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Sustainable Aviation Fuels and their impact in commercial airport operation

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ABSTRACT

With global air traffic projected to grow annually by approximately 3.8%, the aviation sector faces increasing pressure to implement effective strategies for mitigating its environmental impact, particularly with respect to greenhouse gas emissions. Sustainable Aviation Fuels represent a critical pathway for decarbonizing aviation by offering a lower-emission alternative to conventional jet fuels. This study evaluates the environmental impact of SAFs on specific operational phases of flight, with a focus on the landing and take-off cycle. A case study was conducted at Lisbon Airport using real aircraft movement data over a one-week period. Emissions were calculated by correlating aircraft engine types with data from the ICAO Engine Exhaust Emissions Databank. The analysis identifies the most emission-intensive flight phase, the most polluting fleet, and evaluates the potential GHG reductions achievable through the use of various SAF pathways. Additionally, operational alternatives for reducing emissions during the taxi phase, including APU management strategies, are examined. The results provide actionable insights into the role of SAFs in reducing airport-level emissions and support targeted interventions for more sustainable airport operations.

1. Introduction

With a forecasted growth of approximately 3.8% in annual traffic, the aviation industry must employ effective measures to mitigate their impact on the environment while upholding airworthiness standards (IATA, 2023). In particular, greenhouse gas (GHG) emissions due to the use of carbon-intensive fuels have become the target of long-term mitigation strategies by government bodies, such as net-zero vision (Comission, 2018).

Anthropogenic CO_2 production originating from international and domestic commercial aviation contributes between 2% and 2.6% of total anthropogenic CO_2 emissions (Grote et al., 2014). In aviation, the most significant source of anthropogenic CO_2 is the combustion of fossil fuels, which consumes over five million barrels of crude oil daily, resulting in negative and irreversible environmental impacts. Consequently, there has been increased emphasis on energy consumption efficiency and greenhouse gas production. As aircraft engines are a primary source of CO_2 emissions, some manufacturers, urged by their governments and international bodies, such as the International Civil Aviation Organization (ICAO), have been striving to develop technologies that enhance fuel consumption efficiency while reducing GHG emissions (Grote et al., 2014).

Fig. 1 depicts the annual CO_2 emissions from air transport across the 27 European Union countries from 2013 to 2022. The data retrieved from Eurostat (2024) highlights a stable increasing trend with slight fluctuations until 2019, followed by a significant drop in 2020. This decrease is attributable to reduced air travel due to the COVID-19 pandemic. The subsequent years show a partial recovery in emissions as air travel began to rebound. The grey line represents a two-year moving average, highlighting the overall trend and smoothing out year-to-year variations. This visualization illustrates the impact of external factors on aviation-related emissions and the potential for rapid changes in environmental impacts due to shifts in human activity.

Fig. 2 displays the distribution of CO_2 emissions from air transport among EU-27 countries from 2013 to 2022 (Eurostat, 2024). Each bar represents the total emissions for a year segmented by country, which allows for a detailed examination of each country's contribution to overall emissions. Countries such as Germany, France, the Netherlands, Ireland, and Spain were among the Top-5 contributors. The multi-coloured layers facilitate comparisons between years and highlight trends within individual nations. Notably, the chart demonstrates the persistence of both leading emitters.

To address these aviation environmental concerns, there has been growing focus on integrating renewable energy sources and innovative propulsion technologies within the aviation sector (Abrantes et al., 2024). Specifically, the development and deployment of sustainable

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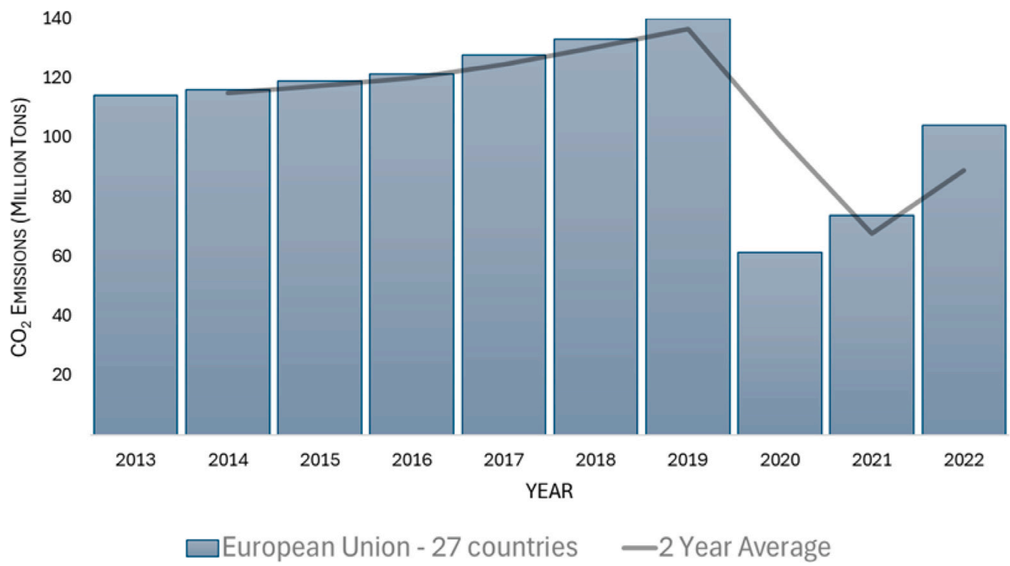

Fig. 1. Air transport CO_2 emissions from EU27 and the 2-year average.

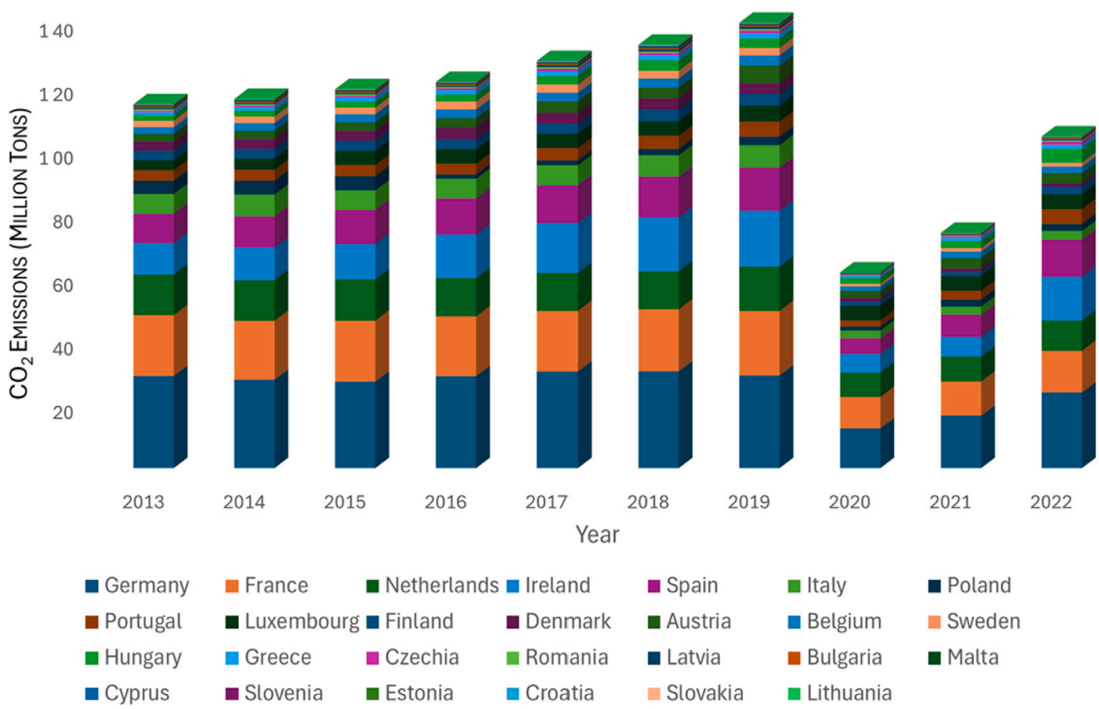

Fig. 2. Air transport CO_2 emissions from each EU country.

aviation fuels (SAFs) are vital for achieving significant reductions in CO_2 emissions. These fuels are a type of aviation fuel produced from sustainable feedstocks, aiming to reduce greenhouse gas emissions compared to conventional jet fuel. It is essentially a drop-in replacement for traditional jet fuel, meaning it can be used in existing aircraft engines without modification. SAF is crucial for the aviation industry's efforts to decarbonize and meet net-zero emission goals, and has the potential to reduce aviation carbon footprints by up to 80% over their lifecycle compared with traditional jet fuels (Abrantes et al., 2021).

It is important to note that "Sustainable Aviation Fuel" (SAF) is a broad policy and regulatory term that encompasses a range of certified synthetic blending components (SBCs) defined under ASTM D7566. These SBCs—such as HEFA-SPK, FT-SPK, ATJ-SPK, and SIP—must be blended with conventional Jet A or Jet A-1 fuel to be considered drop-in fuels. In this sense, SAF represents the blended, ready-to-use product, whereas SBCs refer to the specific synthetic components derived from approved production pathways (ASTM International, 2024; IATA, 2023).

SAFs can originate from multiple sources. Among these, bio-based sustainable aviation fuels (bio-SAFs) and synthetic e-fuels (also known as power-to-liquid or PtL fuels) are two prominent low-carbon alternatives to conventional jet fuel, differing fundamentally in their feedstocks and production methods. Bio-SAFs are derived from biological materials such as used cooking oil, agricultural residues, or energy crops, and are produced through processes like hydroprocessing, fermentation, or gasification. In contrast, synthetic e-fuels are manufactured by combining green hydrogen — produced via renewable electricity-driven electrolysis — with carbon dioxide captured from the atmosphere or industrial sources, typically using Fischer–Tropsch or methanol synthesis pathways.

Furthermore, advancements in aircraft design, such as the incorporation of lighter materials and more efficient aerodynamics, have played a crucial role in reducing the fuel consumption per flight. In addition, operational improvements, including optimized flight routes and enhanced air traffic management systems, contribute to the overall reduction in CO_2 emissions. These combined efforts are crucial as the industry moves towards fulfilling its commitments under the Paris Agreement and other international climate agreements (Abrantes et al., 2021).

To be used in commercial aviation, drop-in SAF must undergo a rigorous testing process to obtain certification and tests that demonstrate chemical and physical characteristics almost identical to those of conventional jet fuel, allowing safe mixing between them. The main difficulty in the transition is related to the low production capacity and higher production cost compared with the currently used jet fuel (Jain et al., 2021).

The GHG emissions of SAF can vary greatly depending on the feedstock used and production path chosen. The function units are provided in CO_2e per MJ, allowing for an easier comparison with fossil jet fuel emissions to calculate the overall GHG emission reduction. As the demand for SAF increases, it is necessary to analyse the production pathways for a drop-in mixture with jet fuel and the mixing ratio certified by ASTM International (Moriarty and Kvien, 2018).

Oslo Airport was the first airport in the world to offer SAF to all airlines in 2016, with the infrastructure put in place allowing a significant cost reduction (Baxter, 2020). Several efforts by airports and airlines to incorporate SAF into aeronautical ecosystems have been described in Aviation (2019). Moreover, companies such as Prat & Whitney, Airbus, and Embraer are striving to approve the use of 100% SAF by 2030 (ICAO, 2023).

Hydrogen is also considered as an option for reducing CO_2 emissions. Arat and Sürer (2017) point out that the most practical and economical way to obtain hydrogen would be through steam methane reforming using fossil fuels. Water electrolysis has been shown to produce fewer adverse effects.

The research gap lies in the limited availability of empirical, airport-specific studies that quantify the environmental impact of implementing SAFs in real-world operational scenarios. For instance, Cao et al. (2023) compared different taxiing methods projecting carbon emission profiles from 2024–2035 concluding taxiing needs to be combined with further emission mitigation technologies for maximum effect. Moreover, Maciejewska and Kurzawska-Pietrowicz (2025) carried out a life cycle analysis to taxi operations at Warsaw and Poznań airports highlighting a significant emission reduction with electric tow trucks compared with taxiing with engines. Pertaining the landing and take-off phases, Dissanayaka et al. (2020) stress the difficulties in evaluating emissions within the LTO cycle due to the lack of real operational data, while Wen et al. (2025) propose an aircraft landing-takeoff time, fuel, and emission model (ALTFEM) to estimate fuel consumption during the LTO cycle at the Shanghai-Pudong-International-Airport.

While previous research has examined the general benefits of SAFs at a macro level (Abrantes et al., 2021; Jain et al., 2021), there remains a limited analysis that captures the emissions profile of commercial airports using actual aircraft movement data and flight-phase emissions. Specifically, the literature does not adequately explore the contribution of different flight phases such as idle, taxi, take-off, and climb, as well as APU usage to overall GHG emissions in the context of SAF deployment. This study addresses that gap by focusing on Lisbon Airport, utilizing real traffic data over a representative week to analyse GHG emissions under different SAF blending scenarios. It quantifies the emissions from various aircraft models and engine types across the LTO (Landing and Take-off) cycle and APU operations, offering a granular comparison between conventional jet fuel and SAF options such as HEFA, FT, and ATJ. By contextualizing SAF benefits within actual airport operations, the study advances the field beyond theoretical models and provides actionable insights for policymakers, airport authorities, and airline operators aiming to reduce aviation-related emissions.

The primary objective of this manuscript is to assess the environmental impact of integrating SAFs into commercial airport operations, with a particular emphasis on localized emissions. This study employs a case analysis based on real-world aircraft movement data at Lisbon Airport to quantify and compare GHG emissions before and after the hypothetical introduction of SAFs. The evaluation encompasses emissions from both engine operations and auxiliary power units (APUs), which are critical yet often underrepresented sources of airport-level pollutants. Specifically, the analysis focuses on key GHG contributors, including carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (HC), nitrogen oxides (NOx), and sulfur dioxide (SO_2). By disaggregating emissions across different aircraft types, engine models, and flight phases, the study aims to provide a granular understanding of the potential emission reductions attainable through SAF deployment, thereby offering actionable insights for policymakers, airport authorities, and industry stakeholders committed to achieving aviation decarbonization targets.

2. Methodology

To quantify the air quality associated with GHG emissions in the area of an airport, the landing and takeoff cycle (LTO) was used as a reference (Agency and Agency, 2022). It comprises four phases: takeoff, climb, approach, and taxi. The takeoff phase assumes a thrust of 100% during $0.7\,\text{min}$, followed by a climbout phase at 85% thrust during $2.2\,\text{min}$. However, the approach is considered below 3000 ft, assuming a thrust of 30% during $4\,\text{min}$. Finally, a taxi is composed of a taxi-in and taxi-out with a 7% engine thrust for $26\,\text{min}$.

Additionally, the APU must be considered for utilization in the takeoff and landing cycles. It is a self-contained unit that allows an aircraft to remain independent of external electrical and pneumatic power supplies (Padhra, 2018). The average APU consumption varies from about $100\,\text{kg}\,\text{h}^{-1}$ up to $300\,\text{kg}\,\text{h}^{-1}$, which seems a residual value. However, if multiplied by the average number of flights operated on a daily basis, a significant value is reached (Schäfer et al., 2003). Moreover, during an aircraft turnaround, the APU is the main source of GHG. Furthermore, the emissions related to APU use can be divided into two periods: one related to the time between an aircraft landing and it reaching the stand (arrival cycle), and the other quantifying the time between passenger boarding to the moment during taxi in which it is turned (departure cycle).

The total APU fuel consumption, F expressed in kg, is obtained using Eq. (1), where $\dot{m}$ is the mass flow rate, given in $\text{kg}\,\text{h}^{-1}$, related to the APU operating mode, and t is the APU utilization period in hours.

$$F = \dot{m} \times t \tag{1}$$

The values of CO_2 and SO_2 resulting from APU usage were evaluated using Eqs. (2) and (3), respectively, Correia (2009): Constants 3.1564 and 0.1 represent the number of tonnes of each compound produced by burning a tonne of jet fuel (ICAO, 2017).

$$CO_2 = 3.1564 \times \text{APU consumption}\,(t) \tag{2}$$

$$SO_2 = 0.1 \times \text{APU consumption}\,(t) \tag{3}$$

In the present work, APU consumption is summarized according to the classification in Table 1.

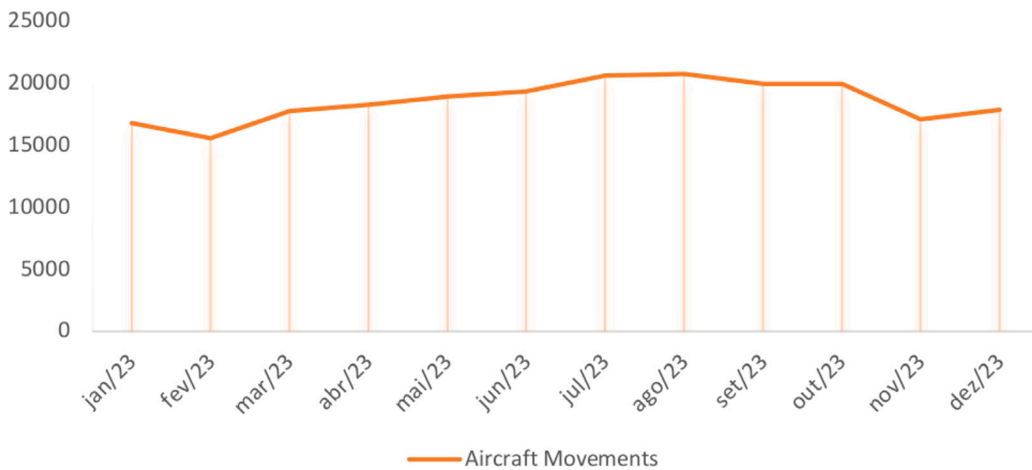

Fig. 3. Monthly aircraft movement.

Table 1
APU consumption for similar aircraft groups.

Group	APU Consumption $(kg\,h^{-1})$
Short and Medium-haul	118
Long-haul	261
Other	100

3. Case study – Lisbon airport

Lisbon's airport is the Portuguese largest and busiest airport, and is close to reaching its full capacity. This is even more concerning owing to its location within the city centre, surrounded by residential areas, which negatively impacts the health of nearby populations (Tokuşlu, 2021).

Fig. 3 depicts the monthly variation in aircraft movement in 2023. For the present work, March was selected, where the airport had a total of 17747 aircraft movements.

To compare the GHG emissions associated with aircraft movements based on carbon-intensive fuel and SAF, several assumptions were considered in the calculations. The LTO cycle was used as the reference, under which all calculations were performed up to an altitude of 3000 ft. Moreover, based on the data availability, the week of 7–13 of March is selected as the sampling period under which the analysis was carried out. Finally, real-time statistics pertaining to the taxi-in and taxi-out periods differ from those established in the LTO cycle. This variation stems from the variability in airport configurations, including distance-to-stand, turnaround time, and delays in normal aircraft operations.

Information regarding specific engine emissions was obtained from the International Civil Aviation Organization (ICAO) engine emission database (ICAO, 2023), where accurate information was supplied by the engine manufacturer after testing and airworthiness certification was carried out. The dataset containing the arrivals and departures movement in available in a public database: http://hdl.handle.net/10400.6/14451 and http://hdl.handle.net/10400.6/14450, labelled by engine type.

4. Results

4.1. Aircraft consumption and emissions using jet fuel

The emission data for unburned hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) are listed in Table 2 as an example extracted from the ICAO engine emissions databank (ICAO, 2023). Moreover, these values have limitations associated with the use of the

Table 2
A220-100/300 (engine PW1524G) emissions (Agency, 2023).

Phase	HC $[g\,kg^{-1}]$	CO $[g\,kg^{-1}]$	NOx $[g\,kg^{-1}]$
T/O	0[a]	0[a]	26
C/O	0[a]	0[a]	20.5
App	0.1	1.8	10.4
Idle	0.1	16.7	6

[a] The 0 represent a value so low it is disregarded.

Table 3
A220-100/300 (engine PW1524G) consumption and emissions.

Phase	Time [min]	Fuel Flow $[kg\,min^{-1}]$	Fuel Total [kg]	HC [kg]	CO [kg]	CO_2 [kg]	NOx [kg]	SO_2 [kg]
T/O	0.7	47.4	33.2	0[a]	0[a]	102.62	0.86	3.32
C/O	2.2	39	85.8	0[a]	0[a]	270.8	1.76	8.58
App.	4	13.8	55.2	0.006	0.099	174.24	0.57	5.52
Idle	26	4.8	124.8	0.012	2.084	393.9	0.75	12.48
Total	32.9	–	299	0.018	2.183	942	3.9	29.9

[a] The 0 represent a value so low it is disregarded.

international standard atmosphere (ISA) and the duration of each phase of the LTO cycle.

Table 3 details the consumption and detailed emissions based on one LTO cycle for the engine PW1524G of the A220-100/300.

CO_2 and SO_2 emissions are calculated following Correia (2009) through Eq. (4), with parameter α taken as 3.1564 for CO_2 and 0.1 for SO_2, obtained by multiplying the fuel flow, FF by the time spent (TM) in each of the four phases (T/O, C/O, approach and idle) detailed in Table 3.

$$\text{emission} = \alpha \sum_{i=1}^{4} FF(i) \times TM(i) \tag{4}$$

The emissions of CO_2 are directly proportional to the fuel burned, with an emission index of 3.16 kg of CO_2 kg^{-1} of the fuel burned.

Fig. 4 shows the major pollutants during the standard LTO cycle of A220-100/300. Here, CO_2 corresponded to a relative percentage of 96%, followed by SO_2 at 3%. These values are aligned with those obtained in the literature (EEA, 2023). Moreover, Fig. 5 shows the pollutant emissions per phase of the LTO cycle.

Fig. 6 shows the emissions of A220-100/300 equipped with the PWG1524G engine across the different phases of a single LTO cycle, including HC, CO, NOx, CO_2, and SO_2. The idle phase accounted for the highest HC emissions, accounting for 67%, or equivalent to 0.012 kg. A similar trend is observed for CO and CO_2, totalling 95% of the emissions or 2.084 kg in the former and 42% or 393.8 kg in the latter. On the

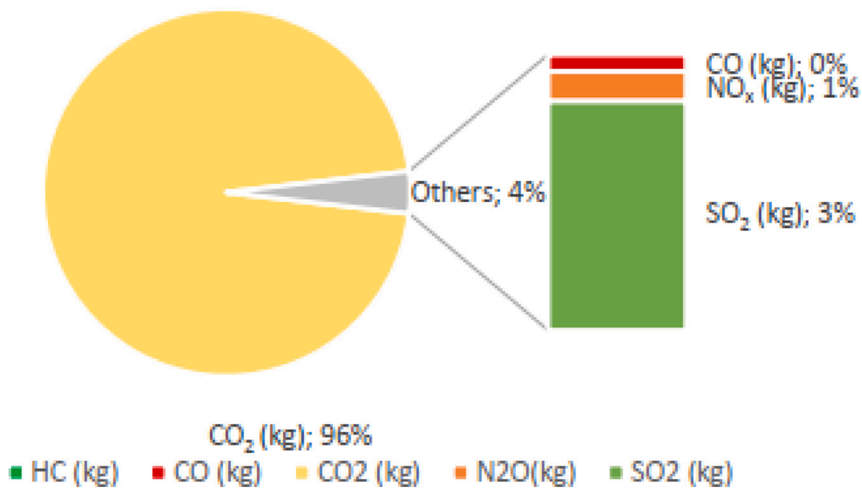

Fig. 4. A220-100/300 (PW1524G) emissions per pollutant.

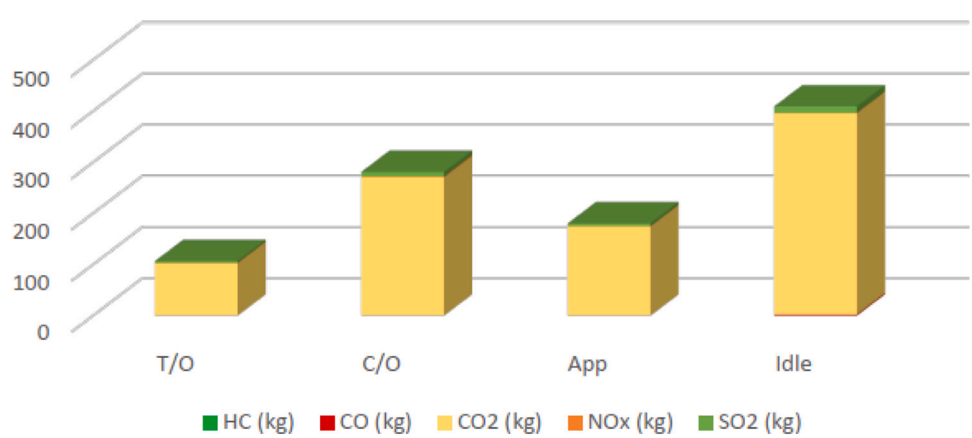

Fig. 5. A220-100/300 (PW1524G) emissions per flight phase.

Table 4
A220-100/300 (engine PW1524G) weekly emission estimation.

Dep.	Arr.	LTO cycle[a]	Fuel [kg]	HC [kg]	CO [kg]	CO_2 [kg]	NOx [kg]	SO_2 [kg]
22	21	43.0	12857	1	94	40506	168	1286

[a] Each LTO cycle represents one departure plus one arrival.

other hand, looking into the NOx emissions, the C/O phase accounts for 44% or 1.76 kg of the emissions. Finally, SO_2 emissions were the highest during idle, totalling 42% or 12.48 kg, making CO_2 an outlier.

Considering the aircraft movements (departures and arrivals) of A220-100/300 during the representative week and the calculation procedure described above, the weekly emissions at Lisbon's airport are estimated in Table 4.

The same process was applied to the remaining movements, resulting in the weekly emissions detailed in Table 5 for each combination of aircraft and engine in the short- and medium-haul movement categories. The A320 CEO equipped with CFMI CFM56-5B4/P engines represents 25% of the total CO_2 emissions, followed by the A321 NEO equipped with CFMI LEAP-1A32 engines (see Table 6).

With regard to the emissions associated with each aircraft model, Table 7 details the CO_2 emissions per seat per LTO cycle, which allows an assessment with the load factor of which models are the most polluting. Assuming a load factor of 100%, the A321 NEO equipped with the CFMI LEAP-1A32 is the least polluting, while the B737-600/700 with the engines CFMI CFM56-7B22 taking the most polluting position within the jet category, and is only surpassed by the ATR72-500/600 in the turboprop category (see Table 8 and Table 9).

The average taxi time at Lisbon's airport varies depending on the runway in use, owing to prevailing winds. Considering the operation of the largest airlines, the average times are listed in Table 10. The difference in taxi time between the two runways is due to the longer route that an aircraft must take. For instance, long-haul flights must cross runway 02, further increasing operational time. It can be observed that the average taxi time when considering runway 20 matches the LTO cycle, whereas runway 02 leads to 4 min reduction. Furthermore, Table 11 details how a variation in 4 min in the aircraft taxi time affects fuel consumption by 15.4%.

The effect of taxi time can be further analysed through Fig. 7, where the 4 min time reduction corresponds to a 6.5% reduction in total emissions in the cycle. Moreover, the trend observed in Fig. 7 comes from the fact that during the LTO cycle, NOx formation is limited by lower combustion temperatures, while nearly all fuel sulfur is converted to SO2. As a result, SO2 emissions can appear elevated relative to NOx and CO, despite the fuel's low sulfur content. As shown in Fig. 6, the idle phase corresponds to the highest emissions of CO and HC because of its duration. During taxi, aircraft engines consume a substantial amount of fuel, which leads to an increase in GHG emissions. Thus, alternative taxi procedures that are supported by alternative energy sources are alternatives (Edem et al., 2017). Another alternative is to carry out a taxi with a single engine; however, it is necessary to take into account the warm up and cool down periods aircraft engines must comply with before take-off and after landing, respectively.

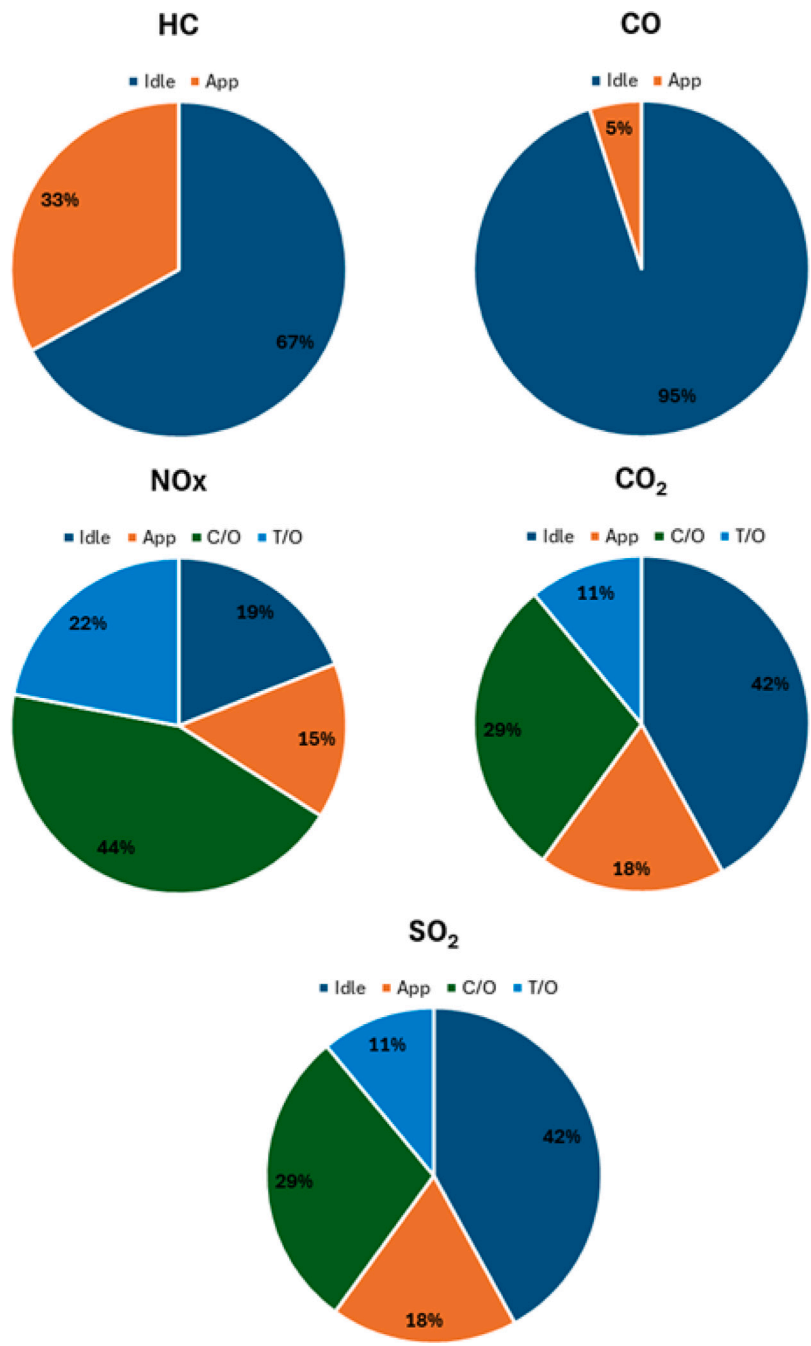

Fig. 6. A220-100/300 (PW1524G) emission distribution by pollutant and LTO cycle phase: upper left: HC, upper right: CO, middle left: NOx, middle right: CO_2, bottom: SO_2.

During a standard LTO cycle, CO_2 represents the largest pollutant with a relative percentage of 96% of the total GHG emissions. Although the Idle phase (Taxi phase) presents the lowest fuel flow and therefore the lowest emissions per minute, the long duration of 26 min puts it as the phase with more emissions during a standard LTO cycle. By analysing CO_2 emissions per LTO cycle, it is possible to conclude which aircraft models and types of engines are more and less polluting, and with that data, influence the industry and airlines to make more sustainable choices. Small and medium-haul aircraft are responsible for the majority of pollutant emissions associated with movements at LIS airport during the period considered. In short- and medium-haul aircraft, the A320 CEO equipped with the CFMI CFM56-5B4/P engines represented 25% of the total CO_2 emissions but was not the most polluting, being the most polluting in terms of CO_2 emissions per cycle. LTO, the A321 CEO equipped with IAE V2533-A5 engines reached 1610 kg CO_2 or LTO cycle. The least polluting jet aircraft in this analysis was A220, equipped with PW1524G engines, with approximately 942 kg CO_2 per LTO cycle. In long-haul aircraft, the A330-900 NEO equipped with RR Trent 7000-72 engines was the long-haul aircraft that contributed the most to pollutant emissions associated with movements at the LIS airport in the period considered (52% of total CO_2 emissions); however, this does not mean that it was the most polluting, as it had 2939 kg of CO_2 per LTO cycle, when the most polluting aircraft model in the analysis was the B757-200 equipped with PW2037 engines, with 7594 kg of CO_2 per cycle, compared to 1850 kg of CO_2 per cycle of the less polluting plane (B777-243(ER) equipped with GE GE90-94B engines).

Table 5
A220-100/300 (engine PW1524G) weekly emission estimation.

Aircraft	Engines,	Dep.	Arr.	Cycles	Fuel [kg]	HC[a] [kg]	CO [kg]	CO_2 [kg]	NOx [kg]	SO_2 [kg]	CO_2[b] [%]
ATR72–500	PWC PW127F	11	9	20	4660	0	30	14700	44	460	0
ATR72–600	PWC PW127M	14	13	27	6291	0	41	19845	59	621	0
A220	PW1524G	22	21	43	12857	1	94	40506	168	1286	1
A319	CFMI CFM56-5B5/3	25	25	50	17150	26	317	54132	253	1715	1
	CFMI CFM56-5B6/P	41	40	81	29766	74	371	93953	347	2977	2
	IAE V2522-A5	7	7	14	5698	0	39	17985	66	570	0
A320CEO	CFMI CFM56-5B6/3	5	5	10	3610	4	59	11395	34	361	0
	CFMI CFM56-5B4/P	415	409	824	338640	681	3420	1068883	4681	33864	25
	IAE V2527-A5	25	23	48	24850	2	138	68967	269	2185	2
A320 NEO	CFMI LEADP-1A26	186	188	374	120528	15	1164	380435	1060	12053	9
	PW1127G	27	26	53	16362	4	182	51645	186	1636	1
A321 CEO	CFMI CFM56-5B1/3	2	2	4	1792	1	20	5656	23	179	0
	CFMI CFM56-5B3/P	33	33	66	31548	47	186	99578	552	3155	2
	IAE V2533-A5	36	37	73	37224	3	161	117494	623	3722	3
A321 NEO	CFMI LEAP-1A32	283	283	566	215080	23	1709	678879	4415	21508	16
	CFMI LEAP-1A33	17	18	35	12920	1	103	40781	265	1292	1
	PW1133G	28	28	56	21000	4	199	66284	296	2100	2
B737-6/700	CFMI CFM 56-7B22	13	12	25	10140	11	104	32006	119	1014	1
	CFMI CFM56-7B24	6	6	12	4944	5	48	15605	62	494	0
B737-8/900	CFM56-7B24E	1	0	1	398	0	6	1256	4	40	0
	CFMI CFM56-7B26	223	219	442	196686	161	1574	620820	2743	19669	14
	CMFI CFM56-7B27	43	41	84	39216	29	296	123781	578	3922	3
B737-43QF	CMFI CFM56-3B2	1	1	2	842	1	12	2858	8	84	0
	CFMI CFM56-3C1	13	13	26	11648	8	145	367666.25	1165	1	
B737 MAX8	CFMI LEAP-1B	39	39	78	29640	6	170	93556	612	2964	2
E190/E195	GE CF34-10E5A1	30	31	61	19380	41	376	61171	200	1938	1
	GE CF34-10E6	38	38	76	23028	65	514	72686	216	2303	2
	GE CF34-10E7	192	188	380	124032	265	2408	391495	1278	12403	9

[a] The value of 0 represents a low value that can be disregarded.

[b] The value of 0% represents a quantity lower than 1% when compared to the total emissions of 1776 departures.

Table 6
Emissions per cycle: short- and medium-haul.

Aircraft	Engine	LTO cycle	CO_2 [kg]	CO_2 emissions per cycle [kg]	Classification
ATR72–500	PWC PW127F	20	14700	735	26
ATR72–600	PWC PW127M	27	19845	735	25
A220	PW1524G	43	40506	942	24
A319	CFMI CFM56-5B5/3	50	54132	1083	18
	CFMI CFM56-5B6/P	81	93953	1160	16
	IAE V2522-A5	14	17985	1285	10
A320CEO	CFMI CFM56-5B6/3	10	11395	1139	17
	CFMI CFM56-5B4/P	824	1068883	1297	9
	IAE V2527-A5	48	68967	1437	4
A320 NEO	CFMI LEADP-1A26	374	380435	1017	20
	PW1127G	53	51645	974	22
A321 CEO	CFMI CFM56-5B1/3	4	5656	1414	5
	CFMI CFM56-5B3/P	66	99578	1509	2
	IAE V2533-A5	73	117494	1610	1
A321 NEO	CFMI LEAP-1A32	566	678879	1199	13
	CFMI LEAP-1A33	35	40781	1165	15
	PW1133G	56	66284	1184	14
B737-6/700	CFMI CFM 56-7B22	25	32006	1280	11
	CFMI CFM56-7B24	12	15605	1300	8
B737-8/900	CFM56-7B24E	1	1256	1256	12
	CFMI CFM56-7B26	442	620820	1405	6
	CMFI CFM56-7B27	84	123781	1474	3
B737-43QF	CMFI CFM56-3B2	2	2658	1329	7
	CFMI CFM56-3C1	26	36766	1414	5
B737 MAX8	CFMI LEAP-1B	78	93556	1199	13
E190/E195	GE CF34-10E5A1	61	61171	1003	21
	GE CF34-10E6	76	72686	956	23
	GE CF34-10E7	380	391495	1030	19

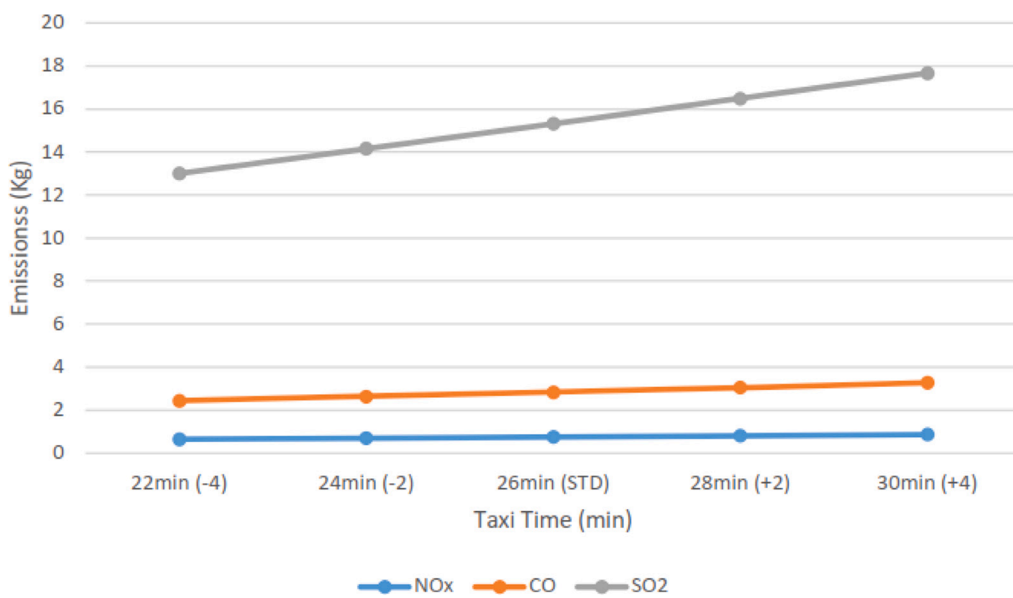

Fig. 7. Effect of taxi time in LTO emissions.

Table 7
CO_2 emissions per seat/LTO cycle for different aircraft models.

Aircraft	Engine	Seat Capacity[a]	CO_2 emissions per cycle [kg]
ATR72–500	PWC PW127F	68	10.81
ATR72–600	PWC PW127M	70	10.50
A220	PW1524G	145	6.50
A319	CFMI CFM56-5B5/3	156	6.94
	CFMI CFM56-5B6/P	146	7.94
	IAE V2522-A5	143	8.98
A320CEO	CFMI CFM56-5B6/3	174	6.55
	CFMI CFM56-5B4/P	186	6.97
	IAE V2527-A5	180	7.98
A320 NEO	CFMI LEADP-1A26	174	5.85
	PW1127G	168	5.80
A321 CEO	CFMI CFM56-5B1/3	219	6.46
	CFMI CFM56-5B3/P	216	6.98
	IAE V2533-A5	220	7.32
A321 NEO	CFMI LEAP-1A32	216	5.55
	CFMI LEAP-1A33	190	6.13
	PW1133G	182	6.50
B737-6/700	CFMI CFM 56-7B22	142	9.02
	CFMI CFM56-7B24	189	6.88
B737-8/900	CFM56-7B24E	189	6.65
	CFMI CFM56-7B26	189	7.43
	CMFI CFM56-7B27	189	7.80
B737-43QF	CMFI CFM56-3B2	[b]	[b]
	CFMI CFM56-3C1	[b]	[b]
B737 MAX8	CFMI LEAP-1B	197	6.09
E190/E195	GE CF34-10E5A1	118	8.50
	GE CF34-10E6	106	9.02
	GE CF34-10E7	118	8.73

[a] Based on the most relevant configuration in operation.
[b] Cargo aircraft.

4.1.1. The auxiliary power unit

The Tables 12 and 13 represents the APU usage and consumption in function of flight profiles from departure and arrival aircraft respectively. Direct measurements from real-operational scenarios assessed that the average time of use of the APU at Lisbon Airport is 44 min for outbound flights and 20 min for inbound flights, regardless of whether the aircraft is short-, medium-, or long-haul. No significant variations were detected, which should be highlighted. The total consumption resulting from the use of the APU can be obtained by multiplying the total aircraft movement by the APU usage time of each group by the APU fuel consumption per hour.

The emission values of carbon monoxide (CO), oxides of nitrogen (NOx), and total hydrocarbons (THC), presented in Table 14 were obtained directly through an analysis of several previously published studies.

Taking into considerations the total CO_2 emissions from aircraft during their LTO cycles at Lisbon airport in the period considered, emissions related to the use of the APU represent around 13.9% of total CO_2 emissions, as depicted in Table 15.

4.2. Aircraft consumption and emissions using SAF

Through the introduction of SAFs at Lisbon Airport, a reduction in GHG emissions associated with aircraft movements on the airside of the airport is expected. Three scenarios were created to estimate this possible reduction. The SAF fuels previously analysed were based on SAFs, which present a higher FRL/TRL and, at the same time, present a greater estimated production and distribution capacity for the coming years (HEFA, FT, and ATJ). In addition, the GWP defines a projection for a 100-year time-horizon global warming potential. The GWP can be used to compare the ability of each GHG to trap heat in the atmosphere over a specified period of time.

As shown in Table 16, the GWP value for N_2O was much higher than the GWP value for CO_2. For the values under analysis, the specific case of Lisbon Airport, and assuming the total emissions during the period under analysis, the index that results from multiplying each of the GHGs under analysis by its GWP, despite the absolute value of NOx emissions representing only 0.49% when compared to CO_2 emissions, the global harmful power for just one week was more than 20% higher

Table 8
Weekly emissions: long-haul movements.

Aircraft, Engine, and Dep.	Arr.	Cycles	Fuel	HC[a]	CO [kg]	CO_2 [kg]	NOx [kg]	SO_2 [kg]	CO_2[b] [kg]	[kg]	[%]
A330-200	GE CF6-80E1A4	17	17	34	32742	127	471	103347	614	3274	9
A330-300	RR Trent 772B-60	10	9	19	21700	21	212	68494	353	2170	6
A330-90 NEO	RR Trent 7000–72	97	97	194	180614	0	559	570090	4086	18061	52
A340-312	CFMI CFM56-5C3/F	5	5	10	9660	20	129	30491	155	966	3
B757-200	PW2037	2	2	4	2344	2	22	7399	32	234	1
	PW2040	2	2	4	2524	2	21	7967	40	252	1
	RR RB211-535 E4	1	1	2	1366	0	8	4312	23	137	0
B767-200	GE CF6-80A2	1	1	2	1462	3	15	4615	24	146	0
	GE CF6-80C2B2F	3	3	6	4410	21	90	13920	50	441	1
B767-300	PW4056	5	4	9	8360	7	76	26388	120	836	2
	PW4060	7	7	14	12418	8	101	39196	197	1242	4
B767-400	GE CF6-80C2B7F	7	7	14	11676	43	195	36854	170	1168	3
B777-243(ER)	GE GE90-94B	1	0	1	2406	0	12	7594	61	241	1
B787-900	RR Trent 1000	6	6	12	10608	0	37	33483	219	1061	3
B777-31H	GE90-115B	15	14	29	43590	59	571	137587	1023	4359	13

[a] The value of 0 represents a low value that can be disregarded.

[b] The value of 0% represents a quantity lower than 1% when compared to the total emissions of 1776 departures.

Table 9
Emissions per cycle: long-haul.

Aircraft	Engine	LTO cycle	CO_2 [kg]	CO_2 emissions per cycle [kg]	Classification
A330-200	GE CF6-80E1A4	34	103347	3040	5
A330-300	RR Trent 772B-60	19	68494	3605	3
A330-90 NEO	RR Trent 7000–72	194	570090	2939	6
A340-312	CFMI CFM56-5C3/F	10	30491	3049	4
B757-200	PW2037	4	7399	1850	15
	PW2040	4	7967	1992	14
	RR RB211-535 E4	2	4312	2156	13
B767-200	GE CF6-80A2	2	4615	2308	12
	GE CF6-80C2B2F	6	13920	2320	11
B767-300	PW4056	9	26388	2932	7
	PW4060	14	36854	2632	10
B767-400	GE CF6-80C2B7F	14	36854	2632	10
B777-243(ER)	GE GE90-94B	1	7594	7594	1
B787-900	RR Trent 1000	12	33483	2790	9
B777-31H	GE90-115B	29	137587	4744	2

Table 10
Average taxi times at LIS airport.

Scenario	Taxi-in [min]	Taxi-out [min]	LTO Cycle [min]
Runway 02	7	15	22
Runway 20	6	20	26

Table 11
LTO emission for idle phase.

Time min	Fuel Flow [$kg\,min^{-1}$]	Total Fuel [kg]	HC [kg]	CO [kg]	CO_2 [kg]	NOx [kg]	SO_2 [kg]
22	4.8	105.6	0.01	1.763	333.32	0.63	10.56
26		124.8	0.012	2.084	393.9	0.75	12.48
30		144	0.014	2.405	454.52	0.87	14.4

for N_2O. CO concentrations due to its short-lived in the atmosphere and spatially variable it is not possible to accurately determine GWP values related to the CO concentrations, although there are studies that indicate some ranges of values.

Table 12
APU weekly consumption - departures.

Group	Departures	APU usage [h]	Consumption [kg]
Short- and Medium-haul	1176	1302	153636
Long-haul	179	131	34191
Other	22	16	1600
Total	1977	1449	189427

Table 13
APU weekly consumption - arrivals.

Group	Departures	APU usage [h]	Consumption [kg]
Short- and Medium-haul	1755	585	69030
Long-haul	175	58	15138
Other	22	7	700
Total	1952	650	84868

To enable a comparison of the possible reduction in GHGs through the use of various SAFs under analysis, the following assumptions were made:

Table 14
Average APU emissions values.

HC $g\,kg^{-1}$	CO $[g\,kg^{-1}]$	NOx $[g\,kg^{-1}]$
0.204	2.973	8.011

Table 15
APU weekly consumption and emissions.

	APU usage [h]	Total Fuel [kg]	HC [kg]	CO [kg]	CO_2 [kg]	NOx [kg]	SO_2 [kg]
Departures	1449	189427	39	563	597907	1518	19
Arrivals	650	84868	17	252	267877	680	9
Total	2099	274295	56	815	865784	2198	28

Table 16
Global warming potential.

	CO_2	N_2O	SO_2
Total [kg]	6241695	28554	170307
GWP	1	265	Negative
Index	6241695	7556810	–

Table 17
LHV and baseline life cycle emissions for 50% HEFA/50% jet fuel.

SAF HEFA (mixing ratio 50%)	Quantity kg	LHV [MJ]	Baseline $[gCO_2eMJ^{-1}]$
Jet Fuel	998751	42615168	4005826000
HEFA	955079	41927968	586991552
Total	1943830	84543136	4677360688

Table 18
LHV and Baseline life cycle emissions value for jet fuel vs HEFA.

Jet Fuel 100%	Quantity kg	LHV [MJ]	Baseline $[gCO_2eMJ^{-1}]$
Values	1977503	85230397	8.011657000
Variation	+0.9%	+0.9%	+71%

- Jet fuel density at 15 °C: $807.5\,kg\,m^{-3}$ (775–840) (Colket and Heyne, 2021)
- Jet fuel LHV medium value: $43.1\,MJ\,kg^{-1}$ (Colket and Heyne, 2021)
- Fossil fuel baseline: 94 g CO_2e MJ^{-1} (Mellios and Gouliarou, 2020)

Considering the estimated total fuel consumption of the aircraft engines and APU throughout the week under the analysis of 197 750 kg and assuming an SAF HEFA with a mix ratio of 50%, we arrived at the values listed in Table 17. Another point worthy of notice relates to the LHV range of conventional jet fuel and SAFs. While SAFs have a higher LHV than conventional jet fuel because of the lack of aromatic compounds. However, they have lower volumetric energy density (MJ/L) compared to conventional jet fuel. The resulting operational impacts — such as modest range reduction or tank volume constraints — are generally minor for typical blend ratios but could become more significant at very high SAF fractions.

In Table 18 it is possible to observe the values of LHV and the baseline life-cycle emissions for 100% jet fuel, and a comparison in percentage with the values obtained in Table 17 for the mixture of 50% HEFA/50% jet fuel.

Because of the lower density of HEFA compared to Jet Fuel, for the period under analysis, the quantity of Jet Fuel to be transported would be 0.9% higher than if the mixture was used (jet fuel 50% + SAF HEFA 50%). The lower heating value (LHV) assumes a variation identical to that of the quantity because of the very similar LHV between them. The most drastic and expected variation lies in the analysis of gCO2e/MJ, where the use of only jet fuel represents an increase in CO_2 emissions equivalent to approximately 71% compared with the mixture under analysis. This value represents only a period of one week. When extrapolated to monthly and annual periods, the period under analysis in this study represents an increasingly overwhelming difference between the two options, thus reinforcing the need to continue with the adoption of this type of fuel to achieve defined environmental goals.

Table 19
LHV and baseline life cycle emissions for 50% FT/50% jet fuel.

SAF HEFA (mixing ratio 50%)	Quantity kg	LHV [MJ]	Baseline $[gCO_2eMJ^{-1}]$
Jet Fuel	988751	42615168	4005826000
FT	918344	40498996	554836246
Total	1907095	83114164	4560662246

Table 20
LHV and Baseline life cycle emissions value for jet fuel vs FT.

Jet Fuel 100%	Quantity kg	LHV [MJ]	Baseline $[gCO_2eMJ^{-1}]$
Values	1977503	85230397	8.011657000
Variation	+3.7%	+2.5%	+75%

Table 21
LHV and baseline life cycle emissions for 50% ATJ/50% jet fuel.

SAF HEFA (mixing ratio 50%)	Quantity kg	LHV [MJ]	Baseline $[gCO_2eMJ^{-1}]$
Jet Fuel	988751	42615168	4005826000
ATJ	926016	39672005	1388520000
Total	1915667	82287173	5394346000

Table 22
LHV and Baseline life cycle emissions value for jet fuel vs ATJ.

Jet Fuel 100%	Quantity kg	LHV [MJ]	Baseline $[gCO_2eMJ^{-1}]$
Values	1977503	85230397	8.011657000
Variation	+3.2%	+3.6%	+48%

Considering the estimated total fuel consumption of the aircraft engines and APU throughout the week under the analysis of 1 977 503 kg and assuming an SAF FT with a mix ratio of 50%, we arrive at the values listed in Table 19.

In Table 20 it is possible to observe the values of LHV and the baseline life cycle emissions for 100% jet fuel, and a comparison in percentage with the values obtained for a mixture of 50% FT/50% jet fuel.

Owing to the lower density of FT compared to Jet Fuel, for the period under analysis, the quantity of Jet Fuel to be transported would be 3,7% higher than if the mixture was used (jet fuel 50% + SAF FT 50%). The lower heating value (LHV) assumes a variation of 2.5% because of the very similar LHV between them. The most drastic and expected variation lies in the analysis of g CO2e/MJ, where the use of only jet fuel represents an increase in CO_2 emissions, equivalent to approximately 78% of the mixture under analysis. This value only represents the time period of one week. The period under analysis in the study, which, when extrapolated to the monthly and annual periods, represents an increasingly overwhelming difference between the two options, thus reinforcing the need to continue with the adoption of this type of fuel to achieve the defined environmental goals.

Considering the estimated total fuel consumption of the aircraft engines and APU throughout the week under the analysis of 1 977 503 kg and assuming an SAF ATJ with a mix ratio of 50%, we arrived at the values listed in Table 21.

In Table 22 it is possible to observe the values of LHV and baseline life-cycle emissions for 100% jet fuel and a comparison of the percentages with the values obtained in Table 21 for the mixture of 50% ATJ/ 50% jet fuel.

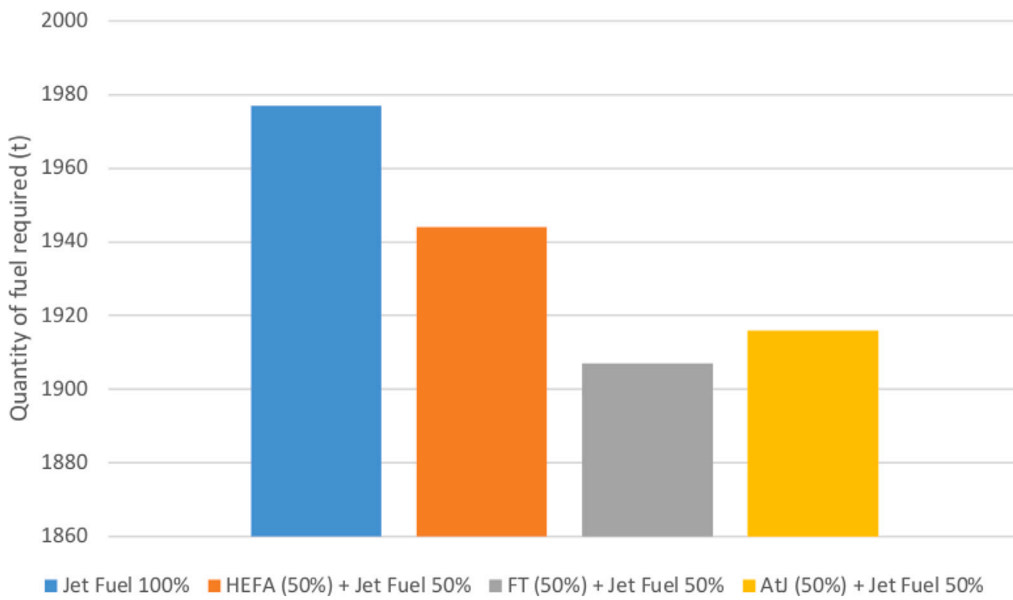

Fig. 8. Comparisons of quantity of fuel required for jet fuel and different SAF options.

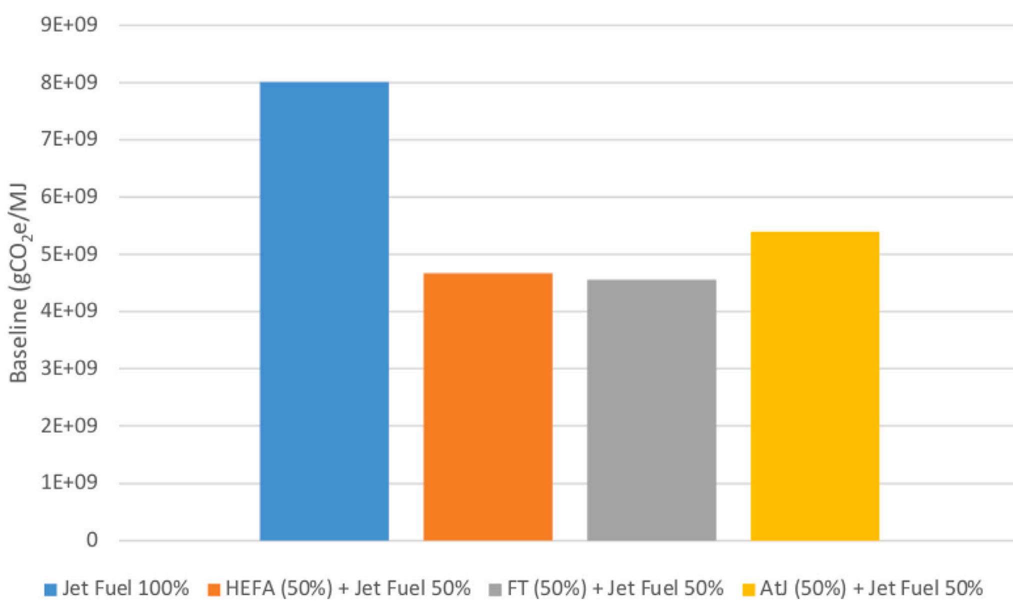

Fig. 9. Comparisons of baseline for jet fuel and different SAF options.

Owing to the lower density of ATJ compared to Jet Fuel, for the period under analysis, the quantity of Jet Fuel to be transported would be 3.2% higher than if the mixture was used (jet fuel 50% + SAF ATJ 50%). The lower heating value (LHV) assumes a variation of 3.6%, due to the very similar LHV between them. The most drastic and expected variation lies in the analysis of g CO2e/MJ, where the use of only jet fuel represents an increase in CO_2 emissions equivalent to approximately 48% compared with the mixture under analysis. This value only represents the time period of one week, the period under analysis in the study, which when extrapolated to the monthly and annual period will represent an increasingly overwhelming difference between the two options, thus reinforcing the need to continue with the adoption of this type of fuel in order to achieve the defined environmental goals.

Figs. 8, 9 and 10 show a simplified comparison of the simulations of the required fuel, LHV and Baseline for each of the SAFs that present a higher FRL/TRL as well as a greater capacity of production in the coming years.

Considering the CO_2 equivalent emissions (g CO2e/MJ) for each type of SAF included in the study, with a mixture of 50% HEFA and 50% jet fuel, using this SAF mix the quantity of jet fuel to be transported was 0.9% lower than that of jet fuel. Compared with the mixtures used in the analysis. The use of only jet fuel represents increase in CO2e/MJ to approximately 71%. For a mixture of 50% FT and 50% jet fuel, the quantity of jet fuel to be transported was 3.7% lower than that of the jet fuel. Compared with the mixture used in the analysis. The use of jet fuel only represents an increase in CO2e/MJ of approximately 75%. Finally, for a mixture of 50% ATJ (Following Abrantes et al. (2021), average values for ATJ produced from corn stover used in the present study corresponds to 35g CO2e/MJ) and 50% jet fuel, the total quantity of jet fuel to be transported was 3.2% lower than that of jet fuel. Compared with the mixture used in the analysis. the use of only jet fuel represents an increase in CO_2 emissions of approximately 48%.

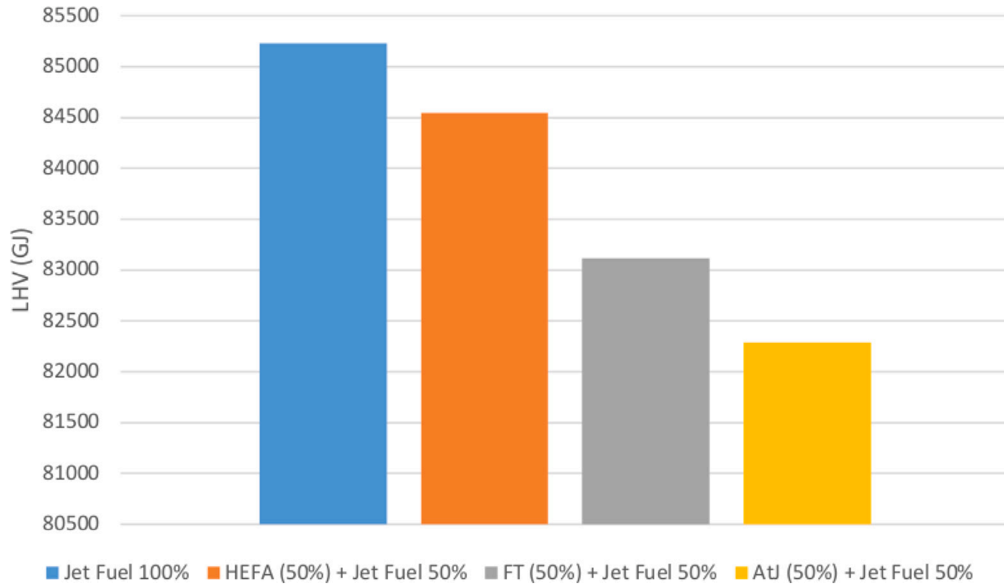

Fig. 10. Comparisons of LHV for jet fuel and different SAF options.

5. Conclusions

This study provides an overview of the environmental impacts of different types of aviation fuels, allowing quantification and evaluation of the overall benefit of introducing SAF in general and in more detail, particularly at Lisbon Airport, through a case study based on aircraft movements and pollutant emissions.

The results obtained are as follows:

- During a standard LTO cycle, CO_2 represents the largest pollutant with 96% of total GHGs emissions, with the Idle phase being the most polluting.
- Comparing to the use of 100% Jet Fuel, the use of SAF (50% FT + 50% Jet Fuel) during the LTO cycle represents a reduction of around 78% emissions CO2e/MJ. The SAF mixture (50% HEFA + 50% Jet Fuel) exhibits a reduction of 71%. The mixture (50% ATJ + 50% jet fuel) represents a reduction of 48%.
- The GWP value for N_2O is much higher than the GWP value for CO_2. Despite the absolute value of NOx emissions representing only 0.49% of CO_2 emissions for this period, the GWP values were 20% higher for N_2O.
- The APU represented around 13.9% of total CO_2 emission during the LTO cycles (at Lisbon airport in the period considered).
- Despite representing only approximately 6% of total departures during 2019, the long-haul fleet represent half of all CO_2 and NOx emissions.

As a final remark, there is currently a slow and gradual transition to introduce the use of SAF at commercial airports, which will lead to a series of environmental benefits through the reduction of GHG emissions as detailed throughout the work. New technologies must continue to be investigated and applied to the sector to reduce GHG emissions from aviation and meet environmental targets for the sector.

CRediT authorship contribution statement

Leandro B. Magalhães: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Luís F.F.M. Santos:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Ana F. Ferreira:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **André R. Silva:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation.

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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Data availability

Data will be made available on request.

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