



Article Climate Change Mitigation in Thailand's Domestic Aviation: Mitigation Options Analysis towards 2050

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Abstract: Thailand's civil aviation industry has expanded rapidly in the past ten years resulting in increasing aviation greenhouse gas (GHG) emissions and energy consumption. The rapid growth in air transport is anticipated to continue further. Presently, domestic aviation and the economy of many countries are recovering rapidly in the post-COVID-19 period, resulting in fuel consumption and GHG emissions gradually increasing again. However, despite implementing the ICAO's CORSIA (International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation) rule for international aviation, GHG emissions in the domestic aviation sector are largely unregulated. Moreover, the literature lacks a GHG emissions analysis that considers this sector's potential growth and mitigation policies for future GHG emissions. To close the gap, this study conducted a GHG emissions analysis from this sector under various scenarios through 2050 using historical data during 2008-2020 to forecast future trends. It evaluates the impact of the mitigation policies, such as fuel switching and aircraft technology, on improving fuel efficiency due to technological advancements in aircraft and carbon pricing. The results show that the fuel switching option would result in a significant long-term reduction in GHG emissions, whereas the carbon pricing option and aircraft technology option are desirable in reducing GHG emissions in the short term. Therefore, to meet GHG emissions reduction targets more successfully, all measures must be simultaneously executed to address short- and long-term mitigation strategies. These findings have significant implications for both present and future GHG emissions reduction measures, supporting Thailand's 2050 climate targets and energy efficiency policies as the domestic aviation industry adjusts.

Keywords: greenhouse gas emissions; aviation sector; mitigation; policy; energy consumption; scenario analysis

1. Introduction

In 2004, the global air transport sector utilized 0.19 billion metric tonnes (Mt) of fuel, producing approximately 0.59 billion tonnes of CO₂ emissions [1]. Air travel flights accounted for 2–3% of global anthropogenic CO₂ emissions in 2012 [2]. Projections indicate that global air traffic will double within 15 years from 2012, with a corresponding doubling of energy consumption and CO₂ emissions within 25 years [3]. The aviation industry is one of the largest markets worldwide, transporting approximately 2.2 billion passengers annually and employing 32 million people globally [4]. This sector has a significant economic impact, contributing approximately 3.56 trillion USD or around 7.5% of the global gross domestic product (GDP) [5].

While it has been established that transportation emissions from rail, road, and water conveyance significantly impact the environment and contribute to climate change [6–9], aviation exhaust is the second-largest contributor to emissions. This constitutes approximately 12% of the annual emissions from all modes of transportation and contributes to



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). around 4% of the current observed global warming caused by human activities [10,11]. In addition to its role in climate change stemming from aircraft operations, the aviation industry bears responsibility for various other environmental issues associated with the supporting systems of aircraft, such as airports and fuel production, as well as all stages of its value chain, including aircraft manufacturing and disposal. Examples of these impacts encompass noise pollution, the limited use of rare metals (like cobalt or chromium in specialized alloys), and potential harmful effects from the release of chemicals, all of which have the potential to harm human health, ecosystems, and deplete natural resources [12,13]. The aviation industry has experienced steady growth in recent years until it was abruptly halted by the onset of the COVID-19 pandemic [14]. In 2018, global CO_2 emissions from aircraft operations, encompassing passenger and cargo transport, amounted to 0.92 billion metric tonnes [15]. This accounted for 2.4% of the estimated 37.9 gigatonnes of CO_2 emitted globally that year due to fossil fuel usage [16]. Commercial aviation's CO_2 emissions increased by 32%, from 0.69 billion tonnes in 2013 to 0.92 billion tonnes in 2018 [17]. Consequently, CO_2 emissions from international aviation are projected to triple by 2050, surpassing the rate forecasted by ICAO, corresponding to a compound annual growth rate of 5.7% [18]. Furthermore, there was a resurgence in worldwide international travel starting around June/July 2020, with notable improvements particularly observed by November 2020. Substantial expansion has persisted since June 2021, and this growth has been consistently maintained in numerous aviation markets. Domestic travel has displayed greater resilience in passenger volume when compared to the international tourism sector [19].

In Thailand, commercial aviation is one of the transportation sectors that contributes significantly to CO_2 emissions. The emissions from international commercial aviation experienced a 29% growth, rising from 10.2 million tonnes of CO_2 in 2014 to 13.2 million tonnes of CO_2 in 2018 (an overall increase of 29%). Another notable source of CO_2 emissions in Thailand is commercial domestic aviation. Emissions from passenger and freight flights grew by 42%, increasing from 1.9 million tonnes of CO_2 in 2014 to 2.7 million tonnes of CO_2 in 2018 [20]. The rapid increase in fuel consumption for commercial, domestic aviation generates substantial CO_2 emissions. The issue of reducing CO_2 emissions in Thailand's domestic aviation industry is gaining more attention, particularly following Thailand's government commitment to reducing GHG emissions during the UNFCC's COP-20 [21].

The Thai government aims for its Nationally Determined Contribution (NDC) in line with global climate efforts. As a result, Thailand aims to reduce its GHG emissions by 20-25% (555 Mt-CO₂-eq) in 2030, compared to the business-as-usual (BAU) scenario [22]. Thailand aims to decrease GHG emissions by approximately 111 to 139 Mt-CO₂-eq. Climate policies are necessary across all industries and countries to achieve the objectives outlined in the 2015 Paris Agreement and limit global warming to 2 °C. Furthermore, a comprehensive study of greenhouse gas emissions in the aviation sector is required [23].

In 2016, following a comprehensive research-driven examination of the aviation industry, the ICAO Assembly reached a consensus to implement a global, market-driven initiative aimed at mitigating greenhouse gas emissions, arising from international aviation. This initiative is known as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [24]. Furthermore, CORSIA mandates that airlines must offset CO₂-eq emissions exceeding the levels recorded in 2019. The CORSIA framework is designed to facilitate offsetting through the use of credits or CORSIA Eligible Fuels (CEFs), with these choices determined by impact assessments and current scientific understanding. The overarching goal of this approach is to ensure that international aviation achieves carbon-neutral growth, commencing in the year 2020 [25].

The current focus on reducing GHG emissions in the aviation sector, particularly seen in ICAO's CORSIA initiative, does not extend to domestic aviation [26,27]. However, the domestic aviation sector plays a role in national GHG mitigation efforts and contributes to the Nationally Determined Contributions (NDC) under the UNFCCC. Unfortunately, policymakers do not actively monitor the emissions from commercial domestic aviation. Thus, this study emphasizes the importance of forecasting energy use and GHG emissions in the commercial, domestic aviation industry. This study highlights the need for appropriate policies to effectively reduce future GHG emissions from the aviation sector, aligning with environmental and climate-related solutions.

Our literature review reveals that numerous studies have examined the issue of CO₂ emissions from the aviation industry, both on a global and national scale. Some of these studies have focused on medium- to long-term scenario analysis [28–30]. Additionally, past research was concentrated on policies aimed at reducing GHG emissions in the medium to long term [29,31–35] and the different factors that influence the growth of GHG emissions [36–41].

Pathways for the mitigation of aviation sector have adopted a comprehensive mitigation strategy that relies on the successful implementation of individual policies or measures and other strategies. The International Civil Aviation Organization (ICAO) proposes five significant measures for reducing emissions in commercial aviation: Operational efficiency improvement; Use of alternative fuels; Demand shift engineering; Technological efficiency improvement; and Carbon pricing (market-based incentives) [33]. These efforts include advancing aircraft-related technologies and standards to encourage their adoption, enhancing air traffic management and aircraft operations (with a primary focus on reducing fuel consumption per flight through measures such as more direct cruise paths and more efficient altitude profiles in air traffic management), promoting the development and use of Sustainable Aviation Fuels (SAFs), and implementing market-based measures (MBMs) at both global and regional scales [42]. The initial two aspects, aircraft technology and operational enhancements, primarily aim to reduce fuel consumption as their main objective, ultimately resulting in a reduction in CO_2 emissions [42]. However, all measures proposed by ICAO can be applied in the domestic aviation sector to reduce greenhouse gas emissions, aligning with national strategies for emission reduction.

This study is timely considering the current COVID-19 situation and the ongoing market restructuring in the aviation industry. This restructuring will impact energy efficiency and technology, bringing changes in the domestic aviation market. The aviation industry was significantly affected by the COVID-19 pandemic between 2020 and 2021, with the government implementing lockdown measures during this period, resulting in a direct impact on the decline in aviation activity. Domestic air travel within Thailand experienced a downturn, leading to a significant decline in both passenger numbers and flight frequencies, affecting both the domestic and international segments of the aviation industry [43]. The domestic aviation sector is currently experiencing a recovery phase. This recovery is expected to lead to structural adjustments and changes in the domestic aviation market. Previous studies have shown that the increase in the tourism industry and domestic air travel demand will correspond to a rise in energy consumption and emissions [44]. Therefore, this period of market adjustment in the domestic aviation sector presents a crucial opportunity to assess future trends in GHG emissions following the market restructuring and address the impact of the COVID-19 situation and the pandemic measures, factors that contribute to making the forecasting of energy consumption in the aviation sector more accurate and precise. Furthermore, it serves as a starting point for implementing policies to reduce greenhouse gas (GHG) emissions in the domestic aviation sector, aligning with the country's targets for GHG reduction under the UNFCCC. Considering the current context, this study holds significant importance in understanding and addressing the future implications of market changes and the recovery of GHG emissions in the domestic aviation sector. It also highlights the need for appropriate policy interventions.

Over the past decade, Thailand has witnessed a significant increase in the number of travelers. The compound annual growth rate (CAGR) for all travelers from 2010 to 2019 was 11.38%, with a CAGR of 10.77% for international travelers and 12.13% for domestic travelers [45]. Before the COVID-19 pandemic, Thailand experienced a notable surge in domestic aviation passengers, rising from 3.482 million in 2008 to 76.256 million in 2019 [46]. These figures demonstrate domestic aviation's substantial growth and importance in Thailand, driven by international and domestic travel demand.

In parallel, jet fuel consumption in Thailand's domestic aviation sector witnessed a notable increase, rising from 246 kilotonnes of oil equivalent (ktoe) in 2008 to 856 ktoe in 2018 [47]. It is noteworthy that Thailand's Nationally Determined Contribution (NDC) sets a greenhouse gas reduction target of 20–25% lower than the Business-As-Usual prediction for 2030 across all sectors [48]. Furthermore, during the UNFCCC's COP-26 in Glasgow, Thailand committed to achieving carbon neutrality by 2050 and net-zero emissions by 2065. It indicates that Thailand's domestic aviation sector can align with its climate commitments even during growth. However, medium-term to long-term GHG emissions forecasting and policies to reduce future emissions in the domestic aviation sector have yet to be developed and implemented. These observations highlight the need for comprehensive GHG emissions forecasting and the implementation of policies to reduce emissions in the domestic aviation sector to align with Thailand's climate targets.

This study aims to contribute to understanding reference future scenarios, quantification of GHG emissions, and the mitigation potential of policies in Thailand's commercial and domestic aviation sector for the medium-term (2030) and long-term (2050). It seeks to fill the research gap by being the first study to assess medium- and long-term mitigation policies tailored to Thailand's commercial domestic aviation sector. Furthermore, the study aims to provide novel insights into the benefits of these policies in reducing GHG emissions. For example, Sustainable Aviation Fuel (SAF) can help mitigate the aviation sector's impact on global warming [49]. Additionally, improving the auxiliary power unit (APU) can contribute to reducing greenhouse gas emissions within the aviation sector [50], aligning with Thailand's greenhouse gas emission reduction targets under the UNFCCC. By conducting this analysis, the study intends to inform decision-makers and stakeholders about the effectiveness and implications of various mitigation policies in the domestic aviation sector. The findings can guide the development and implementation of targeted strategies to reduce GHG emissions in line with Thailand's climate goals.

2. Methodology and Data

This study employs a comprehensive framework, as depicted in Figure 1, to forecast medium-term (2030) and long-term (2050) GHG emissions in Thailand's commercial domestic aviation sector. The forecasting of GHG emissions is based on key factors such as the number of passengers, freight, gross domestic product (GDP), and jet fuel price.

Considering the above variables, this study uses a multiple linear regression method to forecast fuel consumption. By applying this approach, the study aims to provide an estimation of future fuel consumption in the commercial domestic aviation sector. This study also evaluated the impacts of three key policies in shaping reference future scenarios for GHG emissions reduction in Thailand's commercial domestic aviation sector. These policies are fuel switching, carbon pricing, and advancements in aircraft technology. By analyzing these policies, the study aims to identify their potential impacts on reducing GHG emissions.

2.1. Key Data Sources

The data used in this study encompass all 39 airports in Thailand, as reported by [45]. Several key variables were gathered from official data sources from 2008 to 2020 to forecast fuel consumption in Thailand's commercial domestic aviation sector. These variables include the number of passengers, the amount of freight, gross domestic product (GDP), jet fuel prices, and emission factors. The data sources are summarized and presented in Table 1. The data sources provide the necessary information to estimate fuel consumption and assess the factors influencing GHG emissions in Thailand's commercial domestic aviation sector. This comprehensive data set allows for robust analysis and forecasting of reference future scenarios.



Figure 1. The overall framework.

Variables	Period	Description	Sources	
3Jet fuel prices (USD/Litre)	2008–2020	Aviation jet fuel prices	Petroleum Authority of Thailand (PTT Oil and Retail Business Public Company Limited) [51]	
Number of passengers in domestic flight (person)	2008–2020	The number of passengers in domestic aviation sector	The Civil Aviation Authority of Thailand [46]	
Emissions factors (kg/TJ), (kg/LTO)	2006	Emission factors for calculating GHG emissions from fuel consumption	Intergovernmental Panel on Climate Change [52]	
Aviation Jet fuel use (ktoe)	2008–2020	Jet fuel use in domestic aviation sector	Department of Alternative Energy Development and Efficiency [47]	
Number of freights in domestic flight (kg)	2008–2020	The number of freights in domestic aviation sector	The Civil Aviation Authority of Thailand [46]	
Gross domestic product (GDP) (Billion Baht)	2008–2020	Thailand's gross domestic product (Base year is 2008)	Bank of Thailand [53] The World bank [54]	

Table 1. Variables, description, period, sources factors of GHG emissions forecasting, and sources of the estimation of GHG emissions.

2.2. Forecasting Model of Jet Fuel Consumption

2.2.1. Multiple Linear Regression (MLR)

To forecast fuel consumption in the commercial domestic aviation sector, the Multiple Linear Regression (MLR) method was employed in this study. The future estimates were based on 2008, considering planning horizons up to 2030 and 2050. The analysis results were presented at five-year intervals, corresponding to 2025, 2030, 2035, 2040, and 2050. The MLR method has been widely utilized in previous research to predict energy consumption [40,55–59]. In this study, the dependent variable is the aviation jet fuel use in Thailand's commercial domestic aviation sector, while the independent variables include aviation jet fuel prices, the amount of freight, the number of passengers, and GDP. The formula for Multiple Linear Regression is shown in Equation (1).

$$B = c + m_1 a_1 + m_2 a_2 + m_3 a_3 + m_4 a_4 \tag{1}$$

where

B = Dependent variable of aviation jet fuel consumption (Liter);

c = Intercept (constant term);

 $m_1, m_2, m_3, m_4 = Regression coefficient;$

 a_1 , a_2 , a_3 , a_4 = Independent variable of aviation jet fuel prices (USD/Liter), the amount of freight (kg), the number of passengers (person), and GDP (Billion USD).

The MLR method enables the study to establish a quantitative relationship between fuel consumption and the independent variables, allowing for estimating future fuel consumption based on changes in the identified factors.

Linear regression is a statistical technique to model the relationship between an outcome variable and one or more explanatory factors. In this study, linear regression was employed to forecast the amount of freight, the number of passengers, aviation jet fuel prices, and GDP. The relationship is expressed mathematically through Equation (2):

$$B_i = c + m_i a_i \tag{2}$$

where

B_i = Dependent variable; c = Intercept (constant value); m_i = Coefficient values; a_i = Independent variable. By estimating the coefficients through the linear regression analysis, the study could quantify the relationship between the explanatory factors and fuel consumption, enabling the prediction of future fuel consumption based on changes in the identified factors.

The correlation coefficient (r) is a statistical measure that evaluates the strength and direction of the relationship between two quantitative variables. It quantifies the degree to which the variables are linearly related. The correlation coefficient (r) was calculated using Equation (3):

$$\mathbf{r} = \frac{[\mathbf{n}(\Sigma \mathbf{a}\mathbf{b})] - [(\Sigma \mathbf{a})(\Sigma \mathbf{b})]}{\left[\sqrt{\left[\mathbf{n}\Sigma \mathbf{a}^2 - (\Sigma \mathbf{a})^2\right] \times \left[\mathbf{n}\Sigma \mathbf{b}^2 - (\Sigma \mathbf{b})^2\right]\right]}}$$
(3)

where

r = Correlation coefficient;

n = The amount of data;

 $\sum a =$ The first variable's total value;

 $\sum b$ = The second variable's total value;

 \sum ab = The second value and the sum of the products of;

 $\sum a^2$ = Sum of the squares of the first value;

 $\sum b^2$ = Sum of the squares of the second value.

The coefficient of multiple determination (\mathbb{R}^2) is a commonly used statistical metric in multiple regression analysis. It assesses the proportion of the variance in the dependent variable that the independent variables in the model can explain. \mathbb{R}^2 compares the model's accuracy to a basic benchmark model, where the forecast is the data's average. It was calculated using Equation (4):

$$R^{2} = 1 - \left(\frac{\sum_{i}(y_{i} - \hat{y}_{i})^{2}}{\sum_{i}(y_{i} - \overline{y}_{i})^{2}}\right)$$
(4)

where

 R^2 = The coefficient of multiple determination;

y_i = The actual value;

 \hat{y}_i = The predicted value of y;

 \overline{y}_i = The mean of y values.

In linear models, the Adjusted R^2 is a measure commonly used to assess the proportion of variation in the target variable that can be explained by the input or inputs in the model while considering the number of predictors and the sample size. The Adjusted R^2 is calculated using Equation (5):

Adjusted
$$R^2 = 1 - \left(\frac{(1-R^2)(T-1)}{T-v-1}\right)$$
 (5)

where

 $R^2 = R$ -squared sample;

T = Total sample size;

v = The number of independent variables.

2.2.2. Formula for Future Projection

Table 2 presents the Multiple Linear Regression forecasting models for aviation jet fuel consumption in the commercial domestic aviation sector. It includes the sample R-squared (r), which measures the strength of the correlation, and the coefficient of multiple determination (\mathbb{R}^2), which indicates the proportion of variation in fuel consumption explained by the independent variables in the model.

Type of Fuel Used	R ²	R-Value	Adjusted-R ²	Equation
Aviation Jet fuel	0.987	0.994	0.982	$\begin{split} \mathbf{Y} &= (14.170 \times \mathbf{X}_1) - (0.924 \times \mathbf{X}_2) + (190,013.386 \times \mathbf{X}_3) - \\ & (132,057,994.567 \times \mathbf{X}_4) \end{split}$

Table 2. Forecasting model.

2.3. Assumptions and Scenarios for Analysis of Policies or Measure

It is essential to consider the potential reduction in energy-related greenhouse gas (GHG) emissions for each option to evaluate the effectiveness of various mitigation options and inform the development of appropriate regulations. Considering the reference future scenario, this study forecasted the fuel consumption and GHG emissions of Thailand's commercial domestic aviation sector from 2021 to 2050. Three mitigation scenarios were assessed for their potential to reduce GHG emissions in Thailand's domestic commercial aviation sector. The assumptions for each scenario are described below.

2.3.1. Reference Future Scenario

In the reference future scenario, after the recovery of the domestic economy and domestic transportation from the COVID-19 crisis, this study assumed that no changes would happen in the medium-term and long-term trends in demand for commercial domestic aviation fuel consumption. Additionally, no mitigation options are considered from 2021 to 2050. The study analyzed four-factor variables related to GHG emissions growth to create a realistic time series and project future fuel consumption. The study aims to capture each factor's real behavior and realism by reproducing the historical time series of each factor's growth. This approach creates a time series that reflects the continuous behavior cycle observed in the historical data. The analysis of these factor variables helps in understanding their impact on fuel consumption and enables the projection of future fuel consumption based on their historical trends. Figure 2 shows the historical data of four-factor variables related to GHG emissions growth for the analysis and time series.

2.3.2. Fuel Switching Scenario

Using alternative fuels in the aviation industry is of utmost importance for two key reasons: reducing dependency on fossil fuels and mitigating GHG emissions. Aviation specialists and researchers have been actively exploring alternatives to conventional jet fuel [60,61]. Numerous studies have demonstrated the potential of biofuels and synthetic fuels as substitutes for traditional petroleum-derived jet fuels to reduce emissions of pollutants [62,63]. Adopting alternative fuels in aviation presents an opportunity to address environmental concerns and contribute to reducing pollution emissions. Biofuels and synthetic fuels are being investigated as viable options for the industry.

This study focuses on reducing greenhouse gas (GHG) emissions in commercial domestic aviation by using hydro-processed esters and fatty acids (HEFA) as an alternative to conventional jet A-1 fuel. The choice of HEFA was based on the suitability of oil-to-jet technology, which utilizes biomass as a raw material. This approach takes advantage of the underutilized biomass resources available in the country and benefits from indirect biomass utilization, contributing to the reduction of GHG emissions [64]. Palm has a high agricultural yield, with a production rate of 15.7 tons/ha and an oil content ranging from 21% to 37%. Globally, palm production amounts to 282.2 million tons, with major producers including Indonesia (45%), Malaysia (37%), and Thailand (5%) [65]. The European Commission guidelines utilize Sustainable Aviation Fuel (SAF) volume shares. These volume shares indicate the proportion of SAF used in the aviation sector from 2021 to 2050. The European Commission guidelines serve as a reference for reducing conventional jet fuel use and transitioning to SAF to mitigate GHG emissions. The volume shares of SAF are presented in Table 3. This represents the recommended SAF ratios according to European Commission guidelines, illustrating the growing proportion of SAF usage in the domestic aviation sector over time.



Figure 2. The historical data of four-factor variables related to the growth in GHG emissions. (**a**) The number of passengers and the amount of freight 2008–2020. (**b**) Aviation Jet fuel price and GDP 2008–2020.

Year	SAF Percentage (%)
 2021	0
2025	2
2030	5
2035	20
2040	32
2045	38
2050	63

Table 3. Volume shares of SAF fuel from 2021 to 2050.

Sources: [66].

2.3.3. Aircraft Technology Scenario

The primary factor contributing to emissions reduction in the aviation sector is the improvement in fuel efficiency. Effective strategies for enhancing efficiency include using fuel-efficient next-generation aircraft, advancements in air traffic management (ATM), reengineering processes, and implementing technologically enhanced flight patterns [67]. The introduction of advanced aircraft designs has increased fuel economy in the aviation industry. ICAO's predictions for international aviation activities indicate a future decrease in fuel demand. With a projected reduction of 10 MCMOED (million cubic meters of oil equivalent per day) by 2050, the scenario that achieves the 2% yearly fuel efficiency target

yields the most significant savings. The ICAO has set a target of 2% improved efficiency for the global aviation fleet from 2021 to 2050 through non-engine-based efficiency enhancements and fuel efficiency improvements. Non-engine-based efficiency enhancements, such as lighter aircraft components and improved fuel efficiency, are considered crucial in significantly reducing aviation sector GHG emissions [33].

Improving fuel efficiency is crucial for reducing CO_2 emissions in the aviation industry. Fuel costs account for approximately 20% of total operating costs for modern airplanes [68]. Over the years, significant advancements in aircraft fuel efficiency have been achieved. Since 1960, aircraft fuel efficiency has improved by approximately 70–80% [69]. Projections indicate that 40–50% improvements are possible by 2050 [68]. To incorporate the potential fuel efficiency improvements in this study, it is assumed that aircraft technology will continue to advance. Specific engine performance enhancements have been achieved through upgrading programs in recent years, reducing fuel usage by up to 2% [70].

Additionally, new engines and auxiliary power units (APUs) are expected to consume at least 15% less fuel than the aircraft they replace. These improvements are made possible through innovations in engine technologies, including materials, coatings, combustion methods, sensors, and cooling methods [70]. Based on the ICAO target, this study assumes that aircraft technology will continue to improve fuel efficiency by 2% annually from 2021 to 2050. This assumption reflects the ongoing efforts and advancements in aircraft design and technology to achieve greater fuel efficiency and reduce CO_2 emissions.

2.3.4. Carbon Pricing Scenario

Carbon pricing is widely recognized as the primary policy tool for countries to reduce GHG emissions globally [71]. Imposing a price on carbon through taxes, emissions trading, or regulation is considered the foremost objective of mitigation policies [72]. Carbon pricing creates incentives for investments in new technologies that can mitigate global warming and holds emitters accountable for the environmental impact of their emissions [73,74]. By increasing the cost of carbon-intensive production, carbon pricing can reduce demand for fuel-based products, encouraging the substitution of technologies. Therefore, in theory, an effective carbon price should lower aircraft emissions by raising prices and subsequently reducing demand. Thus, market-based measures (MBM) are recognized as one of the international guidelines for reducing GHG emissions. This measure is in line with the existing international policy framework provided by the International Civil Aviation Organization (ICAO). MBMs encompass mechanisms such as carbon offset programs or emissions trading schemes, which create economic incentives and market mechanisms to encourage emissions reductions in the aviation sector. Carbon pricing and market-based measures play significant roles in global efforts to reduce GHG emissions and are particularly relevant in the aviation industry.

Carbon pricing mechanisms, such as cap and trade or direct taxation systems, can impact fuel use and CO_2 emissions. As the price of carbon increases, the effective fuel price also rises, leading to a reduction in consumption due to the demand–price relationship. Hasan et al. [33] anticipated that increasing the high carbon price could result in a 12% reduction in overall emissions, equivalent to 180 MtCO₂ of emissions in the mitigation pathway. To estimate the price elasticity of fuel demand, income elasticities were used to adjust the price elasticity. Hasan et al. [33] estimated that price elasticity of fuel demand is -0.48, indicating that a 10% increase in price will result in a 4.8% decrease in demand. This relationship demonstrates the responsiveness of fuel consumption to changes in price. In Thailand's domestic aviation sector, this study examined the change in demand for fuel consumption and aviation jet fuel prices during 2009–2010 and 2016–2017. Figure 3 illustrates the relationship between jet fuel price increases and the corresponding change in demand for fuel consumption. The jet fuel prices increased and had an impact on decreased

demand twice: first, between 2009 and 2010, when jet fuel prices increased by around 12%, resulting in an average 6% decrease in demand; and second, between 2016 and 2017, when jet fuel prices increased by around 7%, resulting in an average 4% decrease in demand. Therefore, the results show that the average increase in jet fuel prices in both periods was 10%, resulting in an average 4.9% decrease in demand. Based on these observations, the study assumes an annual increase in jet fuel prices by 10% from 2021 to 2050 will result in a 4.9% decrease in fuel demand. This assumption reflects the anticipated impact of carbon pricing on fuel consumption in the domestic aviation sector.



Figure 3. The relationship between fuel consumption and jet fuel prices.

2.4. Calculation Method for GHG Emissions

The Intergovernmental Panel on Climate Change (IPCC) used the tier-I method to calculate GHG emissions from the domestic aviation sector's jet fuel consumption activities [75]. This method is based on the quantity of energy used (aviation fuel consumption) multiplied by an average emission factor. Equation (6) shows the formula to estimate GHG emissions. Firstly, the activity data for aviation mode was established. After that, the amounts of aviation fuel consumed in physical units or other energy units (such as l, ktoe, kg, etc.) were converted to the terajoule (TJ), the common international energy unit; and the fuel consumption was multiplied by the factor for carbon emission to determine the carbon emission. Finally, only the fraction of oxidized carbon was utilized to determine the actual CO₂ emission, as not all the carbon in the fuel is oxidized to generate carbon dioxide.

$$CO_2 = E_f \times N_f \times CE_c \tag{6}$$

where

 CO_2 = An emission of carbon dioxide (t CO_2); E = A specific energy usage (ktoe); N = A net calorific value specific to fuel (TJ/ktoe); CE_c = A factor for carbon emissions (kg/TJ); f = Type of fuel.

The global warming potential (GWP) conversion factors calculated GHG emissions to CO₂ equivalent units. The impact of individual greenhouse gas emissions on global warming cannot be easily compared on a mass basis since the gases' physical and chemical properties vary. Therefore, IPCC advises converting all computed greenhouse gas emissions to CO₂ equivalent units using the GWP conversion factor to precisely compare the global warming effects between individual GHGs. The Global Warming Potential (GWP) value from IPCC, AR5 [76] and IPCC, AR6 [77] is used in this study. Table 4 shows the global warming potential (GWP). Moreover, the default parameters adopted in this study are

those recommended by the IPCC [52], as shown in Table 5 for CO₂ emission and non-CO₂ emission factors and Table 6 for net calorific values.

Table 4. The global warming potential (GWP) in IPCC 5th and 6th Assessment Reports.

Industrial Designation or Standard Name	The Formula for Chamical	The GWP Value for the 100-Year Time Horizon		
	The Formula for Chemical	Fifth Assessment (AR5)	Sixth Assessment (AR6)	
Nitrous oxide	N ₂ O	265	273	
Methane	CH_4	28	29.8	
Carbon dioxide	CO ₂	1	1	

Table 5. CO₂ emission factors.

Fuel	CO ₂ Default (kg/TJ)	CH ₄ Default (kg/TJ)	N ₂ O Default (kg/TJ)
Jet fuel (Jet Kerosene)	71,500	0.5	2

Table 6. Net calorific values.

Fuel	Factors (TJ/10 ³ tonnes)	
Jet Kerosene	44.59	

2.5. Empirical Data

In this study, the forecasting of GHG emissions for 2021–2050 was calculated by forecasting fuel consumption and calculating GHG emissions using IPCC, Tier-I [52]. The data on fuel consumption for the domestic aviation sector was derived from the Department of Alternative Energy Development and Efficiency's statistical data reports for 2008–2020 [47]. Gross domestic product (GDP) figures are available from the World Bank—Thailand Bureau through their statistical data report on gross domestic product [54]. However, GDP was converted into terms representing 'real prices'. The conversion was performed using a deflator derived from the World Bank's national accounts and the Organization for Economic Cooperation and Development's (OECD) national accounts data [71,78]. The number of passengers and freights in the domestic aviation sector was obtained from the Civil Aviation Authority of Thailand (CAAT) [46]. Information on jet fuel prices is sourced from the Petroleum Authority of Thailand's statistics data reports for 2015–2020 (Petroleum Authority of Thailand Oil and Retail Business Public Company Limited) [51]. However, jet fuel prices from 2008 to 2014 were calculated from the estimated rate of change of Brent crude oil futures. Moreover, all jet fuel prices include interior tax, a 7% VAT, and excise tax. For consistency in calculations, prices were converted to USD per liter.

3. Results

3.1. Historical Trends

The results highlight the rapid growth of domestic commercial aviation activities in Thailand, which can be attributed to various strategies to stimulate the economy, particularly targeting air travel and tourism. The implementation of Thailand's Transport Infrastructure Development Strategy 2015–2022 has played a significant role in supporting the growth of the aviation sector. This strategy focuses on constructing domestic airports that meet international standards and cater to the increasing travel needs of the population. Additionally, the strategy emphasizes the utilization of regional airports to enhance their contribution to the country's aviation industry. Through these efforts, the number of passengers in the domestic commercial aviation industry has witnessed a substantial increase of approximately 214% from 2008 to 2019. Similarly, freight volume experienced a remarkable growth of about 793% during the same period. These statistics demonstrate the growing demand and importance of the aviation industry in Thailand. Consequently, the increased activity in the commercial domestic aviation sector has led to a significant rise in aviation fuel consumption. From 2008 to 2019, aviation fuel consumption in this sector increased from 246 ktoe (kilo-tonnes of oil equivalent) to 716 ktoe, representing a surge of approximately 190%.

In 2020, aviation fuel consumption decreased from 716 ktoe in 2019 to 477 ktoe in 2020 due to the COVID-19 pandemic, and Thailand proclaimed a state of emergency in all areas in March 2020 [79]. The pandemic affected the domestic and international aviation sectors [43]. The number of passengers and freight, GDP, fuel price, and aviation fuel consumption from sources mentioned in Table 1 are presented in Table 7.

Table 7. Historical trends of the number of passengers and amount of freight, GDP, fuel price, and aviation fuel consumption in Thailand's commercial domestic aviation industry from 2008 to 2020.

Year	Passengers (Person)	Freight (kg)	GDP Billion Baht (at 2008 Price)	Fuel Prices (USD/Litre)	Fuel Consumptions (ktoe)
2008	24,310,188	8,706,271	7722	1.19	246
2009	26,219,477	9,273,089	7668	0.81	288
2010	27,208,643	9,109,330	8243	1.06	258
2011	31,623,503	10,238,865	8302	1.47	265
2012	36,192,158	10,777,970	8903	1.43	261
2013	42,427,923	11,210,853	9143	1.41	295
2014	50,059,872	12,800,068	9233	1.22	625
2015	62,216,533	14,292,021	9523	0.72	732
2016	70,327,980	119,490,892	9866	0.62	818
2017	75,342,243	112,653,693	10,260	0.73	757
2018	78,625,622	93,682,980	10,692	0.89	856
2019	76,253,599	77,828,059	10,887	0.89	716
2020	41,996,665	32,214,457	10,348	0.60	477

3.2. Forecasting of Fuel Use and GHG Emissions

The analysis of GHG emissions in the reference future scenario is presented in Figure 4, reflecting forecasted trends based on factors such as aviation jet fuel price, the number of passengers and amount of freight, and GDP. Using Equation (6), the study calculated the predicted GHG emissions in the domestic aviation sector. The results indicate that GHG emissions and aviation fuel consumption trends will increase from 2021 to 2050. GHG emissions are expected to rise from 2340 thousand tonnes of CO₂-eq in 2021 to 7200 thousand tonnes of CO₂-eq in 2050, representing an average annual growth rate of 3.99%. This is consistent with other research on future increases in GHG emissions [31,80]. This growth rate signifies a substantial GHG emissions increase over the predicted period. The emissions are projected to increase by more than 9.2 times, reflecting the substantial impact of the sector on overall emissions in the long term. The forecasted increase in GHG emissions, aligning with the country's climate targets.

3.3. Pathways for Mitigation in the Domestic Aviation Industry

The following sections describe mitigation measures or policies that were analyzed and considered to reduce the domestic aviation sector's GHG emissions that could pave the path for sustainable reduction of aviation industry GHG emissions and support Thailand's goal of reducing GHG emissions by 2050. Figure 5 shows the forecasting of the usage of aviation fuel and the mitigation pathways for greenhouse gas (GHG) emissions for each scenario.



Figure 4. Forecasting fuel consumption and GHG emissions for the reference future scenario.



Figure 5. Forecasting aviation fuel consumption and GHG emissions mitigation pathways for each scenario.

3.3.1. Fuel Switching

According to the European Commission regarding volume shares of SAF fuel in Section 2.3.2, the use of alternative fuels in 2025 will be 2% and increase every five years. The results in Figure 5 indicate that GHG emissions in this scenario show a downward trend from 2025 to 2050. The GHG emissions reduction depends on the proportion of alternative fuels. The most considerable GHG emissions reduction is in 2050, when the proportion of alternative fuels is around 63%. It decreased by around 2300 thousand tonnes of CO_2 -eq compared to the reference scenario 2050. In addition, with the reduction of GHG

emissions from alternative fuels compared to other scenarios, alternative fuels can reduce GHG emissions the most, according to the results of calculations and analysis.

3.3.2. Aircraft Technology

One method of reducing GHG emissions in the aviation industry is through increased fuel efficiency and non-engine-based efficiency improvements. This is the main factor and an important factor in reducing GHG emissions. Figure 5 shows that the goal is to enhance fuel efficiency by 2% annually regardless of costs or obstacles. It begins from 2021 to 2050, according to the ICAO target. The trends in GHG emissions are projected to decrease from 2021 to 2050. It decreased from 2340 thousand tonnes of CO_2 -eq to 2293 thousand tonnes of CO_2 -eq compared to the reference future scenario 2021, decreasing yearly. The short-term reductions in GHG emissions will be very effective because the first period (2021–2025) is the beginning of the aviation sector's growth after the COVID-19 situation. As a result, the fuel consumption during that period was not intense compared to the improving fuel efficiency will be less efficient in the long term due to increased fuel consumption, because historical data on the growth of the aviation sector shows that Thailand's aviation sector is growing rapidly, but the efficiency improvement goals will remain stagnant.

3.3.3. Carbon Pricing

Through the demand-price relationship, rising carbon prices lead to rising effective fuel prices, reducing consumption [41]. As mentioned in Section 2.3.4, a 10% increase in jet fuel price will lead to a 4.9% reduction in fuel consumed on demand. The results in Figure 5 show that GHG emissions will decrease from 2021 to 2050. GHG emissions began to decrease in 2021, from 2340 thousand tonnes of CO_2 -eq to 2225 thousand tonnes of CO_2 -eq, decreasing every year. The reduction in GHG emissions from this scenario depends on carbon pricing and the demand–price relationship. However, carbon pricing will be less efficient in the long term due to the forecasted increase in fuel consumption from the reference future scenario (the rapid growth of the aviation sector in the past). It will increase fuel consumption and GHG emissions; however, carbon pricing remains the same, causing a decrease in the efficiency of this scenario.

3.3.4. Creating Multi-Policy Scenarios by Combining Different Policies

The policies outlined in Section 2.3, aimed at reducing GHG emissions in the domestic aviation sector (e.g., fuel switching, aircraft technology, and carbon pricing), have been examined individually in specific areas of improvement. However, in this section, we analyze all these policies concurrently, as this represents the primary strategy for reducing GHG emissions from 2021 to 2050.

The three policies considered in this study have the potential to significantly reduce domestic aviation emissions by 2050 compared to employing only one policy to reduce greenhouse gas emissions. Combining all three scenarios leads to a greater reduction in GHG emissions than any single scenario alone. Specifically, it results in a decrease of approximately 2796 thousand tonnes of CO_2 -eq, equivalent to a 39% reduction compared to the reference future scenario projected for 2050.

4. Discussion

Figure 5 illustrates the mitigation pathways, each with its advantages and challenges. For instance, alternative fuels offer substantial potential for reducing emissions. However, there are limitations, including constraints on arable lands for biofuel production, the high cost of alternative fuels, and the need for policy support to facilitate large-scale production and utilization. Another effective approach to curbing GHG emissions is the implementation of carbon pricing [81]. Carbon pricing, often enacted as a carbon tax, has proven effective in reducing greenhouse gas (GHG) emissions by discouraging carbon

emissions through increased fossil fuel prices, thereby reducing their use [35]. Additionally, carbon pricing mechanisms have been shown to promote biofuels [82].

Despite efforts to enhance fuel efficiency in the aviation industry, GHG emissions from this sector are projected to increase. Thailand's aviation industry has undergone rapid growth, driven by the country's economic development and the implementation of the Transport Infrastructure Development Strategy 2015–2022. Addressing rising GHG emissions requires accurate estimation of future emissions and fuel consumption in the commercial domestic aviation sector. This estimation forms the basis for implementing mitigation strategies over the next three decades, which include fuel switching, aircraft technology improvement, and carbon pricing. The objective of these mitigation measures is to reduce GHG emissions in Thailand's aviation sector, aligning with the country's commitment to decreasing GHG emissions under the UNFCCC. Accurate estimation of GHG emissions and fuel usage provides essential guidance for policymakers and stakeholders, aiding in the development of effective strategies to mitigate emissions and attain climate targets.

5. Conclusions

The forecasted growth in aviation fuel consumption in Thailand's domestic commercial aviation sector indicates an average annual increase of approximately 4% over the past decade. In the reference future scenario, GHG emissions from the domestic commercial aviation industry are anticipated to more than triple, which is in line with other research that predicts a significant increase in the aviation sector's GHG emissions [31,80]. This signifies a substantial increase in emissions over the three-decade period, highlighting the urgent need for mitigation strategies to address the environmental impact of the aviation sector. Adopting fuel switching, particularly alternative fuels, can significantly reduce greenhouse gas (GHG) emissions from Thailand's domestic aviation sector. By 2050, the potential reduction in GHG emissions is projected to be as high as 2279.4 thousand tonnes of CO_2 equivalent. This signifies a substantial decrease in emissions, highlighting the effectiveness of fuel switching as a mitigation strategy for reducing the environmental impact of the domestic aviation sector. The achievement of these reductions depends on the implementation of fuel switching measures and the gradual increase in the utilization of alternative fuels.

The aircraft technology and carbon pricing scenarios play important roles in reducing greenhouse gas (GHG) emissions from the domestic aviation sector in the short term. In the case of aircraft technology, the scenario will reduce 145.2 thousand tonnes of CO_2 equivalent in GHG emissions by 2050. Similarly, the carbon pricing scenario aims to impose a price on carbon, incentivizing fuel consumption and GHG emissions reduction. This scenario will reduce 355.8 thousand tonnes of CO_2 equivalent in GHG emissions by 2050. However, it is important to note that the effectiveness of these scenarios diminishes in the long term due to the constant goals of aircraft technology and carbon pricing.

All of the individual scenarios for reducing GHG emissions have differences in efficiency in short- and long-term reductions. However, each scenario has limitations and relevance to reducing GHG emissions in the future. For example, alternative fuels require arable lands that are limited for biofuel production, alternative fuels are currently expensive, and policy support is required for large-scale use and production. In addition, carbon pricing has been effective in promoting biofuels [82]. Therefore, combining all scenarios can reduce GHG emissions by about 2796 thousand tonnes of CO₂-eq or 39% compared with the reference future scenario in 2050.

Indeed, reducing GHG emissions in Thailand's aviation sector requires implementing significant ICAO measures and collaborating with various stakeholders. While the identified policies can potentially reduce emissions, it is important to acknowledge the obstacles and limitations associated with their implementation. Factors such as the availability of personnel and expertise, budgetary support, technological advancements, societal acceptance, and policy frameworks play significant roles in determining the success of emission reduction measures. Governmental policymakers and industry executives should engage in ongoing discussions, surveys, and assessments to identify and address barriers to implementation, prioritize effective policies, and promote best practices. By actively involving relevant stakeholders, including government bodies, industry players, research institutions, and civil society, developing comprehensive strategies that consider the unique context of Thailand's aviation sector will be possible. Continuous dialogue and collaboration are essential to foster a supportive environment for adopting effective policies and measures to drive significant GHG emission reductions while aligning with national goals and international commitments. Through these efforts, Thailand can progress in achieving its GHG emission reduction targets, contributing to global climate change mitigation efforts and creating a more sustainable aviation sector.

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References

- Kim, B.; Fleming, G.; Balasubramanian, S.; Malwitz, A.; Lee, J.; Waitz, I.; Klima, K.; Locke, M.; Holsclaw, C.; Morales, A.; et al. SAGE System for Assessing Aviation's Global Emissions, Version 1.5; Federal Aviation Administration Office of Environment and Energy: Washington, DC, USA, 2005.
- Edwards, H.A.; Dixon-Hardy, D.; Wadud, Z. Aircraft cost index and the future of carbon emissions from air travel. *Appl. Energy* 2016, 164, 553–562. [CrossRef]
- Chiaramonti, D.; Prussi, M.; Buffi, M.; Tacconi, D. Sustainable bio kerosene: Process routes and industrial demonstration activities in aviation biofuels. *Appl. Energy* 2014, 136, 767–774. [CrossRef]
- Álvarez-Gil, M.J.; Yan, W. Is Environmental Innovation Worth It? The Case of the Civil Aviation Industry of Emerging Markets. IFIP Adv. Inf. Commun. Technol. 2013, 415, 294–301. [CrossRef]
- Norton, T.M. Aircraft Greenhouse Gas Emissions during the Landing and Takeoff Cycle at Bay Area Airports. 2014. Available online: https://repository.usfca.edu/capstone/15 (accessed on 24 May 2022).
- 6. Uherek, E.; Halenka, T.; Borken-Kleefeld, J.; Balkanski, Y.; Berntsen, T.; Borrego, C.; Gauss, M.; Hoor, P.; Juda-Rezler, K.; Lelieveld, J.; et al. Transport impacts on atmosphere and climate: Land transport. *Atmos. Environ.* **2010**, *44*, 4772–4816. [CrossRef]
- Shon, Z.H.; Kim, K.H.; Song, S.K. Long-term trend in NO₂ and NO_x levels and their emission ratio in relation to road traffic activities in East Asia. *Atmos. Environ.* 2011, 45, 3120–3131. [CrossRef]
- 8. Lee, D.S.; Pitari, G.; Grewe, V.; Gierens, K.; Penner, J.E.; Petzold, A.; Prather, M.J.; Schumann, U.; Bais, A.; Berntsen, T.; et al. Transport impacts on atmosphere and climate: Aviation. *Atmos. Environ.* **2010**, *44*, 4678–4734. [CrossRef]
- Lee, D.S.; Fahey, D.W.; Skowron, A.; Allen, M.R.; Burkhardt, U.; Chen, Q.; Doherty, S.J.; Freeman, S.; Forster, P.M.; Fuglestvedt, J.; et al. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos. Environ.* 2021, 244, 117834. [CrossRef]
- Klöwer, M.; Allen, M.R.; Lee, D.S.; Proud, S.R.; Gallagher, L.; Skowron, A. Quantifying aviation's contribution to global warming. Environ. Res. Lett. 2021, 16, 104027. [CrossRef]
- Planès, T.; Delbecq, S.; Pommier-Budinger, V.; Bénard, E. Simulation and evaluation of sustainable climate trajectories for aviation. *J. Environ. Manag.* 2021, 295, 113079. [CrossRef]
- 12. Rupcic, L.; Pierrat, E.; Fricke, K.; Moll, T.; Hauschild, M.Z.; Laurent, A. Improving environmental performances of integrated bladed rotors for aircraft. *CIRP Ann.* **2022**, *71*, 13–16. [CrossRef]
- Héroux, M.-E.; Babisch, W.; Belojevic, G.; Brink, M.; Janssen, S.; Lercher, P.; Paviotti, M.; Pershagen, G.; Waye, K.P.; Preis, A.; et al. WHO Environmental noise guidelines for the European Region. In Proceedings of the European Congress and Exposition on Noise Control Engineering, Maastricht, The Netherlands, 31 May–3 June 2015; pp. 2589–2593.
- 14. Air Transport Bureau. *Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis;* ICAO–International Civil Aviation Organization: Montréal, QC, Canada, 2020.
- Brandon, G.; Kevin, Z.; Dan, R. CO₂ Emissions from Commercial Aviation; International Council on Clean Transportation: Washington, DC, USA, 2018. Available online: https://theicct.org/publication/co2-emissions-from-commercial-aviation-2018/ (accessed on 24 May 2022).

- Crippa, M.; Oreggioni, G.; Guizzardi, D.; Muntean, M.; Schaaf, E.; Lo Vullo, E.; Solazzo, E.; Monforti-Ferrario, F.; Olivier, J.G.J.; Vignati, E. Fossil CO2 and GHG Emissions of all World Countries. 2019. Available online: https://op.europa.eu/en/publicationdetail/-/publication/9d09ccd1-e0dd-11e9-9c4e-01aa75ed71a1/language-en (accessed on 24 May 2022).
- 17. IATA—International Air Transport Association. Economic Performance of the Airline Industry: 2015 Mid-Year Report. 2015. Available online: https://www.iata.org/en/publications/economics/ (accessed on 24 May 2022).
- ICAO—International Civil Aviation Organization. Assembly-40th Session Executive Committee Agenda Item 15: Environmental Protection-General Provisions, Aircraft Noise and Local Air Quality-Policy and Standardization Icao Global Environmental Trends-Present and Future Aircraft Noise and Emissions; ICAO: Montreal, QC, Canada, 2019.
- 19. Dube, K. Emerging from the COVID-19 Pandemic: Aviation Recovery, Challenges and Opportunities, 2022. *Aerospace* 2023, 10, 19. [CrossRef]
- OECD—The Organisation for Economic Co-Operation and Development. Air Transport CO₂ Emissions. 2022. Available online: https://stats.oecd.org/Index.aspx?DataSetCode=AIRTRANS_CO2# (accessed on 18 July 2022).
- C2ES—Center for Climate and Energy Solutions. Outcomes of the U.N. Climate Change Conference in Lima. 2016. Available online: https://www.c2es.org/wp-content/uploads/2017/10/outcomes-of-the-u-n-climate-change-conference-in-lima.pdf (accessed on 24 July 2022).
- UNFCCC—United Nations Framework Convention on Climate Change. Thailand's Intended Nationally Determined Contribution (INDC). 2016. Available online: https://www4.unfccc.int/sites/SubmissionsStaging/NationalReports/Documents/347251 _Thailand-BUR2-1-SBUR%20THAILAND.pdf (accessed on 26 July 2022).
- 23. IATA—International Air Transport Association. Fact Sheet Climate Change & CORSIA a CO2 Standard for Aircraft. 2017. Available online: www.iata.org/policy/environment (accessed on 22 July 2022).
- 24. ICAO—International Civil Aviation Organization. *Introduction to the ICAO Basket of Measures to Mitigate Climate Change*; ICAO: Montreal, QC, Canada, 2007.
- ICAO—International Civil Aviation Organization. CORSIA Eligible Fuels. Available online: https://www.icao.int/ environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx (accessed on 9 October 2023).
- Maertens, S.; Grimme, W.; Scheelhaase, J.; Jung, M. Options to Continue the EU ETS for Aviation in a CORSIA-World. Sustainability 2019, 11, 5703. [CrossRef]
- 27. Tawatchai, S. Global Commitment of ICAO to the Development of the Low-Carbon Aviation Industry (Global Aspirational Goal); Thailand Greenhouse Gas Management Organization: Bangkok, Thailand, 2019.
- Gudmundsson, S.V.; Anger, A. Global carbon dioxide emissions scenarios for aviation derived from IPCC storylines: A metaanalysis. *Transp. Res. Part D Transp. Environ.* 2012, 17, 61–65. [CrossRef]
- Owen, B.; Lee, D.S.; Lim, L. Flying into the future: Aviation emissions scenarios to 2050. *Environ. Sci. Technol.* 2010, 44, 2255–2260. [CrossRef]
- Macintosh, A.; Wallace, L. International aviation emissions to 2025: Can emissions be stabilised without restricting demand? Energy Policy 2009, 37, 264–273. [CrossRef]
- Zhou, W.; Wang, T.; Yu, Y.; Chen, D.; Zhu, B. Scenario analysis of CO₂ emissions from China's civil aviation industry through 2030. *Appl. Energy* 2016, 175, 100–108. [CrossRef]
- 32. Kousoulidou, M.; Lonza, L. Biofuels in aviation: Fuel demand and CO₂ emissions evolution in Europe toward 2030. *Transp. Res. Part D Transp. Environ.* **2016**, *46*, 166–181. [CrossRef]
- 33. Hasan, M.A.; Mamun, A.A.; Rahman, S.M.; Malik, K.; Al Amran, M.I.U.; Khondaker, A.N.; Reshi, O.; Tiwari, S.P.; Alismail, F.S. Climate Change Mitigation Pathways for the Aviation Sector. *Sustainability* **2021**, *13*, 3656. [CrossRef]
- 34. Bows-Larkin, A. All adrift: Aviation, shipping, and climate change policy. Clim. Policy 2015, 15, 681–702. [CrossRef]
- 35. Fageda, X.; Teixidó, J.J. Pricing carbon in the aviation sector: Evidence from the European emissions trading system. *J. Environ. Econ. Manag.* **2022**, *111*, 102591. [CrossRef]
- Agencia Portuguesa do Ambiente, Portuguese National Inventory Report on Greenhouse Gases, 1990–2016. Submitted Under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. 2019. Available online: https://unfccc.int/ documents/194464 (accessed on 30 August 2022).
- 37. Andrés, L.; Padilla, E. Driving factors of GHG emissions in the EU transport activity. Transp. Policy 2019, 61, 60–74. [CrossRef]
- Environment Agency Austria. Austria's National Inventory Report 2019, Submission to the UNFCCC Secretariat. 2019. Available online: https://unfccc.int/documents/194891 (accessed on 30 August 2022).
- Environmental Protection Agency. Ireland's National Inventory Report 2019. Greenhouse Gas Emissions 1990–2017. Submission to the UNFCCC Secretariat. 2019. Available online: https://unfccc.int/documents/194638 (accessed on 30 August 2022).
- Tavakoli, A. A journey among top ten emitter country, decomposition of 'Kaya Identity. Sustain. Cities Soc. 2018, 38, 254–264. [CrossRef]
- 41. Sgouridis, S.; Bonnefoy, P.A.; Hansman, R.J. Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation. *Transp. Res. Part A Policy Pract.* **2011**, *45*, 1077–1091. [CrossRef]
- Zaporozhets, O.; Isaienko, V.; Synylo, K. Trends on current and forecasted aircraft hybrid electric architectures and their impact on environment. *Energy* 2020, 211, 118814. [CrossRef]

- 43. CAAT—The Civil Aviation Authority of Thailand, State of Thai Aviation Industry, 2019 report. 2019. Available online: https://www.caat.or.th/wp-content/uploads/2020/06/STATE-OF-THAI-AVIATION-INDUSTRY-2019.pdf (accessed on 24 May 2022).
- 44. Ozturk, I.; Al-Mulali, U.; Saboori, B. Investigating the environmental Kuznets curve hypothesis: The role of tourism and ecological footprint. *Environ. Sci. Pollut. Res.* **2015**, *23*, 1916–1928. [CrossRef]
- 45. CAAT—The Civil Aviation Authority of Thailand. Announcement of the Civil Aviation Authority of Thailand: Guidelines for Airport Operators and Air Operators on Domestic Routes during the Coronavirus Disease 2019 Epidemic Situation. 2020. Available online: https://www.caat.or.th/th/archives/59631 (accessed on 24 May 2022).
- 46. CAAT—The Civil Aviation Authority of Thailand. State of Thai Aviation Industry, 2020 Report; CAAT: Bangkok, Thailand, 2020.
- DEDE—Department of Alternative Energy Development and Efficiency. Energy Statistics, Energy Balance of Thailand. 2019. Available online: https://webkc.dede.go.th/testmax/sites/default/files/Energy_Balance_of_Thailand_2019.pdf (accessed on 24 May 2022).
- 48. TGO—Thailand Greenhouse Gas Management Organization. Greenhouse Gas Management Organization Strategic Plan 2018–2022. 2019. Available online: http://www.tgo.or.th/2020/index.php/en/page/tgo-strategy-plan (accessed on 24 May 2022).
- 49. Narciso, M.; Melo de Sousa, J.M. Influence of Sustainable Aviation Fuels on the Formation of Contrails and Their Properties. *Energies* **2021**, *14*, 5557. [CrossRef]
- Baxter, G. Mitigating Aircraft Auxiliary Power Unit Carbon Dioxide (CO₂) Emissions During the Aircraft Turnaround Process from the Use of Solar Power at the Airport Gate: The Case of Moi International Airport, Kenya. *Int. J. Environ. Agric. Biotechnol.* 2022, 7, 14–22. [CrossRef]
- PTTOR—Petroleum Authority of Thailand Oil and Retail Business Public Company Limited. Aviation Jet Fuel Prices Report. 2020. Available online: https://www.pttplc.com/en/Products/Ourbusinessbyaffiliates/Oilandretailbusiness.aspx (accessed on 5 February 2023).
- 52. IPCC—Intergovernmental Panel on Climate Change. Guidelines for National Greenhouse Gas Inventories. Available online: https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed on 26 July 2022).
- 53. BOT—Bank of Thailand. Rates of Exchange of Commercial Banks. 2021. Available online: https://www.bot.or.th/english/ _layouts/application/exchangerate/exchangerate.aspx (accessed on 24 May 2022).
- 54. The World Bank. GDP (Current US\$)—Thailand | Data. 2021. Available online: https://data.worldbank.org/indicator/NY.GDP. MKTP.CD?locations=TH (accessed on 24 May 2022).
- Yin, L.; Yao, T.; Zhou, J.; Liu, G.; Liao, Y.; Ma, X. Prediction of CO₂ Emissions Based on Multiple Linear Regression Analysis. Energy Procedia 2017, 105, 4222–4228. [CrossRef]
- 56. Zhou, Y.; Zhang, J.; Hu, S. Regression analysis and driving force model building of CO₂ emissions in China. *Sci. Rep.* **2021**, *11*, 6715. [CrossRef]
- 57. Maaouane, M.; Zouggar, S.; Krajačić, G.; Zahboune, H. Modelling industry energy demand using multiple linear regression analysis based on consumed quantity of goods. *Energy* 2021, 225, 120270. [CrossRef]
- 58. Geem, Z.W.; Roper, W.E. Energy demand estimation of South Korea using artificial neural network. *Energy Policy* 2009, 37, 4049–4054. [CrossRef]
- Parikh, J.; Purohit, P.; Maitra, P. Demand projections of petroleum products and natural gas in India. *Energy* 2007, 32, 1825–1837. [CrossRef]
- 60. Blakey, S.; Rye, L.; Wilson, C.W. Aviation gas turbine alternative fuels: A review. *Proc. Combust. Inst.* 2011, 33, 2863–2885. [CrossRef]
- 61. Williams, P.I.; Allan, J.D.; Lobo, P.; Coe, H.; Christie, S.; Wilson, C.; Hagen, D.; Whitefield, P.; Raper, D.; Rye, L. Impact of alternative fuels on emissions characteristics of a gas turbine engine—Part 2: Volatile and semivolatile particulate matter emissions. *Environ. Sci. Technol.* **2012**, *46*, 10812–10819. [CrossRef]
- 62. Corporan, E.; Edwards, T.; Shafer, L.; Dewitt, M.J.; Klingshirn, C.; Zabarnick, S.; West, Z.; Striebich, R.; Graham, J.; Klein, J. Chemical, Thermal Stability, Seal Swell, and Emissions Studies of Alternative Jet Fuels. *Energy Fuels* **2011**, *25*, 955–966. [CrossRef]
- 63. Murgan, M.; Hamid, A.; Mustapha, M. Rethinking the potency of ICAO SARPS on global reduction of aviation emission and protection of global environment. *Bratisl. Law Rev.* 2017, 1, 28–37. [CrossRef]
- 64. DEDE—Department of Alternative Energy Development and Efficiency. The Study of Sustainable Biojet Promotion Plan for Thailand. 2020. Available online: https://www.statista.com/statistics/655057/fuel-consumption-of-airlines-worldwide/ (accessed on 15 August 2022).
- 65. ICAO—International Civil Aviation Organization. Sustainable Aviation Fuels Guide Version 2. 2018. Available online: https://www.icao.int/environmental-protection/Documents/Sustainable%20Aviation%20Fuels%20Guide_100519.pdf (accessed on 1 September 2022).
- European Commission. Regulation of the European Parliament and of the Council on Ensuring a Level Playing Field for Sustainable Air Transport. 2021. Available online: https://ec.europa.eu/transport/themes/mobilitystrategy_en (accessed on 1 September 2022).
- Keramidas, K.; Diaz-Vazquez, A.R.; Vandyck, T.; Rey Los Santos, L.; Schade, B.; Soria-Ramirez, A. Global Energy and Climate Outlook 2018: Sectoral Mitigation Options towards a Low-Emissions Economy. 2018. Available online: https://op.europa.eu/en/publication/edff2046-f2c1-11e8-9982-01aa75ed71a1/language-en (accessed on 16 August 2022).

- 68. Kahn Ribeiro, S.; Kobayashi, S.; Beuthe, M.; Gasca, J.; Greene, D.; Lee, D.S.; Muromachi, Y.; Newton, P.J.; Plotkin, S.; Sperling, D.; et al. Transport and Its Infrastructure. In *Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2007. Available online: https://archive.ipcc.ch/publications_and_data/ar4/wg3/en/ch5.html (accessed on 4 September 2022).
- OECD—The Organisation for Economic Co-Operation and Development. Transport Outlook 2012: Seamless Transport for Greener Growth. 2012. Available online: https://www.itf-oecd.org/transport-outlook-2012-seamless-transport-greener-growth (accessed on 16 January 2023).
- ICAO—International Civil Aviation Organization. Environmental Report Aviation and Climate Change. 2010. Available online: https://www.icao.int/environmental-protection/Documents/Publications/ENV_Report_2010.pdf (accessed on 4 September 2022).
- 71. World Bank. State and Trends of Carbon Pricing 2014; The World Bank: Washington, DC, USA, 2014. [CrossRef]
- Stern, N. *The Stern Review: The Economics of Climate Change*; Cambridge University Press: Cambridge, UK, 2007. Available online: https://www.cambridge.org/core/books/economics-of-climate-change/A1E0BBF2F0ED8E2E4142A9C878052204 (accessed on 17 August 2022).
- 73. Baranzini, A.; Van den Bergh, J.C.J.M.; Carattini, S.; Howarth, R.B.; Padilla, E.; Roca, J. Carbon pricing in climate policy: Seven reasons, complementary instruments, and political economy considerations. *Wiley Interdiscip. Rev. Clim. Chang.* 2017, *8*, e462. [CrossRef]
- 74. Shen, X.J.; Liu, B.H.; Zhou, D.W. Spatiotemporal changes in the length and heating degree days of the heating period in Northeast China. *Meteorol. Appl.* 2017, 24, 135–141. [CrossRef]
- 75. IPCC—Intergovernmental Panel on Climate Change. Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme; IGES: Hayama, Japan, 2006. Available online: https://www.ipcc-nggip.iges.or.jp/support/ Primer_2006GLs.pdf (accessed on 24 May 2022).
- IPCC—Intergovernmental Panel on Climate Change. Anthropogenic and Natural Radiative Forcing. 2018. Chapter 8. Available online: https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf (accessed on 24 May 2022).
- 77. IPCC—Intergovernmental Panel on Climate Change. The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. In *Climate Change 2021–The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021. [CrossRef]
- 78. OECD—The Organisation for Economic Co-Operation and Development. Economic Surveys Economic Assessment. 2020. Available online: www.oecd.org/economy/thailand-economic-snapshot/ (accessed on 24 May 2022).
- 79. CAAT—The Civil Aviation Authority of Thailand. The Report Predicts the Demand for Air Travel of the Country. 2020. Available online: https://www.caat.or.th/th/archives/53358 (accessed on 24 May 2022).
- Guo, X.; Ning, C.; Shen, Y.; Yao, C.; Chen, D.; Cheng, S. Projection of the Co-Reduced Emissions of CO₂ and Air Pollutants from Civil Aviation in China. *Sustainability* 2023, 15, 7082. [CrossRef]
- 81. Hasan, M.A.; Frame, D.J.; Chapman, R.; Archie, K.M. Curbing the car: The mitigation potential of a higher carbon price in the New Zealand transport sector. *Clim. Policy* 2020, *20*, 563–576. [CrossRef]
- Rahman, S.M.; Khondaker, A.N.; Hasan, M.A.; Reza, I. Greenhouse gas emissions from road transportation in Saudi Arabia—A challenging frontier. *Renew. Sustain. Energy Rev.* 2017, 69, 812–821. [CrossRef]

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