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Research article

Greenhouse gas emissions trends and drivers insights from the domestic aviation in Thailand

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ABSTRACT

Domestic aviation is a swiftly expanding contributor to global greenhouse gas (GHG) emissions. Presently, economic volatility and the Coronavirus disease (COVID-19) crisis have resulted in the decline of domestic aviation, but domestic aviation is rapidly recovering in many countries. However, from a GHG emissions viewpoint, the domestic aviation sector is largely unenforced even though the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) provision for international aviation is currently in place. Accordingly, the knowledge base on emissions and their drivers from domestic aviation is weak, especially in developing countries, thus hindering an evidence-based policy debate. In this context, we have estimated and analyzed the pre-COVID-19 GHG emissions and their trends from commercial domestic aviation in Thailand; and provided insights on the role of key drivers that influence GHG emissions that are expected to be useful not only for Thailand but also for other developing countries. Emissions are estimated following Intergovernmental Panel on Climate Change (IPCC) Tier-II. Specifically, activity-based landing/take-off (LTO) cycle and cruise. This is compared to the Tier-I method, and key drivers were analyzed using an index decomposition method. The total annual average GHG emissions for all LTO cycles and cruises of commercial domestic aviation for 2015–2020 was 2254 Th. tonnes of CO_2-eq. During the LTO cycle of the aircraft, GHG emissions were at an average of 983 Th. tonnes of CO_2-eq. Additionally, during the cruise stage, emissions averaged 1270 Th. tonnes of CO_2-eq. The choice of accounting methods (i.e., IPCC Tier II vs. Tier I) seems to have had only nominal implications. Our analysis showed that, in the 2008–2020 period, the aviation activity effect and economic growth were the key decisive factors in this sector's GHG emissions growth. It was followed by the fuel energy intensity levels and the population effect in descending order of impact. These findings have significant ramifications for present and future policies aimed at decreasing GHG emissions, aiding Thailand in achieving its climate targets by 2050, and enhancing energy efficiency as the domestic aviation market adapts.

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Nomenclature

AEM	Advanced Emission Model
AMDI	Arithmetic mean Divisia Index
AR	Assessment Report
ASEAN	Association of Southeast Asian Nations
CAGR	Compound annual growth rate
C_{effect}	Carbon intensity effect
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COVID-19	Coronavirus disease of 2019
CO_2-eq	CO_2 equivalents
Cr	Cruise
Cr_E	GHG emissions of all aircraft activities that occur at altitudes above 914 m (3000 feet)
C_t	Carbon intensity
E_{effect}	Energy intensity effect
EF_{Cr}	Emissions factor during the cruise
EF_{LTO}	Emissions factor LTO of each aircraft type
EC_t	Commercial domestic aviation fuel use
E_t	Energy intensity
Fcf_{LTO}	Quantity of fuel used during the LTO cycle of aircraft of each type
Fc_{LTO}	Quantity of fuel used during the LTO cycle
Fc_{total}	Quantity of fuel used
F_{Distance}	Flight distance
Fr_t	Freight tonne carried
FTKM	Freight tonne-kilometer
GDP	Gross domestic product
GDP_t	GDP of the country (Real Price)
G_{effect}	GDP intensity effect
GHG	Greenhouse gas
G_t	GDP intensity
GWP	Global warming potential
HS	Thai Nationality Mark
ICAO	International Civil Aviation Organization
IDA	Index Decomposition Analysis
IPCC	Intergovernmental Panel on Climate Change
LI	Laspeyres Index
LMDI	Logarithmic Mean Divisia Index
LTO	Landing/take-off
LTO_E	GHG emissions of all aircraft activities that occur under 914 m (3000 feet)
MLI	Methods Linked To Laspeyres Index
M_t	Mail tonne carried
MTKM	Mail tonne-kilometer
N	Fuel-specific net calorific value
NDCs	Nationally Determined Contributions
N_{LTO}	Number of landing/take-off (LTO) for the aircraft type (airplane-LTO)
OD	Origin and destination
OECD	Organisation for Economic Cooperation and Development
PDA	Production decomposition analysis
P_c	Passengers carried
P_{effect}	Population effect

POP_t	Number of Thai population
P_t	Population effect
PTKM	Passenger tonne-kilometer
Q_t	Commercial domestic aviation CO_2 emissions from fuel use
RAMS	Reorganized Air Traffic Control Mathematical Simulator
R_{effect}	Aviation activity effect
R_t	Aviation activity
RTK	Revenue tonne kilometer
T_E	Combination of GHG emissions during LTO emissions and cruise emissions
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

The aviation sector is one of the world's major markets. Approximately 4.5 billion passengers were carried by air traffic in 2019, with 87.7 million workers employed worldwide [1]. The industry's economic impact is estimated to be 2.7 trillion USD, accounting for around 3.6 % of the global gross domestic product (GDP) [2].

Transportation emissions from rail, road, and water conveyance have been proven to have a significant impact on both the atmosphere and climate change [3–9], emissions from aviation transportation are estimated to be the second largest contributor to this change. This mode of transportation steadily grew in recent years, only to be stopped when the COVID-19 pandemic began [10]. Total global CO_2 emissions from aviation operations, including passenger and cargo carriage, were 918 million metric tons in 2018 [11]. The figure amounted to 2.4% of the anticipated 37.9 gigatonnes of CO_2 generated worldwide as a result of fossil fuel consumption during that particular year [12]. CO_2 emissions from commercial flights have increased from 694 million tons in 2013 to 916 million tons in 2018, a total increase of 32 % [13]. The compound annual growth rate of 5.7 % indicates that CO_2 emissions from international aviation will triple by 2050, which is 70 % greater than the rate used in the ICAO prediction [14].

Commercial aviation is one of the highest CO_2 emissions sources of Thailand's transport sector. The CO_2 emissions resulting from international commercial aviation in Thailand have experienced a significant rise, going from 10.2 million tons of CO_2 in 2014 to 13.2 million tons of CO_2 in 2018. This is a total increase of 29 %. Moreover, Thailand's commercial domestic aviation is another important source of CO_2 emissions. The emissions resulting from commercial domestic aviation in Thailand, including both commercial passenger and freight flights, have experienced a significant increase from 1.9 million tons of CO_2 in 2014 to 2.7 million tons of CO_2 in 2018, representing a total growth of 42 % [15].

Globally, a fairly accurate perception of GHG emissions drivers has been documented within the aviation sector. But there is little understanding of how these drivers influence emissions, for example, which drivers are influencing more than the others and which drivers are dampening emissions. As such, clarity in the total picture of domestic aviation is incomplete. Liu et al. [16] conducted a study on the factors that influence carbon emissions in Chinese civil aviation between 1985 and 2015. They [17] also introduced a production decomposition analysis (PDA) method to determine the driving carbon emissions in Chinese civil aviation. Kito et al. [18] used decomposition analysis to assess the individual contributions of different factors to changes in CO_2 emissions resulting from fuel combustion in Japan. However, concerning domestic aviation and developing countries, the knowledge-based quantified emissions from domestic aviation sectors is very weak, with little focus on the key drivers and their influence on emissions [19]. Unless we consider these factors, we cannot see the full picture and the impact of carbon emissions and their relationship with climate change. In ICAO's CORSIA emission reduction measures and other provisions to reduce GHG emissions in aviation sectors, domestic aviation is not on the radar [20,21]. However, the domestic aviation sector contributes to national GHG mitigation and Nationally Determined Contributions (NDCs) according to the United Nations Framework Convention on Climate Change (UNFCCC). Yet commercial domestic aviation is not kept under observation by policymakers. This study highlights the necessity of precise data gathering with accurate factors for environmental climatic solutions.

Accurate accounting of GHG emissions is the first step to gaining better insights. The availability of data for collecting GHG emissions is constrained due to the lack of widely accessible or collected information on jet fuel consumption, aircraft type-specific LTO (landing and takeoff) data, Origin and Destination (OD) data by aircraft type, full-flight movements with aircraft, and engine data, which are not readily available or obtained by 3rd party organizations. Much research relies on only IPCC Tier-I estimates because of this lack of data and information. The IPCC Tier-II is better based on a more accurate estimation because it is calculated during the landing/take-off cycle (LTO) and cruise phases. For the first time, this study used Tier-II in conjunction with Tier-I available data to accurately identify GHG emissions in Thailand.

In addition, numerous studies have looked at global and national estimates of the aviation industry's GHG emissions. Some have focused on GHG emissions estimation in the domestic and international aviation sectors [11,22–24], as well as GHG emissions during the COVID-19 period [25–27]. Tarr et al. [25] calculated the amount of carbon dioxide ($CO_{2)}$ emissions produced by international aviation in relation to New Zealand in 2017. This study referenced the travel limitations and interruptions caused by COVID-19 [25]. Liu et al. [27] carried out a study to quantify the decrease in CO_2 emissions caused by the influence of COVID-19 on overseas students. The research also encompasses an examination of the consequences of current mitigation programs on these reductions in emissions [27]. Moreover, some studies have assessed CO_2 emissions by using air traffic data and using the Amdvanced Emission Model (AEM III) and the Reorganized Air Traffic Control Mathematical Simulator (RAMS Plus) to analyze the consumption of aviation fuel and CO_2 emissions [28]. He and Xu calculated the CO_2 emissions produced by airplanes in the Chinese civil aviation sector between 1960 and

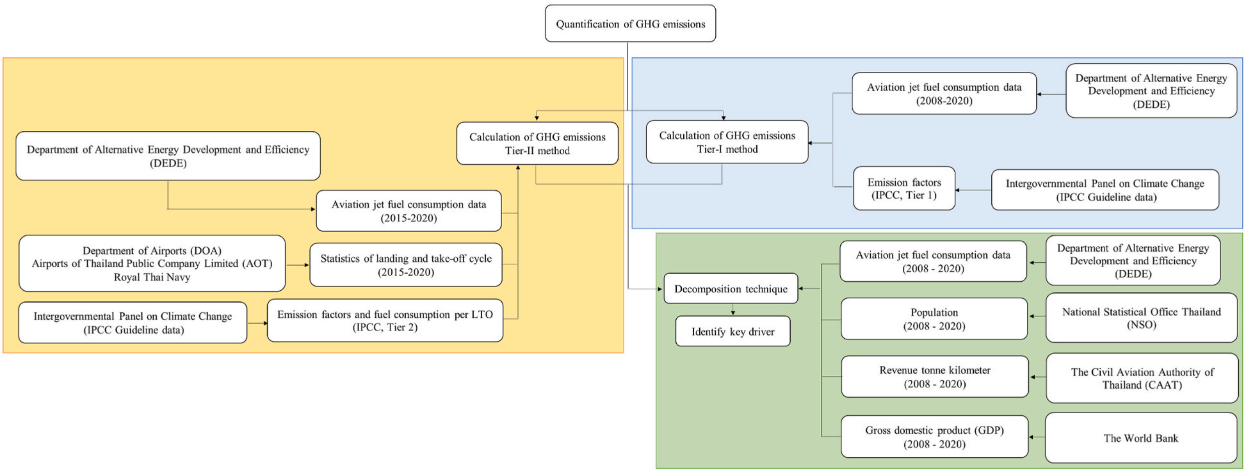

Fig. 1. The overall framework.

2009 [29]. Sajid et al. [26] studied to estimate carbon emissions associated with emergency-supply transportation. The study primarily aimed to quantify the CO_2 emissions resulting from the worldwide air transportation of COVID-19 vaccines [26]. Their study focuses on CO_2 emissions only, and their CO_2 emission calculation is according to the IPCC's recommendations. By calculating the product of jet kerosene and aviation gasoline consumption, emissions factors, and the net calorific value for each fuel type, researchers determined that China's aircraft emitted a total of 120 thousand tons of CO_2 in1960–2009, However, this number climbed significantly to 41.44 million tons during the same period [29].

This study is particularly timely since market restructuring is rapidly taking place with the ease of COVID-19. This restructuring will also influence technology and energy efficiency. Despite the significant impact of COVID-19 on the aviation industry between 2020 and 2021, the domestic aviation sector is currently experiencing a recovery from the effects of the pandemic. This recovery is anticipated to result in some structural changes and domestic aviation market adaptations. Past studies have shown that a greater domestic demand for air transportation and increased energy usage would result in higher emissions as the tourism industry grew [30]. This new window of adjustment for the domestic aviation industry, therefore, will be an important opportunity where considerations of energy efficiency and GHG emissions (and their drivers) could find an entry point in regulatory and data collection policies.

Thailand is a mixed developing economy and a newly industrialized country. Thailand is situated in mainland Southeast Asia, north of the equator, and forms part of the Indochina Peninsula. The country comprises 77 provinces and covers an area of 514,000 square kilometers. Thailand shares its borders with neighboring territories totaling approximately 8031 km in length. The country has a total of 5326 km of land borders and 2705 km of coastal borders. This includes 1840 km along the Gulf of Thailand and 865 km along the Andaman Sea [31].

Between 2007 and 2018, Thailand experienced a steady annual economic growth of 3.5% [32]. Nevertheless, this growth took a significant hit in 2019 and 2020, mainly due to the COVID-19 pandemic. Despite the pandemic's adverse effects on the economy during those years, Thailand maintained its population growth at 0.4% per year from 2007 to 2020 [32]. Thailand presents an illustrative case of developing countries with relatively advanced domestic aviation as Thailand's economy is currently progressing alongside its tourism and service industries. In Thailand, 39 airports received the Public Aerodrome Operation Certificate in 2020. However, only 32 commercial airports were among the 39 public airports [33]. Thailand's passenger numbers have risen gradually every year since 2010 with a compound annual growth rate (CAGR) of 11.38% for all passengers till 2019: 10.77% for international passengers and 12.13% for domestic passengers [33]. Prior to the COVID-19 pandemic, the passenger count for domestic flights in Thailand rose from 3.482 million in 2008 to 76.256 million in 2019 [34]. In parallel, the consumption of jet fuel in domestic aircraft rose from 246 kilotons of oil equivalent (ktoe) in 2008 to 856 ktoe in 2018 [35]. Thailand has set a greenhouse gas reduction target in its NDC that aims to reduce emission by 20–25% below the projected levels in 2030 in all sectors [36]. Thailand has made a pledge at the Conference of the Parties – 26 (COP-26) of the UNFCCC in Glasgow. The pledge is to achieve carbon neutrality by the year 2050 and to reach net zero emissions by 2065. It implies that Thailand's domestic aviation, even in a period of growth, can meet its climate commitments, whereas its quantified emissions and their macro drivers are not yet well understood. Hence, the objective of this study is to measure and examine the trends and patterns of GHG emissions from Thailand's commercial domestic aviation industry between 2008 and 2020. Additionally, it seeks to recognize the primary factors that have influenced these GHG emissions. This study will be the first to calculate the past greenhouse gas emissions from the commercial domestic aviation industry in Thailand. It will utilize the IPCC Tier-I as well as Tier-II criteria for emission accounting. The calculation according to the IPCC Tier-I and Tier-II has been performed in numerous previous studies [35–37]. Suryati et al. [37] conducted a study to estimate greenhouse gas (GHG) emissions from increased vehicular activity. The study particularly focuses on the transportation sector in Medan City and utilizes the Tier II methodolgy developed by the Intergovernmental Panel on Climate Change (IPCC) to quantify these emissions [37]. Pongthanaisawan and

Sorapipatana conducted a study to estimate GHG emissions from Thailand's transport sector using the calculation method from Tier-I of the Intergovernmental Panel on Climate Change (IPCC) [38]. In their study, Singh et al. [39] examined the greenhouse gas emissions generated by the road transport industry in India between 1980 and 2000. For this estimation, they employed the Tier-I methodology developed by the Intergovernmental Panel on Climate Change (IPCC) [39]. Thus, this study would provide unrecorded insights into the benefits of using Tier-II as a methodological choice. Moreover, this study (via factor decomposition techniques) will reveal the components influencing carbon emissions in Thailand such as GDP, aviation activity demand, and population. Furthermore, the results of this study can be analyzed to identify measures or policies for the aviation sector in Thailand aimed at reducing greenhouse gas emissions in alignment with Thailand's 2050 climate targets.

2. Methodology and data

Fig. 1 illustrates the comprehensive framework of this investigation. This study utilizes GHG emission estimations derived from the fuel consumption and statistical data of landing and take-off cycles in Thailand's commercial domestic aircraft industry. The estimation of GHG emissions in this study covers the landing/take-off (LTO) cycle and cruise, including CO_2, CH_4, N_2O.

2.1. *Key data sources*

This study encompasses data from all 39 airports in Thailand. There were 638 airplanes registered with the Thai Nationality Mark (HS), of which 380 were commercial airplanes, accounting for 59.56% of all airplanes, and 258 were private airplanes, accounting for the remaining 40.44%. The number and quantity of commercial aircraft registered with Thai Nationality Mark (HS) are as follows: A320 (all models): 123 planes, B737: 64 planes, B777: 39 planes, A330: 33 planes, ATR: 15 planes, A350: 12 planes, B747: 10 planes, Q400: 8 planes, B787: 8 planes, A380: 6 planes, B767: 3 planes and Other: 59 planes [33].

The GHG emissions estimation data, which include jet fuel consumption, landing/take-off (LTO) cycle statistics, and emission factors, were obtained from many official data sources spanning the years 2015–2020. The data on major factors influencing emissions, including energy consumption, fuel costs, revenue ton kilometer, and gross domestic product (GDP), for the period 2008–2020, were also gathered from multiple government sources. They are summarized and presented in Table 1.

2.2. *GHG emissions estimation methods*

The emissions resulting from aircraft flights are mainly influenced by key parameters such as the frequency of landings and take-offs, the duration of flights, and the type and efficiency of the engines. Flying altitude also affects the aircraft emission though the effect is less significant than other factors [47]. In order to determine the total aircraft emissions, all aircraft activities were categorized into two phases: landing/take-off cycle (LTO) and cruise. In general, there are three types of aviation emission estimation methods, namely, Tier I, II and III [47]. The Tier-I approach relies on the multiplication of overall aviation energy consumption data by an average emission factor. The Tier-II approach relies on quantifying the domestic and international aviation LTO operations, and categorizing them into distinct landing/take-off (LTO) cycles and cruise phases. It is essential to have this information available for each aircraft type, if possible. The Tier-III approach relies on real aircraft movement data, utilizing either the trip's origin or destination information (Tier 3A) or the complete flight trajectory data (Tier 3B) [47].

Utilizing data over the years 2015–2020, this study employed LTO cycles to approximate the amount of greenhouse gas emissions in Thailand's domestic aviation industry. The estimation of GHG emissions was computed using the Tier-II methodology [43]. Emissions refer to the discharge of greenhouse gases and/or their precursors into the atmosphere within a defined geographical region and time frame. An emission factor is a numerical value that indicates the quantity of gas emissions or removal per unit of activity per fuel consumption [43]. Fuel consumption refers to the quantity of fuel consumed by a vehicle to cover a specific distance at a specific

Table 1
Variables, description, period, sources of GHG emissions estimation and sources to identify key drivers.

Variables	Description	Period	Sources
Fuel consumption (ktoe)	Fuel consumption in domestic aviation sector	2008–2020	Department of Alternative Energy Development and Efficiency [35]
Number of domestic flights and aircraft types (airplane per year)	Landing/take-off (LTO) cycle statistics	2015–2020	Department of Airports [40] Airports of Thailand Public Company Limited [41] U-Tapao Rayong Pattaya International Airport [42]
Emissions factors (kg/TJ), (kg/LTO)	Emission factors for GHG emissions calculation from fuel consumption and landing/take-off statistics	2006	Intergovernmental Panel on Climate Change [43]
Population (1000 inhabitants)	The number of Thai population	2008–2020	National Statistical Office of Thailand [44]
Revenue tonne kilometer (Tonne - Km)	The number of passengers, mails, and freights in domestic aviation sector	2008–2020	The Civil Aviation Authority of Thailand [34]
Gross domestic product (GDP) (Trillion Baht)	Gross domestic product of Thailand (Base year is 2008)	2008–2020	The World bank [45] Bank of Thailand [46]

speed. Cruise refers to all aviation operations conducted at altitudes over 914 m (3000 feet), which may include any additional ascent or descent maneuvers above this altitude without a specified upper limit. The Landing and Take–off cycle (LTO) encompasses all aircraft operations that take place below an altitude of 914 m (3000 feet). This comprises activities such as aircraft engine idle, taxiing out, taking off, climbing up to 914 m, descending, approaching, and taxiing in Refs. [23,24,48–50].

The Tier–II Intergovernmental Panel on Climate Change (IPCC) methodology [43] calculates GHG emissions resulting from aircraft operations and fuel usage within the domestic aviation industry. This methodology is based on aviation jet fuel consumption, the number of aircraft and model configuration during the LTO cycle, and the industry recognized emission from each unit of fuel type used (called “the emission factor”).

Eq. (1) presents a formula to estimate total emissions. It was calculated by combining GHG emissions during all LTO and cruise emissions. Landing/take-off (LTO) emissions and cruise emissions are then calculated by Eq. (2) and Eq. (3), respectively. This study utilized the default parameters specified by the IPCC, including elements such as CO_2 emission factors, non-CO_2 emission factors, and net calorific values. Moreover, this research uses the emissions factor per LTO cycle and fuel consumption per LTO cycle from the IPCC.

$$\mathrm{T_E} = \mathrm{LTO_E} + \mathrm{Cr_E} \tag{1}$$

where the subscript E denotes emissions. $\mathrm{T_E}$ refers to the total GHG emissions resulting from both takeoff and landing (LTO) emissions and emissions throughout the cruising phase of the aircraft. These emissions are measured in thousand tons of CO_2. On the other hand, $\mathrm{LTO_E}$ represents the GHG emissions from all aircraft activities that take place at altitudes below 914 m (3000 feet). The activities encompassed in this category are: aircraft engine idle; taxiing out; taking off; initial climbing up to 914 m; descending; approaching; and taxiing in (thousand tons of CO_2). These activities result in the emission of thousands of tons of CO_2. $\mathrm{Cr_E}$ refers to GHG emissions produced by all aircraft activities taking place at altitudes higher than 914 m (3000 feet), which includes any extra climb or descent operations. The emissions are measured in thousand tons of CO_2.

Eq. (2) presents a formula to estimate GHG emissions during LTO cycles. The emissions during LTO cycles were calculated by multiplying the number of aircraft and the LTO cycle duration for each type of aircraft at the airport by the emissions factor LTO specific to each aircraft type. The emission factors for several components, including CO_2, CH_4, N_2O, NO_x, CO, NMVOC, and SO_2 (specific to the type of aircraft), are provided. After that, it is converted to the thousand-tonne equivalent of CO_2 by multiplying the global warming potential.

$$\mathrm{LTO_E} = \mathrm{N_{LTO}} \times \mathrm{EF_{LTO}} \tag{2}$$

where $\mathrm{N_{LTO}}$ is the number of landing/take-off (LTO) for the aircraft type (airplane-LTO), $\mathrm{EF_{LTO}}$ is the emissions factor LTO of each aircraft type (kg/LTO).

Eq. (3) presents a formula to estimate GHG emissions during cruise mode. The emissions during the cruise were estimated using the quantity of fuel used (aviation jet fuel consumption) minus the quantity of fuel used during the LTO cycle. After that, GHG emissions during the cruise are estimated by multiplying the emissions factor cruise (kg/TJ) by net calorific values (TJ/ktoe). It is then converted to the thousand-tonne equivalent of CO_2 by multiplying by the global warming potential.

$$\mathrm{Cr_E} = \left(\mathrm{Fc_{total}} - \mathrm{Fc_{LTO}}\right) \times \mathrm{EF_{Cr}} \times \mathrm{N} \tag{3}$$

where $\mathrm{Fc_{total}}$ is the quantity of fuel used (ktoe), $\mathrm{Fc_{LTO}}$ is the quantity of fuel used during the LTO cycle (ktoe) by which LTO fuel consumption is calculated using Eq. (4), $\mathrm{EF_{Cr}}$ is emissions factor during the cruise (kg/TJ), N is a fuel-specific net calorific value (TJ/ktoe) and Cr is cruise.

Eq. (4) presents a formula to estimate LTO fuel consumption. Fuel consumption per LTO is calculated from the number of aircraft during the LTO cycle of each type in the airport multiplied by fuel consumption per LTO factors. After that, it was converted to ktoe.

$$\mathrm{Fc_{LTO}} = \mathrm{N_{LTO}} \times \mathrm{Fcf_{LTO}} \tag{4}$$

where $\mathrm{N_{LTO}}$ is the number of LTO for the aircraft type (airplane-LTO), and $\mathrm{Fcf_{LTO}}$ is the quantity of fuel used during the LTO cycle of aircraft of each type (kg/LTO).

Comparing the influence of individual greenhouse gas emissions on global warming is challenging since the gases have varying physical and chemical properties. In order to obtain a precise comparison of the impact of global warming caused by different GHGs, the IPCC advises utilizing the Global Warming Potential (GWP) conversion factor. This factor allows for the conversion of all calculated emissions of greenhouse gases into units equivalent to CO_2. This study uses the Global Warming Potential (GWP) value from IPCC, AR5

Table 2

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

Industrial designation or common name	Chemical formula	GWP values for 100 year time horizon	
		Fifth Assessment	Sixth Assessment
Carbon dioxide	CO_2	1	1
Methane	CH_4	28	27.9
Nitrous oxide	N_2O	265	273

Source: Intergovernmental Panel on Climate Change (IPCC), AR5 [51].

Table 3
Identification of drivers influencing GHG emissions in Thailand's commercial domestic aviation sector.

Drivers	Description of driver	Input factors	What do 'changes' mean here?
C_t – Carbon intensity of commercial domestic aviation sector	Amount of CO_2-eq emitted per unit of fuel use by commercial domestic aviation sector	$C_t = \frac{Q_t}{EC_t}$	This essentially represents change in fuel type/quality for aviation sector. Unless alternative fuels are used, this does not change.
E_t – Energy intensity of commercial domestic aviation sector	Total fuel consumption of domestic commercial aviation sector per unit aviation activity demand expressed as RTK	$E_t = \frac{EC_t}{RTK_t}$	This essentially represents an airplane's energy efficiency, choice of airplane type, short vs long route journeys, LTO vs cruise energy consumption, etc.
R_t – Aviation activity intensity	Total aviation activity demand per unit economic activity in the market. This represents to the extent GDP induces aviation demand	$R_t = \frac{RTK_t}{GDP_t}$	This component is variable due to changes in the type and structure of GDP growth, including choice of passenger mobility and freight transfer modes (such as road, water, air).
G_t – GDP intensity of population	Total GDP per population. This represents how sensitive is a country's GDP with respect to population. Specifically, how much GDP changes if the population changes by one unit. Population is related to GDP through income factors.	$P_t = \frac{GDP_t}{POP_t}$	The increase in population has the effect of driving the economy and changing the country's income.
P_t – Population effect	Population effect	POP_t	The main factors affecting changes to economic growth and transportation modes.

[51]. The global warming potential (GWP) is shown in Table 2.

2.3. Identification of key drivers of GHG emissions

Driver analysis can be conducted through many different methods. This study used Index Decomposition Analysis (IDA) because it has a reasonable rationale, requires less data, and provides excellent applicability and interpretation of the results [52,53]. The IDA technique comprises the Laspeyres Decomposition Method and the Divisia Index Decomposition Method. The Divisia Index Decomposition Method comprises the log-mean Divisia Index (LMDI) and the arithmetic mean Divisia Index (AMDI) [54]. As such, and in the viewpoint of this study, Index Decomposition Analysis is the leading 'best practice' method in energy and climate analysis providing a comprehensive and inclusive framework to capture everything in the form of its identities [52,55–67]. The decomposition of identity can take many forms, and there are different methodologies to provide accurate decomposition. Liu et al. [17] used the production theoretical decomposition analysis approach to identify the driving factors for CO_2 emissions from Chinese civil aviation. Wang et al. [68] used the index decomposition analysis approach to examine the elements driving China's energy consumption change. González and Martínez [53] employed decomposition analysis to examine CO_2 emissions in the industrial sector of Mexico. Timilsina and Shrestha [54] employed an LMDI (Logarithmic Mean Divisia Index) decomposition analysis to examine the factors that contribute to the increase in CO_2 emissions in nations of Latin American and the Caribbean. This study employed the Laspeyres Index (LI) to pinpoint the primary factors that influence GHG emissions in the commercial domestic aircraft industry. In addition, this study used the complementary analytical tool Methods Linked To Laspeyres Index (MLI). This approach allows the comparison of yearly data using a period decomposition [69].

Our decomposition method focuses on several factors [17,70–72]. This study considered the main drivers affecting the aviation sector's GHG emissions, including insights from previous studies [17,73–75]. Specifically, Eq. (5) and Eq. (6) are employed to elucidate the relationship between GHG emissions and fluctuations in energy consumption, population, gross domestic product (GDP), and revenue ton kilometer (RTK). The time series used in decomposition analysis occurred in 2008–2020. The equation for decomposition, which determines the amount of greenhouse gas (GHG) emissions in a given year t (measured in thousand tons of CO_2 eq), can be calculated by multiplying the carbon intensity (C_t), energy intensity (E_t), aviation activity (R_t), GDP intensity (G_t), and population (P_t) of the commercial domestic aviation sector, as represented by Eq. (5).

$$Q_t = \frac{Q_t}{EC_t} \times \frac{EC_t}{RTK_t} \times \frac{RTK_t}{GDP_t} \times \frac{GDP_t}{POP_t} \times POP_t \tag{5}$$

where Q_t is commercial domestic aviation CO_2 emissions from fuel use for year t (thousand. tonne $CO_2 - eq$), EC_t is commercial domestic aviation fuel use for year t (TJ), GDP_t is GDP of the country (Real Price) for year t (10^5 USD), RTK_t is revenue tonne kilometer (thousand tonne-kilometer), and POP_t is the number of Thai population (1000 inhabitants).

Eq. (5) can also be rewritten as Eq. (6)

$$Q_t = C_t \times E_t \times R_t \times G_t \times P_t \tag{6}$$

where C_t, E_t, R_t, G_t and P_t are the primary factors affecting GHG emissions from the commercial domestic aviation sector in Thailand. This is further discussed in Table 3 below.

With respect to Methods Linked To Laspeyres Index (MLI) decomposition, the change in Q_t (ΔQ) is noted at time t. It is compared with the level in a base year $t = 0$ as Eq. (7) and Eq. (8).

$$\Delta Q = Q_t\text{-}Q_0 = C_tE_tR_tG_tP_t\text{-}C_0E_0R_0G_0P_0 \tag{7}$$

$$\Delta Q = \Delta C + \Delta E + \Delta R + \Delta G + \Delta P \tag{8}$$

where ΔC, ΔE, ΔG, ΔR and ΔP are the factors of the changes in greenhouse gas emissions (GHG).

The equations presented in Eq. (5) and Eq. (6) provide the calculation for each component and are utilized to decompose the variation in GHG emissions. These equations determine the sum for each sector value.

Eq. (9) calculates the carbon intensity effect:

$$\begin{aligned} C_{effect} = {} & \Delta C \times E_0 \times R_0 \times G_0 \times P_0 + \frac{\Delta C}{2}[P_0[G_0[\Delta E \times R_0 + \Delta R \times E_0] + E_0 \times R_0 \times \Delta G] + E_0 \times R_0 \times G_0 \times \Delta P] + \frac{\Delta C}{3}[\Delta E[P_0[\Delta R \times G_0 \\ & + \Delta G \times R_0] + R_0 \times G_0 \times \Delta P] + E_0[\Delta R[\Delta G \times P_0 + \Delta P \times G_0] + R_0 \times \Delta G \times \Delta P]] + \frac{\Delta C}{4}[\Delta E[\Delta R[\Delta G \times P_0 + \Delta P \times G_0] \\ & + \Delta G \times R_0 \times \Delta P] + E_0 \times \Delta R \times \Delta G \times \Delta P] + \frac{1}{5} \times \Delta C \times \Delta E \times \Delta R \times \Delta G \times \Delta P \end{aligned} \tag{9}$$

Eq. (10) calculates the energy intensity effect:

$$\begin{aligned} E_{effect} = {} & C_0 \times \Delta E \times R_0 \times G_0 \times P_0 + \frac{\Delta E}{2}[P_0[G_0[\Delta C \times R_0 + \Delta R \times C_0] + C_0 \times R_0 \times \Delta G] + C_0 \times R_0 \times G_0 \times \Delta P] + \frac{\Delta E}{3}[\Delta C[P_0[\Delta R \times G_0 \\ & + \Delta G \times R_0] + R_0 \times G_0 \times \Delta P] + C_0[\Delta R[\Delta G \times P_0 + \Delta P \times G_0] + R_0 \times \Delta G \times \Delta P]] + \frac{\Delta E}{4}[\Delta C[\Delta R[\Delta G \times P_0 + \Delta P \times G_0] \\ & + \Delta G \times R_0 \times \Delta P] + C_0 \times \Delta R \times \Delta G \times \Delta P] + \frac{1}{5} \times \Delta C \times \Delta E \times \Delta R \times \Delta G \times \Delta P \end{aligned} \tag{10}$$

Eq. (11) calculates the aviation activity effect:

$$\begin{aligned} R_{effect} = {} & C_0 \times E_0 \times \Delta R \times G_0 \times P_0 + \frac{\Delta R}{2}[P_0[G_0[\Delta C \times E_0 + \Delta E \times C_0] + C_0 \times E_0 \times \Delta G] + C_0 \times E_0 \times G_0 \times \Delta P] + \frac{\Delta R}{3}[\Delta C[P_0[\Delta E \times G_0 \\ & + \Delta G \times E_0] + E_0 \times G_0 \times \Delta P] + C_0[\Delta E[\Delta G \times P_0 + \Delta P \times G_0] + E_0 \times \Delta G \times \Delta P]] + \frac{\Delta R}{4}[\Delta C[\Delta E[\Delta G \times P_0 + \Delta P \times G_0] \\ & + \Delta G \times E_0 \times \Delta P] + C_0 \times \Delta E \times \Delta G \times \Delta P] + \frac{1}{5} \times \Delta C \times \Delta E \times \Delta R \times \Delta G \times \Delta P \end{aligned} \tag{11}$$

Eq. (12) calculates the GDP intensity effect:

$$\begin{aligned} G_{effect} = {} & C_0 \times E_0 \times R_0 \times \Delta G \times P_0 + \frac{\Delta G}{2}[P_0[R_0[\Delta C \times E_0 + \Delta E \times C_0] + C_0 \times E_0 \times \Delta R] + C_0 \times E_0 \times R_0 \times \Delta P] + \frac{\Delta G}{3}[\Delta C[P_0[\Delta E \times R_0 \\ & + \Delta R \times E_0] + E_0 \times R_0 \times \Delta P] + C_0[\Delta E[\Delta R \times P_0 + \Delta P \times R_0] + E_0 \times \Delta R \times \Delta P]] + \frac{\Delta G}{4}[\Delta C[\Delta E[\Delta R \times P_0 + \Delta P \times R_0] \\ & + \Delta R \times E_0 \times \Delta P] + C_0 \times \Delta E \times \Delta R \times \Delta P] + \frac{1}{5} \times \Delta C \times \Delta E \times \Delta R \times \Delta G \times \Delta P \end{aligned} \tag{12}$$

Eq. (13) calculates the population effect:

$$\begin{aligned} P_{effect} = {} & C_0 \times E_0 \times R_0 \times G_0 \times \Delta P + \frac{\Delta P}{2}[G_0[R_0[\Delta C \times E_0 + \Delta E \times C_0] + C_0 \times E_0 \times \Delta R] + C_0 \times E_0 \times R_0 \times \Delta G] + \frac{\Delta P}{3}[\Delta C[G_0[\Delta E \times R_0 \\ & + \Delta R \times E_0] + E_0 \times R_0 \times \Delta G] + C_0[\Delta E[\Delta R \times G_0 + \Delta G \times R_0] + E_0 \times \Delta R \times \Delta G]] + \frac{\Delta P}{4}[\Delta C[\Delta E[\Delta R \times G_0 + \Delta G \times R_0] \\ & + \Delta G \times E_0 \times \Delta R] + C_0 \times \Delta E \times \Delta R \times \Delta G] + \frac{1}{5} \times \Delta C \times \Delta E \times \Delta R \times \Delta G \times \Delta P \end{aligned} \tag{13}$$

Eq. (14) presents a formula to estimate the revenue tonne kilometer (RTK) variable. The revenue tonne kilometer gives us the volume of aviation activities and is the total weight of passengers (in tonnes), freight, and mail carried (revenue load) multiplied by the flight distance [76].

$$\text{Revenue Tonne Kilometer} = \text{PTKM} + \text{FTKM} + \text{MTKM} \tag{14}$$

where PTKM is the passenger tonne-kilometer, FTKM is the freight tonne-kilometer, and MTKM is the mail tonne-kilometer, which are calculated from Eq. (15)–(17).

Eq. (15) presents a formula to estimate passenger tonne-kilometer (PTKM). The passenger tonne-kilometer is the number of passengers carried multiplied by flight distance and 100 kg. After that, it is converted to tonnes by multiplying by 1000.

$$\text{Passengertonne-kilometer(PTKM)} = (P_c \times F_{Distance} \times \ 100 \text{ kg}) \ / \ 1000 \tag{15}$$

where P_c is the passengers carried, $F_{Distance}$ is the flight distance, and 100 kg is the standard weight suggested by ICAO for a passenger plus baggage.

Eq. (16) presents a formula to estimate freight tonne-kilometer (FTKM). The freight tonne-kilometer is the number of freight tonnes carried multiplied by flight distance.

$$\text{Freighttonne-kilometer}(\text{FTKM}) = \text{Fr}_t \times \text{F}_{\text{Distance}} \tag{16}$$

where Fr_t is the freight tonne carried.

Eq. (17) presents a formula to estimate mail tonne-kilometer (MTKM). The mail tonne-kilometer is the number of mail tonnes carried multiplied by flight distance.

$$\text{Mailtonne-kilometer}(\text{MTKM}) = \text{M}_t \times \text{F}_{\text{Distance}} \tag{17}$$

where M_t is the mail tonne carried.

2.4. *Empirical data*

In this study, decomposition analysis for 2008–2020 is carried out with the amount of GHG emissions calculated from an estimation of GHG emissions using IPCC, Tier-I [43]. The aggregate fuel usage for the domestic aviation sector is derived from the statistical data reports of the Department of Alternative Energy Development and Efficiency spanning from 2008 to 2020 [77]. The gross domestic product estimates are sourced from the World Bank –Thailand Bureau through their statistical data reports on gross domestic product [45]. Nevertheless, the gross domestic products are transferred into values that reflect 'real prices'. The World Bank national accounts provide deflators that are utilized to convert the GDP from market price to real price. Additionally, the national accounts data from the Organisation for Economic Cooperation and Development (OECD) are also employed for this purpose [45,78]. Revenue tonne kilometer is calculated from a combination of passenger-kilometer, mail-kilometer, and freight-kilometer in the domestic aviation sector. The number of passengers, mails, freights, and domestic flight distances were obtained from the Civil Aviation Authority of Thailand [79,80]. Population data are obtained from the National Statistical Office of Thailand for the years 2008–2020 [44].

3. Results and discussions

Results show that the estimated total turnover (RTK) of domestic commercial transport activity, consisting of passengers, freight, and mails, increased in Thailand by approximately 270 % in the 2008–2019 period (including over 300 % for passenger volume, i.e., from 24 million to 76 million). Table 4 presents the assembled and corrected estimates of RTK, energy consumption, GDP, and population, which were obtained from the sources specified in Table 1.

3.1. *Historical trends in greenhouse gas emissions (GHG) and fuel consumption*

Table 5 presents a concise overview of GHG emissions pertaining to the domestic aviation industry in Thailand from 2008 to 2020. It shows that the GHG emissions have increased three-fold between 2008 and 2019, highlighting the expanding contribution of domestic aviation to Thailand's total GHG emissions. The results also show a moderate increase in GHG emissions through 2013, owing to Thailand's political problems affecting the tourism sector. A sudden jump was seen in 2014 when the Thai aviation sector began to show improved growth due to economic stimulus measures aimed at tourism and air travel. Subsequently, this resulted in increased GHG emissions from 948 tonnes of CO_2-eq in 2013 to 2008 tonnes of CO_2-eq in 2014. Thailand's aviation industry was a key beneficiary of Thailand's Transport Infrastructure Development Strategy 2015–2022. The objective of this on-going strategy is to expedite

Table 4
Estimated turnover of aviation activity (RTK) and other key variables for Thailand's commercial domestic aviation industry, 2008–2020.

Year	GHG emissions	Energy consumption	RTK	GDP	Population
	Th. Ton	TJ	Th. Ton. Km	Billion Baht (at 2008 price)	1000 inhabitants
2008	790	10,969	1,690,861	7722	66,530.984
2009	925	12,842	1,822,603	7668	66,866.839
2010	829	11,504	1,905,787	8243	67,195.028
2011	851	11,816	2,228,393	8302	67,518.388
2012	838	11,638	2,521,760	8903	67,835.962
2013	948	13,154	2,936,849	9144	68,144.518
2014	2008	27,869	2,772,700	9233	68,438.746
2015	2352	32,640	3,453,987	9523	68,714.511
2016	2628	36,475	4,274,515	9867	68,971.308
2017	2432	33,755	4,576,630	10,260	69,209.810
2018	2750	38,169	4,741,004	10,692	69,428.453
2019	2300	31,926	4,593,365	10,887	69,625.582
2020	1532	21,269	2,528,453	10,348	69,799.978

Table 5
Estimated historical trends of GHG emissions for Thailand’s domestic aviation sector by gas types.

Year	CO_2 (Th. tonne of CO_2)	CH_4 (Th. tonne of CH_4)	N_2 O (Th. tonne of N_2O)	Total GHG emissions (Th. tonne of CO_2-eq)
2008	784.29	0.154	5.81	790.26
2009	918.20	0.18	6.81	925.18
2010	822.55	0.161	6.1	828.81
2011	844.87	0.165	6.26	851.30
2012	832.12	0.163	6.17	838.45
2013	940.51	0.184	6.97	947.67
2014	1992.62	0.39	14.77	2007.78
2015	2333.75	0.457	17.3	2351.51
2016	2607.94	0.511	19.33	2627.78
2017	2413.46	0.473	17.89	2431.82
2018	2729.09	0.534	20.23	2749.85
2019	2282.74	0.447	16.92	2300.11
2020	1520.76	0.298	11.27	1532.33

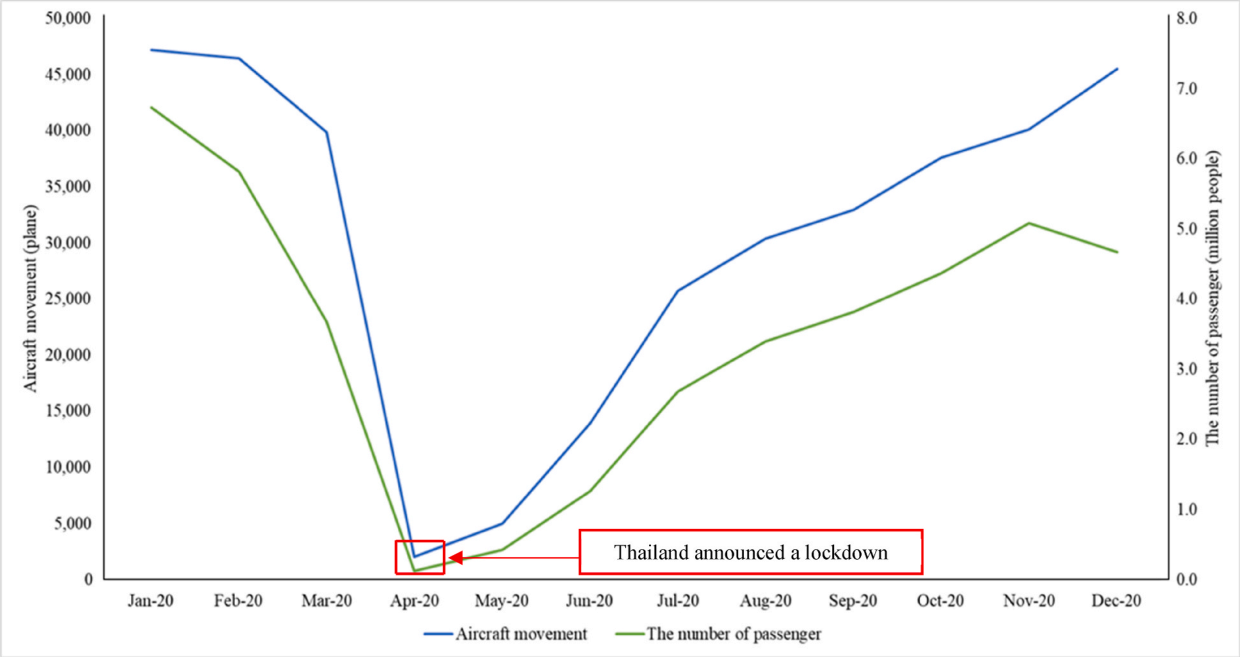

Fig. 2. Aircraft movement during the COVID crisis in 2020.

Table 6
Historical trends of GHG emissions during the landing/takeoff cycle (LTO) and cruise in the Thai domestic aviation sector.

Year	GHG emissions						
	Landing/Take-off (LTO) Cycle			–	Cruise		
	CO_2 (Th. tonne of CO_2)	CH_4 (Th. tonne of CH_4)	N_2O (Th. tonne of N_2O)		CO_2 (Th. tonne of CO_2)	CH_4 (Th. tonne of CH_4)	N_2O (Th. tonne of N_2O)
2015	931.00	0.048	0.035		1324.30	0.009	0.037
2016	996.56	0.052	0.038		1527.48	0.011	0.043
2017	1083.52	0.026	0.041		1239.55	0.009	0.035
2018	1121.00	0.026	0.042		1514.73	0.011	0.042
2019	1057.24	0.025	0.040		1137.43	0.008	0.032
2020	642.92	0.017	0.024		824.10	0.006	0.023

the progress of domestic airports that adhere to global benchmarks and cater to the requirements of individuals for convenient travel. This strategy also promotes the full utilization of regional airports, making them play a greater role in Thailand’s aviation industry, an economic sector projecting continued growth comparable to aviation trends seen during the intermediate years (2015–2018). It should be noted that Thailand entered the ASEAN Economic Community in 2015, further stimulating domestic and commercial aviation activities from 2015 to 2016. This resulted in a GHG emissions growth rate of 11.75 %. However, fuel consumption in the domestic aviation sector dropped sharply in 2019–2020 due to the COVID-19-induced slowdown in aviation activity demand. Since the COVID-19 Emergency Decree on Public Administration in Emergency Situations was announced on March 26, 2020, Thailand's domestic air transport began to suffer, resulting in a substantial drop in passengers and flights, affecting both the domestic and the international sectors [34]. In March 2020, Thailand announced a lockdown and a suspension of domestic travel, reducing the number of aircraft movements and fuel consumption, as shown in Fig. 2. The aviation industry was deeply affected throughout 2020, with fuel consumption and GHG emissions dropping by approximately 33% in 2019–2020 (see Tables 4 and 5).

3.2. GHG emissions estimates using landing/take-off cycle (LTO) and cruise approach

Table 6 presents a concise overview of the projected GHG emissions from the takeoff and landing (LTO) cycle and cruise phase of Thailand's domestic aviation sector. The emissions estimates are based on the IPCC Tier-II methodology and cover the period from 2015 to 2020. Results show that, from 2015 to 2018, GHG emissions during the cruise were higher than landing/take-off emissions by about 35.8%. However, in 2019 and again in 2020, it was higher than landing/take-off by approximately 17.5%. This was only due to Thailand having declared in March 2020 a state of emergency in all localities due to the COVID-19 pandemic [81], and it has subsequently extended the enforcement of that emergency declaration periodically due to infection spikes and variant discoveries. A ban on flying domestic passengers in strictly controlled/highly infected areas affected the distance traveled in those areas (according to a declaration of the Civil Aviation Authority of Thailand). In these areas where flights were not being carried out, a reduction in cruise emissions was affected. However, GHG emissions during landing/take-off remained consistent with typical cruise emissions for flights scheduled in other non-banned areas during that period. The GHG emissions during the cruise fluctuated from 2015 to 2018 and witnessed a sharp drop in 2019/2020 (due to the COVID crisis and disruption of aviation activity). The cruise emissions were reduced from 1526 thousand tonnes of CO_2-eq in 2018 to 1146 thousand tonnes of CO_2-eq in 2019, and 830 thousand tonnes of CO_2-eq in 2020. Nevertheless, the emissions resulting from the LTO cycle had a rise between 2015 and 2018, increasing from 941.66 thousand tons of CO_2-eq in 2015 to 1132.90 thousand tons of CO_2-eq in 2018. This increase might be attributed to the expansion of the aviation industry. This was under Thailand's Transport Infrastructure Development (for Airport Improvement) Strategy 2015–2022, which was necessary to accommodate the increasing number of passengers. The increase in the number of passengers using domestic airlines for short-distance traveling is due to the convenience of domestic flights. After 2018, emissions in the LTO cycle decreased in 2019 and 2020. The emissions in the LTO cycle reduced from 1132.90 thousand tonnes of CO_2-eq in 2018 to 1068.51 thousand tonnes of CO_2-eq in 2019, and 649.87 thousand tonnes of CO_2-eq in 2020. These results, including total GHG emissions, LTO emissions, cruise emissions, and fuel consumption from 2015 to 2020, are shown in the Tier-II estimation chart below (Fig. 3).

Fig. 4 shows the consolidated summary of estimated GHG emissions estimated using Tier-I and Tier-II methods for 2015–2020. The GHG emissions by Tier-II were only possible for 2015–2020 due to the unavailability of earlier data. This summary shows that the differences in GHG emissions between Tier-I and Tier-II methods in 2015–2020 are small and range from 3.1 to 3.8% (with the Tier-I method slightly overestimating the emissions).

Aviation is responsible for around 2.5 % of global CO_2 emissions, but its overall contribution to climate change is more substantial [82]. This is due to the fact that air travel not only emits CO_2, but also has a multitude of other intricate impacts on the climate. In addition to CO_2 produced by fuel combustion, planes contribute to the atmosphere's concentration of additional gases, causing

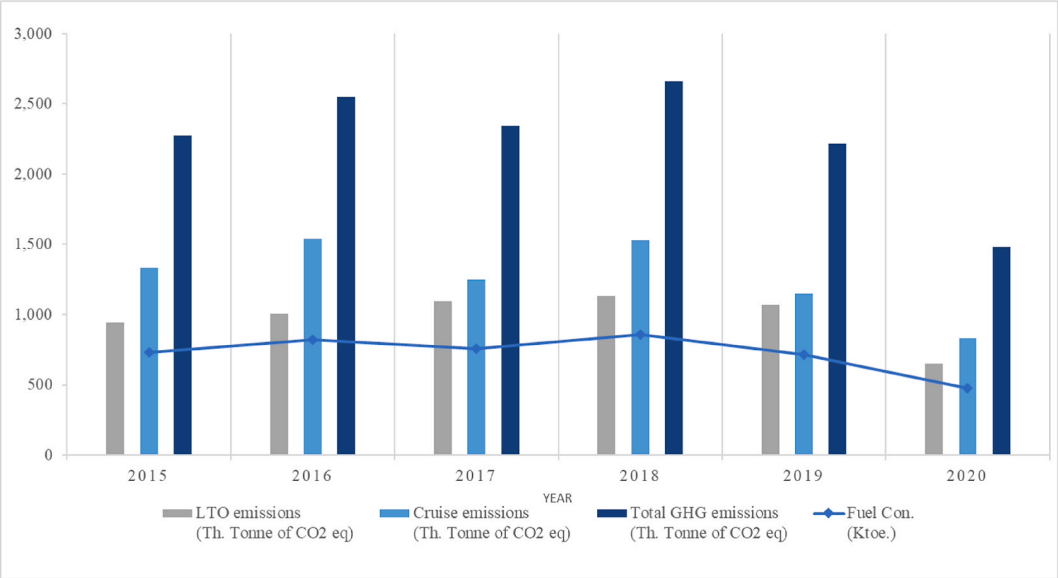

Fig. 3. GHG emissions during the landing/takeoff cycle (LTO), cruise, total GHG emissions and fuel consumption since 2015–2020.

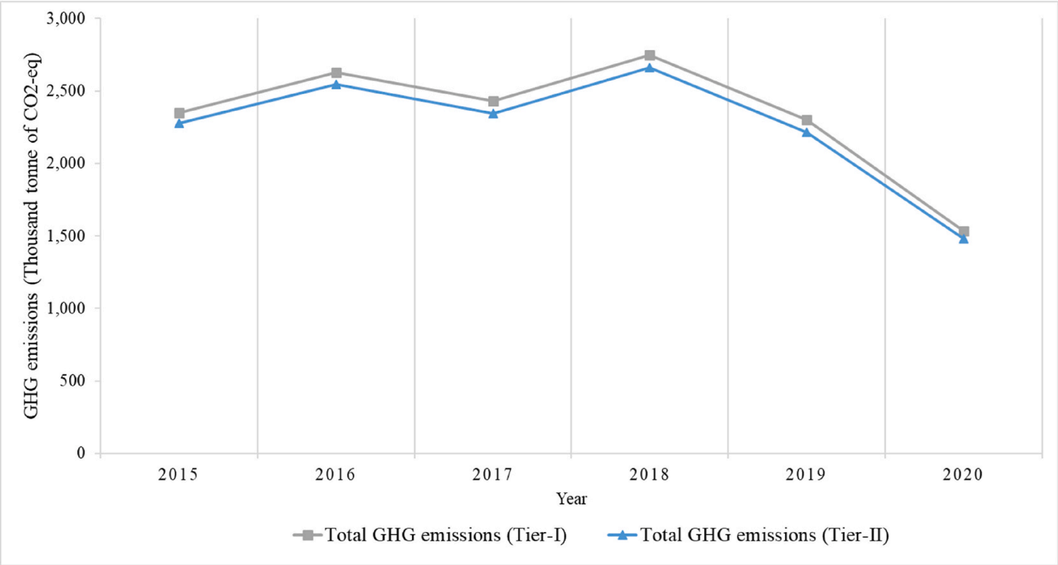

Fig. 4. Comparative historical trends of GHG emissions in Thai domestic aviation 2015–2020 Tier-I and Tier-II.

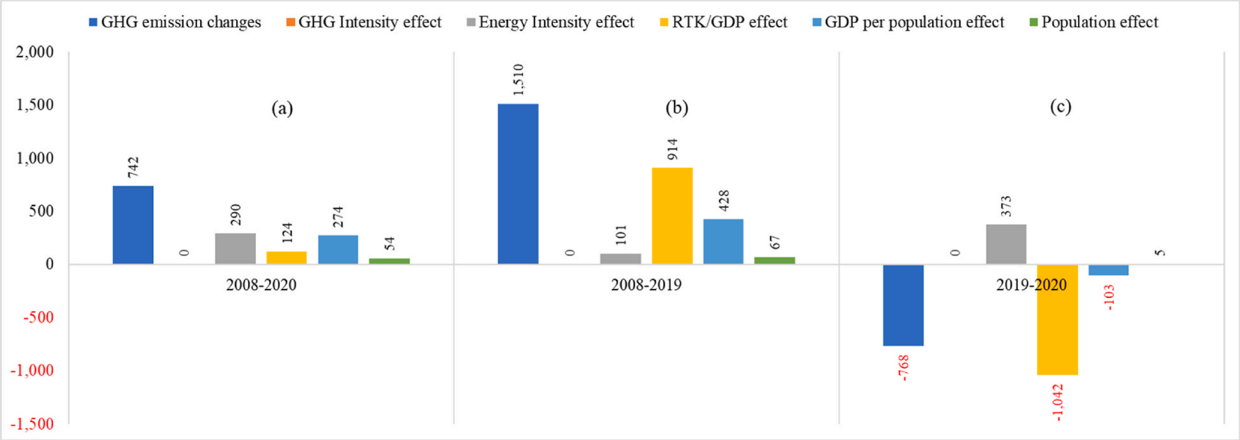

Fig. 5. Changes in GHG emissions and the contribution of various factors in that change, 2008–2020, Th. Tons of CO_2 -eq.

short-term increases but long-term decreases in ozone (O_3), methane (CH_4), soot, water vapor, water contrail, and sulfur aerosols. Moreover, nitrous gases have a dual effect on temperature: warming and cooling. The chemical reaction that produces ozone (O_3) from nitrogen oxides in the exhaust has a warming impact. While some of these effects result in warming, others result in cooling. When all things are considered, the warming effect is stronger. As a result, estimates of GHG emissions from the domestic aviation sector show GHG emissions and their contribution to global warming, with the transportation sector accounting for approximately 26 % of Thailand's GHG emissions [83]. Moreover, Thailand's domestic aviation sector contributed 0.004 % to total global emissions and 0.24 % to global emissions from the aviation sector from 2013 to 2019.

3.3. Key drivers of GHG emissions

As seen in the above sections, GHG emissions from the commercial domestic aviation sector have increased by 1950 thousand tonnes CO_2-eq per year between 2008 to the peak emission year of 2018. The emission's contribution to changes in carbon intensity (C_t), energy intensity (E_t), aviation activity intensity (R_t), GDP (G_t), and population effect (P_t) are shown in Fig. 5. Factor decomposition analysis is a well-established energy and emissions research method for understanding the underlying dynamics. The methodologically examined factors provide a comprehensive understanding of the variations in emissions within the specified period.

Results show that GHG intensity of energy use is not a meaningful factor for GHG emissions since fuel switching does not occur in the aviation sector. Moreover, CO_2 from aviation fuel is 3.15 g per gram [84]. The three primary factors influencing emissions during the 2008–2020 period are shown in Fig. 5 (a): GDP, which played a significant role in the growth of GHG emissions; the correlation

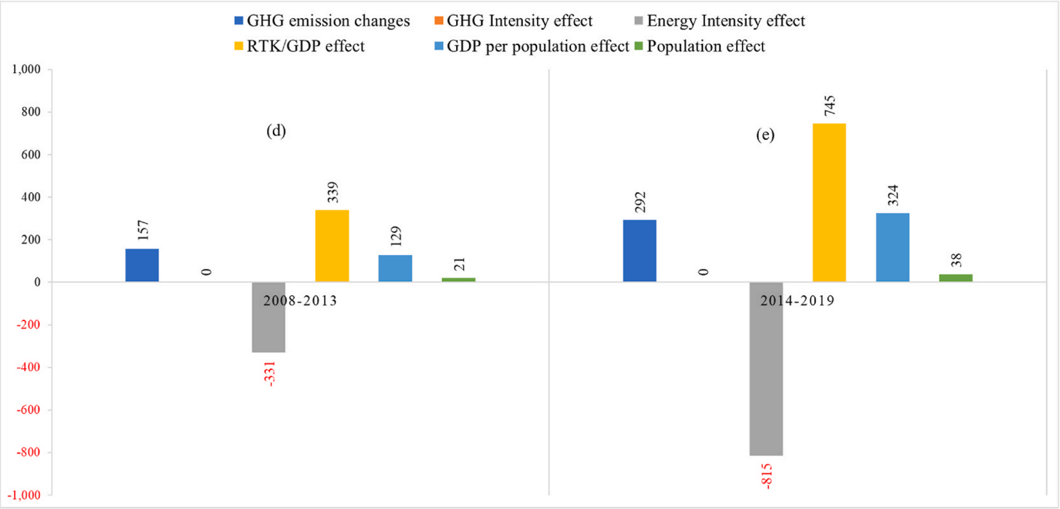

Fig. 6. Changes in GHG emissions from the contribution of various factors in selected years, Th. Tons of CO_2-eq.

between aviation activity and GDP, which drove GHG emissions; and the association between GDP and population, which greatly contributed to the increase in GHG emissions. This finding aligns with the research by Andreoni and Galmarini [62], which highlighted GDP as the primary driver of carbon dioxide emissions in the aviation sector, and Andreoni and Galmarini [85], which identified GDP as the main factor behind the rise in carbon dioxide emissions across 31 countries worldwide. As expected, 2019-20 as shown in Fig. 5 (c) was a turbulent COVID-19 period where GDP, and thus the aviation demand reduction, reduced GHG emissions.

Decomposition analyses for four time periods are presented below. They are: 2008–2013 as shown in Fig. 6 (d) (moderate market period); 2013–2014 (abrupt market spike due to lessening political tension); 2014–2019 as shown in Fig. 6 (e) (high market period), and 2019–2020 as shown in Fig. 5 (c) (COVID-19 period).

a) 2008–2013 as shown in Fig. 6 (d): GHG emissions from the commercial domestic aviation sector began to rise gradually. The popularity of the domestic aviation industry as a travel option and its average economic growth of approximately 3 % per year impacted this period with a rapid increase in passenger numbers amid a continuous rise in GDP and population growth. There was a notable average annual growth of 12 % in the number of passengers during this period.
b) 2013–2014: A turbulent year for emissions due to political changes and economic volatility in the country.
c) 2014–2019 as shown in Fig. 6 (e): GHG emissions steadily increased domestically due to lessening political problems and the government's 2013 launch of an airline industry promotion. It caused a marked growth in tourism. During this period, tourism was further stimulated due to: on-going preparations for entering the ASEAN Community in 2015, incentives pursuant to the Thai Tourism Strategy 2015–2017, and Thailand's aviation industry developments in accordance with Transport Infrastructure Development Strategy 2015–2022. It can be clearly seen that the major driver affecting GHG emissions in this period was economic activity (i.e., GDP). The expansion of the aviation industry's infrastructure and economic growth resulted in a rapid increase in passenger numbers, estimated to be 52 million more in 2019 compared to 2008.
d) 2019–2020 as shown in Fig. 5 (c): Record low GHG emissions were recorded in this period because the COVID crisis greatly affected the aviation industry. Since the Emergency Decree on Public Administration in Emergency Situations was announced on March 26, 2020, Thailand's domestic air transport began to shrink dramatically, resulting in a substantial drop in the number of passengers and flights (domestic and international). This was coupled with the general decline in economic growth.

This study believes that the all-inclusive data within the scope of our research showed that two turbulent subperiods, specifically 2013–2014 and 2019–2020 as shown in Fig. 5 (c), mask the underlying dynamics of the larger 2008–2020 period, as shown in Fig. 5 (a).

Therefore, 2008–2013, as shown in Fig. 6 (d) and 2014–2019, as shown in Fig. 6 (e) are separately presented in Fig. 6. This chart demonstrates that the impact of energy intensity on the demand for aviation industry's activities was a significant role in reducing the growth of GHG emissions during these periods of relative stability.

3.4. *Temporal characteristics of GHG emissions vis-a-vis demand of domestic commercial aviation activities*

The results show that from 2012 to 2018 total GHG emissions fluctuated but with a steady upward trend. However, GHG emissions per RTK were steadily declining trend both in 2009–2013 and 2014–2017, as shown in Fig. 7. Thailand's civil aviation industry has proliferated over the past seven years, especially after 2014. The number of passengers experienced a 320 % rise from 2008 to 2018, with an average yearly growth rate of 12.6 %. Thailand experienced an annual growth rate of above 10 % in its overall transport

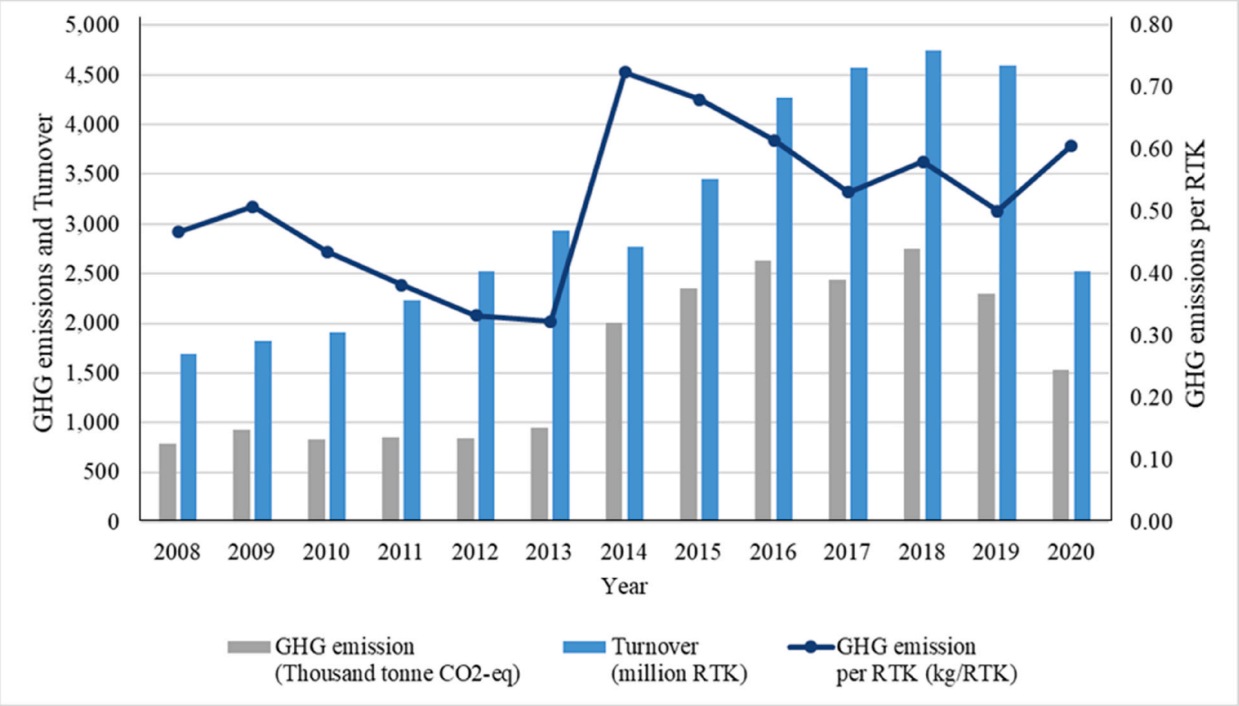

Fig. 7. Historical trends of total transport turnover and GHG emissions in Thai commercial domestic aviation.

turnover from 2008 to 2018. Significantly, this expansion corresponds to the overall pace of transport activity in China's civil aviation sector throughout their period of rapid growth from 1979 to 2014 [86]. However, Thailand saw a slight decline in 2014 due to political problems that affected foreign tourists' arrival. This resulted in a 6.7 % decline from the previous year and the first decline in four years [87,88]. The COVID-19 crisis of 2019–2020 saw an abrupt decline in the transport turnover rate. During the first quarter of 2020, this turnover rate amounted to only 30.8 % of the prior year's 1st quarter figure [89]. In the stable period of 2009–2013, the trend of GHG emissions per RTK witnessed an annual decrease of around 10.6 %, going from 0.51 kg CO_2 e per RTK in 2009 to 0.32 kg CO_2e per RTK in 2013. This was also true for the other stable period of 2014–2019, where a decline in GHG emission per RTK from 0.72 kg CO_2e/RTK to 0.5 kg CO_2e/RTK was recorded.

4. Conclusions and policy implications

Between 2008 and 2019, greenhouse gas (GHG) emissions from the domestic aviation sector in Thailand have tripled. However, GHG emissions dropped by about 25 % in 2019–2020 due to the COVID-19 crisis. Methodologically, a marginal difference (3.1–3.8 %) was found in the values of GHG emissions from Tier-I and Tier-II methods of IPCC in the period 2015–2020, with the Tier-I method slightly overestimating the emissions. Furthermore, the 2008–2013 emissions were characterized by slow growth. Emissions in this period increased by only an estimated 20%. In 2014, after the political unrest was alleviated, the domestic aviation sector began to show improved economic performance vis-à-vis revitalized tourism. It resulted in sharp increase in GHG emissions. Thailand entering into the ASEAN Economic Community, along with its attendant economic growth, airspace deregulation, and the lifting of travel restrictions, predictably contributed to increased GHG emissions. This unprecedented integration of national economies was further boosted by the dramatic effect of Thailand's Transport Infrastructure Development Strategy 2015–2022. It was found that the stable periods' GHG cruise emissions were higher by approximately 36% than landing/take-off emissions. However, it changed in 2020. COVID-19 altered the consumer's choices of available travel options, thus making the cruise emission's share of GHG shrink. Indeed, cruise levels were higher than the landing/take-off emissions by only 17.5%. A highly skewed ratio compared to stable periods of aviation activity when cruise levels were dramatically higher. Presently, Thailand's domestic aviation sector is undergoing a slow recovery, with many COVID-19 restrictions continuing to be in effect. Post-COVID GHG emissions will be determined not only by the level of domestic air transport's pent-up demand but also by the breadth and depth of the structural changes unleashed in the global economic marketplace in a post-COVID scenario.

Several additional factors from the aviation sector influenced GHG emissions. When considered in its entirety, aviation activity demand induced by GDP, and the GDP's effect on population, were the most important influencing factors driving GHG emissions in Thailand. Subsequently, the energy intensity of aviation activity, as depicted in Fig. 4, had a role in the rise of GHG emissions. The population effect demand was a key factor in dampening the growth of GHG emissions in relatively stable periods only, while GHG intensity of fuel was not a meaningful factor at all since fuel switching does not occur in the aviation sector.

In conclusion, our findings strongly suggest that GHG mitigation will be difficult to achieve in Thailand's domestic aviation industry during growth periods. It is due to the link between economic growth and aviation activity and GDP's connection to the population being key GHG drivers. This relationship is difficult to counter for the sake of GHG mitigation alone. However, there remains a degree of leverage in the use of energy intensity of aviation activity demand as follow.

i. The allocation of suitable aircraft types to its market demand is a key area for improvement. Where economically viable, flying smaller capacity planes with a resultant fuel reduction benefits a business concern's financial health and to our climate control goals.
ii. The use of modernized aircraft with such innovations as winglets (which can improve fuel efficiency); and the use of lightweight materials in aircraft construction are just 2 examples of the industry's constant efforts to reduce drag and lighten the energy needed to effect flight.
iii. While still in their early introductory stages, biojet fuels should be aggressively pursued as an alternative fuel source with their smaller carbon footprint. As improved technology, economies of scale and government policy initiatives are implemented, this fuel type will become less price-prohibitive. And finally, a government fee structure for carbon pricing should be a strong motivator for efficient energy use as more detailed identification of energy consumers becomes a check on excessive energy waste. In these areas, industry executives and governmental policymakers must turn to further discussion and exploration of best practice measures and regulatory proposals.

5. Limitations and scope of the future study

Given that the study's scope is limited to data spanning from 2008 to 2020, it does not evaluate the GHG emissions in Thailand's commercial domestic aviation sector during the timeframe of 2021–2023. In this study, data is based on aviation fuel consumption and statistics of aircraft landings and take-offs, but it lacks information on specific aircraft details and flight timing. Due to this missing data, the study focuses on calculating GHG emissions following IPCC Tier-I-II methods. Furthermore, there are additional factors that have not yet been examined in order to determine the causes behind the rise or decline of greenhouse gas emissions in the aviation industry of Thailand. Nevertheless, this research can serve as a valuable guide for analyzing appropriate policies to reduce future greenhouse gas emissions in Thailand's aviation sector. Future studies should focus on assessing greenhouse gas emissions in the Thai aviation industry through the utilization of more precise and accurate calculations. This will enable the provision of comprehensive information regarding Thai aviation activities.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Arthit Champeecharoensuk: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Shobhakar Dhakal:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Investigation, Conceptualization. **Nuwong Chollacoop:** Software, Resources, Data curation. **Aumnad Phdungsilp:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Air Transport Action Group, Facts & Figures, 2020. https://atag.org/facts-figures.

[2] Air Transport Action Group, Powering Global Economic Growth, Employment, Trade Links, Tourism and Support for Sustainable Development through Air Transport, 2018. https://aviationbenefits.org/media/166712/abbb18_global-summary_web.pdf.

[3] E. Uherek, T. Halenka, J. Borken-Kleefeld, Y. Balkanski, T. Berntsen, C. Borrego, M. Gauss, P. Hoor, K. Juda-Rezler, J. Lelieveld, D. Melas, K. Rypdal, S. Schmid, Transport impacts on atmosphere and climate: land transport, Atmos. Environ. 44 (37) (2010) 4772–4816, https://doi.org/10.1016/J.ATMOSENV.2010.01.002.

[4] Z.H. Shon, K.H. Kim, S.K. Song, Long-term trend in NO2 and NOx levels and their emission ratio in relation to road traffic activities in East Asia, Atmos. Environ. 45 (18) (2011) 3120–3131, https://doi.org/10.1016/J.ATMOSENV.2011.03.009.

[5] D.S. Lee, G. Pitari, V. Grewe, K. Gierens, J.E. Penner, A. Petzold, M.J. Prather, U. Schumann, A. Bais, T. Berntsen, D. Iachetti, L.L. Lim, R. Sausen, Transport impacts on atmosphere and climate: aviation, Atmos. Environ. 44 (37) (2010) 4678–4734, https://doi.org/10.1016/J.ATMOSENV.2009.06.005.

[6] D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De León, L. L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, L.J. Wilcox, The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmos. Environ. 244 (2021) 117834, https://doi.org/10.1016/J.ATMOSENV.2020.117834.

[7] A. La Notte, S. Tonin, G. Lucaroni, Assessing direct and indirect emissions of greenhouse gases in road transportation, taking into account the role of uncertainty in the emissions inventory, Environ. Impact Assess. Rev. 69 (2018) 82–93, https://doi.org/10.1016/J.EIAR.2017.11.008.

[8] H. Hao, F. Liu, Z. Liu, F. Zhao, Measuring energy efficiency in China's transport sector, Energies 10 (5) (2017) 660, https://doi.org/10.3390/EN10050660, 2017.

[9] J. Domagala M. Kadlubek, Economic, energy and environmental efficiency of road freight transportation sector in the EU, Energies 16 (1) (2022) 461, https://doi.org/10.3390/EN16010461, 2023.

[10] International Civil Aviation Organization, Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis Air, Transport Bureau Contents, 2020.

[11] G. Brandon, Z. Kevin, R. Dan, CO2 emissions from commercial aviation, 2018, Int. Counc. Clean Transp. https://theicct.org/publication/co2-emissions-from-commercial-aviation-2018/, 2018.

[12] M. Crippa, G. Oreggioni, D. Guizzardi, M. Muntean, E. Schaaf, E. Lo Vullo, E. Solazzo, F. Monforti-Ferrario, J.G.J. Olivier, E. Vignati, Fossil CO2 and GHG Emissions of All World Countries, 2019. https://op.europa.eu/en/publication-detail/-/publication/9d09ccd1-e0dd-11e9-9c4e-01aa75ed71a1/language-en.

[13] International Air Transport Association, Economic Performance of the Airline Industry: 2015 Mid-year Report, 2015. https://www.iata.org/en/publications/economics/.

[14] 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.

[15] The Oraganisation for Economic Co-Operation and Development, Air Transport CO2 Emissions, 2022. https://stats.oecd.org/Index.aspx?DataSetCode=AIRTRANS_CO2#.

[16] X. Liu, Y. Hang, Q. Wang, D. Zhou, Flying into the future: a scenario-based analysis of carbon emissions from China's civil aviation, J. Air Transport. Manag. 85 (2020) 101793, https://doi.org/10.1016/J.JAIRTRAMAN.2020.101793.

[17] X. Liu, D. Zhou, P. Zhou, Q. Wang, What drives CO2 emissions from China's civil aviation? An exploration using a new generalized PDA method, Transp. Res. Part A Policy Pract. 99 (2017) 30–45, https://doi.org/10.1016/J.TRA.2017.03.002.

[18] M. Kito, F. Nagashima, S. Kagawa, K. Nansai, Drivers of CO2 emissions in international aviation: the case of Japan, Environ. Res. Lett. 15 (10) (2020) 104036, https://doi.org/10.1088/1748-9326/AB9E9B.

[19] G.R. Timilsina, A. Shrestha, Transport sector CO2 emissions growth in Asia: underlying factors and policy options, Energy Pol. 37 (11) (2009) 4523–4539, https://doi.org/10.1016/J.ENPOL.2009.06.009.

[20] S. Maertens, W. Grimme, J. Scheelhaase, M. Jung, Options to continue the EU ETS for aviation in a CORSIA-world, Sustain. Times 11 (20) (2019) 5703, https://doi.org/10.3390/SU11205703.

[21] S. Tawatchai, Global Commitment of ICAO to the Development of the Low-Carbon Aviation Industry (Global Aspirational Goal), Thail. Greenh. Gas Manag. Organ., 2019.

[22] S.K. Song, Z.H. Shon, Emissions of greenhouse gases and air pollutants from commercial aircraft at international airports in Korea, Atmos. Environ. 61 (2012) 148–158, https://doi.org/10.1016/J.ATMOSENV.2012.07.035.

[23] X. Bo, X. Xue, J. Xu, X. Du, B. Zhou, L. Tang, Aviation's emissions and contribution to the air quality in China, Atmos. Environ. 201 (2019) 121–131, https://doi.org/10.1016/J.ATMOSENV.2019.01.005.

[24] C.C. Chao, Assessment of carbon emission costs for air cargo transportation, Transp. Res. Part D Transp. Environ. 33 (2014) 186–195, https://doi.org/10.1016/J.TRD.2014.06.004.

[25] A.P. Tarr, I.J. Smith, C.J. Rodger, Carbon dioxide emissions from international air transport of people and freight: New Zealand as a case study, Environ. Res. Commun. 4 (7) (2022) 075012, https://doi.org/10.1088/2515-7620/ABF15D.

[26] M.J. Sajid, G. Ali, E.D.R. Santibanez Gonzalez, Estimating CO2 emissions from emergency-supply transport: the case of COVID-19 vaccine global air transport, J. Clean. Prod. 340 (2022) 130716, https://doi.org/10.1016/J.JCLEPRO.2022.130716.

[27] J. Liu, J. Tian, W. Lyu, Y. Yu, The impact of COVID-19 on reducing carbon emissions: from the angle of international student mobility, Appl. Energy 317 (2022) 119136, https://doi.org/10.1016/J.APENERGY.2022.119136.

[28] T. Pejovic, R.B. Noland, V. Williams, R. Toumi, Estimates of UK CO2 emissions from aviation using air traffic data, Clim. Chang. 88 (3) (2007) 367–384, https://doi.org/10.1007/S10584-007-9370-0, 2008.

[29] J.C. He, Y.Q. Xu, Estimation of the aircraft CO2 emissions of China's civil aviation during 1960–2009, Adv. Clim. Chang. Res. 3 (2) (2012) 99–105, https://doi.org/10.3724/SP.J.1248.2012.00099.

[30] I. Ozturk, U. Al-Mulali, B. Saboori, Investigating the environmental Kuznets curve hypothesis: the role of tourism and ecological footprint, Environ. Sci. Pollut. Res. 23 (2) (2015) 1916–1928, https://doi.org/10.1007/S11356-015-5447-X, 2016.

[31] Ministry og Public Health (Moph), Thailand Information, 2023.

[32] T. Champeecharoensuk, P.A. Salam, S. Dhakal, N. Chollacoop, Key driver analysis of greenhouse gas emissions in Thailand's public bus transport with comparative study on metropolitan Bangkok hotspots, Energy Sustain. Dev. 70 (2022) 456–465, https://doi.org/10.1016/J.ESD.2022.08.019.

[33] 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. https://www.caat.or.th/th/archives/59631.

[34] The Civil Aviation Authority of Thailand, State of Thai Aviation Industry, 2019. https://www.caat.or.th/wp-content/uploads/2020/06/STATE-OF-THAI-AVIATION-INDUSTRY-2019.pdf.

[35] Department of alternative energy development and efficiency, energy statistics, energy balance of Thailand. https://weben.dede.go.th/webmax/, 2020.

[36] Thailand Greenhouse Gas Management Organization, Greenhouse Gas Management Organization Strategic Plan 2018 – 2022, 2019. http://www.tgo.or.th/2020/index.php/en/page/tgo-strategy-plan.

[37] I. Suryati, B.D.L. Manik, F. Syavira, G.N. Karina, N. Herlina, N.H. Hasibuan, R.L. Siregar, Alternative study of reducing Carbon Dioxide (CO2) from the transportation sector in Medan city, IOP Conf. Ser. Mater. Sci. Eng. 801 (1) (2020) 012072, https://doi.org/10.1088/1757-899X/801/1/012072.

[38] J. Pongthanaisawan, C. Sorapipatana, Greenhouse gas emissions from Thailand's transport sector: trends and mitigation options, Appl. Energy 101 (2013) 288–298, https://doi.org/10.1016/J.APENERGY.2011.09.026.

[39] A. Singh, S. Gangopadhyay, P.K. Nanda, S. Bhattacharya, C. Sharma, C. Bhan, Trends of greenhouse gas emissions from the road transport sector in India, Sci. Total Environ. 390 (1) (2008) 124–131, https://doi.org/10.1016/J.SCITOTENV.2007.09.027.

[40] Department of Airports, Air Transport Statistics of Airports under the Department of Airports 2015 – 2020, 2020. https://www.airports.go.th/th/content/349.html.

[41] Airports of Thailand, air transport statistic. https://www.airportthai.co.th/en/airports-of-thailand-plc/about-aot/air-transport-statistic/, 2020.

[42] U-Tapao Rayong-Pattaya International Airport, Air Transport Statistics 2015 - 2020 Report, 2020. https://www.utapao.com/th/home.

[43] Intergovernmental Panel on Climate Change, Guidelines for National Greenhouse Gas Inventories: Mobile Combustion, 2006. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf.

[44] National Statistical Office Thailand, Demography Population and Housing Branch, 2020. http://statbbi.nso.go.th/staticreport/page/sector/th/01.aspx.

[45] The World Bank, GDP (Current US$) - Thailand Data, 2021. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=TH.

[46] Bank of Thailand, Rates of Exchange of Commercial Banks, 2021. https://www.bot.or.th/en/statistics/exchange-rate.html.

[47] Prepared by the National Greenhouse Gas Inventories Programme. Published, Intergovernmental Panel on Climate Change, Guidelines for National Greenhouse Gas Inventories, IGES, Japan, 2006, https://www.ipcc-nggip.iges.or.jp/support/Primer_2006GLs.pdf.

[48] W. Liao, Y. Fan, C. Wang, Z. Wang, Emissions from intercity aviation: an international comparison, Transp. Res. Part D Transp. Environ. 95 (2021) 102818, https://doi.org/10.1016/J.TRD.2021.102818.

[49] J. Jiao, Y. Huang, C. Liao, Co-benefits of reducing CO2 and air pollutant emissions in the urban transport sector: a case of Guangzhou, Energy Sustain. Dev. 59 (2020) 131–143, https://doi.org/10.1016/J.ESD.2020.10.005.

[50] J.S. Kurniawan, S. Khardi, Comparison of methodologies estimating emissions of aircraft pollutants, environmental impact assessment around airports, Environ. Impact Assess. Rev. 31 (3) (2011) 240–252, https://doi.org/10.1016/J.EIAR.2010.09.001.

[51] Intergovernmental Panel on Climate Change, Anthropogenic and Natural Radiative Forcing, 2018 (Chapter 8), https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf.

[52] T. tian Feng, Y. sheng Yang, S. yan Xie, J. Dong, L. Ding, Economic drivers of greenhouse gas emissions in China, Renew. Sustain. Energy Rev. 78 (2017) 996–1006, https://doi.org/10.1016/J.RSER.2017.04.099.

[53] D. González, M. Martínez, Decomposition analysis of CO2 emissions in the Mexican industrial sector, Energy Sustain. Dev. 16 (2) (2012) 204–215, https://doi.org/10.1016/J.ESD.2012.01.005.

[54] G.R. Timilsina, A. Shrestha, Factors affecting transport sector CO2 emissions growth in Latin American and Caribbean countries: an LMDI decomposition analysis, Int. J. Energy Res. 33 (4) (2009) 396–414, https://doi.org/10.1002/ER.1486.

[55] Q. Wang, X. Han, R. Li, Does technical progress curb India's carbon emissions? A novel approach of combining extended index decomposition analysis and production-theoretical decomposition analysis, J. Environ. Manag. 310 (2022) 114720, https://doi.org/10.1016/J.JENVMAN.2022.114720.

[56] A. Rose, S. Casler, Input-output structural decomposition analysis: a critical appraisal, Econ. Syst. Res. 8 (1) (1996) 33–62, https://doi.org/10.1080/09535319600000003.

[57] M. Liu, X. Zhang, M. Zhang, Y. Feng, Y. Liu, J. Wen, L. Liu, Influencing factors of carbon emissions in transportation industry based on CD function and LMDI decomposition model: China as an example, Environ. Impact Assess. Rev. 90 (2021) 106623, https://doi.org/10.1016/J.EIAR.2021.106623.

[58] X. Chen, C. Shuai, Y. Zhang, Y. Wu, Decomposition of energy consumption and its decoupling with economic growth in the global agricultural industry, Environ. Impact Assess. Rev. 81 (2020) 106364, https://doi.org/10.1016/J.EIAR.2019.106364.

[59] Q. Wang, M. Su, Drivers of decoupling economic growth from carbon emission – an empirical analysis of 192 countries using decoupling model and decomposition method, Environ. Impact Assess. Rev. 81 (2020) 106356, https://doi.org/10.1016/J.EIAR.2019.106356.

[60] M. Jiang, H. An, X. Gao, N. Jia, S. Liu, H. Zheng, Structural decomposition analysis of global carbon emissions: the contributions of domestic and international input changes, J. Environ. Manag. 294 (2021) 112942, https://doi.org/10.1016/J.JENVMAN.2021.112942.

[61] J.J. Andreas, C. Burns, J. Touza, L. Zhou, L. Qiu, C. Gu, Qiang Jiang, W.J. Xie, W.X. Zhou, Z. Mi, J. Meng, D. Guan, Y. Shan, Z. Liu, Y. Wang, K. Feng, Y.M. Wei, Pattern changes in determinants of Chinese emissions, Environ. Res. Lett. 12 (7) (2017) 074003, https://doi.org/10.1088/1748-9326/AA69CF.

[62] V. Andreoni, S. Galmarini, European CO2 emission trends: a decomposition analysis for water and aviation transport sectors, Energy 45 (1) (2012) 595–602, https://doi.org/10.1016/J.ENERGY.2012.07.039.

[63] F. Fan, Y. Lei, Decomposition analysis of energy-related carbon emissions from the transportation sector in Beijing, Transp. Res. Part D Transp. Environ. 42 (2016) 135–145, https://doi.org/10.1016/J.TRD.2015.11.001.

[64] T.R. Lakshmanan, X. Han, Factors underlying transportation CO2 emissions in the U.S.A.: A decomposition analysis, Transp. Res. Part D Transp. Environ. 2 (1) (1997) 1–15, https://doi.org/10.1016/S1361-9209(96)00011-9.

[65] A. Malik, J. Lan, M. Lenzen, Trends in Global Greenhouse Gas Emissions from 1990 to 2010, Environ. Sci. Technol. 50 (9) (2016) 4722–4730, https://doi.org/10.1021/acs.est.5b06162.

[66] Z. Mi, J. Meng, D. Guan, Y. Shan, M. Song, Y.M. Wei, Z. Liu, K. Hubacek, Chinese CO2 emission flows have reversed since the global financial crisis, Nat. Commun. 8 (1) (2017), https://doi.org/10.1038/S41467-017-01820-W.

[67] S. Ren, H. Yin, X.H. Chen, Using LMDI to analyze the decoupling of carbon dioxide emissions by China's manufacturing industry, Environ. Dev. 9 (1) (2014) 61–75, https://doi.org/10.1016/J.ENVDEV.2013.11.003.

[68] W. Wang, X. Liu, M. Zhang, X. Song, Using a new generalized LMDI (logarithmic mean Divisia index) method to analyze China's energy consumption, Energy 67 (2014) 617–622, https://doi.org/10.1016/J.ENERGY.2013.12.064.

[69] N. Sobrino, A. Monzon, The impact of the economic crisis and policy actions on GHG emissions from road transport in Spain, Energy Pol. 74 (2014) 486–498, https://doi.org/10.1016/J.ENPOL.2014.07.020.

[70] Y. Wu, H. Huang, J. Hong, X. Wang, Y. Wu, Y. Wu, Transfer patterns and driving factors of China's energy use in trade: Evidence from multiregional input–output analysis and structural decomposition analysis, Energy Rep. 8 (2022) 10963–10975, https://doi.org/10.1016/J.EGYR.2022.08.239.

[71] J. Chontanawat, P. Wiboonchutikula, A. Buddhivanich, An LMDI decomposition analysis of carbon emissions in the Thai manufacturing sector, Energy Rep. 6 (2020) 705–710, https://doi.org/10.1016/J.EGYR.2019.09.053.

[72] M. Shao, M. Xue, Decomposition analysis of carbon emissions: Considering China's energy efficiency, Energy Rep. 8 (2022) 630–635, https://doi.org/10.1016/J.EGYR.2022.05.114.

[73] Q. Cao, J. Lv, J. Zhang, Productivity efficiency analysis of the airlines in China after deregulation, J. Air Transport. Manag. 42 (2015) 135–140, https://doi.org/10.1016/J.JAIRTRAMAN.2014.09.009.

[74] Q. Cui, Y. Li, C. lu Yu, Y.M. Wei, Evaluating energy efficiency for airlines: An application of Virtual Frontier Dynamic Slacks Based Measure, Energy 113 (2016) 1231–1240, https://doi.org/10.1016/J.ENERGY.2016.07.141.

[75] I.M. Semenick Alam, R.C. Sickles, The Relationship between Stock Market Returns and Technical Efficiency Innovations: Evidence from the US Airline Industry, J. Product. Anal. 9 (1) (1998) 35–51, https://doi.org/10.1023/A:1018368313411.

[76] The Civil Aviation Authority of Thailand, Thailand's Action Plan to Reduce Aviation Emission, 2018.

[77] Department of Alternative Energy Development and Efficiency, Energy Statistics, Energy Balance of Thailand. https://www.dede.go.th/uploads/1_Energy_Balance_of_Thailand_2564_for_web_compressed_bcc2ba9aad.pdf?updated_at=2023-03-25T16:59:19.504Z, 2019.

[78] The Organisation for Economic Co-operation and Development, OECD Economic Survey S Economic Assessment, 2020. https://www.oecd.org/economy/thailand-economic-snapshot/.

[79] The Civil Aviation Authority of Thailand, Domestic Flight Distance and Fare Ceiling Information, 2021. https://www.caat.or.th/th/archives/36895.

[80] The Civil Aviation Authority of Thailand, State of Thai Aviation Industry, 2020.

[81] The Civil Aviation Authority of Thailand, The Report Predicts the Demand for Air Travel of the Country, 2020. https://www.caat.or.th/th/archives/53358.

[82] H. Ritchie, Climate Change and Flying: what Share of Global CO2 Emissions Come from Aviation? - Our World in Data, 2020. https://ourworldindata.org/co2-emissions-from-aviation.

[83] N. Bamrungwong, V. Vongmanee, W. Rattanawong, The development of a CO2 emission coefficient for medium- and heavy-duty vehicles with different road slope conditions using multiple linear regression, and considering the health effects, Sustain. Times 12 (2020), https://doi.org/10.3390/SU12176994, 17.
[84] European Environment Agency, European Environment Agency CORINAIR Manual, 2001. https://www.carbonindependent.org/files/B851vs2.4.pdf.
[85] V. Andreoni, S. Galmarini, Drivers in CO2 emissions variation: A decomposition analysis for 33 world countries, Energy 103 (2016) 27–37, https://doi.org/10.1016/J.ENERGY.2016.02.096.
[86] J. Yu, C. Shao, C. Xue, H. Hu, China's aircraft-related CO2 emissions: Decomposition analysis, decoupling status, and future trends, Energy Pol. 138 (2020) 111215, https://doi.org/10.1016/J.ENPOL.2019.111215.
[87] Office of the National Economic and Social Development Council, Economic and Social News, Thai Economy in the First Quarter of 2014 and Outlook for 2014, 2014.
[88] Bank of Thailand, Economic Issues in 2014, 2014. https://www.bot.or.th/content/dam/bot/documents/en/research-and-publications/reports/financial-stability-report/FSR2014e.pdf.
[89] Ministry of Tourism and Sports, Tourism Economic report. https://www.mots.go.th/download/TourismEconomicReport/4-1TourismEconomicVol4.pdf, 2020.