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An Analysis of the Annual Carbon Dioxide Emissions (CO_2) of a Major European Hub Airport: A Case Study of Frankfurt Airport

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Abstract**—***Underpinned by an in-depth longitudinal case study research design, this study examines Frankfurt Airport's annual carbon dioxide (CO_2) emissions as well as the methods and technologies that have been implemented to reduce the environmental impact of carbon dioxide (CO_2) emissions at the airport. The study period was from 2008 until 2019. The study's data was examined by document analysis. Frankfurt Airport's total annual carbon dioxide (CO2) emissions increased from 1,653,658 tonnes in 2008 to 1,744,201 tonnes in 2019. Frankfurt Airport's annual climate gas intensity of traffic performance ratio largely displayed a downward trend decreasing from a high of 3.4 kg CO_2 per traffic unit in 2009 to 1.5 kg CO_2 per traffic unit in 2019. Despite the strong traffic growth in passenger traffic, the airport's annual direct carbon dioxide emissions per traffic unit largely exhibited an overall downward trend, declining from a high of 0.51kg CO_2 per traffic unit in 2010 to a low of 0.41kg CO_2 per traffic unit in 2019. The airport's annual indirect carbon dioxide emissions per traffic unit decreased from a high of 2.88 kg CO_2 per traffic unit in 2009 to a low of 1.46 kg CO_2 per traffic unit in 2019. Frankfurt Airport has implemented extensive carbon dioxide (CO2) reduction measures which include the hydraulic balancing of heating systems, upgrading windows and doors, optimizing lighting, air conditioning and heating systems, optimizing the energy usage of the airport's baggage handling system, the use of highly efficient LED lighting, the use of low emission vehicles, the electrification of ground service equipment, the optimization of energy usage in all new buildings at the airport, and the planned widespread use of renewable energy sources (wind and solar power).*

Keywords**—** ***Airport, carbon dioxide emissions (CO_2), case study, environment, Frankfurt Airport.***

I. INTRODUCTION

The global commercial airline industry has grown over the past twenty years or so at an annual rate of 4.5–5% in the passenger and 6% in the air cargo segments (Janić, 2014). However, while this growth has created significant economic and social benefits, air transport has had an adverse impact on the environment and is leading to climate change (Arif Hasan et al., 2021). Moreover, the strong growth in commercial air transport traffic, both passenger and air cargo, has especially driven concerns over air quality (Daley, 2016; Harrison et al., 2015). Because of the increasing demand for air transportation globally combined with the decreasing marginal fuel efficiency improvements, the contribution of air transportation to climate change relative to other sectors is predicted to increase in the future. Consequently, the growing public and political pressures are envisaged to further target the air transportation industry to reduce its greenhouse gas emissions, and thus, its environmental impact (Sgouridis et al., 2011). This is because the global aviation industry generates a substantial carbon footprint which is predicted to increase in the future (Filimonau et al., 2018). It has been estimated that the world air transport industry produces around 2% of all human induced emissions (Air Transport Action Group, 2022b; Ansell & Haran, 2020). Moreover, the aviation industry constitutes approximately 2.5% of all global energy-related carbon dioxide (CO_2) emissions (Greer et al., 2020; Larsson et al., 2019).

Airports play a significant role in local economy's and help to facilitate a country's integration into the global economy thus providing social benefits to society. However, despite these socioeconomic benefits, airports have an adverse impact on the surrounding environments, ecology, and society (Chourasia et al., 2021). Consequently, airports are increasingly under pressure to support the position that the industry should have a low carbon energy future (Ryley et al., 2014). As a result, many airports have implemented extensive programs and strategies to mitigate the impact of carbo dioxide (CO_2) emissions have on the environment (Mosvold Larsen, 2015). Furthermore, many airports have become increasingly committed to becoming more "green," or environmentally friendly (Budd et al., 2015; Comendador et al., 2019; Sun et al., 2021).

With the growing focus on the impact of climate change, the embodied carbon dioxide (CO_2) emissions are now frequently used as an environmental performance indicator for products or production activities (Laurent et al., 2010). The objective of this study is to empirically examine the aircraft and airport-related carbon dioxide (CO_2) emissions at Frankfurt Airport, Germany's largest airport, and their impacts on air quality at the airport. A second aim of the study was to examine how increases in air traffic have influenced the level of carbon dioxide (CO_2) at Frankfurt Airport throughout the study period. A final aim was to examine the measures that have been implanted at Frankfurt Airport to reduce its annual carbon dioxide (CO_2) emissions. Frankfurt Airport was selected as the case airport as it is a key global hub airport that is served by both full-service network carriers (FSNCs) and low-cost carriers (LCCs) as well as dedicated freighter aircraft operators. The airport has been committed to sustainable operations throughout its history. The availability of a comprehensive data set covering the period 2008 to 2019, was a further factor in selecting Frankfurt Airport as the case company.

The remainder of the paper is organized as follows: The literature review that sets the context of the case study is presented in Section 2. The research method that underpinned the case study is presented in Section 3. The Frankfurt Airport case study is presented in Section 4. Section 5 presents the findings of the study.

II. BACKGROUND

2.1 A Brief Overview of Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) is a colorless, odorless, and non-poisonous gas that is regarded as being a greenhouse gas (GHG) (Cook, 2012). Carbon dioxide (CO_2) is naturally present in the atmosphere and form's part of the Earth's carbon cycle (that is: the natural circulation of carbon among the atmosphere, oceans, soil, plants, and animals) (United States Environmental Protection Agency, 2022b). Typically, carbon is extracted from the ground in the forms of oil, gas, or coal and is subsequently released into the atmosphere as carbon dioxide (CO_2) during their combustion. Carbon dioxide (CO_2) emissions may remain in the atmosphere for more than a century (Broutin & Coussy, 2010). Importantly, carbon dioxide (CO_2) has a direct impact on the Earth's climate (Panneer Selvam et al., 2014; Nery dos Santos et al., 2020) as carbon dioxide (CO_2) emissions has a significant impact on the earth's climate warming (Chilongola & Ahyudanari, 2019). As such, carbon dioxide (CO_2) is acknowledged as being the most important anthropogenic greenhouse gas (GHG) (Silva-Olaya et al., 2013). Furthermore, carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities. Carbon dioxide (CO_2) is an important heat-trapping (greenhouse) gas, which is released through natural processes such as respiration and volcanic eruptions (NASA Jet Propulsion Laboratory, 2021). However, the principal human activity that emits carbon dioxide (CO_2) is the combustion of fossil fuels (for example, coal, natural gas, and oil) for energy and transportation. Importantly, some other industrial processes and land-use changes also emit carbon dioxide (CO_2) (Glaeser & Kahn, 2010).

Following water vapor, carbon dioxide (CO_2) is regarded as the second most important of all the greenhouse gases (Drewer et al., 2018; Ngo & Natowitz, 2016). Carbon dioxide (CO_2) emissions from the transportation sector is one of the principal contributors of the world's overall greenhouse gases (GHG) (Koiwanit, 2018). Furthermore, carbon dioxide (CO_2) emissions produced from air transportation services have an adverse environmental impact because of their potential greenhouse effects (Boussauw & Vanoutrive, 2019; Postorino & Mantecchini, 2014).

2.2 The Sources of Airport Emissions

The sources of emissions at an airport come from a variety of sources. The global air transport industry relies almost solely on the combustion of carbon-based fossil fuels, principally kerosene. When the fuel is burnt in the aircraft engines, jet fuel emits a variety of greenhouse gases. These emissions include carbon dioxide (CO_2), nitrous oxides as well as water vapor (Budd, 2017; Janić, 2011). The amount of aircraft carbon dioxide (CO_2) emissions is a product of hydrocarbon combustion, and the amount of these gases is directly related to the volume of fuel consumed. This, in turn, is a function of the aircraft and its engine fuel efficiency, as well as the length of time that an aircraft's engines or auxiliary power unit (APU) are running (Marais et al., 2016). Carbon dioxide (CO_2) is the largest component of aircraft emissions, accounting for around 70 percent of an aircraft's exhaust emissions (Overton, 2019). In addition, aircraft taxi-out procedures, which form part of the aircraft Landing and Take-Off (LTO) cycle, generate significant amounts of carbon emissions (Postorino et al., 2019). Aircraft emissions are a function of the number of annual aircraft movements at the airport, the aircraft fleet mix, that is, the types of aircraft and their engines serving an airport, and the length of time that an aircraft spend in various modes of the landing and take-off cycle. Another source of emissions come from the aircraft auxiliary power units (APU). Because jet fuel is utilized as the power source for APUs, they emit exhaust gases (Culberson, 2011). APU's supply the essential power requirements for an aircraft whilst it is on the ground in between flights (Ashford et al., 2013; Kazda & Caves, 2015). They are used when the main engines are not running or there is no other alternative power source (Smith, 2004).

Aircraft parked at the airport gates during their turnaround require power and air conditioning, which is typically provided by fossil fuel-combusting equipment (Greer et al., 2021), all of which produce harmful emissions. Ground support equipment (GSE): such as aircraft push-back tugs, aircraft loaders, and catering trucks also produce exhaust emissions. Furthermore, in the area surrounding airports, road traffic can be the principal source of emissions (Thomas & Hooper, 2013).

Construction emission sources can include the vehicles and equipment used in construction projects, land development activities, asphalt paving activities, asphalt batch plants, and painting activities. These vehicles and equipment generate pollutant emissions at the airport. Stationary sources: can include heating and cooling plants, emergency power generators, and other industrial facilities located within the airport precinct (Culberson, 2011). Other emissions are produced from maintenance and cleaning processes at an airport (Graham, 2018) as well as fuel evaporation on refuelling off aircraft (Suryati et al., 2018).

The operation of an airport can be the largest source of some pollutants in a particular locality and within the airport itself, aircraft emissions dominate. Hence, as noted earlier, many airports have implemented comprehensive programs to mitigate the impact of carbon dioxide (CO_2) emissions (Masiol & Harrison, 2014).

2.3 The "Scope" Categories of the Sources of Airport-Related Greenhouse Gas Emissions

Airports around the world are increasingly calculating their annual carbon dioxide (CO_2) emissions and have also implemented specific carbon reduction targets (Baxter et al., 2018). As part of this process, airports engage with third parties, such as airlines and various service providers, including independent ground handling firms, air traffic control (ATC), or others operating within the airport precinct, to reduce the wider carbon footprint. This process also requires the involvement of the relevant authorities as well as passengers in matters relating to the airport's surface access modes (road, rail, metro) (Airports Council International Europe, 2021).

Despite differences in air quality regulations between countries, airport operators are now recording and reporting their Scope 1, 2, or 3 emissions (Baxter et al., 2018; Giuffre & Granà, 2011). Scope 1 emissions come from sources that are owned and directly controlled by the airport. Scope 1 emissions are produced by fuel-powered vehicles owned and operated by the airport, together with stationery sources, for example, heating systems that burn fuel to service the airport. Other sources of Scope 1 emissions are from vehicles used to transport passengers and vehicles used for airport maintenance, airport-related maintenance activities, ground support equipment (GSE) for handling aircraft when they are on the ground, fire-fighting training and waste disposed onsite through incineration or treatment (Airports Council International, 2009). Scope 2 indirect emissions are those generated from the purchase of electricity to power the various airport facilities and infrastructure. Scope 3 emissions are a result of the activities that are performed at an airport. An airport's Scope 3 emissions come from sources that are owned and operated by another party (Airports Council International, 2009; Budd, 2017; Kim et al., 2009).

2.4 Measures Available to Airports to Mitigate Their Carbon Dioxide (CO_2) Emissions

There are a range of carbon dioxide (CO_2) emissions mitigation measures available to airports. Airports can reduce their impact on climate change by addressing emissions in ground transportation, energy use in buildings and other related infrastructure as well as addressing the associated indirect emissions present at the airport (Giuffre & Granà, 2011). Airports can adopt a low-cost energy efficiency strategy and in line with this they can improve building insulation. Such measures simultaneously reduce greenhouse gas (GHG) emissions whilst also providing savings in an airport's operating costs. Airports can also purchase energy from renewable energy sources, and they can also install airport renewable energy systems (provided they are compatible with airport operations). Airports can also aim to reduce their energy consumption. The efficient monitoring of heating, ventilation, and cooling systems will assist the energy consumption. A further measure available to airports is the acquisition of low or zero-emission vehicles and ground service equipment (GSE) (Federal Aviation Administration, 2021). Some airports have moved to the use of electric powered vehicles which are environmentally more favorable (Graham, 2018) as they reduce vehicle emissions at an airport (Gellings, 2011).

Airports can also reduce the emissions associated with running aircraft engines while the aircraft are on the ground by minimizing aircraft taxiing times and encouraging the use of taxiing using a single engine. Airports can also encourage airlines to use fixed electrical ground power (FEGP) systems during the aircraft turnaround process (Giuffre & Granà, 2011; Graham, 2018). The optimization of an airport's runway layout can also help to mitigate carbon dioxide (CO_2) emissions. In addition, the design of new airport infrastructure and terminal buildings, as well as retrofit projects for existing buildings, could employ greenhouse gas abatement technology (Giuffre & Granà, 2011).

III. RESEARCH METHODOLOGY

3.1 Research Approach

The study's qualitative analysis was underpinned by an in-depth longitudinal case study research design (Baxter & Srisaeng, 2021; Derrington, 2019; Hassett & Paavilainen-Mäntymäki, 2013; Neale, 2019). The primary advantage of this research approach is that it reveals change and growth in a phenomenon or outcome over time (Kalaian & Kasim, 2008). A case study also allows for the exploration of complex phenomena (Remenyi et al., 2010; Yin, 2018) and enables the collection of rich, explanatory information (Ang, 2014; Mentzer & Flint, 1997). Case studies also enable researchers to connect with practice in a real-world context (McCutchen & Meredith, 1993).

3.2 Data Collection

The qualitative data gathered for this study was obtained from Fraport AG's annual sustainability reports as well as the company's annual abridged environmental statements. Thus, in this study, secondary data was used to investigate the research objectives. The study followed the guidance of Yin (2018) in the data collection phase, that is, the study used multiple sources of case evidence, the data was stored and analyzed in a database on the subject, and there was a chain of case study evidence.

3.3 Data Analysis

The qualitative data collected was examined using document analysis. Document analysis is frequently used in case studies and focuses on the information and data from formal documents and company records (Grant, 2019; Oates, 2006; Ramon Gil-Garcia, 2012). Existing documents are a vital source of qualitative data and may be publicly available or private in nature (Woods & Graber, 2017). Documents are one of the principal forms of data sources for the interpretation and analysis in case study research (Olson, 2010). The documents collected for the present study were examined according to four criteria: authenticity, credibility, representativeness, and meaning (Fitzgerald, 2012; Fulcher & Scott, 2011; Scott, 2014).

The key words used in the database searches included "Fraport AG environmental management policy", "Fraport AG climate policy", "Frankfurt Airport's annual direct Scope 1 and Scope 2 carbon dioxide (CO_2) emissions", "Frankfurt Airport's annual direct carbon dioxide (CO_2) emissions", "Frankfurt Airport's annual intensity of the traffic performance emissions", "Frankfurt Airport's annual direct carbon dioxide (CO_2) emissions", "Frankfurt Airport's annual direct carbon dioxide (CO_2) emissions from fuel consumption and combustion plants", Frankfurt Airport's annual indirect carbon dioxide (CO_2) emissions from energy provided", Frankfurt Airport's annual compensated carbon dioxide (CO2) emissions", Frankfurt Airport's annual Scope 3 direct carbon dioxide (CO_2) emissions from air traffic", Frankfurt Airport's annual carbon dioxide (CO_2) emissions from passenger traffic", Frankfurt Airport's annual carbon dioxide (CO_2) emissions from staff working at Frankfurt Airport", Frankfurt Airport's annual direct carbon dioxide (CO_2) emissions from energy consumption of third parties", and Frankfurt Airport's annual carbon dioxide (CO_2) emissions from business trips undertaken by Fraport AG staff".

The study's document analysis was conducted in six distinct phases. The first phase involved planning the types and required documentation and ascertaining their availability for the study. In the second phase, the data collection involved sourcing the documents from Fraport AG and developing and implementing a scheme for managing the gathered documents. In the third phase, the documents were examined to assess their authenticity, credibility and to identify any potential bias in them. In the fourth phase, the content of the collected documents was carefully examined, and the key themes and issues were identified and recorded. The fifth phase involved the deliberation and refinement to identify any difficulties associated with the documents, reviewing sources, as well as exploring the documents content. In the sixth and final phase, the analysis of the data was completed (O'Leary, 2004).

The documents were all in English. Each document was carefully read, and key themes were coded and recorded in the case study (Baxter, 2022; Baxter & Srisaeng, 2021).

IV. RESULTS

3.1 A Brief Overview of Frankfurt Airport

Frankfurt Airport (IATA Code: FRA) is one of the world's largest airports and is Germany's busiest airport (Miyoshi & Torrell, 2019; Zintel, 2007). The airport is in Hesse at a location that was chosen by the German government in 1936 (Niemeier, 2014). In addition to being a major passenger hub, Frankfurt is also a major European air cargo hub and is served by more than 20 cargo airlines. Frankfurt is the principal hub airport of German national carrier Lufthansa (Centre for Aviation, 2022; Janić, 2017; Zintel, 2007) and its subsidiary Lufthansa Cargo. The airport is served by more than 100 airlines who operate scheduled, charter and cargo services. Europe, the Middle East, Asia, Africa, South America, and North America are served directly by the airlines operating from Frankfurt (Centre for Aviation, 2022).

Frankfurt Airport has two operating passenger terminals. Terminal 1 is divided into concourses A, B, C and Z and has a capacity of around 50 million passengers per year. Terminal 2, which has a capacity of 15 million passengers a year, was opened in 1994. Terminal 2 comprises concourses D and E (Frankfurt International Airport, 2018). Frankfurt Airport has four runways: 07C/25C, 07L/25R, 07R/25L, and 18/36. The longest runway at Frankfurt Airport is Runway 07C/25C, which is 4,000 metres in length (Airport Guide, 2020). Frankfurt Airport has the terminal and runway infrastructure to handle the largest aircraft types in operation, that is, the Airbus A380 and the Boeing 747-8.

Frankfurt Airport is owned and operated by Fraport AG (Airport Technology, 2021a). Fraport AG also provides the facilities to airlines and other key actors, including DFS German Air Navigation Services, as well as many agencies and airport concessionaires (a total of more than 500 businesses and institutions) (Fraport AG, 2019b). Fraport AG is an international airport operator whose corporate office is based at Frankfurt Airport. Apart from the Frankfurt Airport site, Fraport has operations at 25 airports that are located on three continents. These airports are in Lima, Fortaleza, Porto Alegre, St. Petersburg, Ljubljana, Varna, Burgas Antalya, Delhi, Xi'an as well as a further 14 Greek airports (Fraport AG, 2019a).

Figure 1 presents the total annual enplaned (domestic and international) passengers handled at Frankfurt Airport from 2008 to 2019. One passenger enplanement measures the embarkation of a revenue passenger, whether originating, stop-over, connecting or returning (Holloway, 2016). Figure 1 shows that the growth in Frankfurt Airport's annual enplaned passengers exhibited an upward trend, increasing from 53.4 million passengers in 2008 to 70.5 million passengers in 2019. Figure 1 also shows that there was a decrease in the number of passengers in 2009, when they declined by 4.74% on the 2008 levels. The global airline industry was adversely impacted by the global financial crisis (GFC) in 2008 and 2009, which resulted in a downturn in passenger demand (Samunderu, 2020; Serebrisky, 2012). There was also a small decrease in enplaned passengers recorded in 2016 (-0.4%) (Figure 1).

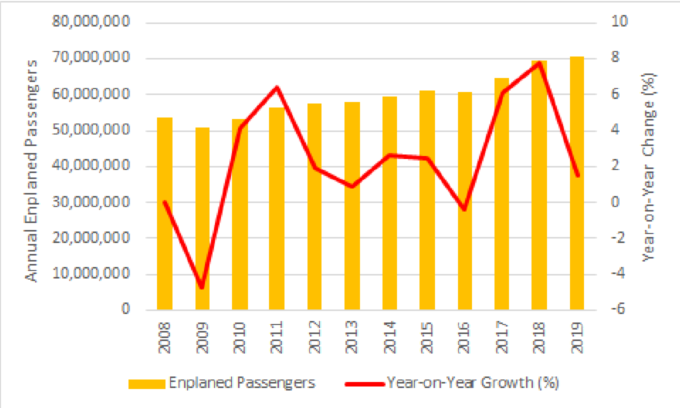

Fig.1: Frankfurt Airport's annual enplaned passengers and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020a)

Frankfurt Airport's total annual aircraft movements are depicted in Figure 2. The aircraft movements at Frankfurt Airport include domestic and international commercial passenger flights, domestic and international commercial air cargo flights, domestic and international general aviation flights as well as State Aviation Flights, which may be operated domestically or internationally (Fraport AG, 2020a). As can be observed in Figure 2, the annual number of aircraft movements at Frankfurt fluctuated during the period 2008 to 2019. The highest number of annual aircraft movements at Frankfurt Airport was recorded in 2019, when the airport handled 513,912 aircraft movements. The lowest annual number of aircraft movements occurred in 2016, when the airport handled a total of 462,885 aircraft movements. The factors affecting aircraft movements at a specific airport are airport slot constraints, market demographics, airport characteristics, airline characteristics and route characteristics. Moreover, hub airports, like Frankfurt Airport, are associated with larger aircraft sizes and higher flight frequencies (Pai, 2016).

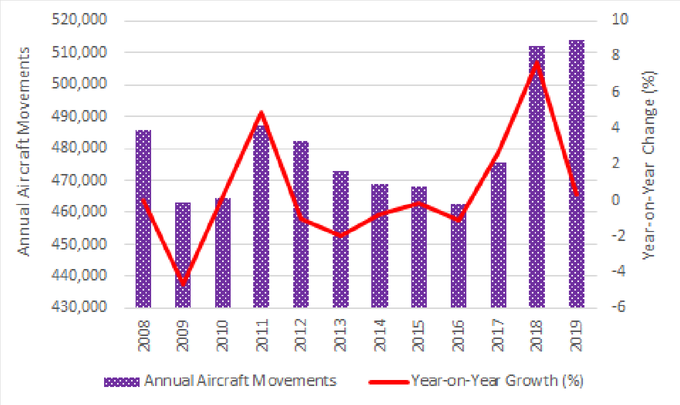

Fig.2: Frankfurt Airport's total annual aircraft movements and year-on-year change (%): 2008-2019: 2008-2019

Source: Data derived from Fraport AG (2012, 2016, 2020a)

3.2 Fraport AG Environmental Management Framework and Climate Policy

From 1999 onwards, Fraport AG, as the manager and operator of Frankfurt Airport, has been regularly validated by government accredited and inspected environmental management auditors. The basis for such audits is the European regulation "Eco-Management and Audit Scheme" (EMAS) (Fraport AG, 2019a). EMAS is a voluntary instrument of the European Union, which enables firms of any size and industry to examine and continuously enhance their environmental performance (International Airport Review, 2014). Since 2002, Frankfurt Airport's environmental audits have been carried out in compliance with the international standard ISO 14001 (Fraport AG, 2019a). ISO 14001 is a global meta-standard for implementing Environmental Management Systems (EMS) (Heras-Saizarbitoria et al., 2011). The ISO 14001 Environmental Management System (EMS) has become one of the most widely used systems for managing corporate environmental aspects (Oliveira et al., 2011). Fraport AG's environmental audits, which comply with EMAS and ISO 14001 standards, also include the following Fraport AG subsidiaries: Fraport Cargo Services GmbH (FCS) since 2008, N*ICE Aircraft Services & Support GmbH (N*ICE) since 2009, and Energy Air GmbH since 2014. Energy Air GmbH is also validated in accordance with the international standard ISO 50001. There were several new additions to the EMAS network in 2017 which included the subsidiary firms Fraport Ground Services GmbH (FraGround) and GCS Gesellschaft für Cleaning Service GmbH & Co (Airport Frankfurt/Main KG [GCS]) (Fraport AG, 2019a).

In the global air transport industry, several organizations and programs have been established to assist airports in reducing their carbon emissions. Such programs aid airports to establish systems to identify, monitor and reduce sources of air pollution (Vanker et al., 2013). The "Airport Carbon Accreditation Program" is an independent program which requires yearly accreditation criteria for airports (Attanasio, 2018; Ritter et al., 2011). The objective of this program is to assist airports to reduce their carbon footprint and ultimately move it to a zero value (Benito & Alonso, 2018). A further objective of the program is to enable airports to implement carbon and energy management best practices, whilst at the same time gaining public appreciation for their achievements (Postorino et al., 2017). Since 2009, Frankfurt Airport has been accredited at the high optimization level by the Airport Carbon Accreditation (ACA) program (Fraport AG, 2022). At the start of 2012, Frankfurt Airport environmental reporting was expanded so that the airport could upgrade to Level 3. This expanded reporting requirement included information on Scope 3 emission sources which need to be allocated in accordance with the Greenhouse Gas Protocol (GHG Protocol). To meet this reporting requirement, Frankfurt Airport reports on the operation of aircraft in their parking positions at the airport apron and ground run-ups, the aircraft landing and take-off cycle up to 3,000 feet (914.4 metres), the operation of buildings and ground handling vehicles and equipment of third-party service providers, the provision of aircraft with ground power supply, travel to and from the airport by passengers and employees, and business trips of employees. During 2012, the relevant dialogue with companies based at the airport was also intensified (Fraport AG, 2020b). In 2020, Fraport AG was once again awarded the "Optimization" level for Frankfurt Airport (Fraport, 2020c).

Fraport AG set a target of reducing carbon dioxide (CO2) emissions per passenger or per 100kgs of air freight by 2020 as compared to the company's baseline year of 2005. The company also had an objective to reduce its absolute carbon dioxide (CO_2) emissions. By 2014, the aim was to avoid exceeding the value from the 2005 baseline year (264,000 tonnes of CO_2) (Scope 1 and 2) up until 2020. This objective considered the increase in Frankfurt Airport capabilities and the increase in traffic volumes. The airport subsequently adjusted the target downward to 238,000 tonnes of carbon dioxide (CO_2) emissions because of the postponement in the construction of the new Terminal 3 passenger terminal (Fraport AG, 2015). In 2016, Frankfurt

Airport achieved its 2020 climate targets with this achievement being substantially ahead of schedule (Fraport AG, 2017).

Fraport AG has set an objective to significantly reduce carbon dioxide (CO_2) emissions within the Fraport Group as well as at Frankfurt Airport by 2030. The goal is to reduce emissions to 125,000 metric tons of carbon dioxide (CO_2) per annum in the Group as a whole and to 80,000 metric tons at Frankfurt Airport. Fraport's carbon dioxide (CO_2) reduction targets for its Group airports are based on those established by the countries in which they are located. Frankfurt Airport's 2030 target is from the German government's Climate Action Plan to 2050. Fraport AG envisages that by 2050, Fraport's carbon dioxide (CO_2) emissions at Frankfurt Airport will be reduced to zero (Fraport AG, 2022).

3.3 Frankfurt Airport annual Scope 1 carbon dioxide (CO_2) emissions

Carbon dioxide emissions (CO_2) means the release of greenhouse gases and/or their precursors into the atmosphere over a specified area and for a given period (Organization for Economic Cooperation and Development, 2013). Frankfurt Airport's total annual Scope 1 direct carbon dioxide (CO_2) emissions and the year-on-year change (%) for the period 2008 to 2019 are presented in Figure 3. A firm's direct emissions are those emissions from sources that are owned or controlled by the reporting entity (Indian GHG Program, 2013). The fuel sources used at Frankfurt Airport are heating oil, natural gas, and propane gas. As can be observed in Figure 3, Frankfurt Airport's total annual Scope 1 direct carbon dioxide (CO_2) have oscillated throughout the study period, increasing from a low of 33,924.0 tonnes in 2008 to a high of 37,200.0 tonnes in 2018. In 2019, these emissions decreased by 0.26% to 37,100.0 tonnes (Figure 3). Figure 3 shows that there was a pronounced spike in 2010, when such emissions increased by 13.48% on the previous year's levels. The largest single annual decrease in the airport's annual Scope 1 carbon dioxide (CO_2) emissions was recorded in 2014, when they decreased by 6.75% on the 2013 levels. There was also a slightly smaller annual decrease in these emissions in 2011, when they decreased by 5.19% on the 2010 levels (Figure 3). As discussed below, Frankfurt Airport has introduced a wide range of carbon dioxide (CO_2) reduction measures that have played a key role in reducing the airport's annual carbon dioxide (CO_2) emissions over the study period.

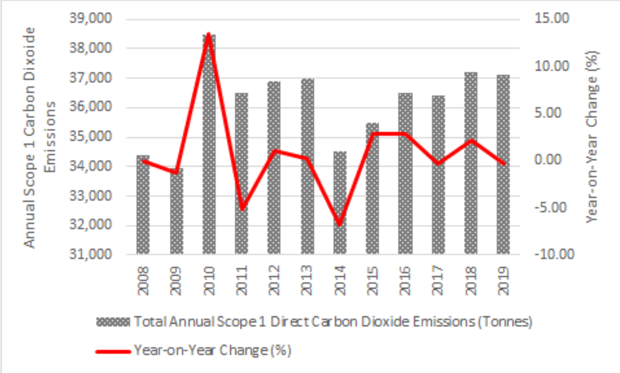

Fig.3: Frankfurt Airport's annual direct Scope 1 carbon dioxide (CO2) emissions and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a)

Fig.4: Frankfurt Airport's total annual direct carbon dioxide (CO_2) emissions per traffic unit and year-on-year change: 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

Frankfurt Airport's total annual direct (CO_2) emissions per traffic unit and the year-on-year change (%) for the period 2008 to 2019 are presented in Figure 4. A workload (WLU) or traffic unit is equivalent to one passenger or 100kgs of air freight (Doganis, 2005; Graham, 2005; Teodorović & Janić, 2017). Figure 4 shows that the airport's annual direct carbon dioxide (CO_2) emissions per traffic unit have largely exhibited a downward trend over the period 2010 to 2019, declining from a high of 0.51 kg CO_2 per traffic unit in 2010 to a low of 0.41 kg CO_2 per traffic unit in 2018 and 2019, respectively (Figure 4). The largest single annual increase in this metric was recorded in 2010 when the CO_2 per traffic unit increased by 6.52% on the 2009 levels (Figure 4). The largest single annual decrease was recorded in 2011, when there was a 7.84%

decrease in the CO_2 per traffic unit (Figure 4). Figure 4 shows that in 2011, 2012, and 2013, the CO_2 per traffic unit remained constant at 0.47 CO_2 per traffic unit, respectively. This is a very favorable trend and shows that despite the increase in the number of passengers using the airport there has not been a concomitant increase in carbon dioxide (CO_2) emissions per traffic unit.

3.4 Frankfurt Airport annual Scope 2 carbon dioxide (CO_2) emissions

Frankfurt Airport's total annual Scope 2 indirect carbon dioxide (CO_2) emissions and the year-on-year change (%) for the period 2008 to 2019 are presented in Figure 5. Indirect emissions comprise those emissions that are produced because of the activities of the reporting entity but are produced from sources owned or controlled by another entity (United States Environmental Protection Agency, 2016). The indirect emissions at Frankfurt Airport are consist of the standard supply of electricity, district heating, and district cooling (Fraport AG, 2010). As can be observed in Figure 5, Frankfurt Airport's annual indirect carbon dioxide (CO_2) emissions have principally displayed a downward trend throughout the study period. This is demonstrated by the year-on-year percentage change line graph, which is more negative than positive, that is, more values are below the line than above. Figure 5 shows that there were three years when the airport's annual indirect carbon dioxide (CO_2) emissions increased on a year-on-year basis. These increases were recorded in 2009 (+12.49%), 2012 (+7.24%), and 2013 (1.57%), respectively. The largest single decrease in this metric occurred in 2009, when the airport's annual indirect emissions decreased by 12.49% on the 2008 levels (Figure 5). The general downward trend is quite favorable given the increase in passengers and aircraft movements recorded at Frankfurt Airport over the study period.

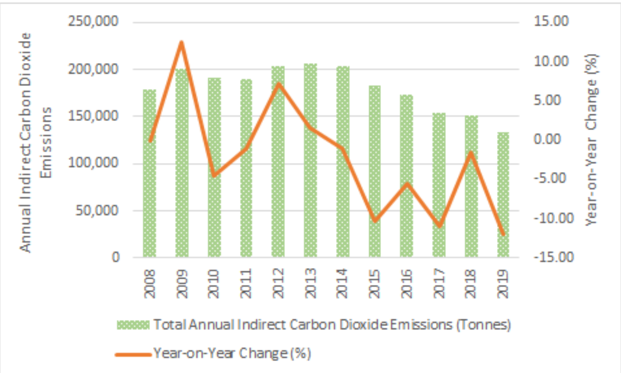

Fig.5: Frankfurt Airport's annual indirect Scope 2 carbon dioxide (CO2) emissions and year-on-year change (%): 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a)

Frankfurt Airport's annual indirect carbon dioxide (CO_2) emissions per traffic unit and the year-on-year change from 2008 to 2019 are depicted in Figure 6. Like Frankfurt Airports direct carbon dioxide (CO_2) emissions per traffic unit, the airport's annual indirect carbon dioxide (CO_2) emissions per traffic unit have also generally shown a downward trend (Figure 6). Once again this is demonstrated by the year-on-year percentage change line graph, which is more negative than positive, that is, more values are below the line than above. As can be observed in Figure 5, there were three years in the study period where this metric increased on a year-on-year basis. These increases occurred in 2009 (+20.00%), 2012 (+7.88%), and 2013 (+0.38%), respectively. Figure 6 also shows that there was no change in the level of this metric in 2019 as it remained the same as in 2018 (1.66 kg CO2 per traffic unit). The largest single annual decrease in this metric occurred in 2017, when the airport's indirect carbon dioxide (CO_2) emissions per traffic unit decreased by 24.17% on the 2016 levels (Figure 6).

Fig.6: Frankfurt Airport's total annual indirect carbon dioxide (CO_2) emissions intensity per traffic unit and year-on-year change: 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

3.5 Frankfurt Airport annual Scope 3 carbon dioxide (CO_2) emissions

Frankfurt Airport's total annual Scope 3 carbon dioxide (CO_2) emissions from air traffic and the year-on-year change from 2008-2019 are depicted in Figure 7. The measurement of air traffic at Frankfurt Airport is based on aircraft in the landing and take-off cycle up to 914 metres (includes all aircraft landing and taking off) as well as the use of aircraft auxiliary power units (APU's) (Fraport AG, 2010). As can be observed in Figure 7, the annual Scope 3 carbon dioxide (CO_2) from air traffic have predominantly exhibited an upward trend, which is line with the growth in aircraft movements at the airport over the study period. This upward trend is demonstrated by the year-on-year percentage change line graph, which is more positive than negative, that is, more values are above the line than below. Figure 7 shows that there were two significant spikes in this metric, which occurred in 2011 (+4.86%), and in 2018 (+7.66%), respectively. These increases were in line with the growth in the annual aircraft movements, which increased by 4.89% in 2011 and by 7.69% in 2018, respectively. During the study period, there were four years when the annual Scope 3 carbon dioxide (CO_2) emissions from air traffic decreased on a year-on-year basis. These decreases occurred in 2012 (-0.30%), 2014 (-2.58%), 2016 (-1.68%), and in 2019 (-0.21%), respectively (Figure 7). There was a decrease in the annual number of aircraft movements at the airport in 2012, 2014, and in 2016, which may be a contributory factor in the decreases in this metric recorded in those years. Airline fleet deployment could have been a key factor in the 2019 decrease.

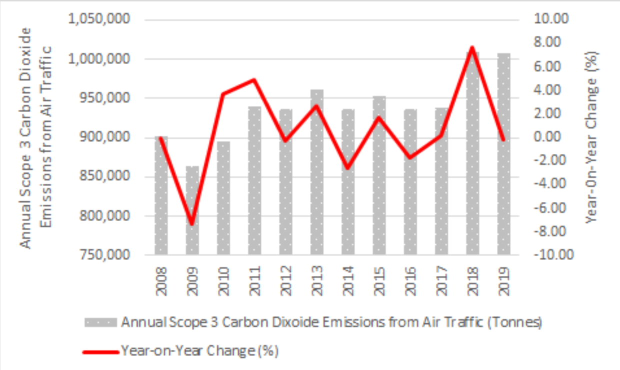

Fig.7: Frankfurt Airport's annual Scope 3 carbon dioxide (CO_2) emissions from air traffic and year-on-year change: 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

Frankfurt Airport's total annual Scope 3 carbon dioxide (CO_2) from passenger traffic originating at the airport and the year-on-year change for the period 2008-2019 is presented in Figure 8. Prior to examining this trend, it is informative to note that an important environmental efficiency metric used by airports is the carbon dioxide (CO_2) emissions per passenger (Graham, 2005). Frankfurt Airport measures the passengers travel in private cars and public transport to and from the airport (Fraport AG, 2010). As can be observed in Figure 8, the total annual Scope 3 carbon dioxide (CO_2) emissions from passenger traffic has oscillated over the study period. Figure 8 shows that there were four years during the study period where the annual Scope 3 carbon dioxide (CO_2) emissions from passenger traffic decreased on a year-on-year basis. These decreases were recorded in 2009 (-7.88%), 2014 (-7.88%), 2015 (-12.97%), and in 2016 (-13.95%), respectively (Figure 8). As previously noted, there was a decrease in the annual number of enplaned passengers at the airport in 2009. Over the period 2014 to 2016, there was an annual increase in the number of passengers using the airport. Thus, it was a favorable trend for the airport to handle more passengers whilst at the same time reducing the amount of carbon dioxide (CO_2) emissions from passengers. Figure 8 also shows that there were two quite pronounced spikes in this metric during the study period. The first spike occurred in 2010 (+12.77%), and the second spike was in 2019 (+37.70%) (Figure 8). There were quite marked increases in the passengers using the airport in 2010 and 2019, and thus, this may have resulted in the higher carbon dioxide emissions (CO_2) in those years.

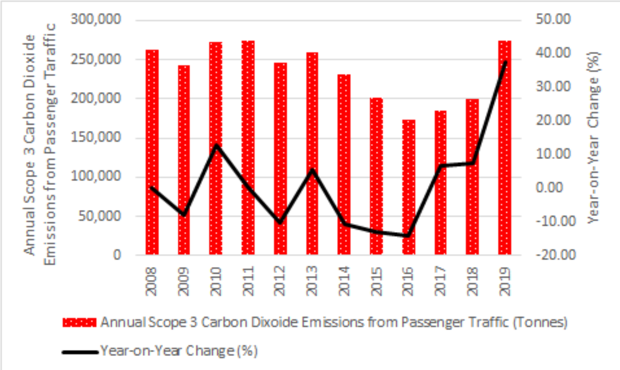

Fig.7: Frankfurt Airport's annual Scope 3 carbon dioxide (CO_2) emissions from passenger traffic and year-on-year change: 2008-2019 Note: Passengers originating at Frankfurt Airport

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

Figure 8 presents Frankfurt Airport's total annual Scope 3 carbon dioxide (CO_2) emissions from third parties' energy consumption for vehicles and infrastructure and the year-on-year change during the period 2008-2019. Prior to examining this trend, it is important to note that airports are extremely energy-intensive areas (Akyuz et al., 2019; Baxter et al., 2018; Cardona et al., 2006). The large energy requirements are due to the large buildings, particularly passenger terminals), that are equipped with heating and air-conditioning that are energy intensive. Also, at airports there is a high-power demand for lighting and electric equipment and the energy requirements as well as the many facilities located within the airport precinct (Cardona et al., 2006). Thus, electrical energy needs to be provided for airport buildings, aircraft hangers, and other airport facilities and infrastructure (Kazda et al., 2015). Like airports, airlines are extremely energy intensive as well. Airlines use a lot of electricity to power their airport and non-airport located buildings, facilities, and equipment. Airlines, as well as ground handling agents and maintenance organizations use electrical power to operate machinery, heating, ventilating, and air conditioning (HVAC) systems, building lighting, computer systems, and so forth (Baxter et al., 2021). Frankfurt typically has a cold winter and the occasional hot spells in summer (Mercer, 2009), and thus, the actors operating at the airport will require heating and cooling for their facilities. The level of heating and cooling will be driven by the temperatures experienced at the airport, and hence, the annual carbon dioxide emissions (CO_2) will be in line with the level of energy consumption. Figure 8 shows that there were two quite discernible trends in Frankfurt Airport's total annual Scope 3 carbon dioxide (CO_2) emissions from third parties' energy consumption for vehicles and infrastructure. From 2008 to 2016, there was a general upward trajectory, with the total annual carbon dioxide (CO_2) emissions increasing from 160,200 tonnes in 2008 to a high of 202,300 tonnes in 2016 (Figure 8). From 2017 to 2019, there was a downward trend with the total annual carbon dioxide (CO2) emissions decreasing from 189,700 tonnes in 2017 to 164,700 tonnes in 2019. Figure 8 also shows that there were two pronounced increases in this metric, which occurred in 2011 (+14.26%) and 2016 (+12.70%), respectively. the largest single annual decrease was recorded in 2019, when the annual Scope 3 carbon dioxide (CO_2) emissions from third parties' energy consumption for vehicles and infrastructure decreased by 10.24% on the 2018 levels. The downward trend in the latter years of the study, that is, 2017 to 2019, is extremely favorable given the increase in the number of passengers handled as well as the growth in aircraft movements in these years.

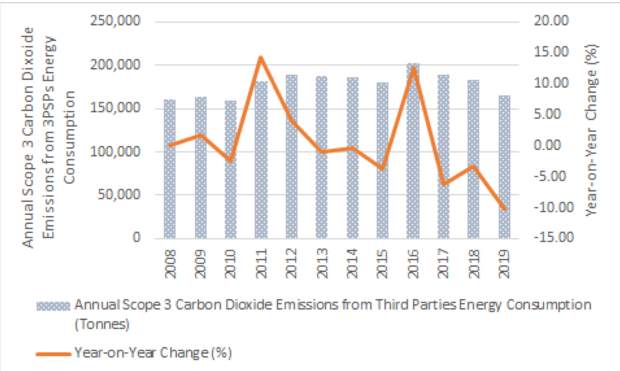

Fig.8: Frankfurt Airport's annual Scope 3 carbon dioxide (CO_2) emissions from third parties' energy consumption and year-on-year change: 2008-2019

Legend: 3PSPs=Third party service provider

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

Frankfurt Airport's total annual Scope 3 carbon dioxide (CO_2) emissions from Frankfurt Airport-based employees and year-on-year change from 2008-2019 is shown in Figure 9. This metric measures the travel for airport employees to and from their workplace at Frankfurt Airport (Fraport, 2010). Figure 9 shows that there were two key trends in this environmental metric. Firstly, there were increases in the total amount of carbon dioxide (CO_2) emissions from 2008 to 2010, when they increased from 116,200 tonnes in 2008 to 122,300 tonnes in 2010, which was the highest annual level of carbon dioxide (CO_2) emissions during the study period. The second trend shows that there was a general downward trend from 2011 to 2018, before a quite steep increase in 2019 (+19.88%). The increase in 2019 was the largest single annual increase in emissions throughout the study period. The lowest amount of carbon dioxide (CO_2) emissions was recorded in 2018 (106,600 tonnes) (Figure 9).

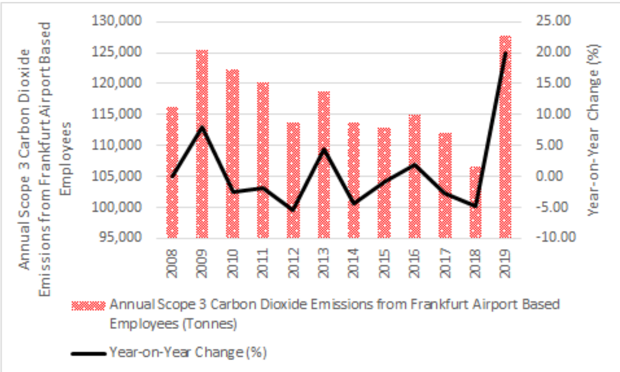

Fig.9: Frankfurt Airport's annual Scope 3 carbon dioxide (CO_2) emissions from Frankfurt Airport Based Staff and year-on-year change: 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

Figure 10 presents Frankfurt Airport's total annual Scope 3 carbon dioxide (CO_2) emissions from Fraport AG employee travel and the year-on-year change from 2008-2019. As can be observed in Figure 10, the annual Scope 3 carbon dioxide (CO_2) emissions from Fraport AG employee travel declined from a high of one tonne in 2008 to 0.75 tonnes in 2019. The lowest level of carbon dioxide (CO_2) emissions from Fraport AG travel was recorded in 2015, when staff travel equated to 0.70 tonnes of carbon dioxide (CO_2) (Figure 10). Figure 10 shows that the largest single annual increase in this metric occurred in 2016 (+15.71%), whilst the lowest single annual decrease was recorded in 2012 (-22.68%). The annual fluctuations reflect Fraport AG employee travel patterns.

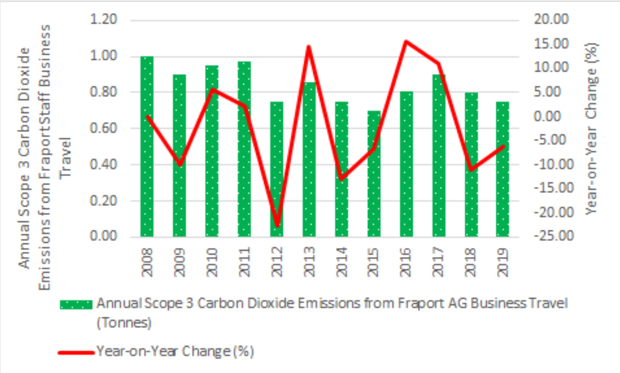

Fig.10: Frankfurt Airport's total annual Scope 3 carbon dioxide (CO2) emissions from Fraport AG employee business travel and year-on-year change: 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

3.6 Frankfurt Airport total annual carbon dioxide (CO_2) emissions

Frankfurt Airport's total annual carbon dioxide (CO_2) emissions and the year-on-year change (%) from 2008 to 2019 are presented in Figure 11. As can be observed in Figure 11, the airport's total annual carbon dioxide (CO_2) emissions increased from 1,653,658 tonnes in 2008 to 1,744,201 tonnes in 2019. Figure 11 shows that there were five years in the study period when the airport's total annual carbon dioxide (CO_2) emissions increased on a year-on-year basis. These increases were recorded in 2010 (+3.15%), 2011 (+3.66 %), 2013 (+2.60 %), 2018 (+4.50%), and 2019 (+3.37 %), respectively (Figure 11). In 2010, the annual carbon dioxide (CO_2) emissions from air traffic increased by 3.74 %, the annual carbon dioxide (CO_2) emissions from passenger traffic increased by 12.77 %, and the annual carbon dioxide (CO_2) emissions from Fraport AG employee business travel increased by 5.55%. In 2011, the annual carbon dioxide (CO_2) emissions from air traffic increased by 4.86%, and the annual carbon dioxide (CO_2) emissions from third party energy consumption increased by 14.26%. During 2013, the airport's annual Scope 1 direct carbon dioxide (CO2) emissions increased by 0.27%, the airport's annual Scope 2 indirect carbon dioxide (CO_2) emissions increased by 1.57%, the annual carbon dioxide (CO_2) emissions from air traffic increased by 2.65%, the annual carbon dioxide (CO_2) emissions from passenger traffic increased by 5.41%, the annual Scope 3 Carbon dioxide (CO_2) emissions from Frankfurt Airport based employees increased by 4.48%, and the annual carbon dioxide (CO_2) emissions from Fraport AG employee business travel increased by 14.66%. In 2018, there was a significant growth in air traffic (+7.66%) and in the annual direct carbon dioxide (CO_2) emissions from passenger traffic (+7.51%). During 2019, the airport experienced strong growth in the annual direct carbon dioxide (CO_2) emissions from Frankfurt Airport based employees (+19.88%) and in the annual direct carbon dioxide (CO_2) emissions from passenger traffic using the airport (+37.70%).

Figure 11 shows that the airport's total annual carbon dioxide (CO_2) emissions decreased by 1.54 % in 2009 and by 0.94 % in 2012. Figure 11 also shows that from 2014 to 2017, the airport's total annual carbon dioxide (CO_2) levels decreased on a year-on-year basis. The highest single annual decrease in these emissions was recorded in 2014, when these emissions decreased by 3.57 % on the 2013 levels (Figure 11). In 2009, Frankfurt Airport's total annual Scope 1 carbon dioxide (CO_2) emissions decreased by (-1.34%), the airport's air traffic decreased by 7.29%, the annual direct carbon dioxide (CO_2) emissions from passenger traffic decreased by 7.88%, and the annual direct carbon dioxide (CO_2) emissions from Fraport AG business travel declined by 2.54%, respectively. The decrease in Frankfurt Airport's total annual carbon dioxide (CO_2) emissions in 2012 could be attributed to a decrease in the volume of air traffic at the airport (-0.30%), a decrease in the annual direct carbon dioxide (CO_2) emissions from Fraport AG business travel -22.68%), a decrease in the carbon dioxide emissions associated with employee travel to the airport (-5.32%), as well as a decrease in the annual direct carbon dioxide (CO_2) emissions from passenger traffic (-10.39%). Frankfurt Airports and its participating actors were once again able to reduce the total annual carbon dioxide (CO_2) emissions recorded at the airport in 2014. These decreases came from a decrease in the airport's annual Scope 1 carbon dioxide (CO_2) emissions (-6.75%), the airport's annual Scope 2 carbon dioxide (CO_2) emissions (-1.11%), a decrease in air traffic (-2.58%), a decrease in the emissions from employee travel (-4.29%), a decrease in the annual emissions from passenger traffic at the airport (-10.69%), a decrease in the emissions from Fraport AG business travel (-12.79%), and a decrease in the annual direct carbon dioxide (CO_2) emissions from third parties' energy consumption (-0.37%). During 2017, the reduction in Frankfurt Airport's total annual carbon dioxide (CO_2) could be attributed to a decrease in the airport's annual Scope 1 carbon dioxide (CO_2) emissions (-0.27%), the airport's annual Scope 2 carbon dioxide (CO_2) emissions (-11.05%), a decrease in airport employee travel related emissions (-2.60%), and a decrease in the annual direct carbon dioxide (CO_2) emissions from third parties' energy consumption (--6.22%). It is important to note that during the latter years of the study, airlines using Frankfurt

Airport have introduced services that are operated by Airbus A350-900XWB and the Boeing 787-9 aircraft. These aircraft types reduce emissions by between 15 and 20% as compared to the older generation Airbus A340-300 and Boeing B767, when operating on the same route (Szymczak, 2021). Lufthansa operates a fleet of the Boeing 747-8 Intercontinental passenger aircraft. The Boeing 747-8 Intercontinental passenger aircraft is more fuel efficient than the Boeing 747-400 passenger aircraft (Benito & Alonso, 2018), and thus, has lower emissions levels.

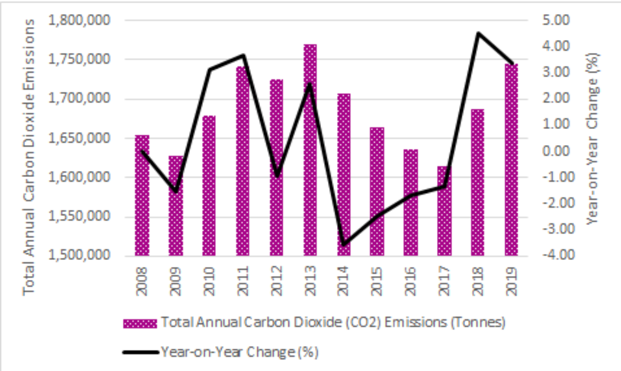

Fig.11: Frankfurt Airport's total annual carbon dioxide (CO_2) emissions and year-on-year change: 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

Figure 12 presents Frankfurt Airport's annual climate gas intensity of traffic performance ratio and the year-on-year change for the period 2008-2019. As can be observed in Figure 12, this annual ratio declined from 2.9 kgs CO_2 per traffic unit in 2008 to 1.5 kgs CO_2 per traffic unit in 2019. The overall downward trend is demonstrated by the year-on-year percentage change line graph, which is more negative than positive, that is, more values are below the line than above. Figure 12 shows that there were two years in the study period where there was a year-on-year increase in this ratio. These increases were recorded in 2009 (+17.2%), and in 2012 (+6.9%), respectively. The overall downward trend is very favorable from an environmental perspective and suggests that the various carbon reduction measures (discussed below) have had a favorable impact on Frankfurt Airport's total annual carbon dioxide (CO_2) emissions.

Fig.12: Frankfurt Airport's climate gas intensity of traffic performance ratio: 2008-2019

Source: Data derived from Fraport AG (2013, 2016, 2019a, 2020a).

In terms of magnitude, the Scope 3 carbon dioxide (CO_2) emissions represented the largest source of emissions at the airport, these were followed by the Scope 2 emissions, with the Scope 1 emissions representing the smallest portion of the airport's overall carbon dioxide (CO2) emissions throughout the study period.

3.7 Frankfurt Airport abated carbon dioxide (CO_2) emissions

Prior to examining Frankfurt Airport's carbon dioxide (CO_2) abatement scheme, it is important to note that many airports around the world have implemented carbon offset schemes as part of their aim to become carbon neutral (Baxter, 2021; Boussauw & Vanoutrive, 2019; Falk & Hagsten, 2020). A carbon offset represents one metric tonne of carbon dioxide equivalent ($MTCO_2e$) (Airports Council International, 2020). Carbon offset schemes have important environmental benefits as they enable businesses to invest in environmental projects around the world to balance out their own carbon footprints. A carbon offset program may involve the implementation of clean energy technologies or alternatively the purchase of carbon credits from an emissions trading scheme. Other carbon offset schemes include the capture of carbon dioxide (CO_2) directly from the air from the planting of trees (Clark, 2011).

During the period 2008 to 2012, Frankfurt Airport compensated their annual carbon dioxide (CO_2) emissions through the acquisition of certificates. The amounts of carbon dioxide (CO_2) emissions compensated were as follows: 2008 133,200 tonnes, 2009 133,320 tonnes, 2010 144,100 tonnes, 2011 149,500 tonnes, and 2012 154,400 tonnes, respectively.

3.8 Fraport AG measures to mitigate carbon dioxide (CO_2) emissions at Frankfurt Airport

In 2008, Fraport AG combined all climate-related activities into a project which was principally focused on three areas: energy savings arising from the operation of the airport's buildings and infrastructure; the efficient use of energy in new buildings; and limiting the fuel consumption of the airport's fleet of vehicles. Since 2007, Frankfurt Airport implemented a rolling refurbishment program for the air conditioning control in Terminal 1. This project delivered considerable carbon dioxide (CO_2) emissions savings. The first phase of the project produced annual savings of 8,300 tonnes of carbon dioxide (CO_2) emissions, whilst the second phase delivered saving of 5,300 tonnes of carbon dioxide (CO_2) emissions. At the same time, energy-saving measures were optimized in the Fraport AG parent company buildings. These energy saving measures included the replacement of pumps and fans with more efficient components, the hydraulic balancing of heating systems, and the upgrade of windows and doors (Fraport AG, 2015, 2017). In 2009, these measures delivered an annual reduction in carbon dioxide (CO_2) emissions of around 4,000 tonnes. Other operational measures included a reduction in lighting in the terminal buildings when they were not being used through the adjustment of switching times, the turning off air conditioning systems in the terminal buildings at night, dimming lighting in parking garages at Terminal 1 and the employee car parking garage from midnight through to 4AM, and equipping lighting located within the vicinity of exterior walls of the parking garages with sensors that would detect exterior light. These additional measures enabled annual savings of around 300 tonnes of carbon dioxide (CO_2) emissions. Commencing in 2004, the airport upgraded its baggage conveyor system, and this upgrade project included the replacement of old motors, the installation of new, more efficient conveyor belts with reduced frictional resistance, and the implementation of a systematic shutdown in the sections of the system not being used. Importantly, it was estimated that these measures would deliver aggregated annual savings of 2,000 tonnes of carbon dioxide (CO_2) emissions by 2020 (Fraport AG, 2015). As a key part of its environmental policy, Fraport AG remains committed to a variety of measures in relation to its baggage handling system and these measures include the exchange of old motors for more efficient models, downsizing of power units, systematic shutdowns of conveyors if utilization capacity permits, and the installation of lower-friction components in the system (Fraport, 2020b).

In recent times, airports have increasingly installed light-emitting diodes (LED) systems (Freyssinier, 2014) as LED lighting is more environmentally friendly (Atlas, 2013; Lee et al., 2020; Roland, 2018). Frankfurt Airport is one such airport that transitioned to the use of LED lighting systems. From 2010 onwards, the airport's signage on the apron and around the take-off and landing runways has been illuminated with a LED lighting system (Fraport AG, 2015). The apron is the area where individual aircraft stands interface with the airport's passenger terminal building and is the area where aircraft are ground handled in between their flights (Budd & Ison, 2017). In addition, the green taxiway lighting, the blue taxiway margin lighting, and the red stop lighting were gradually replaced with LED lighting. Commencing in the 2013 summer, the airport trialed the use of LEDs for apron lighting. In addition, Fraport AG conducted field trials with LED lamps in selected areas located in both passenger terminals, for example, in the B and C arrival halls. The test in Terminal 2 proved successful, and consequently, the airport began the process of installing LEDs from 2013 onwards. Fraport Cargo Services GmbH (FCS) also trialed the use of LED technology in its truck station area. The objective of this trial was to save energy and to reduce carbon dioxide (CO_2) emissions. During 2014, Fraport Cargo Services GmbH (FCS) installed LED lamps in its FCS airfreight handling hall (Fraport AG, 2015). Importantly, LED Lighting enables a firm to reduce their carbon dioxide (CO_2) emissions (Carbon Reduction Institute, 2022).

As noted earlier, air pollution at an airport is also produced from the ground service equipment (GSE) used during aircraft turnaround and ground handling operations (Testa et al., 2014). Accordingly, aircraft-based ground operations carbon dioxide (CO_2) emissions can also be significant at airports (International Airport Review, 2010). Frankfurt Airport has been cognizant of the impact that ground service equipment (GSE) and vehicle emissions can have on the environment. Consequently, the acquisition and deployment of low-emission vehicles is a key focus of the company's climate change protection measures. Low-emission vehicles are quite suitable for the short distances covered by airport vehicles and GSE, and thus, they contribute to limiting the impact on air pollution. In 2014, around ten percent of Fraport AG's vehicles operating at the airport were powered by electric motors. These vehicles and equipment comprised a lot of energy-intensive special-purpose vehicles, for example, pallet loaders, and conveyor-belt trucks (Fraport AG, 2015). In 2017, around 14 per cent of Fraport AG's vehicles were powered by electric motors. As at the end of March 2017, 46 electric vehicles had been successfully tested in the airport operational environment and this testing funded from the "Fraport E-Fleet" project. Thirteen of the vehicles were specifically adapted for use in aircraft ground handling (Fraport AG, 2017). Fraport AG has also established a carpool for use by its employees. From 2012, 2000 employees located across five sites had access to this carpool. In 2014, there was a total of 70 cars in the carpool of which seven were purely battery-driven electric vehicles and a further eight were plug-in hybrid vehicles (Fraport AG, 2015). In 2017, the carpool fleet had grown to 100 vehicles of which ten were electric or hybrid drives (Fraport AG, 2017). At the end of 2019, there were around 500 electric vehicles in use at the airport. Furthermore, in 2020, as part of a funding project from the State of Hesse, Fraport began testing two electric powered buses for passenger transport (Fraport, 2020b). Because these buses electric motors are exhaust free, they are consequently more environmentally friendly than traditional diesel-powered buses (Faulks, 1999).

At Frankfurt Airport all new buildings are planned for optimum energy usage. Accordingly, all new buildings are designed to ensure the efficient use of energy when they become operational. As part of this process, dynamic building simulations are performed for selected building projects with the goal of reviewing energy use in the building plans and optimizing efficiency measures at the planning stage (Fraport AG, 2022).

Fraport AG commenced the construction of Terminal 3 in October 2015. The building work was anticipated to take around seven years, with opening of the facility expected to take place in 2022. Once completed Terminal 3 will have optimal energy efficiency with the lowest carbon dioxide (CO_2) emissions possible by following highly efficient energy standards. The new building has been designed to avoid the use of fossil energy sources and the supply of external heating energy (Airport Technology, 2021b). The energy efficiency measures include satisfying cooling requirements through free cooling and highly efficient refrigerating machinery, the use of internal loads and dissipated heat from the airport's baggage handling system to provide heat, the use LED lighting, the intelligent use of daylight as well as the use of short pipe and wiring distances with local configuration of air-conditioning centres (Fraport AG, 2020b).

Fraport AG and the Lufthansa Group are collaborating with support from the State of Hesse on an initiative titled "E-PORT AN – Electromobility at Frankfurt Airport" whereby the two actors are bundling their individual activities at Frankfurt Airport. The goal is this initiative is to convert aircraft handling to alternative drives over the long term. The use fuel-cell drive technologies for individual types of vehicles is being explored this is increasingly becoming the focus for Fraport AG (Fraport AG, 2020b). The E-PORT AN partnership began in 2012 with the aim of converting ground movements from fuel-burning to electric propulsion wherever feasible and sensible. Vehicles that under review in the program include those that carry passengers, personnel, baggage, cargo, catering, fuel, jet bridges and mobile stairways. This initiative was expected to save around 1,500 tonnes of carbon dioxide (CO_2) emissions per year by 2020 (Air Transport Action Group, 2022a).

In June 2020, Fraport AG concluded a power-purchase agreement for supply of green electricity (Fraport, 2020b). Fraport AG plans to use wind power to source most of the electricity at Frankfurt Airport. This strategic decision was part of its efforts to meet its climate protection targets (Airport Technology, 2020; Bates, 2020). A very important environmental benefit for the airport is that the new agreement significantly reduces its carbon dioxide (CO_2) emissions by around 90,000 tonnes per annum (Fraport AG, 2020b)

Fraport AG is committed to producing its own electricity at Frankfurt Airport. In 2020, the first large-scale photovoltaic (PV) plant at Frankfurt Airport was constructed on the roof of a new cargo terminal located in the airport's "CargoCity South" precinct. Once completed, the new PV system will generate more than 1.5 million kilowatt hours (kWh) of electricity each year. Fraport AG has also planned to construct a photovoltaic plant on the parking garage for the airport's new Terminal 3 building. This new PV system would be able to supply the charging stations located in this parking garage with renewable electricity (Fraport AG, 2020b). from an environmental perspective, it is important to note that renewable energy is more environmentally friendly as it does not produce any greenhouse gas emissions from the use of fossil fuels. Furthermore, renewable energy reduces some forms of air pollution (United States Environmental Protection Agency, 2022a). In addition, renewable energy contains no carbon emissions; therefore, they are more environmentally friendly (Nunez, 2019).

V. CONCLUSION

In conclusion, this study has examined the aircraft and airport-related carbon dioxide (CO_2) emissions at Frankfurt Airport, one of Europe's major hub airports and Germany's largest airport, and their impacts on air quality at the airport. To achieve the study's research objectives, Frankfurt Airport was selected as the case airport. The study's research was underpinned by an-in depth qualitative longitudinal research approach. The data collected for the study was analyzed by document analysis. The period of the study was from 2008 to 2019.

The case study found that Frankfurt Airport's total annual carbon dioxide (CO_2) emissions increased from 1,653,658 tonnes in 2008 to 1,744,201 tonnes in 2019. In terms of magnitude, the airport's Scope 3 carbon dioxide (CO_2) emissions are the largest source of emissions at Frankfurt Airport, followed by the airport's Scope 2 carbon dioxide (CO_2) emissions, with the Scope 1 carbon dioxide (CO_2) emissions being the lowest source of carbon dioxide (CO_2) emissions at the airport.

Airport operators are increasingly recording and publishing their Scope 1, 2, or 3 emissions. From 2008 to 2019, Frankfurt Airport's annual Scope 1 direct carbon dioxide (CO_2) emissions fluctuated throughout this period reflecting differing energy requirements at the airport. The highest level of Scope 1 carbon dioxide (CO_2) emissions was recorded in 2010 (38,500.0 tonnes), whilst the lowest level was recorded in 2009 (33,924.0 tonnes), respectively. Frankfurt Airport's annual Scope 2 indirect carbon dioxide (CO_2) emissions largely exhibited a downward trend decreasing from 178,070.00 tonnes in 2008 to 133,200.00 tonnes in 2019. The case study revealed that in the latter years of the study, that is, from 2014 to 2019, Frankfurt Airport has been able to decrease these emissions on a year-on-year basis, which is a very favorable outcome given the increase in passengers and aircraft movements at the airport.

The emissions from air traffic operations are the largest source of Scope 3 annual carbon dioxide (CO_2) emissions. The airport's Scope 3 carbon dioxide (CO_2) emissions from passenger traffic are the second highest source of carbon dioxide (CO_2) emissions. The third most significant source of Scope 3 carbon dioxide (CO_2) was from the annual carbon dioxide (CO_2) emissions from third parties' energy consumption.

Throughout the study period, there was very significant annual growth in the airport's enplaned passengers and aircraft movements. Yet, despite this strong traffic growth, the airport's annual direct carbon dioxide emissions per traffic unit largely exhibited an overall downward trend, declining from a high of 0.51kg CO_2 per traffic unit in 2010 to a low of 0.41kg CO2 per traffic unit in 2019. The airport's annual indirect carbon dioxide emissions per traffic unit largely followed a similar trend decreasing from a high of 2.88 kg CO_2 per traffic unit in 2009 to a low of 1.46 kg CO_2 per traffic unit in 2019. This is a very favorable result and suggests that the airport has been able to handle the significant growth in passenger traffic without the same concomitant rate of growth in carbon dioxide (CO_2) emissions. Frankfurt Airport's annual climate gas intensity of traffic performance ratio also largely displayed a general downward trend over the study period, decreasing from a high of 3.4 kg CO_2 per traffic unit in 2009 to a low of 1.5 kg CO_2 per traffic unit in 2019.

The study also found that carbon dioxide (CO_2) emissions can be reduced at an airport through the application of technologies and the optimization of energy efficiency. This is especially important as airport's consume large amounts of energy. Throughout the study period, Frankfurt Airport has implemented a wide range of carbon dioxide (CO_2) emissions reduction measures in both its airside and landside precincts. These carbon dioxide (CO_2) emissions reduction measures include replacement of pumps and fans with more efficient models, the hydraulic balancing of heating systems, upgrading windows and doors, optimizing lighting, air conditioning and heating systems, optimizing the energy usage of the airport's baggage handling system, the use of highly efficient LED lighting, the use of low emission vehicles, the electrification of ground service equipment (GSE), the optimization of energy usage in all new buildings at the airport, and the widespread use of renewable energy sources (wind and solar power). These carbon dioxide (CO_2) emissions reduction measures have demonstrated that it is possible for an airport to reduce their annual carbon dioxide (CO_2) emissions through the application of emergent technologies and energy usage optimization.

Fraport AG has set an objective to significantly reduce carbon dioxide (CO_2) emissions within the Fraport Group as well as at Frankfurt Airport by 2030. Fraport AG envisages that by 2050, Fraport's annual carbon dioxide (CO_2) emissions at Frankfurt Airport will be reduced to zero.

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