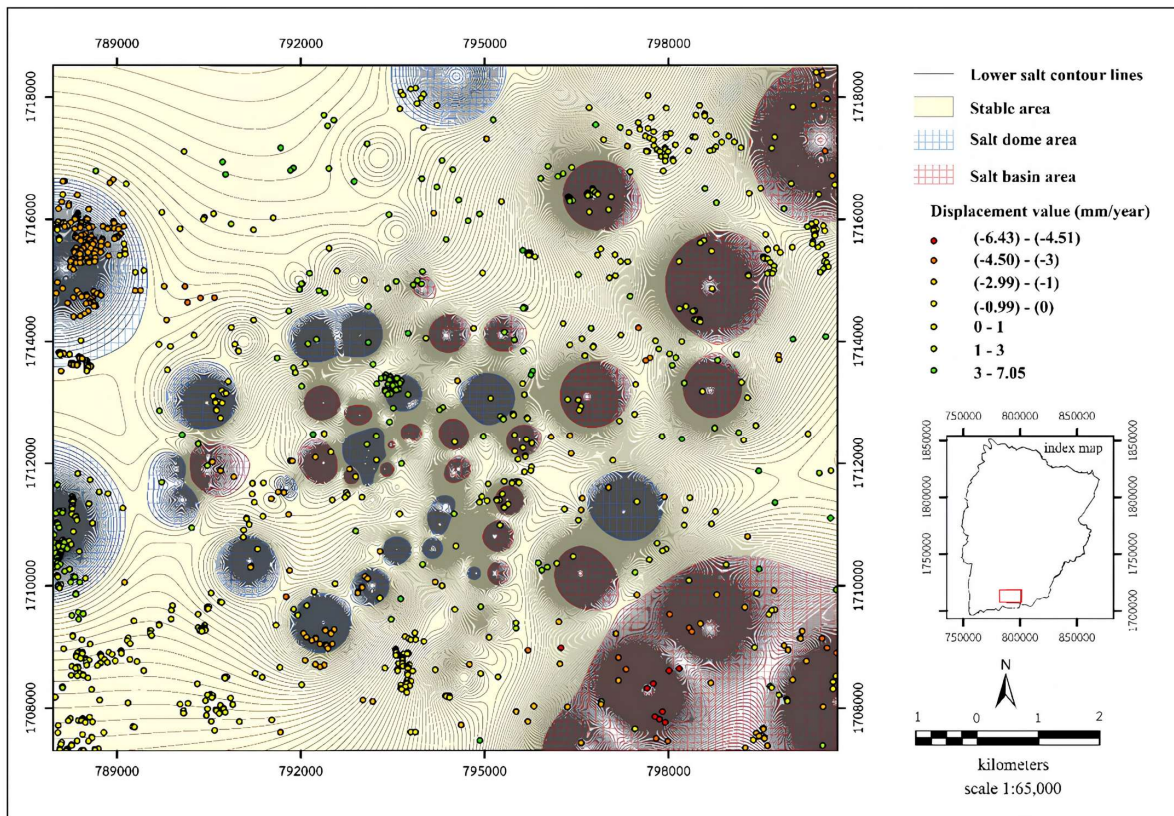
1) Salt dome areas

The area overlying salt dome structures covers approximately 15.32 km² and contains 415 PSI points. Among these, 219 points indicate subsidence, with values ranging from -2.77 to -1.01 mm/year and an average of -1.37 mm/year. In contrast, 81 points show uplift, ranging from 1.00 to 4.11 mm/year, with an average of 1.52 mm/year. The remaining values are relatively stable, ranging from -0.99 to 0.99 mm/year, with an average of 0.12 mm/year. The distribution of subsidence, uplift, and average values in the salt dome areas is illustrated in **Fig. 13a**. In terms of deformation characteristics, the most intense surface deformation occurs directly above the crest (**Fig. 13b**) of the salt dome. The deformation rate is closely related to both land-use activities and geological conditions. Notably, uplift patterns generally correspond to the crest of the salt dome, whereas subsidence is commonly associated with salt dissolution processes.

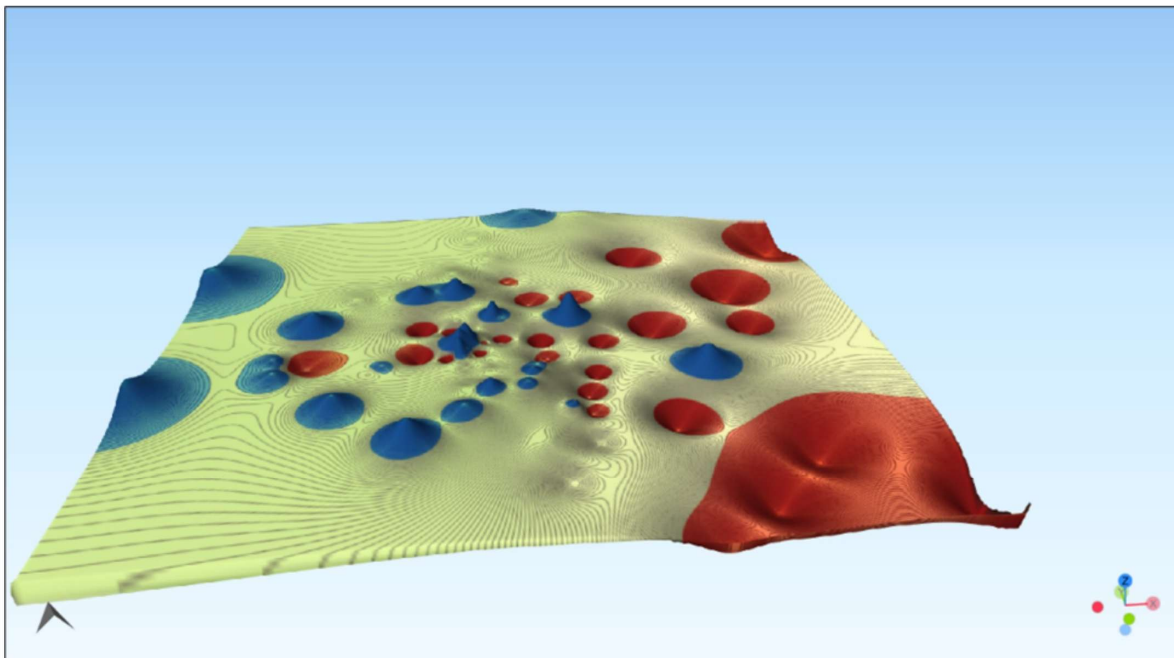
2) Salt basin areas

The area overlying salt basin structures covers approximately 24.52 km² and contains 170 PSI points. Of these, 59 points indicate subsidence, ranging from -5.92 to -1.05 mm/year, with an average of -2.53 mm/year. Meanwhile, 16 points exhibit uplift, with values between 1.04 and 3.01 mm/year and an average of 1.56 mm/year. Stable values range from -0.94 to 0.98 mm/year, with an average of 0.27 mm/year. The distribution of subsidence, uplift, and average values in the salt basin areas is shown in **Fig. 13b**.

In contrast to salt dome areas, deformation over salt basin structures is characterized by gradual subsidence. This is primarily influenced by the compaction of overlying sediment. Furthermore, slow salt dissolution processes at depth also contribute to the observed subsidence.



(a)



(b)

Fig. 12: Representation of areas overlying three types of salt structures: (a) map showing the distribution of PSI points across different salt structure types; (b) areas overlying salt structures on a 3D model, where red indicates subsidence (negative values) in the salt basin, blue indicates uplift (positive values) in the salt dome, and yellow indicates stable areas.

3) Undeformation area

The areas overlaying undeformed area cover approximately 103.43 km² and include a total of 657 PSI points. Among these, 67 points indicate subsidence, with values ranging from -6.44 to -1.01 mm/year and an average of -1.93 mm/year. In contrast, 117 points show uplift, ranging from 1.01 to 7.05 mm/year, with an average of 2.26 mm/year.

The remaining points are relatively stable, with displacement values between -0.99 and 0.99 mm/year and an average of -0.01 mm/year. The distribution of subsidence, uplift, and average values in areas overlying relatively stable structures is illustrated in **Fig. 13c**. In general, deformation patterns in these relatively stable or flat areas-representing the majority of the study area are less pronounced. This may be attributed to the absence of significant changes in underlying salt structures, as well as the limited availability of borehole data required for accurately assessing deformation rates. Nevertheless, the observed deformation includes subsidence, uplift, and relatively stable conditions. Notably, areas exhibiting the highest uplift may potentially correspond to underlying salt dome structures; therefore, further investigation and continuous monitoring are necessary to verify this interpretation.

Furthermore, the spatial proportions of each structural type indicate that salt dome areas account for approximately 11% of the study area, salt basin areas for 17%, and relatively flat areas for 72%, as shown in **Fig. 13d**.

4.5 Seasonal DInSAR trend analysis

The assessment of ground deformation trends using DInSAR was conducted based on on-demand processing through the HyP3 platform,

provided by the Alaska Satellite Facility (ASF), which is integrated with the Vertex system. This platform enables cloud-based processing without the need for local data downloading or processing. The dataset provides high spatial resolution, with a pixel size of 30 × 30 cm and deformation sensitivity at the centimeter scale.

For this analysis, two representative locations were selected: one point exhibiting the highest uplift within the salt dome structure and one point showing the highest subsidence within the salt basin structure. The maximum uplift area is located at Ban Chuan, Ban Chuan Subdistrict, Bamnet Narong District, whereas the maximum subsidence area is situated in the lowland region to the southwest of Ban Nong Yai But, Hua Thale Subdistrict, Bamnet Narong District. The objective was to examine annual deformation trends from 2015 to 2024 across different seasons. However, the period between 2016 and 2017 was excluded due to limitations in satellite data, specifically differences in polarization that prevented interferometric processing.

Each season includes eight interferometric pairs, resulting in a total of 24 image pairs. Pixel values derived from raster data were converted into point-based measurements representing vertical displacement in centimeters. Subsequently, the average displacement values for each image pair were calculated and analyzed using line graphs for comparative purposes. Examples of InSAR processing results using the GAMMA software via HyP3 (ASF) illustrate vertical ground displacement over the salt dome structure for ascending orbit and descending orbit.

The results of the average deformation rate analysis for ground movement over salt dome and salt basin structures are described as follows:

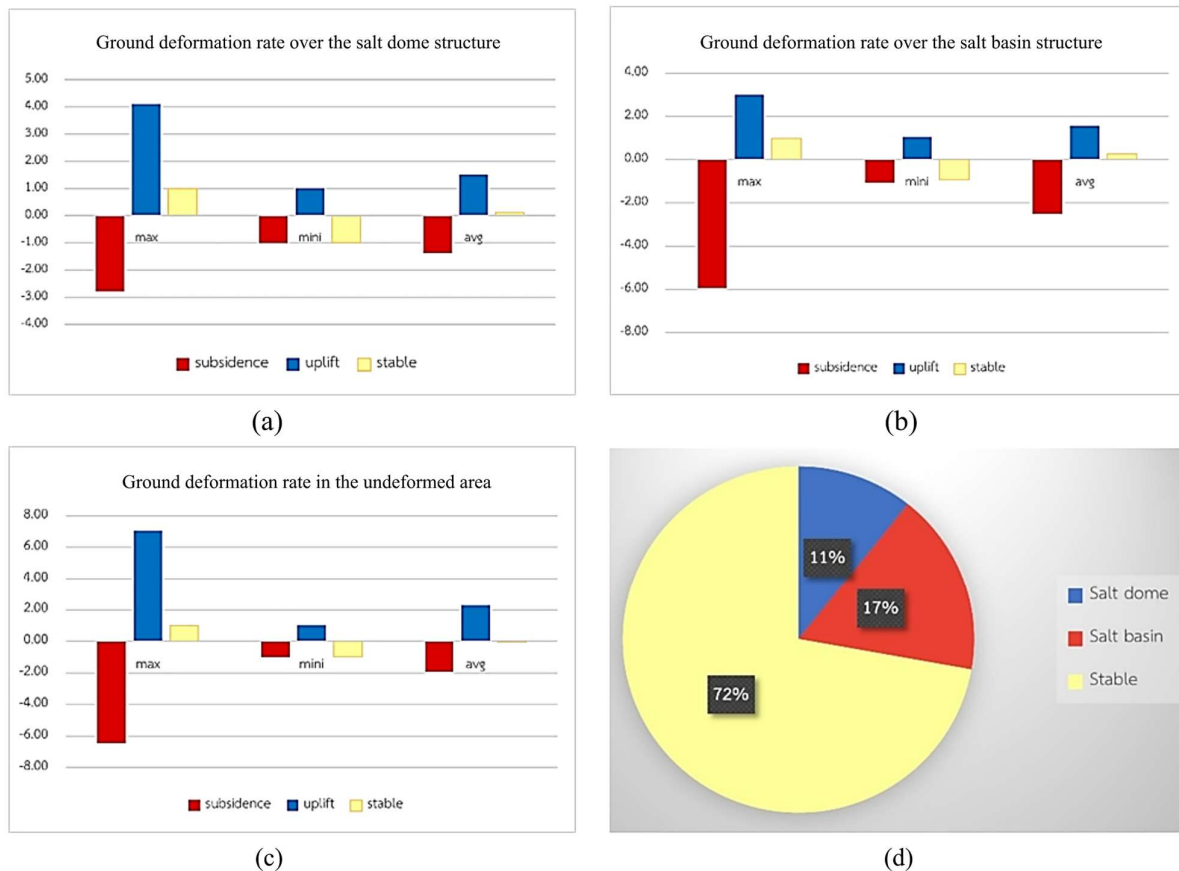


Fig. 13: A chart illustrating subsidence and uplift rates in areas overlying different salt structure types: (a) deformation rate in the area above the salt dome structure, (b) deformation rate in the area above the salt basin structure, (c) deformation rate in the area above the plain; and (d) proportion of the three area types discrepancies.

4.5.1 Ground deformation trends over salt dome structures

Ground deformation over salt dome structures in April exhibits both uplift and subsidence trends. Initially, a slight uplift was observed during 2015–2016, followed by a continuous decrease that reached maximum subsidence in 2019–2020. Subsequently, deformation values returned to positive, indicating a gradual uplift trend from 2020 onward, with minor fluctuations during 2022–2024 (Table 5 and Fig. 14a).

Ground deformation over salt dome structures in July derived from ascending and descending datasets exhibit both agreement and discrepancies. In general, the patterns are partially consistent; however, notable inconsistencies, particularly during 2019–2021, are likely influenced by

meteorological factors such as soil moisture, vegetation cover, groundwater, and radar signal scattering during the rainy season. In contrast, improved consistency between both datasets during 2021–2024 reflects enhanced signal stability and more continuous ground movement. Consequently, the reliability of deformation assessment is significantly increased (Table 6 and Fig. 14b).

Ground deformation trends in November show a generally consistent pattern. Initially, uplift is observed during 2019–2020, followed by continuous subsidence until 2022–2023, which is particularly pronounced in the ascending orbit data. This discrepancy between datasets can be attributed to differences in radar acquisition

Table 5: Average deformation rate over the salt dome area during April.

Image pair	Year	Average deformation rate (ascending orbit) (cm)	Average deformation rate (descending orbit) (cm)
1	2015–2016	0.0040	-0.0718
2	2017–2018	-0.0384	0.0410
3	2018–2019	-0.0543	-0.0202
4	2019–2020	-0.0719	0.0038
5	2020–2021	0.0273	-0.0020
6	2021–2022	0.0258	-0.0020
7	2022–2023	-0.0157	-0.0512
8	2023–2024	0.0185	-0.0010

Table 6: Average deformation rate over the salt dome area during July.

Image pair	Year	Average deformation rate (ascending orbit) (cm)	Average deformation rate (descending orbit) (cm)
1	2015–2016	-0.0222	0.0228
2	2017–2018	0.0536	-0.0301
3	2018–2019	0.0442	-0.0004
4	2019–2020	-0.0348	-0.055
5	2020–2021	0.0751	-0.0708
6	2021–2022	0.0082	0.0225
7	2022–2023	0.0543	-0.0001
8	2023–2024	-0.0488	-0.0097

geometry, including viewing direction, as well as local topographic variability of the salt dome. Nevertheless, both datasets converge again during 2023–2024, thereby indicating improved signal stability and more consistent ground deformation behavior (**Table 7** and **Fig. 14c**).

The correlation coefficient (r) between ascending and descending orbit data across eight locations ($r1$ – $r8$) was used to assess the consistency of ground surface deformation over the salt dome area for April, July, and November. The results show very strong correlations in

April ($r = 0.8171$ to 0.9692 ; avg. 0.91) and November ($r = 0.8150$ to 0.9799 ; avg. 0.92), indicating high data consistency and stable radar signal conditions. In contrast, July exhibits more variable correlations ($r = -0.3654$ to 0.9435 ; avg. 0.80), with some locations showing low or negative relationships due to meteorological influences during the rainy season. Overall, the findings demonstrate that data consistency is higher during dry periods and decreases under wet conditions, highlighting the influence of climatic factors on radar data reliability (**Table 8**).

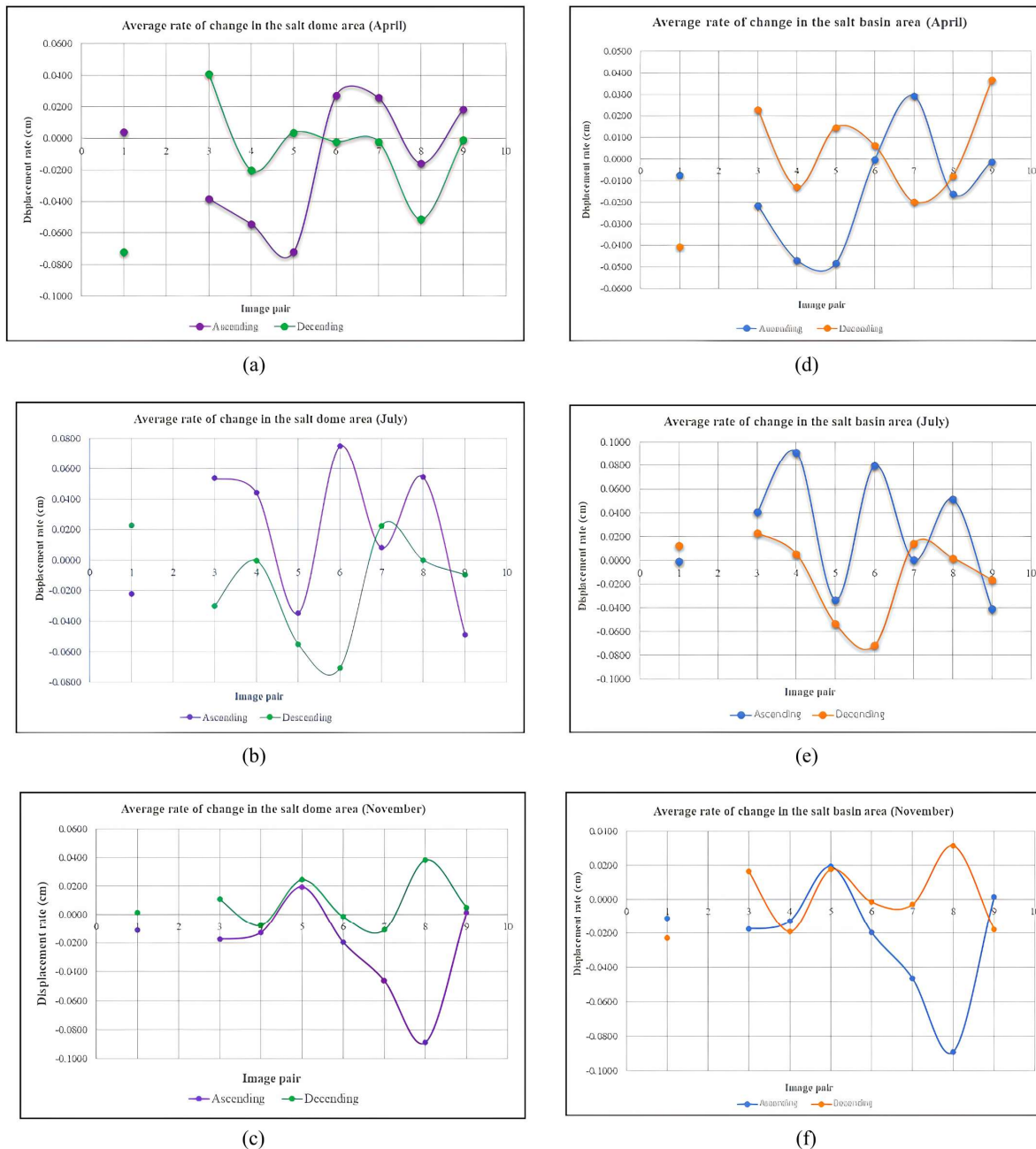


Fig. 14: Vertical ground deformation rates over the salt structure in each season. (a), (b), and (c) salt dome area. (d), (e), and (f) salt basin area.

4.5.2 Trend of Ground Surface Deformation above the Salt basin

Ground deformation trends over the salt basin during April (2015–2024) indicate generally consistent patterns between ascending and descending orbit data. In general, both datasets demonstrate similar directional changes, with

slight uplift observed during 2017–2020, followed by a decline and subsequently an increase in 2023–2024. However, minor discrepancies between the datasets may be attributed to differences in radar acquisition geometry and spatial resolution. Overall, the consistency between both datasets reflects stable radar signal conditions during the

Table 7: Average deformation rate over the salt dome area during November.

Image pair	Year	Average deformation rate (ascending orbit) (cm)	Average deformation rate (descending orbit) (cm)
1	2015–2016	-0.0111	0.0013
2	2017–2018	-0.0175	0.0109
3	2018–2019	-0.0128	-0.0076
4	2019–2020	0.0193	0.0244
5	2020–2021	-0.0196	-0.0015
6	2021–2022	-0.0464	-0.0109
7	2022–2023	-0.0889	0.0382
8	2023–2024	0.0014	0.0051

Table 8 : Correlation coefficient (r) between ascending and descending orbit data over the salt dome area.

Monthly	<i>r1</i>	<i>r2</i>	<i>r3</i>	<i>r4</i>	<i>r5</i>	<i>r6</i>	<i>r7</i>	<i>r8</i>
April	0.8787	0.8180	0.9681	0.9692	0.9338	0.9646	0.8171	0.9280
July	0.4333	-0.3654	0.9043	0.9111	0.9134	0.8260	0.9435	0.8442
November	0.8927	0.9799	0.9784	0.9048	0.9479	0.9475	0.8150	0.9208

Table 9: Average deformation rate over the salt basin area during April.

Image pair	Year	Average deformation rate (ascending orbit) (cm)	Average deformation rate (descending orbit) (cm)
1	2015–2016	-0.0074	-0.0405
2	2017–2018	-0.0215	0.0229
3	2018–2019	-0.0469	-0.0129
4	2019–2020	-0.0483	0.0147
5	2020–2021	-0.0001	0.0063
6	2021–2022	0.0293	-0.0198
7	2022–2023	-0.0161	-0.0078
8	2023–2024	-0.0012	0.0366

dry season, thereby supporting reliable long-term deformation analysis (**Table 9** and **Fig. 14d**).

In July, deformation trends from both ascending and descending datasets exhibit synchronized

fluctuations. Initially, deformation values increase from 2015 to 2017–2018, followed by a notable decline during 2018–2020. Subsequently, a partial recovery is observed in 2020–2023, before decreasing

again in 2023–2024. Overall, the variation remains within approximately ± 0.1 cm, indicating alternating uplift and subsidence. These fluctuations are likely associated with hydrological changes and land-use activities within the salt basin area, thereby influencing the observed deformation patterns (**Table 10** and **Fig. 14e**).

During November, deformation trends from both datasets remain consistent. Initially, relatively stable conditions are observed during 2015–2017, followed by a significant increase reaching peak uplift in 2018–2019. Subsequently, deformation values decline continuously, reaching maximum subsidence during 2022–2023, before slightly increasing again in 2023–2024. Overall, the deformation range (approximately -0.09 to 0.03 cm) reflects alternating uplift and subsidence. This pattern is likely influenced by seasonal variations and groundwater level changes, which in turn affect soil moisture balance (**Table 11** and **Fig. 14f**).

The correlation coefficient (r) between ascending and descending orbit data over the salt basin area exhibits seasonal variability. Specifically, April and July show high correlation values ($r > 0.7$ – 0.9), indicating strong agreement and stable data conditions, which are suitable for analyzing ground surface deformation trends. In contrast, November presents lower correlation values ($r < 0.6$), suggesting that the datasets are more strongly influenced by external environmental factors, particularly soil moisture and vegetation cover following the rainy season. Therefore, the use of data from April and July provides more reliable results for assessing ground surface deformation rates in salt basin structures (**Table 12**).

Ground surface deformation rates during April, July, and November over the period 2015–2024 indicate that salt dome and salt basin systems exhibit distinctly different movement behaviors depending on seasonal conditions. In April, which corresponds to the transition from the late dry season to the early rainy season, deformation values are generally low to moderate, with alternating subsidence and uplift, thereby reflecting a temporary equilibrium of pressure within the salt system.

In contrast, during July, representing the peak of the rainy season, the highest deformation rates are observed, including both significant uplift and subsidence, particularly over salt dome and basin structures in the ascending direction. This pattern suggests a strong response of salt masses to increased overburden pressure from water and elevated pore fluid pressure, thus indicating that salt movement processes are most active during this period.

Meanwhile, in November, corresponding to the transition from the late rainy season to the early cool season, deformation values decrease and tend toward greater stability. Subsidence occurs more gradually rather than abruptly, and the magnitude of deformation is lower compared to the rainy season. This reduction reflects a diminished role of plastic salt flow and a gradual return of the system toward equilibrium conditions. Overall, the results demonstrate that ground surface deformation in the study area is controlled by the interaction between salt structures and seasonal factors, with halokinesis acting as the primary mechanism governing these changes (**Fig. 15**).

Table 10 : Average deformation rate over the salt basin area during July.

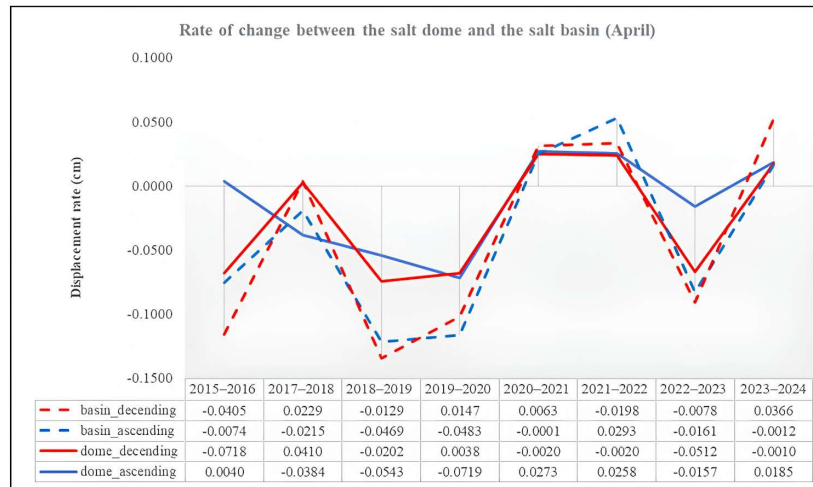
Image pair	Year	Average deformation rate (ascending orbit) (cm)	Average deformation rate (descending orbit) (cm)
1	2015–2016	-0.0011	0.0125
2	2017–2018	0.0405	0.0229
3	2018–2019	0.0915	0.0054
4	2019–2020	-0.0332	-0.0535
5	2020–2021	0.0798	-0.0714
6	2021–2022	0.0004	0.0140
7	2022–2023	0.0512	0.0019
8	2023–2024	-0.0408	-0.0164

Table 11 : Average deformation rate over the salt basin area during November.

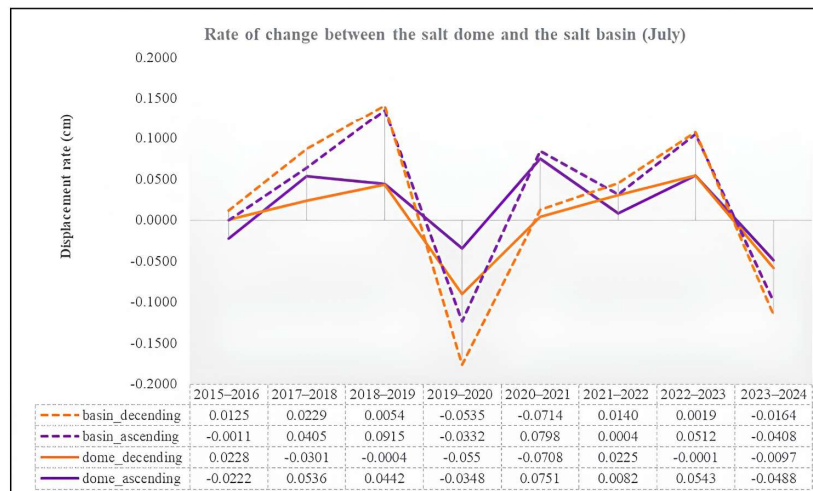
Image pair	Year	Average deformation rate (ascending orbit) (cm)	Average deformation rate (descending orbit) (cm)
1	2015–2016	-0.0111	-0.0230
2	2017–2018	-0.0175	0.0163
3	2018–2019	-0.0128	-0.0191
4	2019–2020	0.0193	0.0175
5	2020–2021	-0.0196	-0.0016
6	2021–2022	-0.0464	-0.0030
7	2022–2023	-0.0889	0.0315
8	2023–2024	0.0014	-0.0180

Table 12 : Correlation coefficient (r) between ascending and descending orbit data over the salt basin area.

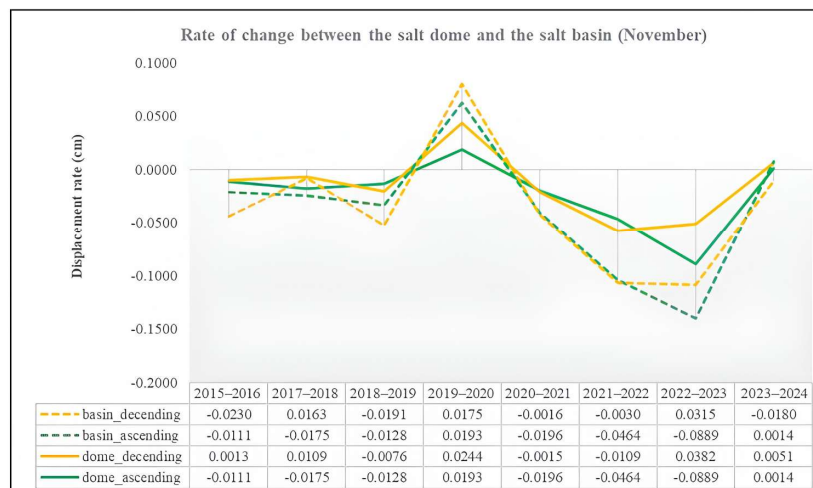
Monthly	<i>r1</i>	<i>r2</i>	<i>r3</i>	<i>r4</i>	<i>r5</i>	<i>r6</i>	<i>r7</i>	<i>r8</i>
April	0.9021	0.9678	0.3653	0.7722	0.8821	0.2515	0.8004	0.7044
July	0.8463	0.9025	0.9440	0.9239	0.8858	0.8364	0.8291	0.7968
November	0.5134	0.0368	0.4888	0.5510	0.5648	0.5341	0.6465	0.5571



(a)



(b)



(c)

Fig. 15: Chart illustrating the variation between areas overlying the salt dome and the salt basin: (a) deformation rate in April, (b) deformation rate in July, and (c) deformation rate in November.

5. Discussion and conclusions

5.1 Discussion

5.1.1 Reliability and limitation of 3D model

1) The 3D geological model generated using the Inverse Distance Weighting (IDW) interpolation technique demonstrates moderate effectiveness in representing the spatial distribution of rock salt and sedimentary layers, based on 72 borehole datasets.

2) Model accuracy is strongly influenced by borehole density and spatial distribution. Areas with dense borehole coverage yield higher accuracy and clearer representation of geological structures, whereas sparsely distributed data result in greater interpolation uncertainty and reduced spatial continuity.

3) The IDW method inherently exhibits decreasing accuracy with increasing distance between data points, leading to potential distortion in areas with limited data control.

4) Despite these limitations, IDW is suitable for preliminary modeling and regional-scale analysis. However, for detailed interpretation or engineering and resource applications, more advanced technique such as geostatistical models (e.g., kriging) and machine learning approaches are recommended to improve prediction accuracy and reliability.

5.1.2 Relationship between deformation and geological structures

1) Ground deformation reflects the interaction between anthropogenic activities and natural geological processes. Subsidence is commonly associated with structural loading, groundwater fluctuations, soft soil conditions, land reclamation, and geological structural controls.

2) In the study area, deformation is closely related to salt dome and salt basin structures, which are governed by the mechanical behavior of rock salt and evaporite minerals.

3) Borehole data spanning 1977–2018 (approximately 40 years) represent only a negligible fraction ($\sim 0.00001\%$) of the geological timescale, indicating that temporal variability is insignificant relative to the age of the formation.

4) Structural parameters such as salt thickness, depth, and vertical boundaries exhibit minimal temporal variation, supporting the assumption of temporal stability for spatial analysis.

5) The integration of temporally heterogeneous datasets does not significantly affect spatial accuracy due to the long-term stability of geological structures. Therefore, the application of IDW to such datasets yields reliable and geologically acceptable results for large-scale structural interpretation. For more complex geological settings or areas with high morphological variability, advanced approaches such as adaptive IDW or kriging can further enhance model accuracy.

6) In areas associated with salt dome structures, ground uplift may result from the upward movement of ductile salt under overburden pressure. It may also indicate natural land recovery processes, groundwater re-equilibration, or relatively stable geological and foundation conditions, leading to more stable ground deformation compared to surrounding areas.

7) The results indicate a strong relationship between subsurface geological structures and long-term ground deformation patterns. Salt domes tend to show uplift, likely due to internal pressure and upward movement of ductile salt under overburden stress (**Fig. 12, 13**).

8) The limited number of Sentinel-1 scenes used in the PS-InSAR analysis may have reduced the density of persistent scatterers and increased uncertainty in the estimated deformation rates. Therefore, the PS-InSAR results were interpreted primarily as indicators of long-term deformation trends and were evaluated together with SBAS-InSAR results.

In contrast, salt basins exhibit more pronounced subsidence, potentially caused by low-density sediment accumulation (**Fig. 9**), salt dissolution due to groundwater infiltration, and changes in subsurface stress equilibrium.

Comparison of ascending and descending orbit data from Sentinel-1 reveals a high correlation ($r > 0.8$), indicating strong consistency and reliability of InSAR measurements for ground deformation monitoring.

However, discrepancies between orbital datasets are observed during certain periods, particularly in the rainy season. These differences may result from soil moisture variation, vegetation cover, and increased radar signal scattering. Such factors should be considered in the selection of satellite imagery for future ground deformation monitoring to ensure data quality and interpretability.

5.1.3 Seasonal effects on InSAR signal and deformation

1) Seasonal variations in groundwater and surface water conditions can significantly influence land deformation behavior. Increased rainfall during the wet season promotes groundwater recharge and infiltration, leading to changes in pore pressure and subsurface loading that may modify deformation responses.

2) Seasonal variations influence InSAR signal quality through changes in atmospheric conditions, vegetation cover, and soil moisture, which affect signal coherence and phase stability. Wet-season conditions generally reduce interferometric coherence and deformation measurement accuracy, whereas dry-season conditions tend to enhance InSAR performance.

3) Deformation patterns differ between salt dome and salt basin settings due to variations in salt geometry, overburden thickness, and hydrological conditions.

4) InSAR deformation signals should be interpreted with consideration of seasonal variability and combined geological hydrological influences, requiring long-term, multi-seasonal observations for reliable assessment.

5) Seasonal understanding enhances geohazard monitoring in evaporite terrains and supports risk assessment, infrastructure management, groundwater monitoring, and sustainable land-use planning.

5.1.4 Implication for monitoring and land-use planning

1) Continuous monitoring of ground deformation is essential in areas underlain by rock salt structures to detect uplift and subsidence associated with salt-related geological processes.

2) Integrated monitoring of groundwater conditions and surface deformation should be implemented, as hydrological variations may influence deformation patterns and subsurface stability.

3) Ground deformation information can support geohazard assessment and risk mitigation for infrastructure, agricultural land, and settlements located in evaporite terrains.

4) Geological structural characteristics, including salt dome and salt basin settings, should be incorporated into land-use planning and resource management to reduce long-term environmental and geotechnical risks.

5) Long-term geospatial monitoring using InSAR and geological datasets can provide a scientific basis for sustainable land-use planning and groundwater management in regions affected by rock salt deformation. such as restricting construction in unstable areas, prioritizing groundwater management, and identifying safer zones for future land development

6) The application of InSAR for monitoring surface deformation in salt-structure areas

should account for the influences of land use and seasonal variation, as differences in vegetation cover, soil moisture, and surface conditions across time may affect radar signal backscatter and data coherence, potentially leading to uncertainty in the interpretation of surface change.

5.2 Conclusion

This study integrates geoinformatics technologies, including GIS and remote sensing, to investigate ground surface deformation over salt dome and salt basin structures in Chaiyaphum Province, northeastern Thailand. The analysis is based on multi-source datasets, including boreholes, seismic data, 3D geological modeling using the IDW method, and InSAR (2015–2024), supplemented by UAV observations. The results indicate that the study area is underlain by the Khok Kruat Formation, with tectonic activity and halokinesis processes forming salt domes in the west and salt basins in the east. Deformation rates range from -4.18 to +7.05 mm/year over salt domes and -6.43 to +5.13 mm/year over salt basins, with uplift predominantly associated with domes and subsidence with basins, particularly in low-lying areas.

Ground deformation is spatially continuous and occurs at the millimeter scale, reflecting the plastic behavior of rock salt and seasonal influences, especially during the rainy season. Variations in deformation between salt domes and salt basins are controlled by factors such as salt thickness, structural continuity, and overlying sediments. The integration of long-term geological data with recent InSAR observations is considered reliable due to the temporal stability of geological structures. However, limitations arise from heterogeneous data resolution, uneven borehole distribution, and the constraints of the IDW interpolation method, which may reduce accuracy in areas with sparse data.

Future research should enhance data density and apply advanced techniques, such as machine learning, deep learning, and geostatistical methods, to improve modeling accuracy. Continuous monitoring is recommended in subsidence-prone areas, particularly urban zones, alongside detailed geotechnical investigations to assess structural risks. The integration of high-resolution satellite data with InSAR and GNSS, supported by corner reflectors, is suggested for precise monitoring. Additionally, land-use planning should incorporate geological risk assessments, while future studies should focus on groundwater dynamics, expand to other regions, and improve methodological robustness through the use of consistent datasets and comparative interpolation approaches.

The analysis of rock salt structures in this study was based on borehole data acquired from exploration campaigns conducted between 1977 and 2018, which were used to characterize the overall structural configuration of the salt basin in the study area. The interpreted structural framework was subsequently integrated with ground deformation rates derived from Sentinel-1 satellite imagery acquired between 2015 and 2024 to evaluate differences in ground movement trends overlying distinct rock salt structural settings. This analysis was intended solely to investigate structural relationships and comparative deformation patterns, rather than to represent the current ground movement conditions above rock salt structures.

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TGJ Contributors

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 Dr. Apivut Veeravinantanakul
 Dr. Apsorn Sardud
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 Assoc. Prof. Dr. Danupon Tonnayopas
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- Consultant, Myanmar Precious Resources Group, Yangon, Myanmar
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 Mahidol University, Kanchanaburi campus, Thailand
 Retired geologist, Independent Researcher, Thailand
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 University of London, England
 Nanjing Center, China Geological Survey, Nanjing, China
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 University of Copenhagen, Denmark
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 North Carolina State University, USA
 Department of Mineral Resources, Thailand
 Global Geoscience, British Geological Survey, UK
 Western Colorado University, Thailand
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 University of California, Riverside, USA
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 Geological Society of Thailand, Thailand
 Department of Mineral Resources, Thailand
 Electricity Generating Authority of Thailand (EGAT), Thailand
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 Department of Mineral Resources, Thailand
 Korea Institute of Geoscience and Mineral Resources, Republic of Korea
 Department of Mineral Resources, Thailand
 Geo-Informatics and Space technology Development Agency,
 Ministry of Science and Technology (GISTDA), Thailand
 Department of Mineral Resources, Thailand
 Coordinating Committee for Geoscience Programmes
 in East and Southeast Asia (CCOP), Thailand
 Burapha University, Chanthaburi Campus, Thailand
 Department of Mineral Resources, Thailand
 Department of Mineral Resources, Thailand
 Department of Mineral Fuels, Thailand
 Chulalongkorn University, Thailand
 Retired geophysicist, Independent Researcher, Japan
 Department of Mineral Fuels, Thailand
 Yamaguchi University, Japan
 Department of Mineral Resources, Thailand
 University of Tsukuba, Japan



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