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# A Blueprint for Data-Driven Climate Action: A Quantified Mitigation Pathway for Chiang Mai Using GHG Accounting and Spatial Analysis

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**Abstract**

This study develops a replicable, data-driven framework for subnational climate action, demonstrated through a case study of Chiang Mai Province, Thailand. The framework integrates a comprehensive greenhouse gas (GHG) inventory with spatial analysis to identify and quantify location-specific mitigation strategies. Using 2019 as the base year, total emissions were 5,387,482 $tCO_2e$ (BASIC+), dominated by stationary energy (40%) and transportation (32%). Under a Business-as-Usual scenario, emissions are projected to reach 6.35 million $tCO_2e$ by 2030, highlighting an urgent need for intervention. As a key mitigation strategy, this research conducts a detailed spatial analysis of solar rooftop potential. The findings reveal a significant opportunity: a conservative 30% adoption rate on suitable rooftops could generate approximately 2070 GWh of clean energy annually, leading to an emissions reduction of over 1 million $tCO_2e$. Crucially, this single intervention could offset 16% of the province's projected 2030 emissions. This study presents a viable pathway for subnational entities to contribute to national climate targets, offering a practical blueprint for other cities and regions globally to develop effective, evidence-based climate action plans.

**Keywords:** climate change; greenhouse gas emissions; mitigation; solar energy; sustainable cities

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## 1. Introduction

Climate change represents a profound and multifaceted environmental challenge, with direct and indirect impacts on both global ecosystems and human societies. At the international level, the Paris Agreement has served as a cornerstone for climate action, establishing a long-term goal to limit the global average temperature increase to "well below 2 °C "above pre-industrial levels, with ambitious efforts to pursue 1.5 °C [1,2]. Anthropogenic activities, primarily through rising concentrations of greenhouse gases (GHGs), are the principal drivers of this warming. Notably, urban communities are significant contributors, with the World Resources Institute estimating that cities account for over 70% of global carbon dioxide ($CO_2$) [3] emissions, mainly from energy consumption [4]. The reliance on

fossil fuels has precipitated an unprecedented climate crisis, threatening planetary stability and altering Earth's internal equilibrium [5].

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), Thailand has committed to Nationally Appropriate Mitigation Actions (NAMAs), initially focusing on the energy and transportation sectors. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report underscores the urgency of this commitment, stating that global net-zero emissions must be achieved in the early 2050s to limit warming to 1.5 °C. In response, a growing number of countries have pledged both near-term policies through their nationally determined contributions and long-term strategies, including net-zero targets [6,7]. The concept of 'net zero'—achieving an overall balance between anthropogenic GHG emissions and their removal from the atmosphere—has emerged as a central pillar of global climate policy, typically achieved through a combination of emissions reduction and offsetting schemes such as afforestation and carbon capture technologies. Several nations have formalized their net-zero ambitions. The UK was the first major economy to legislate for GHG neutrality, targeting net zero by 2050 [8]. Similarly, China has set a 2060 target, while the USA and Canada aim for 2050 [9,10]. Turkey and South Africa have also committed to a 2050 timeline as part of their Paris Agreement obligations, necessitating comprehensive energy transition roadmaps across various sectors [11,12]. India has set a more distant target of 2070, along with a commitment to reduce GHG emission intensity by 45% by 2030 [13].

Thailand has demonstrated a strong commitment to addressing climate change, aiming for carbon neutrality by 2050 and net-zero GHG emissions by 2065. These ambitious goals are being pursued through a range of national policies and strategic plans, including Thailand's Nationally Determined Contribution Roadmap on Mitigation 2021–2030, the National Adaptation Plan (NAP), and the Thailand Climate Change Master Plan 2015–2050 (TCCMP). Despite these national efforts, the pathway to net-zero remains particularly challenging for developing countries. Cities, as major drivers of GHG emissions, are crucial for effective mitigation, yet existing carbon-emission studies often focus on national [14–16] or sectoral [17,18] scales, with limited attention to local or subnational contexts. While single-city studies have proven valuable for identifying key drivers of emissions reduction [19,20], the effectiveness of such policies is often evaluated alongside co-benefits for the environment, public health, and the economy [21].

For a country like Thailand, with its 76 provinces, effective implementation of national climate goals requires tailored subnational strategies. However, existing provincial-level GHG inventories in Thailand suffer from inconsistent accounting methodologies and lack explicit statements on the unit of analysis (e.g., household versus community-wide emissions), making it difficult to formulate precise policies and mitigation actions. Chiang Mai Province, as the economic and cultural hub of Northern Thailand, presents a uniquely complex case study. It faces high growth pressures from tourism and urbanization (which drive energy and transport emissions), coupled with acute environmental conflicts, such as seasonal PM2.5 air pollution, primarily driven by activities in the AFOLU sector. The central research question guiding this study is: How can an integrated, GPC BASIC+ GHG inventory, combined with location-specific spatial analysis, be utilized to develop a quantifiable and effective mitigation pathway for Chiang Mai Province that significantly exceeds the policy effectiveness of previous national or sectoral assessments? Therefore, this study addresses a critical methodological gap by developing a detailed GHG inventory for Chiang Mai Province using the comprehensive BASIC+ framework of the Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories (GPC). We establish a 2019 base-year inventory and project emissions under Business-as-Usual (BAU) scenarios through 2030. Furthermore, this study integrates a location-specific spatial suitability

assessment for solar panel installation, offering an integrated 'inventory-to-action' blueprint essential for managing a complex regional economy like Chiang Mai.

## 2. Materials and Methods

The steps for this study follow those of the GPC [22].

### *2.1. Site and Characteristics of the Study Area*

Chiang Mai Province is located in northern Thailand. It has an area of 20,170 square kilometers, making it the largest area in the North and the second-largest in Thailand, after Nakhon Ratchasima Province. In 2019, the data from the Office of Agricultural Economics [23] in Chiang Mai disclosed that land utilization for forests was 1,540,376.96 ha, accounting for 76.61% of the total area, with land utilization for agricultural purposes at 292,890.40 ha (14.57%), and for non-agricultural purposes at 177,438.4 ha (8.82%). Within the farm area, the largest share was allocated to fruit trees at approximately 113,253.92 hectares, accounting for almost 40% of agricultural land, followed by paddy fields at about 86,631.84 hectares (30%) (Figure 1).

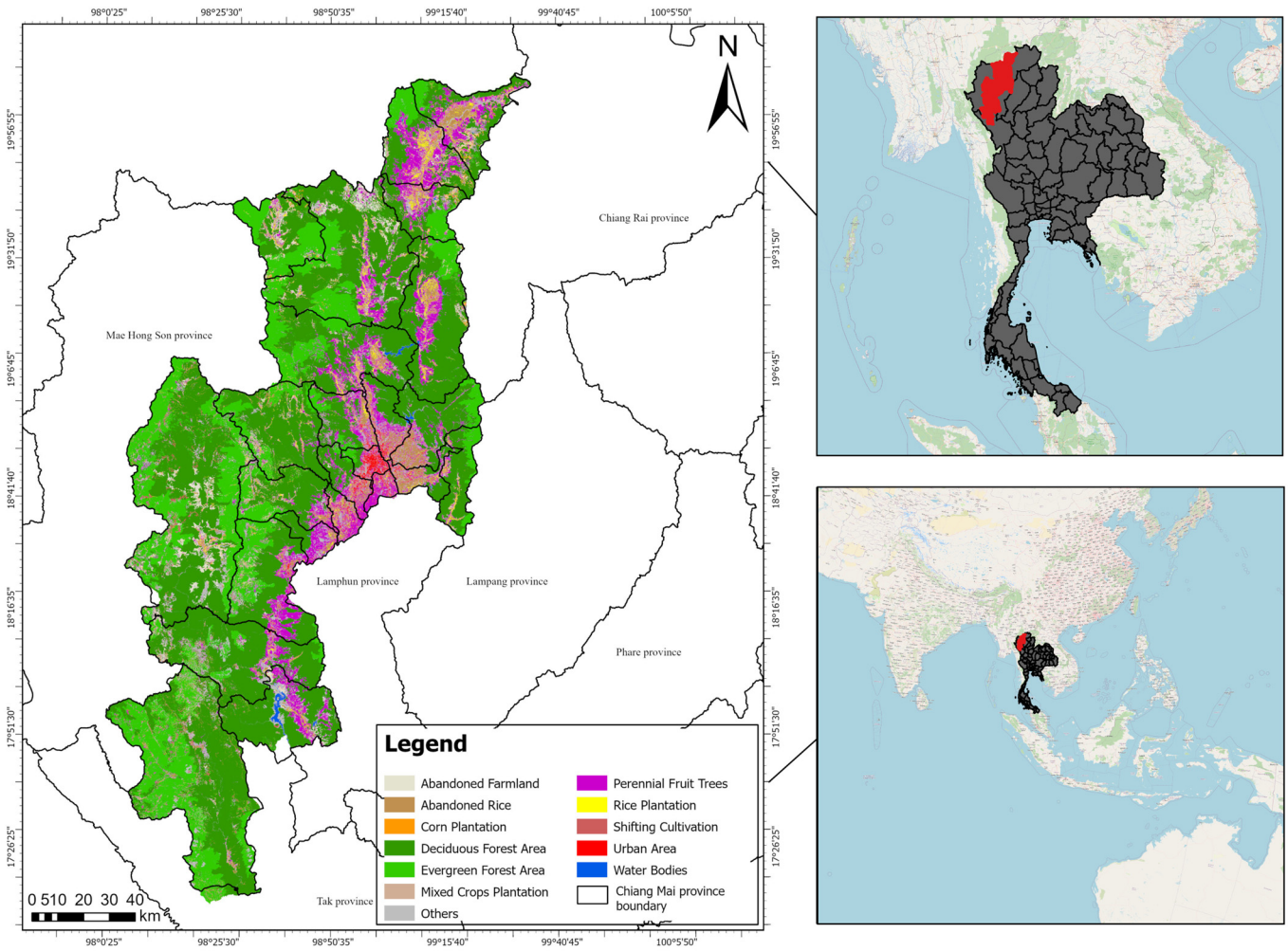


**Figure 1.** Land Utilization in Chiang Mai Province in 2019, with an inset showing its location in Southeast Asia and Thailand. The red area in the inset map of Thailand indicates Chiang Mai Province.

According to the National Statistical Office [24], the total population in 2019 was approximately 1,779,254 people, consisting of 861,692 males and 917,562 females, with 579,380 households and a population density of 88.49 persons per square kilometer. Most of the population was in the labor force (58.81%), young children (0–14 years) made up

13.99%, and the elderly (60 years and over) accounted for 18.75%. The data indicated a trend of population growth, especially within the labor force, increasing by 0.38% per year. The Gross Provincial Product (GPP), based on 2019 prices, was 264.067 billion baht (roughly 7.23 billion USD), with the GPP per capita (per person income) at 146,433 baht annually. The primary sector of production was dominated by the service industry, valued at 185.527 billion baht, or 70.25% of the total GPP. In comparison, the agricultural sector was valued at 51.951 billion baht, or 19.67%, while the industrial sector was worth 26.590 billion baht, or 10.07%.

### *2.2. GHG Emission Assessment*

#### 2.2.1. Setting the Inventory Boundary

The GHG emissions assessment of Chiang Mai Province was conducted within its geographic boundary. This boundary includes the entire administrative area of Chiang Mai Province, covering the urban core, all peri-urban areas, and rural or forested zones, totaling 20,170 square kilometers. The assessment and reporting of GHG emissions were guided by five key principles: relevance, completeness, consistency, transparency, and accuracy [25].

GHG emission sources are categorized for GHG reporting by GPC into six main sectors: (1) Stationary Energy, (2) Transportation, (3) Waste, (4) Industrial Process and Product Use (IPPU), (5) Agriculture, Forestry, and Other Land Use (AFOLU), and (6) any other emissions outside the geographic boundary that result from city activities may be reported separately [26].

A total of seven types of greenhouse gases were considered, including carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride ($SF_6$), and nitrogen trifluoride ($NF_3$) [27]. These seven gases were selected because they are part of the comprehensive list of Kyoto Protocol gases officially mandated and tracked by the Thailand Greenhouse Gas Management Organization (TGO) for national and subnational reporting. By focusing on this set, the inventory ensures full comparability and aligns with Thailand's Nationally Determined Contribution (NDC) and the IPCC Guidelines for National and Subnational Inventories. Minor or emerging gases are not included because they are not currently quantified or prioritized within the national greenhouse gas accounting framework, as their contribution to the country's total emissions is negligible.

All emissions are categorized into three reporting scopes to cover all activities both inside and outside the city boundary: Scope 1 includes direct GHG emissions from sources within the city; Scope 2 involves indirect emissions from the use of grid-supplied electricity, heat, steam, and cooling within the city; Scope 3 accounts for all other indirect GHG emissions that occur outside the city as a result of activities within it [22]. These three scopes help organize emissions and avoid double-counting [28].

This inventory acknowledges potential methodological limitations in measuring indirect emissions. Specifically, Scope 3 emissions, while important for completeness, often rely on proxy data and allocation factors (e.g., transboundary transport and aviation), which introduce more uncertainty than direct Scope 1 and Scope 2 measurements. Additionally, although the geographic boundary covers the entire province, the level of detail in some activity data—particularly in remote and rural areas—may vary, limiting the ability to accurately reflect the spatial variation in emissions outside the main urban center. This warrants caution when interpreting disaggregated policy impacts.

In accordance with the GPC guidelines, the city should report GHG emissions annually, using activity data collected over a 12-month calendar period. Although some government agencies in Thailand collect data annually from 1 October to 30 September, GHG assessment data is based on the calendar year. As a result, the one-year data may span two fiscal years.

However, the data must be verified for accuracy before use. This research collected data from 2017 to 2022, with the base year from 1 January 2019, to 31 December 2019. Data from earlier years was also used to forecast GHG emission trends in Chiang Mai. The base year was chosen as the period before the COVID-19 outbreak. In line with the GPC, the base year was selected to reflect typical activities within the city's boundaries to accurately represent baseline GHG emissions.

#### 2.2.2. Data Collection

Research shows that the accounting method used for greenhouse gases (GHGs) can greatly affect the outcomes of urban GHG inventories [29,30]. The chosen approach may cause certain emission sources to be overlooked or underestimated [27], highlighting the need for accurate GHG reporting. These reports help identify different emission sources within a city, guiding targeted efforts to cut emissions from the biggest contributors. Evaluating urban GHG emissions is difficult because assessors cannot directly measure the total GHG amount. Instead, inventory data are often based on calculations or secondary sources. It is important to distinguish between two key terms: emissions and inventories. Emissions refer to the amount of GHGs released from specific sources, like an economic sector or household, and from activities such as fuel burning or industrial processes [31]. An inventory is a systematic and thorough compilation of all GHG emissions within a set boundary, offering a complete view of a city's GHG emissions.

Data collection of GHG emissions or GHG inventory data within the city boundary involves several sub-activities in each relevant sector, where assessors must gather all necessary data for each sub-activity. The stationary energy sector is considered the largest source of GHG emissions, mainly stemming from fuel combustion and leaks during production, storage, and transportation. According to GHG emissions assessments following GPC guidelines, activities in the stationary energy sector are divided into eight sub-activities: (1) Residential buildings; (2) Commercial and institutional buildings and facilities; (3) Manufacturing industries and construction; (4) Energy generation supplied to the grid; (5) Agriculture, forestry, and fishing activities; (6) Non-specified sources; (7) Fugitive emissions from mining, processing, storage, and transportation of coal; and (8) Fugitive emissions from oil and natural gas systems.

Transportation includes GHG emissions from fuel combustion, categorized by type such as gasoline, diesel, natural gas, and aviation fuel. The GHG emissions assessment evaluated overall transportation within and between the cities. When using GPC to assess GHG emissions, it can be divided into five categories: (1) On-road transportation, (2) Railways, (3) Waterborne transportation, (4) Aviation, and (5) Off-road transportation.

On-road transportation, railways, and water navigation occur both inside and outside the city. In this study, the allocation uses the induced activity method, as guided by GPC. The models commonly used in U.S. cities track the origin and destination of each trip, providing a detailed view of travel patterns. To fairly share responsibility for emissions from transboundary travel, cities can apply an origin-destination allocation approach, where 50% of the emissions from each trip (excluding those simply passing through) are assigned to the originating and destination cities. The Chiang Mai Land Transport Office collected data on public on-road transportation, including origin-destination routes in Chiang Mai Province, round-trip distances, vehicle types, annual trip counts, fuel types, vehicle fuel consumption rates in liters per kilometer, and the distance each vehicle traveled per trip (calculated as 50% for the provincial area and 50% for non-provincial areas, multiplied by the number of trips and fuel consumption to estimate diesel use). Data on railways was gathered from the total amount of oil fuel used at the fuel dispenser by the State Railway of Thailand (STR) for fuel allocation within and outside the city. Waterborne navigation data came from

the Marine Department, including types and numbers of boats, trips, navigation times (minutes), fuel types, and fuel consumption rates (liters/hour), with fuel use calculated by multiplying the number of trips, navigation time, and fuel rate, then dividing by 60 to convert minutes to hours. Aviation data, covering domestic and international flights, was obtained from Chiang Mai International Airport, including aircraft types, flight counts, and the associated GHG emissions produced by each aircraft type.

Waste includes community and industrial waste, such as solid waste or wastewater with organic components. When waste stays in the environment for a long time, the decomposing organic material emits certain greenhouse gases (GHGs), like carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). Waste management can take place both inside and outside the city. According to GPC guidelines, GHG emissions assessments are divided into four categories: (1) solid waste disposal; (2) biological waste treatment; (3) incineration and open burning; and (4) wastewater treatment and discharge.

GHGs released through Industrial Process and Product Use (IPPU) stem from industrial activities, product applications, and non-energy uses of fossil fuels, such as lubricants. According to the methodologies established by GPC, these can be categorized into two groups: industrial process and product use. Industrial processes include sectors like mining, chemicals, and metals. Meanwhile, product use encompasses applications such as solvents, electronics, and fluorine-based substances that harm the ozone layer—examples include hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Agriculture, Forestry, and Other Land Use (AFOLU) includes GHG emissions from activities related to farming, forestry, and land management, which release key greenhouse gases like carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). According to GPC guidelines, these sources are divided into categories such as livestock, land use, and other broad sources, including non-$CO_2$ emissions on land.

The GPC offers basic principles for emission calculation based on IPCC guidelines but does not specify a particular methodology. As a result, cities need to gather activity data and emission factors depending on what data is available and how closely it matches their country's reported emissions [32].

Therefore, the accuracy assessment in this study is based on activity data collected from various sources. While some data were used directly for calculations, others required allocation, such as when transitioning from national to provincial-level data. This research adopts the accuracy assessment approach outlined in Table 1, which provides a straightforward, adaptable framework for evaluating data quality. This methodology is particularly suitable for assessing data accuracy in any province in Thailand.

**Table 1.** Data Accuracy Levels and Scoring.

| Score | Level | Description |
|---|---|---|
| 5 | A | High-Quality Provincial Data: Data are derived from official statistics or reports specific to the province and are published annually. |
| 4 | B | Official Provincial Data: Data come from official government reports or surveys specific to the province but are not published on an annual basis. |
| 3 | C | Calculated Data (High Reliability): Data are obtained through simple calculations based on high-quality provincial data (Levels A and/or B), ensuring strong reliability. |
| 2 | D | Processed Data (Medium Reliability): Data have been processed from a combination of high-quality sources (Levels A and B), with some level of associated uncertainty. |
| 1 | E | Extrapolated/Composite Data (Low Reliability): Data are sourced from academic literature, external parameters, or a combination of diverse sources, making them the least reliable. |

2.2.3. GHG Emissions Calculation

This study calculated GHG emissions following the GPC guidelines, which are based on the IPCC methodology. The total GHG emissions were obtained by adding emissions from various sectors, according to the main principle shown in Equation (1) [29].

$$GHG_i = \sum(A_i \times EF_i) \quad (1)$$

Activity data ($A_i$) refers to the data associated with the local GHG emission activities during a certain period of time. Activity data can be collected from measurements, documents, or reports from government agencies, state enterprises, private organizations, and other concerned agencies. The principles of activity data collection include (1) creating a collection system for activity data to ensure consistency of data preparation and revision, (2) prioritizing the collection of activity data, e.g., the priority of emissions capacity or change in GHG emissions or uncertainty of activity data, (3) studying the activities and principles for data collection regularly for an effective GHG data development, and (4) collaborating with activity data collectors directly for data compliance and consistency. The emission factor ($EF_i$) quantifies the amount of GHG emitted per unit of activity data, with the unit of kilograms of carbon dioxide equivalent per unit of activity data ($kgCO_2e$/unit). The emission factors used in this research were primarily sourced from the Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [33], with additional values from the IPCC's Fifth Assessment Report.

The GHG emissions from the energy sector are categorized into Scope 1 and Scope 2 emissions. Scope 1 emissions, derived from stationary fuel combustion, are calculated using Equation (2). This method multiplies the volume or mass of fuel consumed by its specific emission factor, which is sourced from IPCC guidelines.

$$GHG_f = (A_f \times EF_f) \times 10^{-3} \quad (2)$$

where $GHG_f$ denotes emissions from stationary combustion ($tCO_2e$); $A_f$ is the amount of fuel consumed (in units); and $EF_f$ is the fuel-specific emission factor ($kgCO_2e$/unit). Similarly, Scope 2 emissions from grid-supplied electricity are calculated using a comparable approach detailed in Equation (3). This calculation uses the amount of electricity consumed and an electricity-specific emission factor. In this case, the factor is sourced from TGO, valued at 0.4999 $kgCO_2e$/kWh.

$$GHG_{elec} = (A_{elec} \times EF_{elec}) \times 10^{-3} \quad (3)$$

where $GHG_{elec}$ denotes emissions from electricity consumption ($tCO_2e$); $A_{elec}$ is the electricity consumption (kWh); $EF_{elec}$ is the emission factor for electricity ($kgCO_2e$/kWh).

Emissions from solid waste disposal are calculated using Equation (4). This formula quantifies the total methane ($CH_4$) generated from waste, accounting for any recovered methane and an oxidation factor. The result is then converted to carbon dioxide equivalent ($CO_2e$) using the 100-year Global Warming Potential (GWP) of methane, which is 28.

$$GHG_{waste} = A_{SW} \times \left[\sum_x \left(CH_4gen_{(x,T)} - R_T\right)\right] \times (1 - OX_T) \times 28 \quad (4)$$

where $GHG_{waste}$ are the total emissions from waste management ($tCO_2e$); $A_{SW}$ is the mass of solid waste (tonnes); $CH_4$ gen is the quantity of methane produced ($tCH_4$/year); $R_T$ is the methane recovery in year T; $OX_T$ is the annual oxidation factor. Furthermore, emissions from wastewater management are calculated separately using the GPC guidelines (Equation (5)). This calculation is designed to comprehensively estimate emissions from

the total volume of wastewater generated (including both treated and untreated effluent). The calculation considers the total volume of water consumption ($V_i$, sourced from the Provincial Waterworks and groundwater data) and its Biochemical Oxygen Demand (BOD) concentration, along with a default maximum methane-producing capacity (0.6 $kgCH_4/kg$ BOD), and a methane correction factor ($MCF_j$) specific to the treatment system.

$$GHG_{WW} = (V_i \times BOD_i) \times 0.6 \times MCF_j \times 28 \quad (5)$$

where $GHG_{WW}$ represents the GHG contribution from wastewater management ($tCO_2e$); $V_i$ is the monthly volume of wastewater ($m^3$). $BOD_i$ is the BOD concentration (mg/L); 0.6 is the default value for maximum methane-producing capacity ($kgCH_4/kg$ BOD); $MCF_j$ is the system-specific methane correction factor. Emissions from the agricultural sector are calculated in accordance with GPC guidelines. Enteric fermentation emissions are determined using Equation (6), which multiplies the number of animals by an emission factor.

$$GHG_{ent,CH_4} = N_{(T)} \times EF_{(Ent,T)} \times 10^{-3} \times 28 \quad (6)$$

where $GHG_{ent,CH_4}$ is the enteric fermentation methane emissions ($tCO_2e$); $N_{(T)}$ is the livestock population (head); $EF_{(Ent,T)}$ is the enteric fermentation emission factor (kg of $CH_4$ per head per year); 28 is the GWP100 of methane. Emissions from manure management are calculated separately for $CH_4$ and nitrous oxide ($N_2O$) using Equations (7) and (8), respectively.

$$GHG_{man,CH_4} = \left(N_{(T)} \times EF_{(T)}\right) \times 28 \times 10^{-3} \quad (7)$$

where $GHG_{man,CH_4}$ is the manure management methane emissions ($tCO_2e$); $EF_{(T)}$ is the manure management emission factor ($kgCH_4$ per head per year).

$$GHG_{man,N_2O} = \left\lceil \sum_s \left( \sum_T (N_T \times Nex_T \times MS_{T,S}) \times EF_s \right) \right\rceil \times \frac{44}{28} \times 10^{-3} \times 298 \quad (8)$$

where $GHG_{man,N_2O}$ is the manure management nitrous oxide emissions ($tCO_2e$); $N_T$ is the number of animals in a specific livestock category T; $Nex_T$ is the annual nitrogen (N) excretion per animal for livestock category T (kgN per animal per year). $MS_{T,S}$ is the fraction of total annual nitrogen excretion from livestock category T that is managed in a specific manure management system S. 298 is the GWP100 of nitrous oxide, which is used to convert the emissions to a carbon dioxide equivalent ($CO_2e$).

Finally, the calculation of GHG emissions from the forestry sector accounts for carbon sequestration by above-ground biomass. This uptake is subsequently subtracted from the gross emissions to yield the net GHG emissions for the area.

#### 2.2.4. GHG Emissions Prediction

The projection of future GHG emissions is the usual GHG emissions assessment when the city does not implement GHG mitigation measures or follows Business-As-Usual (BAU). This can be considered by projecting future activity data from previous activity data. The forecasting utilized a linear model based on the longest available historical time series data for each activity, ranging from 2014 to 2022, depending on the specific data source (e.g., fuel consumption, electricity use). This approach ensures the projected growth rate ($GR_i$) reflects the actual observed trend of that specific activity. The linear equation for identifying the growth rate of activity data is given by Equation (9).

$$AF_i = A_i \times GR_i \quad (9)$$

where $AF_i$ is activity data of i in the future (unit); $A_i$ is the activity data in the base year (unit); $GR_i$ is the activity growth rate, the projection of future activity data will be considered as if the provincial administration still implemented the same activities as in the present, except where there is an indicator for changes in technologies or processes that contribute to more GHG emissions. Upon the complete projection of activity data, the amount of GHG emissions in the future can be predicted using Equation (1).

The prediction of GHG amount is based upon an emission factor with a constant value, or in other words, a value equivalent to the base year, irrespective of changes in EF values of such activity. According to BAU, the amount of provincial GHG emissions will be estimated for 2019–2030, allowing the results to be used for planning provincial GHG reduction in conformity with the Thailand GHG Reduction Roadmap, which aims to reduce GHG emissions by 30–40% by 2030. Forecasting greenhouse gas (GHG) emissions is vital for developing effective energy policies and meeting international climate change targets. The accurate projection of future emissions is essential for setting and achieving reduction goals [34,35].

Various methods are available for forecasting emissions from a base year to a target year. Some studies, such as [36], rely on simple linear trend extrapolation based on historical inventory data. More advanced techniques, like those used in [37], employ linear and logarithmic models to project emissions for specific sectors such as energy, industry, and agriculture, while considering factors like population and economic growth. Reference [38] utilized linear regression to estimate emissions in Delhi, India, including variables like population and GDP. Similarly, [39,40] applied linear regression and gray prediction methods, respectively, to forecast energy-related carbon dioxide ($CO_2$) emissions. Gray prediction models, often chosen for forecasting with limited data, have also been used by [41,42] to project Turkey's emissions based on future energy policies.

Given the limited availability of detailed historical and activity-specific data for Chiang Mai Province, a linear forecasting approach was selected. This method aligns with similar studies [37,39] that have successfully applied linear models under data-constrained conditions, demonstrating their effectiveness for future emission projections. Crucially, the growth rate ($GR_i$) for each activity data ($AF_i$) was derived directly from these available historical time series data. While we did not use GPP or population as direct input variables in the regression model due to the data limitations and the choice of the linear forecasting approach, these historical activity trends implicitly capture the influence of Chiang Mai's economic and demographic changes, such as the growth in the service sector (impacting commercial energy) and population growth (impacting residential energy and transport demand). This method ensures that the BAU scenario is grounded in the observed local realities.

#### 2.2.5. Solar Energy for GHG Mitigation

This study evaluates the suitability of areas for installing solar panels using a two-step method. The first step involves identifying and analyzing the main factors that affect site suitability through a comprehensive review of existing literature. The studies examined indicate that site suitability relies on various physical land features. Based on this, six essential factors were selected for analysis: slope, elevation, aspect (sunlight direction), average solar radiation, average temperature, and proximity to major roads. A geospatial database was then developed using Geographic Information System (GIS) technology.

In the second step, spatial analysis was conducted using the Weighted Overlay Analysis method. This technique calculates the overall suitability score (S) as the sum of the products of each factor's weight (W) and its corresponding rating (R), using Geographic Information System (GIS) software (ArcGIS Pro, version 3.4.0). The methodology fol-

lows the approach proposed by Khiaosalap and Tongdenok (2015) [43] (Equation (10)). Elevation data (ALOS DEM 2006–2011) and historical temperature and radiation data (ERA5-Land/Solargis 2007–2024) primarily reflect conditions prior to the base year (2019). We acknowledge that this introduces minor uncertainty, as changes in building stock and forest cover since 2011 may alter local solar exposure. However, since large-scale topographical features (Elevation and Slope) and macro-climatic averages (Temperature and Radiation) remain largely constant, the overall validity of the macro-level suitability assessment is preserved.

$$S = (W_1R_1) + (W_2R_2) + (W_3R_3) + \cdots + (W_nR_n) \quad (10)$$

The factor weights influencing the potential of solar panel installation sites were determined through a Systematic Literature Review (SLR). The SLR examined the frequency and emphasis given to each physical criterion in relevant geospatial solar planning literature to establish the relative importance of each factor. The analysis identified six major factors, which were then assigned the following percentage weights: solar radiation intensity (35%), average temperature (20%), slope (15%), elevation (10%), distance from main roads (10%), and aspect (10%). These factors were classified and rated on a four-level suitability scale ranging from 1 (least suitable) to 4 (most suitable).

The analysis intentionally focused on these physical and infrastructural factors (including 'Distance from Road' as a proxy for accessibility) to establish the province's technical potential. Non-physical factors, such as local land price, specific zoning regulations, and grid interconnection capacity, were excluded from this macro-level suitability assessment. This exclusion was necessary due to the high variability and lack of consistent, province-wide spatial data for these socio-economic criteria. The resulting map therefore represents the physically suitable land, which serves as a foundational baseline for subsequent, more detailed economic and policy-based feasibility studies.

For data processing, all factors were resampled to a consistent spatial resolution of 250 m to ensure uniformity across datasets with different original resolutions, balancing precision and computational efficiency. The composite suitability scores were then reclassified using the Natural Breaks method [44], which captures the natural grouping of the data, to establish the final suitability range. The weighted scores are presented in Table 2.

**Table 2.** Weighting and Rating of Each Factor.

| Factor | Classification | Weighting | Rating | Reference |
|---|---|---|---|---|
| Solar Radiation Intensity | >5 kWh/m$^2$/day | 35 | 4 | [45] |
| | 4–5 kWh/m$^2$/day | | 3 | |
| | 3–4 kWh/m$^2$/day | | 2 | |
| | <3 kWh/m$^2$/day | | 1 | |
| Average Temperature | 25–30 °C | 20 | 4 | [45] |
| | 30–35 °C | | 3 | |
| | <25 °C | | 2 | |
| | >35 °C | | 1 | |
| Slope | <5% | 15 | 4 | [46] |
| | 5–15% | | 3 | |
| | 15–30% | | 2 | |
| | >30% | | 1 | |
| Elevation | <500 m | 10 | 4 | [46] |
| | 500–1000 m | | 3 | |
| | 1000–1500 m | | 2 | |
| | >1500 m | | 1 | |

**Table 2.** *Cont.*

| Factor | Classification | Weighting | Rating | Reference |
|---|---|---|---|---|
| Distance from Road | <500 m | 10 | 4 | [47] |
| | 500–1000 m | | 3 | |
| | 1000–2000 m | | 2 | |
| | >2000 m | | 1 | |
| Aspect | South/Southwest | 10 | 4 | [47] |
| | West | | 3 | |
| | East | | 2 | |
| | North | | 1 | |

### 2.3. Data Quality and Uncertainty Assessment

Due to data limitations at the sub-national level, certain activity data, such as lubricant consumption and other small-source emissions, were estimated using the GPP allocation method based on the national inventory. We acknowledge that this allocation process introduces greater uncertainty than direct measurements. This approach assumes a linear relationship between provincial GPP and national consumption, which may not fully capture local structural specificities. However, given that these sources generally account for a small share of total emissions, their overall impact on the final inventory remains limited.

Furthermore, this study acknowledges the uncertainty inherent in the Scope 2 emissions calculation. We utilized the official, national-average grid emission factor (0.4999 $kgCO_2e/kWh$) published by TGO. This single factor represents an annual average and thus does not capture real-time (hourly) variations in the grid's carbon intensity (e.g., higher emissions at night vs. lower emissions midday). Moreover, as a national average, it may not perfectly reflect the specific regional electricity mix supplied to Chiang Mai. However, employing the official TGO-published national factor is the standard, GPC-compliant practice for sub-national inventories in Thailand, ensuring consistency, comparability, and alignment with national reporting. We prioritized using High-Quality Provincial Data (Score 4 and 5, as detailed in Table 1) for the largest emission sources (Stationary Energy and Transportation) to maintain the overall integrity of the GHG inventory.

### 2.4. Data Availability and Transparency

To improve research reproducibility and transparency, the access channels for the foundational datasets used in this study are described as follows. Most activity data, including energy consumption (Department of Energy Business (DOEB)), agricultural statistics (Office of Agricultural Economics (OAE)), forest areas (Royal Forest Department), and pollution data (Pollution Control Department (PCD)), were sourced from publicly accessible online portals and annual statistical reports published by the respective government agencies. Key datasets for the mitigation analysis were accessed via publicly available platforms, including building footprints and elevation models (ALOS DEM) from Google Earth Engine (GEE) and solar radiation data from Solargis (CC BY-SA 4.0 license). Specific high-resolution activity data that are not publicly available, such as infectious waste figures (Chiang Mai Provincial Public Health Office) and waste disposal quantities from neighboring provinces (Tha Chiang Thong Co., Ltd., Chiang Mai, Thailand), were obtained through formal data requests and direct interviews with the relevant organizations.

## 3. Results

### 3.1. GHG Inventory Data

Identifying GHG emission sources in Chiang Mai Province includes the stationary energy sector, activities within Scope 1 caused by fuel use in buildings, industries, agriculture,

forestry, fishing activities, and fugitive emissions from oil systems. The electricity used by Provincial Electricity Authority (PEA) in certain city sub-sectors is in Scope 2. Scope 3 includes GHGs released from energy use beyond Scope 1 and Scope 2, as well as energy loss in transmission lines.

Within the transportation sector, activities include on-road transportation, railways, waterborne navigation, aviation, and off-road transportation. On-road and railway transportation is within and between cities. Waterborne navigation includes small boats used in the tourism sector. Regarding aviation, Chiang Mai International Airport offers both domestic and international routes. Off-road transportation is available in various sectors, including agriculture, industry, tourism, and services.

The waste sector consists of waste generated in the city, which is buried in landfills. Waste is also brought from other areas in Chiang Rai and Lamphun City for landfill management. In addition, some waste generated in the city is disposed of through biological treatment. However, hazardous and infectious waste generated in the city is managed through incineration outside Chiang Mai Province. Wastewater is treated in the city. Within the IPPU sector, there are no existing industrial production processes in Chiang Mai Province that result in direct greenhouse gas emissions. However, emissions are generated from the use of industrial products, particularly lubricants. For the AFOLU sector, activities are associated with livestock, changing land use in forests and agricultural areas, rice cultivation, open burning in forests and agricultural areas, and using fertilizers for soil supplements and maintenance.

To obtain the GHG emission activity data in this research, data were collected from various relevant agencies and departments in Chiang Mai Province through annual statistical reports, questionnaires, or interviews. Data are sourced from various ministerial, provincial, or organizational agencies. The GHG inventory and valid data sources are shown in Table 3, along with the assessed data quality level for each data category. In this regard, data on fuel use in stationary energy and transportation were compiled with the report of oil fuel sales in each province (classified by business categories) by the Department of Energy Business (DOEB).

**Table 3.** GHG inventory and the accuracy level of Chiang Mai Province in 2019.

| Sectors and Sub-Sectors | Data | Quantity | Unit | Level | Score |
|---|---|---|---|---|---|
| **Stationary Energy** | | | | | |
| Residential Building | LPG | 13,748,761 | kg | A | 5 |
| Commercial and institutional buildings and facilities | LPG | 54,987,711 | kg | A | 5 |
| | Diesel | 6,281,890 | L | A | 5 |
| | Gasohol 91, 95 | 888,737 | L | A | 5 |
| | Fuel Oil | 456,686 | L | A | 5 |
| Manufacturing industries and construction | LPG | 660,770 | kg | A | 5 |
| | Diesel | 9,315,905 | L | A | 5 |
| | Biodiesel B10 | 233,050 | L | A | 5 |
| | Biodiesel B20 | 936,000 | L | A | 5 |
| | Fuel Oil | 7,469,567 | L | A | 5 |
| Agriculture, forestry, and fishing activities | Diesel | 4,375,988 | L | A | 5 |
| Non-specified sources | Diesel | 12,820,592 | L | A | 5 |
| | Gasoline | 240,261 | L | A | 5 |
| | Gasohol 91, 95 | 51,850 | L | A | 5 |
| | Fuel Oil | 1,077,623.04 | L | A | 5 |

**Table 3.** *Cont.*

| Sectors and Sub-Sectors | Data | Quantity | Unit | Level | Score |
|---|---|---|---|---|---|
| Fugitive emissions from oil systems | Oil | 42,920 | $m^3$ | B | 4 |
| Residential Building | Electricity | 1,299,972,610 | kWh | B | 4 |
| Commercial/institutional buildings/facilities | Electricity | 888,206,667 | kWh | B | 4 |
| Manufacturing industries and construction | Electricity | 1,212,024,773 | kWh | B | 4 |
| Agriculture, forestry, and fishing activities | Electricity | 19,581,766 | kWh | B | 4 |
| Non-specified sources | Electricity | 126,993,360 | kWh | B | 4 |
| **Transportation** | | | | | |
| On-road transportation | Diesel | 269,740,895 | L | C | 3 |
| | Biodiesel B10 | 196,660 | L | A | 5 |
| | Biodiesel B20 | 9,524,383 | L | A | 5 |
| | Gasoline | 9,346,817 | L | C | 3 |
| | Gasohol E85 | 201,886,636 | L | A | 5 |
| | Gasohol E20 | 11,425,552 | L | A | 5 |
| | Gasohol 91,95 | 68,256,684 | L | A | 5 |
| | LPG | 11,018,470 | kg | A | 5 |
| | NGV | 257,000,000 | scf | A | 5 |
| Railway | Diesel uses outside the city | 27,623,804 | L | C | 3 |
| | Diesel uses within the city | 881,754 | L | C | 3 |
| | Diesel uses outside the city | 881,754 | L | C | 3 |
| Water-borne transportation | Gasoline uses within the city | 98,502 | L | C | 3 |
| | Gasoline uses outside the city | 20,090 | L | C | 3 |
| Aviation | Jet fuel (Domestic) | 53,308 | flights | B | 4 |
| | Jet fuel (International) | 23,368 | flights | B | 4 |
| **Waste** | | | | | |
| Solid waste generated within the city disposed in landfills in the city | Quantity of solid waste | 422,826 | tonnes | A | 5 |
| Solid waste generated within the city disposed in open dumps in the city | Quantity of solid waste | 36,033 | tonnes | A | 5 |
| Solid waste generated outside the city disposed in landfills in the city | Quantity of solid waste | 16,660 | tonnes | B | 4 |
| Solid waste generated in the city incinerated | Quantity of infectious waste | 2145 | tonnes | B | 4 |
| outside the city | Quantity of Hazardous waste | 45 | tonnes | B | 4 |
| Wastewater generated in the city treated in | Volume of tap water | 55,449,408 | $m^3$ | B | 4 |

**Table 3.** *Cont.*

| Sectors and Sub-Sectors | Data | Quantity | Unit | Level | Score |
|---|---|---|---|---|---|
| the city | Volume of groundwater | 13,045,465 | $m^3$ | B | 4 |
| | Volume of wastewater input treatment plant | 8,028,352 | $m^3$ | B | 4 |
| **IPPU** | | | | | |
| Product Use | Amount of lubricant Use | 5,919,142 | L | C | 3 |
| **AFOLU** | | | | | |
| Livestock | Dairy cow | 48,430 | head | A | 5 |
| | Other Cattle | 132,603 | head | A | 5 |
| | Buffalo | 46,437 | head | A | 5 |
| | Sheep | 149 | head | A | 5 |
| | Goats | 1178 | head | A | 5 |
| | Horses | 372 | head | A | 5 |
| | Swine | 360,628 | head | A | 5 |
| | Deer | 71 | head | A | 5 |
| | Elephant | 539 | head | A | 5 |
| | Chicken | 5,760,463 | head | A | 5 |
| | Duck | 48,765 | head | A | 5 |
| | Goose | 943 | head | A | 5 |
| | Quail | 61,131 | head | A | 5 |
| | Ostrich | 6 | head | A | 5 |
| Land | Forest Land | 1,540,377 | ha | A | 5 |
| | Cropland | 273,160 | ha | A | 5 |
| Aggregate sources and non-$CO_2$ emissions sources on land | Urea fertilizer | 47,314 | tonnes | B | 4 |
| | Rice cultivation | 101,920 | ha | A | 5 |
| | Area burnt in forest Land | 5879 | ha | A | 5 |
| | Area burnt in cropland | 2011 | ha | C | 3 |

Liquefied Petroleum Gas (LPG) is utilized in residential, commercial, and institutional buildings and facilities, manufacturing industries, and construction, as well as in on-road transportation. The largest share of LPG consumption, approximately 68%, occurs in commercial and institutional buildings and facilities, followed by 17% in the residential sector, primarily for cooking purposes. LPG is also used in the transport sector, accounting for about 14% of total consumption, especially in vehicles such as trucks used for transporting raw materials and goods, due to its lower cost compared to conventional fuels. Lastly, LPG use in the industrial sector accounts for only 0.82% of total LPG consumption.

Approximately 98% of gasoline was used for on-road transportation. For fuel oil, 83% was used in the industrial sector, 12% in commercial and institutional buildings and facilities, and 5% in other sectors. In addition, diesel B10 (10% blend of biodiesel with 90% diesel) was used in the industrial sector and for on-road transportation, accounting for 54.23% and 45.77%, respectively. Regarding diesel B20 (a 20% blend of biodiesel with 80% diesel), 91.05% was used for on-road transportation, and 8.95% was used in the industrial sector. Generally, gasohol 91 and 95 (10% blend of ethanol with 90% gasoline 91/95) was used for on-road transportation (99.54%), and the remaining amount was used in commercial and institutional buildings and facilities. Moreover, gasohol E20 and E85 (20% and 85% blend of ethanol with gasoline) were all used for on-road transportation. On-

road transportation, railways, and waterborne navigation were found within and outside the city.

Public on-road transportation, railways, and waterborne navigation were found within and outside the province or city and are calculated from the induced activity method. The aviation data were from the Chiang Mai International Airport, categorized into domestic and international flights.

The data collection in the waste sector consisted of the amount of waste, waste management methods, and waste components according to the annual report of the Pollution Control Department (PCD). According to the data collection, Chiang Mai has managed solid waste generated in its area through landfills and open dumps, accounting for 92.15% and 7.85% of the solid waste, respectively. Moreover, waste from neighboring provinces, such as Lamphun and Chiang Rai, was accepted for management via landfills in this area. In both cases, the amount of waste likely exceeded the disposal capacities of Lamphun and Chiang Rai, and this excessive amount was then transported for further disposal in Chiang Mai. In the base year, the total amount of waste transported from Lamphun and Chiang Rai was approximately 16,600 tonnes. These data were obtained through an interview with Tha Chiang Thong Co., Ltd., a company in charge of disposing of waste in those two provinces. According to the GPC Guideline, waste transported into the city from outside areas for disposal must be reported under Scope 1. However, the associated GHG emissions from this waste are not required to be included in the city's GHG inventory under the BASIC or BASIC+ reporting frameworks.

Data on infectious waste from hospitals, healthcare centers, and clinics in the service area were collected through interviews with the Chiang Mai Provincial Public Health Office. The exact process was applied to data collection for hazardous waste, in collaboration with the Chiang Mai Provincial Administrative Organization. In fact, infectious waste and hazardous waste managed by incineration outside the province in the base year were equal to 2145 tonnes and 45 tonnes, respectively. Regarding wastewater management in the provincial area, it was found that 68% of wastewater was discharged untreated, and 12% treated through the aerated lagoon system. The water consumption data comprises the volume of piped water supplied by the Chiang Mai Provincial Waterworks Authority and groundwater usage data provided by the Provincial Office of Natural Resources and Environment, Chiang Mai. In addition, data on the aerated wastewater treatment system—including influent wastewater volume, BOD, and COD values—were obtained from Chiang Mai Municipality.

The lubricant usage data for IPPU was collected from the Office of Industrial Economics. The obtained data represented an overall picture of the industrial sector. The amount of real usage by the province was obtained through the allocation of the national data to each province based on GPP values of the industrial sector. As a result, lubricant use in Chiang Mai Province in the base year was 5,919,142 L.

Livestock breeding data for the AFOLU sector were obtained from OAE. In the base year, 6,461,715 animals were recorded, with chicken, swine, and cattle accounting for the highest shares (89.15%, 5.58%, and 2.05%, respectively), which significantly contribute to emissions from enteric fermentation and manure management. The forest area data were based on the Royal Forest Department. Each type of agricultural area, including rice cultivation, was sourced from Thailand's agricultural statistics published by the Office of Agricultural Economics. The data on fertilizer use were sourced from the Bureau of Agricultural Economic Research on the amount of fertilizer imported into Thailand. Such data represent the total for the country; GPP values were then used to allocate the national-level data to each province. Meanwhile, the area burnt in cropland was compiled by the Geo-Informatics and Space Technology Development Agency (Public Organization)

(GISTDA). The obtained data were the number of hotspots, calculated per hectare, and used as activity data for the GHG emissions assessment.

The inventory was designed to comprehensively address potential minor and dispersed sources, aligning with the GPC principle of completeness. Household-level energy use is fully accounted for through official utility data in the Residential Building sub-sector (electricity and LPG). Small-scale fuel usage and informal transportation modes are substantially covered under the Off-road transportation category and non-specified sources (within stationary energy). For these categories, data for unmetered diesel and gasoline usage were aggregated from provincial fuel sales reports (DOEB) that lacked specific end-user category details. Small-scale industries are largely captured under the Manufacturing industries and construction sub-sector. Additionally, activity data obtained through interviews (e.g., infectious and hazardous waste data) enabled the inclusion of emissions from sources that would otherwise be overlooked in standard statistical reports, ensuring a high level of fidelity to the provincial emission profile.

The confidence level associated with each activity data source is quantitatively assessed using the 5-point scoring system detailed in Table 1 (e.g., score 5 for high-quality provincial data, score 1 for extrapolated or Composite Data). The specific score for each emission activity (Stationary Energy, Transportation, AFOLU, etc.) is presented in the final column of Table 3. Data derived from direct, official sources (e.g., fuel reports, utility bills) are generally classified as level A or B (score 4–5), whereas data relying on interviews, allocation methods (such as GPP allocation for lubricants), or national statistics are typically categorized as level C, D, or E (score 1–3), reflecting higher inherent uncertainty. While a formal, quantitative sensitivity analysis was not performed due to the aggregate nature of the BAU forecasting model, the discussion in Section 2.3 (Data Quality and Uncertainty Assessment) addresses the qualitative impact of these uncertainties, particularly regarding allocated data and the single Scope 2 emission factor.

### 3.2. Assessment of GHG Emissions and Projection

In the base year, Chiang Mai Province's GHG emissions (Table 4) were calculated at 4,095,081 $tCO_2e$ under the BASIC framework and 5,387,482 $tCO_2e$ under the more comprehensive BASIC+ framework. The substantial increase of approximately 1.3 million $tCO_2e$ is attributed to the inclusion of emissions from the AFOLU and IPPU sectors, as well as Scope 3 transboundary travel emissions, which are only accounted for in the BASIC+ inventory. This broader scope provides a more comprehensive view of the province's total GHG emissions.

**Table 4.** GHG emissions summary of Chiang Mai Province in 2019.

| Sector | | GHG Emission ($tCO_2e$) | | | | |
|---|---|---|---|---|---|---|
| | | Scope 1 | Scope 2 | Scope 3 | BASIC | BASIC+ |
| **Stationary Energy** | Energy use | 341,141 | 1,772,907 | Included elsewhere | 2,114,048 | 2,114,048 |
| | Energy generation supplied to the grid | Not estimated | | | | |
| **Transportation** | All emissions | 1,370,974 | Not occurring | 330,763 | 1,370,974 | 1,701,737 |
| **Waste** | Generated in the city | 608,292 | | 1767 | 610,059 | 610,059 |
| | Generated outside the city | 7622 | | | | |
| **IPPU** | All emissions | 3227 | | | | 3227 |
| **AFOLU** | All emissions | 958,411 | | | | 958,411 |
| **Total** | | **3,289,667** | **1,772,907** | **332,530** | **4,095,081** | **5,387,482** |

This broader scope provides a more holistic view of the province's environmental impact, reflected by a significant increase across all normalized indicators when moving from the BASIC to the BASIC+ assessment. For instance, per capita emissions rise from 2.30 to 3.03 $tCO_2e$ for the registered population and from 2.08 to 2.73 $tCO_2e$ for the total population (including non-registered residents and tourists). Concurrently, emissions density increases from 204 to 268 $tCO_2e$ per square kilometer, and economic emissions intensity grows from 15.81 to 20.80 $tCO_2e$ per million-baht GPP.

The increase in total emissions when moving to the BASIC+ level is attributed partly to the inclusion of Scope 3 emissions (332,530 $tCO_2e$). These indirect emissions were primarily estimated using established GPC methodologies, as direct measurement is not feasible at the sub-national level. Specifically, Scope 3 from Transportation was calculated using the GPC Induced Activity Method (50% allocation for transboundary travel), relying on official activity data (Level B). Scope 3 from Waste (incineration outside the city) was calculated using measured activity data (Level B). The primary source of uncertainty in Scope 3 is the application of national default emission factors and allocation proxies (Level C data for some transport categories), a limitation further discussed in Section 2.3.

To validate the methodology and increase the robustness of the 2019 base-year and projected emissions, the total GHG inventory was qualitatively compared with the national GHG inventory reported to the UNFCCC. The methodology was cross-checked to ensure consistency with TGO's reporting structure for Scope 1 and Scope 2 emissions. Minor discrepancies were observed primarily in Scope 3 emissions (specifically, transboundary transport and AFOLU land use categories), as the national inventory often uses different boundaries, activity data collection methods, and allocation factors compared to the GPC sub-national standard. These Scope 3 discrepancies, particularly in transboundary travel, are inherent when disaggregating national-level data and are a known limitation of sub-national inventories that rely on GPC allocation proxies rather than direct measurement.

To ensure that reduction goals and mitigation plans are robust and effective, this research utilized GHG emissions data from the BASIC+ level for its analysis and predictions. The rationale for this selection is critical for effective policy formulation, especially in a province like Chiang Mai. As the inventory results demonstrate (Table 4), the AFOLU and IPPU sectors, which are excluded from the BASIC level, account for approximately 1.3 million $tCO_2e$, representing over 24% of the province's total emissions. Relying solely on the BASIC inventory would create a significant policy blind spot. This would result in a climate action plan that completely overlooks major emissions from livestock (7.35%), rice cultivation (6.13%), and land use change. For a province where agriculture and land use are integral to the economy and landscape, this omission would render any climate plan ineffective. Therefore, adopting the BASIC+ framework is an essential methodological choice. It provides a holistic and accurate baseline that enables policymakers to identify all significant emission sources and develop a comprehensive, multi-sectoral mitigation strategy that addresses not only energy and transport but also the critical agriculture and land use sectors.

The stationary energy sector, contributing 2,114,048 $tCO_2e$ (39.24%) to total emissions, is overwhelmingly dominated by Scope 2 emissions from grid-supplied electricity (1,772,907 $tCO_2e$), which accounts for 84% of the sector's total. The remaining Scope 1 emissions (341,141 $tCO_2e$) come from direct fossil fuel combustion, with major contributions originating from several sub-sectors. The Commercial and Institutional Buildings sub-sector is the largest Scope 1 source (171,523 $tCO_2e$), stemming primarily from LPG used for cooking and heating, followed by diesel for facilities. The next-largest contribution comes from Non-Specified Sources (34,814 $tCO_2e$), predominantly reflecting diesel use in small-scale, decentralized economic activities that lack specific end-user categorization.

Emissions from Manufacturing Industries and Residential Buildings (25,226 $tCO_2e$ and 42,866 $tCO_2e$, respectively) are also significant, driven by fuel oil, diesel, and LPG. Crucially, the calculation of Scope 2 emissions does not include renewable energy contributions from decentralized sources (such as existing rooftop solar in the base year), as GPC guidelines stipulate that onsite generation must be treated as Scope 2 mitigation rather than a factor influencing the baseline grid emission factor (0.4999 $kgCO_2e/kWh$).

The GHG emissions at the BASIC+ level showed that the stationary energy sector accounted for the largest share, totaling 2,114,048 $tCO_2e$, or 39.24% of the province's total GHG emissions. The GHG emissions for energy-use activities in Scope 3 are estimated and presented in the Scope 1 and Scope 2 categories of the inventory.

The inventory uses specific notations to clarify the status of certain emission categories. For instance, if emissions from one activity are accounted for within another sector to prevent double-counting, that category is marked as 'Included elsewhere'. Conversely, for activities where emissions are known to occur, but data are insufficient for quantification, such as 'Energy generation supplied to the grid', the category is marked as 'Not estimated'.

Transportation is the second-largest sector, accounting for 1,701,737 $tCO_2e$, or 31.59% of the province's total GHG emissions. The activities or processes for Scope 2 in the transportation sector did not occur or exist within the province; therefore, it is identified as "Not occurring". This is because transportation activities are overwhelmingly powered by the direct combustion of fossil fuels (classified as Scope 1 emissions), and the consumption of grid-supplied electricity (Scope 2) for transport activities is negligible or not tracked separately in the base year. Inter-city and regional transport emissions, however, were comprehensively accounted for under Scope 3 (330,763 $tCO_2e$), utilizing the GPC Induced Activity Method to allocate 50% of the emissions from transboundary trips (rail, water-borne, and aviation) to Chiang Mai. AFOLU is the third-ranked sector, with GHG emissions of 958,411 $tCO_2e$, accounting for 17.79% of the province's total GHG emissions. Waste management is the fourth-largest sector in terms of GHG emissions, accounting for 610,059 $tCO_2e$, or 11.32% of the province's total GHG emissions. The last sector, IPPU, accounts for 3227 $tCO_2e$, or 0.06% of the province's total GHG emissions.

The top five activities with the highest GHG emissions included on-road transportation (26.80% of the total GHG emissions), followed by energy use in residential buildings (12.81%), energy use in industries and construction (12.23%), energy use in commercial and institutional buildings and facilities (11.08%), and livestock management (7.35%). The total GHG emissions in these five rankings account for more than 70% of the total. Ranking GHG emissions by activity clearly identifies the sources and determines the priority of GHG reduction measures to be properly implemented by the city administration, as shown in Figure 2.

This study projects future GHG emissions for 2023–2030 under a BAU scenario. The projection is based on historical growth rates calculated from real emissions data from 2019 to 2022 (as detailed in Figure 3). The BAU projection shows a consistent upward trend in emissions, assuming no new mitigation measures are implemented by the city administration In 2030, the GHG emission is estimated to reach 6,354,716 $tCO_2e$, wherein the sectors identified with the most GHG emissions are as follows: stationary energy equivalent to 2,649,242 $tCO_2e$ (41.69%), followed by transportation equivalent to 1,928,465 $tCO_2e$ (30.35%), AFOLU equivalent to 1,187,286 $tCO_2e$ (18.68%), waste equivalent to 586,394 $tCO_2e$ (9.23%), and IPPU equivalent to 3329 $tCO_2e$ (0.05%).

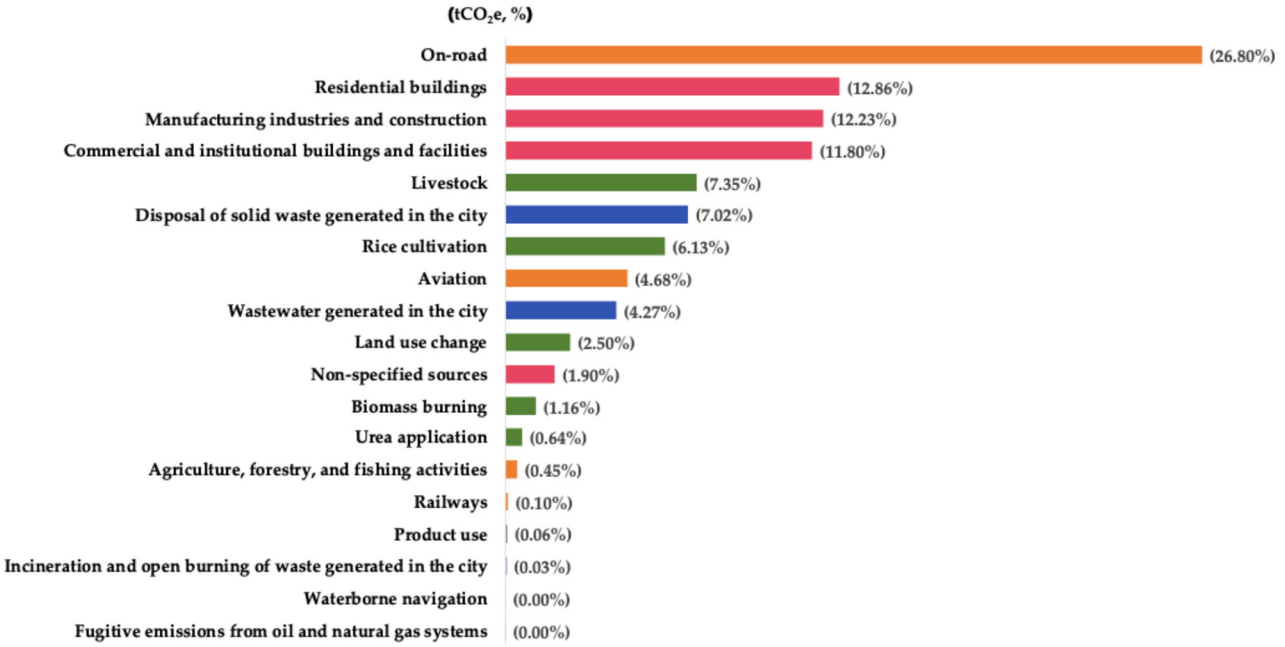


**Figure 2.** GHG emissions of Chiang Mai Province by activity in 2019.

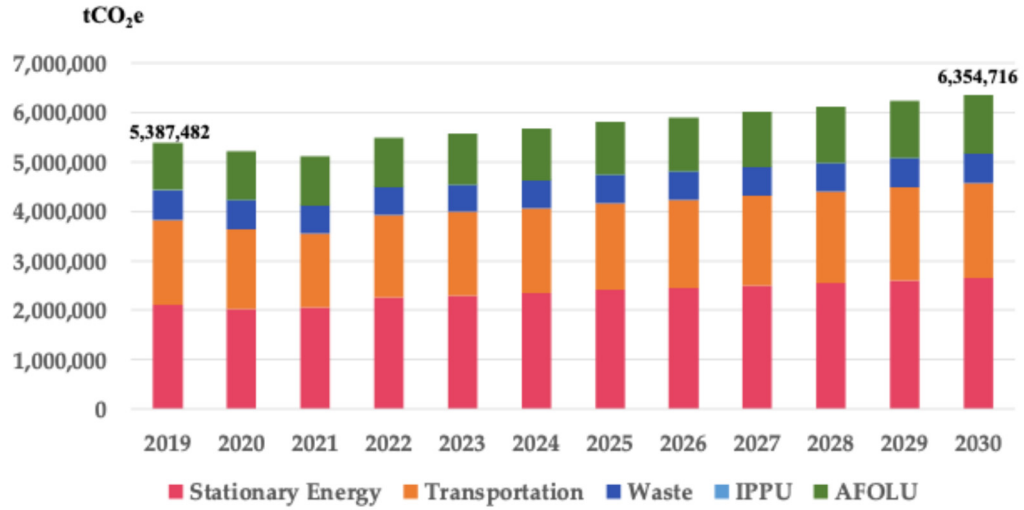


**Figure 3.** Future GHG emissions of Chiang Mai Province on a BAU basis (2019–2030).

The top-five GHG emission activities in 2030 include on-road transportation equivalent to 1,579,976 $tCO_2e$ (24.86%), energy use in residential buildings equivalent to 1,139,355 $tCO_2e$ (17.93%), energy use in commercial and institutional buildings and facilities, livestock management, and energy use in manufacturing industries and construction equivalent to 672,321 (10.58%), 594,619 (9.36%), and 586,755 (9.23%) $tCO_2e$, respectively.

### *3.3. Mitigation Scenario Quantified GHG Reduction Pathway from Solar Energy Deployment*

The findings of this study reveal that Chiang Mai Province's significant GHG emissions are primarily driven by two sectors: electricity consumption and transportation. Electricity consumption, primarily from the national grid, is the largest contributor, accounting for about 37% of total emissions, followed by road transport at 27%.

Given that electricity consumption is the primary emission source, promoting solar rooftop installations is a critical strategy to reduce the province's reliance on the fossil-fuel-intensive national grid. This transition to cleaner, decentralized power also creates a vital opportunity to decarbonize the transportation sector, the second-largest source of

emissions. By ensuring the growing fleet of Electric Vehicles (EVs) is charged with power from these solar rooftops, the province can address its two largest sources of emissions simultaneously. This synergistic approach holds the potential to lower total GHG emissions by over 30% by 2030.

A spatial analysis employing weighted criteria across six physical factors (Figure 4) was conducted to identify areas with high potential for solar panel installation. The analysis revealed that approximately 17.97% of the province (about 3903 $km^2$) is classified as highly suitable, 73.16% (approximately 15,892 $km^2$) as moderately suitable, and 8.87% (approximately 1926 $km^2$) as having low suitability. The most suitable areas were identified in Doi Tao, Chom Thong, and Mae Taeng districts, characterized by open, flat terrain with minimal shading, which facilitates optimal solar exposure.

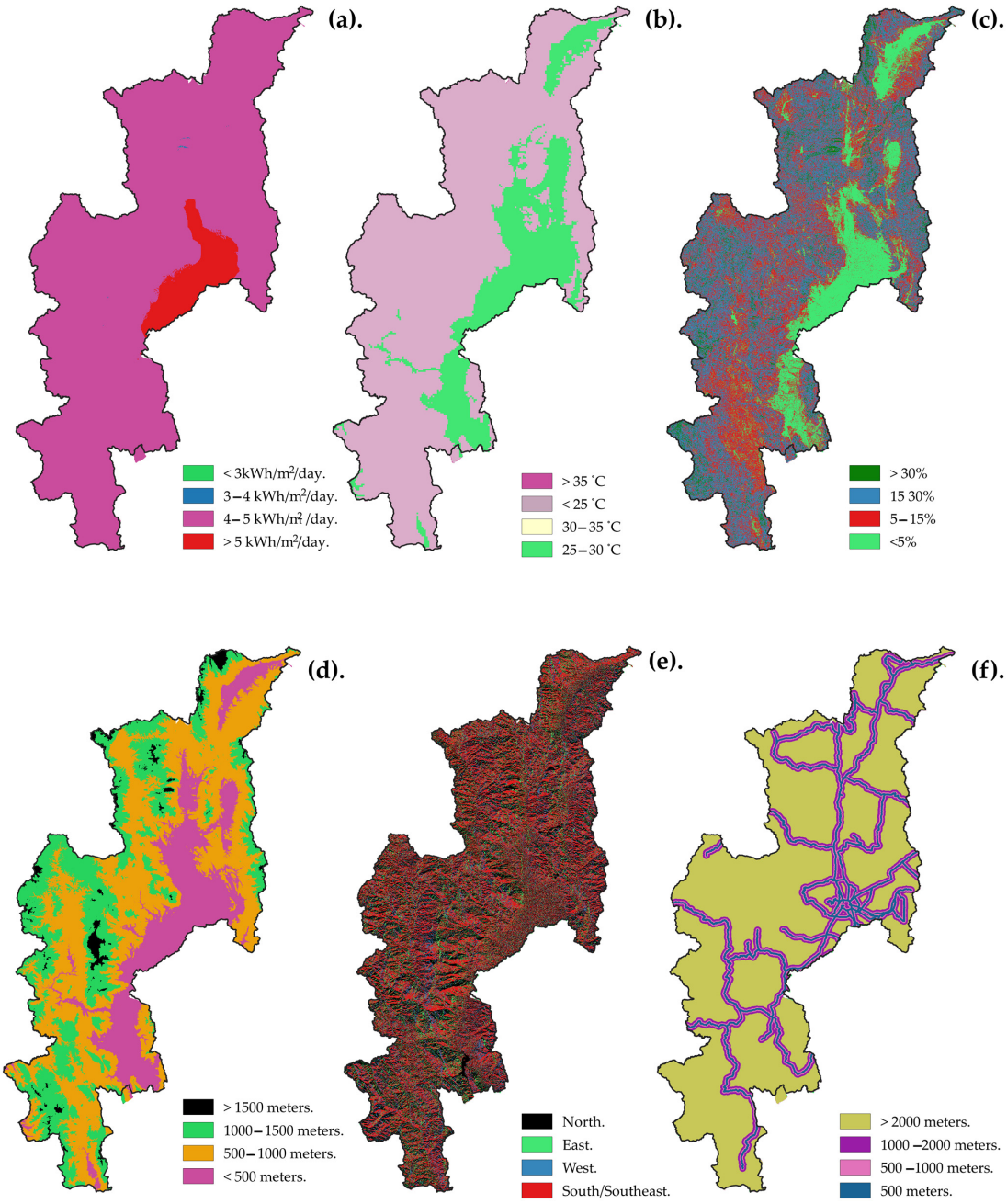


**Figure 4.** Physical factors used in the assessment include: (**a**) Average solar irradiance; (**b**) Average temperature; (**c**) Elevation; (**d**) Slope; (**e**) Sun exposure direction; (**f**) Distance from roads.

Furthermore, this study found that suitable areas generally have average solar irradiance above 5 kWh/m$^2$/day and slopes of less than 5%, often flat terrain. These findings align with the elevation factor: areas below 500 m above sea level tend to be more suitable for installing solar panels.

The optimal operational temperature range for solar panels is between 25 °C and 30 °C; higher temperatures do not appear to enhance suitability. The results of the weighted analysis for each factor are shown in Figure 5.

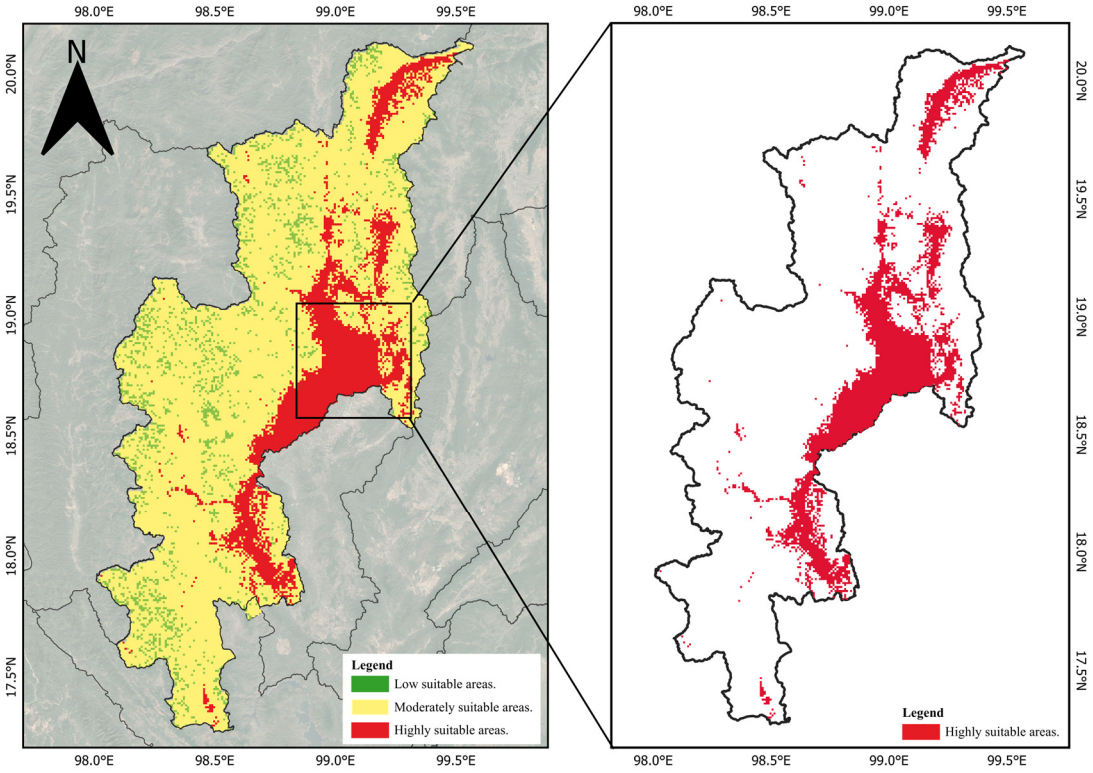


**Figure 5.** The results of suitable areas for solar panel installation in Chiang Mai Province.

To quantify the practical generation potential, this study overlaid the solar suitability map with building footprint data from the Google Earth Engine (GEE) platform (Figure 6). The analysis identified approximately 1.4 million suitable rooftops, encompassing residential, commercial, and government buildings. A conservative scenario was then modeled assuming a 30% adoption rate where these rooftops were equipped with a standard 3 kWp system. Based on an average of 4.5 peak sun hours per day, this scenario would generate an estimated 2069.55 GWh of clean electricity annually. This potential output is highly significant, representing nearly 58% of Chiang Mai Province's total electricity consumption from the grid in the base year.

To analyze the specific mitigation impact pathways in accordance with GPC guidelines, the total solar generation potential was disaggregated. As the available GEE building footprint data identifies total suitable rooftop area but does not differentiate by building type (e.g., residential, commercial), a proxy-based approach was adopted. We allocated the total potential based on the sectoral share of Scope 2 electricity consumption (detailed in Table 3). This method assumes that a sector's potential for rooftop solar is proportional to its current share of electricity demand. The analysis revealed that the potential is distributed across Residential buildings (36.7%), Manufacturing industries (34.2%), Commercial and institutional buildings (25.0%), and other sectors (4.1%). This distributed generation directly reduces demand for grid-supplied electricity, thereby mitigating Scope 2 emissions in each sector.

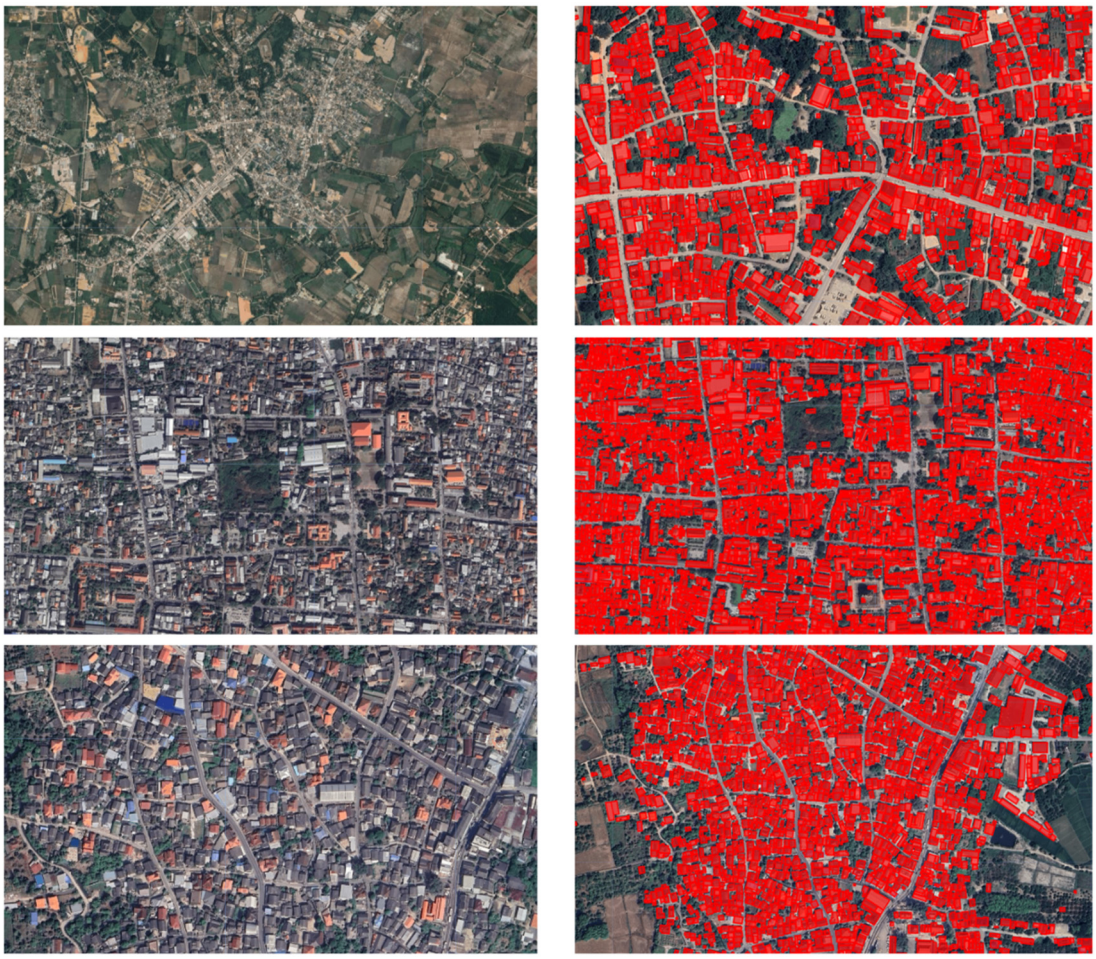

**Figure 6.** Overlay between suitable installation areas and building footprint data.

Consequently, realizing this generation potential would lead to a direct GHG emissions reduction of 1.03 million $tCO_2e$ per year. This mitigation is distributed as follows: approximately 379,000 $tCO_2e$ (36.7%) from the residential sector, 353,000 $tCO_2e$ (34.2%) from the industrial sector, and 259,000 $tCO_2e$ (25.0%) from the commercial sector (with the remaining 4.1% from other sectors). This intervention would effectively mitigate 58.3% of the province's total Scope 2 (electricity) emissions (1.77 million $tCO_2e$). This analysis provides clear, sectoral pathways for decarbonization, offering a powerful contribution towards achieving Thailand's Nationally Determined Contribution (NDC) goal and significantly accelerating the province's transition to a low-carbon economy.

However, installations in remote or mountainous areas are still limited by higher costs and lack of infrastructure. Therefore, government and private sector involvement is crucial through initiatives like financial incentives for rural solar adoption, developing solar farms in suitable zones, and investing in decentralized energy infrastructure. These efforts will be key to achieving an inclusive and sustainable transition to clean energy in Chiang Mai Province.

## 4. Discussion

This study successfully developed a GHG emissions inventory for Chiang Mai Province based on the Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories (GPC) and projected future emissions under a Business-as-Usual (BAU) scenario. The results underscore the importance of subnational inventories for climate action,

particularly in countries like Thailand, where provincial contexts vary significantly and national data aggregation may obscure local emissions trends and opportunities.

The findings reveal that Chiang Mai emitted approximately 5.39 million $tCO_2e$ in 2019 at the BASIC+ level, with stationary energy and transportation being the primary contributors, accounting for over 70% of total emissions, underscoring the need to prioritize energy transition and low-carbon transportation initiatives in the province.

The projected increase in GHG emissions to 6.35 million $tCO_2e$ by 2030 under the BAU scenario demonstrates the urgent need for mitigation strategies. This study identifies a viable pathway to counteract this trend. The analysis reveals that a conservative 30% adoption of solar rooftops could reduce annual emissions by 1.03 million $tCO_2e$. This single intervention could offset approximately 16% of the total projected 2030 emissions and mitigate 58% of all emissions from electricity consumption, fundamentally altering the province's emissions trajectory. Therefore, implementing such data-driven strategies is crucial for Chiang Mai to align with Thailand's national targets of reducing GHG emissions by 30–40% by 2030 and achieving net-zero by 2065, turning a challenging goal into an attainable reality.

To address this challenge, this study evaluated the spatial potential for solar energy deployment as a quantified mitigation strategy, effectively serving as the Policy Intervention Scenario to counteract the BAU growth. Through multi-criteria geospatial analysis incorporating six physical factors—solar irradiance, temperature, elevation, slope, sun exposure, and road proximity—18% of Chiang Mai's land was identified as highly suitable for solar panel installation. If fully utilized, these areas could provide clean electricity to over 1.4 million households, substantially reducing emissions from grid-supplied electricity and supporting the adoption of electric vehicles and agri-voltaic development.

However, the practical implementation of solar technologies, particularly in remote and mountainous regions, faces challenges related to cost and infrastructure access. Therefore, realizing the full 1.03 million $tCO_2e$ reduction potential in this scenario will require targeted policy support, such as subsidies and incentives for decentralized solar systems and public–private partnerships.

This study's framework also contributes to the growing body of literature on subnational climate action. Recent studies (2023–2025) have increasingly focused on two parallel streams: first, the development of robust, standardized GHG inventories for cities in both developed and developing regions [48,49], and second, the use of detailed spatial analysis to understand mitigation potential in specific sectors, such as building energy or land use [50,51]. However, these two streams are often treated in isolation. The key methodological innovation of this research is the direct integration of these two streams: linking a robust, GPC-compliant inventory with a detailed, multi-criteria spatial analysis (solar suitability). While other recent work also integrates spatial and emissions data, the focus is often on analyzing the drivers of emissions [52]. Our research differs by providing a practical, 'inventory-to-action' blueprint. We move a crucial step further by using the inventory results to target the spatial analysis (focusing on solar to mitigate the largest emission source), and then quantify the mitigation impact (1.03 million $tCO_2e$ reduction) directly against the provincial BAU scenario. This integrated approach offers a tangible, replicable model for other subnational entities in developing regions [45] to create evidence-based climate action plans using publicly available data (GEE).

A crucial limitation of this sub-national inventory lies in the uncertainty associated with estimated activity data, particularly those derived from the GPP allocation method (e.g., lubricant use). While these estimated sources account for a small proportion of the total inventory, future work should prioritize developing local statistical collection mechanisms to replace national allocation methods. Improving the spatial and temporal

resolution of this data will be essential for reducing the overall uncertainty and enhancing the accuracy of future BAU projections and mitigation effectiveness assessments.

## 5. Conclusions

This study presents a robust framework for subnational GHG accounting and scenario-based planning. It highlights the critical importance of location-specific mitigation actions and demonstrates that integrating spatial analysis, such as solar suitability mapping, into climate planning significantly enhances the effectiveness of emission reduction strategies.

The methodology offers a replicable model for other provinces in Thailand and similar developing regions. It comprises three key steps: (1) establishing a detailed subnational GHG inventory to pinpoint primary emission sources; (2) conducting spatial analysis using publicly available data (e.g., GEE) to identify high-potential areas for renewable energy; and (3) quantifying the potential impact of targeted interventions, such as solar rooftops, to build a data-driven case for investment.

To be effectively replicated and generalized, this framework relies on leveraging accessible, universal data sources. Specifically, the methodology minimizes reliance on proprietary local surveys by prioritizing: (1) Standardized Protocol: Adopting the GPC structure ensures the inventory is internationally comparable; (2) Open-Source Geospatial Data: Utilizing publicly available platforms like GEE for spatial analysis makes the tool cost-effective and feasible for developing regions with limited budgets for extensive field studies; and (3) Flexible Mitigation Focus. While Chiang Mai focused on solar energy due to high electricity emissions, the framework is flexible. Other regions can simply substitute Steps (2) and (3) with spatial analyses relevant to their dominant emission sector—for instance, mapping optimal locations for waste-to-energy facilities for regions dominated by the waste sector, or identifying optimal public transport routes to address high transportation emissions. This adaptability ensures the model's relevance across diverse sub-national contexts.

Ultimately, this framework serves as a practical blueprint for developing sustainable cities. It enables regions to move beyond generalized climate goals, creating tailored, evidence-based mitigation plans suited to their unique geographical contexts. By doing so, local actions are directly aligned with national and global climate objectives, paving the way for a more resilient and sustainable future.

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