Assessment of Energy and Environmental Impacts of Decarbonization Scenarios in Aviation

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***Abstract*— This work assesses the potential of decarbonising the aviation sector via the use of Sustainable Aviation Fuels (SAF), hydrogen propulsion, and direct electrification in major European airports. The case study builds an emissions inventory following European emissions reporting methods and a later, following an LCA approach, emissions analysis in which GHG emissions avoidance is compared to the baseline considering the assumptions and limitations. The analysis of different decarbonization pathways using electrification, hydrogen, and SAFs as main decarbonization drivers revealed that SAF are currently the best solution for reducing emissions from long-haul flights, with an average emission avoidance of 65%, reducing the average emission intensity from 89 g CO_2e/Pk to 31 g CO_2e/Pk. However, for regional and short-medium haul flights, hydrogen and electrification show higher emissions avoidance, up to 98% of emission avoidance with average emission intensities of 4 g CO_2e/Pk but may take longer to deploy. The study also found that the emission factors of different production methods could compromise the sustainability of both SAFs and hydrogen. Electrification's emissions are highly connected to how electricity is produced, with renewable energy yielding the highest GHG emission avoidance. These findings provide a robust foundation for future research in this area.**

Keywords- Decarbonization, Sustainability, Aviation, SAF, Hydrogen, Electrification

I. INTRODUCTION

Aviation is responsible for around 3% of the world's carbon dioxide (CO_2) emissions [1], and as the world economy expands in the upcoming years and more people enter the middle class, aircraft volumes will rise and so will emissions produced by this [2]. The global air transport sector emitted more than nine hundred million tons (Mt) of CO_2 in 2019 plus an unreported quantity of other emissions including nitrogen oxides, sulfur oxides, and carbon particulates [3].

Aviation in the last 20 years is responsible for almost half of the total cumulative emissions in the aviation sector, this is given to the rising developing economies and the appetite for having next summer vacations on the coast of Spain or Thailand or having an important business meeting on the other side of the world. This has happened, even though aviation has been developing substantial efficiency increases throughout the years, and the latest aircraft are more efficient than the ones from earlier years.

Efforts to decarbonize the aviation sector are gaining momentum, with regulatory documents such as the EU Green Deal and initiatives like Fit for 55 and Refuel EU playing pivotal roles. The EU Green Deal, which introduced the European emission trading system (EU ETS) and incorporated aviation into it, is a significant step towards sustainability. The Fit for 55 packages [4], proposed by the European Union, aims to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels across various sectors including energy, transport, agriculture, and buildings. A key component of this package is the revised EU ETS, which sets more ambitious emissions reduction targets and includes new sectors like shipping and aviation.

The ReFuel Aviation Initiative [5], part of the Fit for 55 packages, seeks to expedite the deployment of sustainable aviation fuels (SAFs) through measures such as blending mandates, tax incentives, and research and development support. Similarly, in the United States, the Inflation Reduction Act (IRA) approved in 2022 includes a new tax credit for clean hydrogen production aimed at reducing inflation. This production tax credit is expected to stimulate the clean hydrogen industry by making it more affordable and competitive with other energy carriers.

The objective of the present study is to assess the potential of decarbonization of the aviation sector via direct electrification where feasible, in-direct electrification through hydrogen propulsion and lastly with the use of sustainable aviation fuels, commonly known as SAFs in the main airports in Europe. This will include the use of three different case studies such as the decarbonization of three different countries such as Portugal, the Netherlands, and Norway. These countries are chosen given what they represent in the European Unions. Norway being forerunner in the decarbonization of their aviation sector, Netherlands being one of the major hubs regarding aviation traffic in Europe, and Portugal being a European country which is considered average in their efforts on decarbonization of its aviation sector.

A. *Energy carriers*

The decarbonization of aviation through alternative propulsion systems necessitates the use of different energy carriers, each with its own unique production methods and sources. These energy carriers, which include Sustainable Aviation Fuels (SAF), hydrogen, and electricity.

Sustainable Aviation Fuel (SAF) is a type of aviation fuel derived from non-fossil sources. It is characterized by three main elements. Firstly, it is sustainable, meaning it can be continually and repeatedly sourced in a way that aligns with economic, social, and environmental goals, while preserving an ecological balance by avoiding the depletion of natural resources. Secondly, SAF uses alternative feedstocks to crude oil. These non-conventional or advanced fuels include a variety of materials or substances that can serve as fuels, other than conventional fossil sources. The feedstocks for SAF are diverse and can range from cooking oil and plant oils to municipal waste, waste gases, and agricultural residues. Lastly, as a fuel, SAF must meet the technical and certification requirements for use in commercial aircraft.

Hydrogen, a promising energy vector, is gaining global attention for its potential in addressing climate change. Its ability to store and deliver substantial energy per unit mass without CO_2 emissions during combustion makes it a key player in decarbonizing the world's energy supply. Demand for hydrogen as an energy carrier is projected to increase from 1,000 tons today to 39–161 million tons annually by 2050 under various scenarios [6]. Green hydrogen is produced through the electrolysis of water using renewable electricity, resulting in significantly lower greenhouse gas emissions. On the other hand, blue hydrogen is derived from natural gas, with its greenhouse gas emissions significantly reduced through carbon capture and storage technologies.

Lastly, Electricity from renewable energy harnesses natural sources such as the sun, wind, and water to generate power, providing a sustainable and environmentally friendly alternative to fossil fuels. Direct electrification through battery systems has made considerable progress in recent years, with several companies investing in new electric and hybrid-electric technologies to make the aviation sector more sustainable. Currently some companies such as Heart Aerospace and Eviation are leading the movement towards electric aviation.

II. MATERIALS AND METHODS

The methodology used for the modeling of this work is based on an energy and environmental analysis to the different alternatives which could be used as energy carriers to reduce emissions in the aviation sector. The first step included a literature review and data gathering. Next an emissions inventory was built upon the data gathered from Eurocontrol R&D and following the methodology from the European Environment Agency (EEA)[7]. Finally, an analysis of multiple decarbonization pathways using different energy carriers such as electrification through batteries, hydrogen and sustainable aviation fuel is done.

A. *Emissions inventory*

Emissions inventory is built using data from flights obtained from Eurocontrol R&D dataset. Later, following the Tier 3A methodology which calculates CCD (Cruise, Climb, and Descent) emissions for various flight distances. It requires specific details about the departure and arrival airports, and the aircraft type for both domestic and international flights. This method uses average fuel consumption and emissions data for the Landing and Take-off (LTO) phase, as well as different lengths of the CCD phase, across a range of representative aircraft categories[8].

B. *Decarbonization options*

To compare the current jet fuel-based propulsion system with alternative energy vectors like hydrogen and electricity, an energy flow analysis was conducted. This analysis transforms the energy from burnt fuel into useful energy for propulsion, then called the energy requirement per flight. The quantity of alternative energy needed is calculated based on this required energy and the efficiency of the alternative propulsion system. This allows for the estimation of energy requirements for hydrogen and electricity. For sustainable aviation fuels (SAF), the fuel burnt equals the jet fuel amount per EMEP/EEA methodology. Assumptions, emission factors, efficiencies, and limitations are further detailed.

C. *Scenarios' definition*

This section will detail and explain three proposed scenarios. The pessimistic scenario suggests a total transition from kerosene, the conventional aviation fuel, to a blend of Sustainable Aviation Fuels (SAF) for all types of flights being studied. This scenario hinges on several key assumptions. It presumes that the volume of fuel consumed would be on par with that of Conventional Aviation Fuel (CAF). The emissions factor used is an average value derived from a variety of SAF options, including Hydro processed Esters and Fatty Acids (HEFA), and Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK), among others. Furthermore, this scenario operates on the premise that SAF could feasibly replace 100% of kerosene, a hypothesis that is supported by certain flight tests.

The "Towards hydrogen development" scenario envisions hydrogen replacing kerosene in regional and short to medium-haul flights, with Sustainable Aviation Fuels (SAF) replacing kerosene in long-haul flights. This scenario assumes the same amount of useful energy is required regardless of fuel type, air traffic levels remain constant, and hydrogen is either green (from renewable sources) or blue (from natural gas with high carbon capture and storage and a 1.5% methane emissions rate).

The "Towards electrification" scenario proposes electricity to replace kerosene in regional flights, and Sustainable Aviation Fuels (SAF) to replace kerosene in short to medium and long-haul flights. This scenario assumes the same amount of useful energy is required regardless of fuel type, air traffic levels remain constant, and electricity is either green (from renewable sources) or grid electricity using the average per country.

D. *Main assumptions*

This subsection outlines the key assumptions. Table 1 provides the energy content comparison for different energy carriers, utilizing the low heating value (LHV) to enable a fair comparison across all energy carriers.

Table 1. Energy content.

Energy content	LHV	Unit
Kerosene [9]	43	MJ/kg
Hydrogen [9]	120	MJ/kg

Table 2 outlines the various emissions factors utilized in the different scenarios. For a fair comparison, all scenarios consider well-to-wake emissions, also known as Life-cycle emissions. These encompass both upstream (well-to-tank) and downstream (tank-to-wake) emissions.

Table 2. Emission factors for different scenarios

Emissions Well to Wake	CO_2e	Unit
Kerosene [10]	89	g CO_2e/MJ
Average SAF [10]	31	g CO_2e/MJ
Blue H2 High-CCS [11]	29	g CO_2e/MJ
Green H2 [11]	3	g CO_2e/MJ
Avg. EF renewable [12]	17	g CO_2e/kWh
Avg. EF Grid PT [13]	234	g CO_2e/kWh
Avg. EF Grid NL [13]	356	g CO_2e/kWh
Avg. EF Grid NO [13]	29	g CO_2e/kWh

Table 3 presents a summary of the efficiencies used for comparing the overall efficiencies in each scenario. These efficiencies are derived from an average of several sources found in literature or as stated on various manufacturers' websites.

Table 3. Efficiencies for different scenarios

Efficiencies	
Conventional (Turbines) [14]	40%
Hydrogen (turbines/fuel cells) [15]	50%
Electric (powertrain/battery) [16]	90%

III. RESULTS

This section presents the characterization of the current situation which is derived from using the EEA methodology to determine the emissions inventory of the commercial aviation industry for the selected countries for the case study the Netherlands, Norway, and Portugal. Following, a comprehensive analysis of the best performing energy carriers which can help decarbonize the hard to abate industry such as the aviation industry. Subsequently, an interpretation and comparison of the results regarding their energy intensity and emissions intensity of each of the options. Lastly, a comparison of the requirements of energy carriers in each of the options stated and the available or current level or production or capacity installed in each of the countries in the case study.

A. *Characterization of current situation*

For characterizing and being able to compare the result with other reports, flight type was separated into three categories, regional flights, short/medium haul flights and long-haul flights. For this, regional flights were considered flights shorter than one hour of flight, short/medium haul flights were considered flights between 1 and 2.5 hours of flight, and long-haul flights were considered flights longer than 2.5 hours. Figure 1 shows the disaggregation of the total number of flights per flight type. From this, it can be grasped that Portugal, and the Netherlands commercial aviation industry is composed of a majority of flights being short, medium, and long haul. In contrast, most of the flights occurring in Norway are regional and short/medium haul flights.

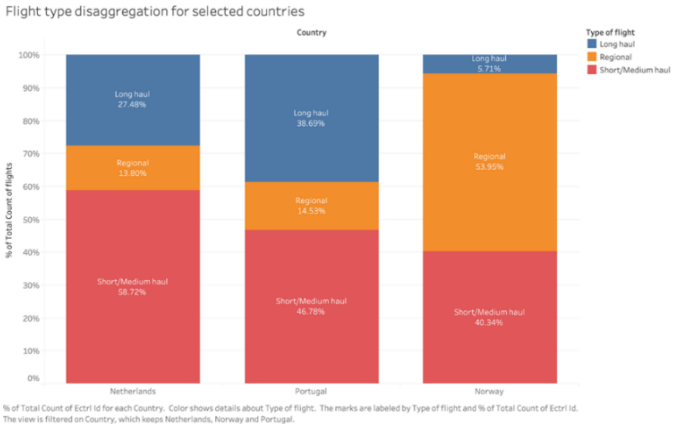

Figure 1. Flight type disaggregation (%) for selected countries.

For the same period, energy used in megajoules was calculated. Figure 2 shows the aviation sector's kerosene consumption for the selected period and selected countries. Here it can be identified how long-haul flights are the ones using most of the energy. This is notably the case for the Netherlands and Portugal where consumption from this category is over 8 petajoules and 3 petajoules respectively. In the case of Norway, every category consumes 1 petajoule of energy. For comparing reasons, 1 petajoule is the same as 278 gigawatt hours of energy which is enough energy to power 19,000 homes in a year, or 868,000 refrigerators in a year.

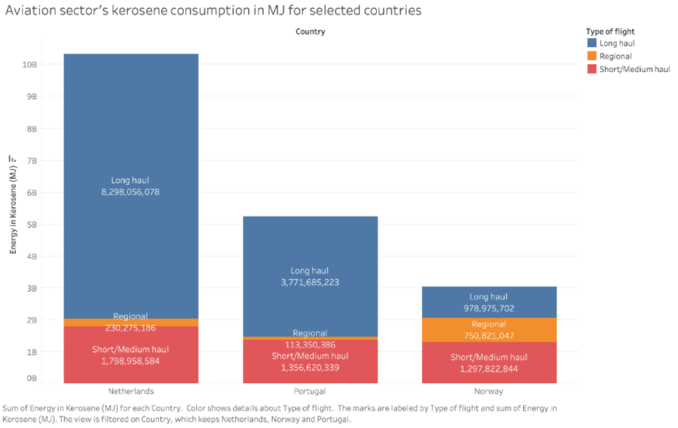

Figure 2. Aviation sector's kerosene consumption in MJ for selected countries

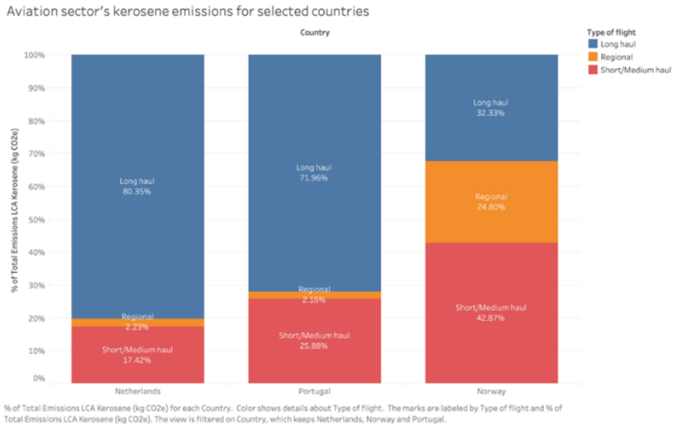

Figure 3. Aviation sector's kerosene emissions for selected countries.

When considering the emissions resulted from the consumption of kerosene from these three countries, it can be observed a similar trend. Figure 3 shows the aviation sector's emissions resulting from kerosene consumption for the selected period and selected countries. The Netherlands has the highest percentage of total emissions of kerosene (CO_2) for long haul flights at 83.25%, which represents 738kt of CO_2 equivalent. Portugal is next of the three with its highest percentage of total emissions of kerosene (CO_2) for long haul flights at 71.96%, which represents 335kt of CO_2 equivalent. Lastly, Norway with its highest percentage of total emissions of kerosene (CO_2) for short/medium haul flights at 42.87%, which represents 115kt of CO_2 equivalent.

This data is crucial for understanding the environmental impact of air travel in these countries and will help to better compare with the emissions intensity of the other decarbonization options in the next section.

B. Case Study: (1) The Netherlands

In this case study, the aviation industry of the Netherlands will be assessed with different decarbonization options in three scenarios. The first scenario is a pessimistic scenario in which sustainable aviation fuel replaces kerosene as the decarbonization energy carrier. Afterwards a second scenario will be assessed, the towards development of hydrogen scenario in which it is supposed that industry pushes into the development of hydrogen aircraft. In this both regional and short/medium haul flights are decarbonized using hydrogen as the energy carrier, and long-haul flights are decarbonized using sustainable aviation fuel. Last, the third scenario will be assessed, the towards electrification scenario in which it is assumed that electrification of regional aircraft is pushed. Here, short/medium, and long-haul flights are decarbonized with sustainable aviation fuel.

1) Scenario A: pessimistic

Figure 4 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under two scenarios: Business as Usual and the Pessimistic scenario.

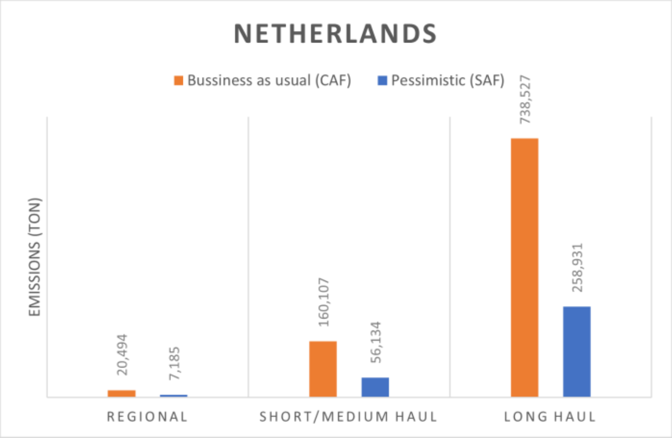

Figure 4. Emissions per flight type, Netherlands, BAU vs pessimistic

In the regional, short/medium, and long-haul categories, the emissions are noticeably lower in the Pessimistic scenario compared to the Business-as-Usual scenario. This suggests that the use of Sustainable Aviation Fuels (SAF) can significantly reduce emissions for these types of flights. This reduction in each of the three categories is 65% in life cycle emissions. While being able to use the same fleet of aircraft and same infrastructure in current airports.

2) *Scenario B: Towards hydrogen development*

Figure 5 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and "towards hydrogen development" using two sources of hydrogen, blue hydrogen produced using natural gas through steam methane reforming process and green hydrogen produced using renewable electricity through water electrolysis process. The flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional, and short/medium, the emissions are noticeably lower in the "towards hydrogen development" scenario compared to the Business-as-Usual scenario. This suggests that the use of hydrogen can significantly reduce emissions for these types of flights. Moreover, the use of green hydrogen can reduce the emissions even further compared to its blue hydrogen counterpart. For the long-haul flights, "towards hydrogen development" keeps sustainable aviation fuels (SAFs) as the alternative and that's why emissions decrease but not as much as for the previous categories.

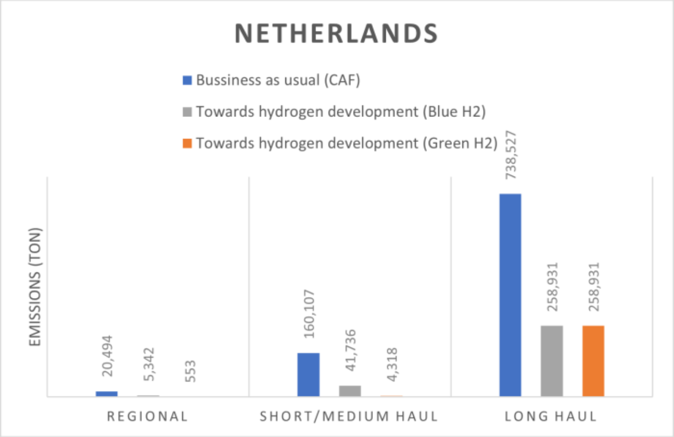

Figure 5. Emissions per flight type, Netherlands, BAU vs Hydrogen development

3) *Scenario C: Towards electrification*

Figure 6 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and "Towards electrification" using two sources of electricity generation, Electricity from the countries' grid with its corresponding average emissions and electricity produced with renewable energy, in this case an average between hydropower and wind energy. Again, the flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional flight category, the emissions are noticeably lower in the "Towards electrification" scenario compared to the Business-as-Usual scenario. This suggests that the use of electric aircraft can significantly reduce emissions for these types of flights. Moreover, the use of renewable energy can reduce the emissions even further compared to using the national grid average, at least while this one is decarbonized. For short/medium haul and long-haul flights the, "towards electrification" keeps sustainable aviation fuels (SAFs) as the alternative and that's why emissions decrease but not as much as for the previous categories.

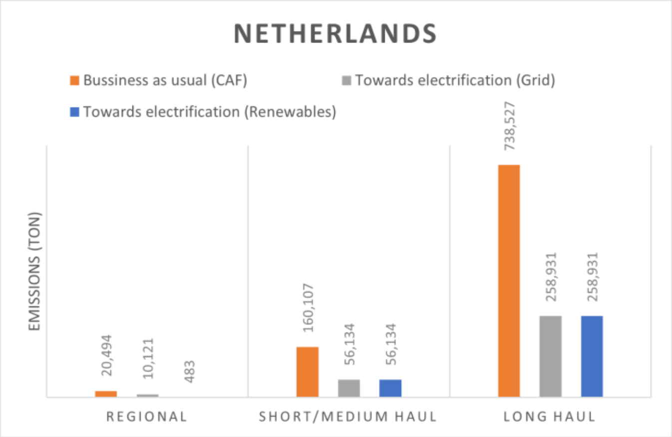

Figure 6. Emissions per flight type, Netherlands, BAU vs electrification

Emissions reductions observed in figure 6 correspond to a reduction in emissions for regional of 51% with the use of electricity from the grid and 98% with the use of renewable energy. For short/medium haul and long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

C. Case Study: (2) Norway

Like previous case study, the aviation sector of Norway will be assessed with different decarbonization options in three scenarios. The first scenario is a pessimistic scenario in which sustainable aviation fuel replaces kerosene as the decarbonization energy carrier. Afterwards a second scenario will be assessed, the development of hydrogen scenario in which it is supposed that industry pushes into the development of hydrogen aircraft. In this both regional and short/medium haul flights are decarbonized using hydrogen as the energy carrier, and long-haul flights are decarbonized using sustainable aviation fuel. Last, the third scenario will be assessed, the towards electrification scenario in which it is assumed that electrification of regional aircraft is pushed. Here, short/medium, and long-haul flights are decarbonized with sustainable aviation fuel.

1) Scenario A: pessimistic

Figure 7 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Norway under two scenarios: Business as Usual and the Pessimistic scenario. The flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional, short/medium, and long-haul categories, the emissions are noticeably lower in the Pessimistic scenario compared to the Business-as-Usual scenario. This suggests that the use of Sustainable Aviation Fuels (SAF) can significantly reduce emissions for these types of flights. This reduction in each of the three categories is of 65% in life cycle emissions. While being able to use the same fleet of aircrafts and same infrastructure in current airports.

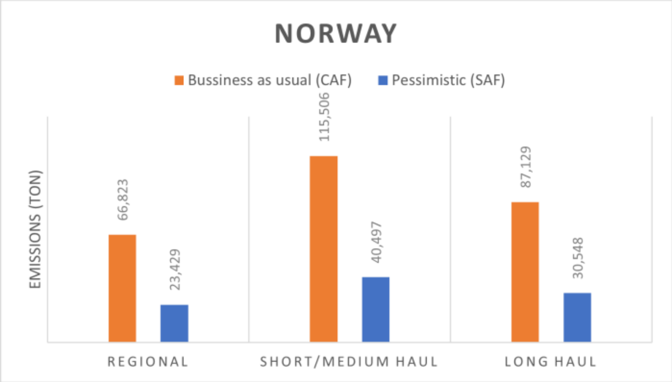

Figure 7. Emissions per flight type, Norway, BAU vs pessimistic

2) Scenario B: Towards hydrogen development

Figure 8 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Norway under three scenarios: Business as Usual and "towards hydrogen development" using two sources of hydrogen, blue hydrogen produced using natural gas through steam methane reforming process and green hydrogen produced using renewable electricity through water electrolysis process. The flights are once again, categorized into three types: regional, short/medium haul, and long haul.

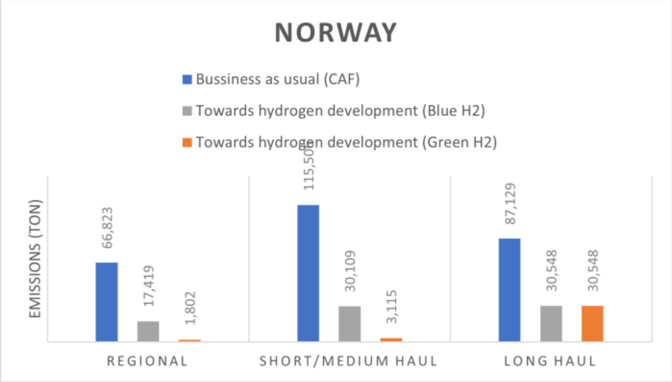

Figure 8. Emissions per flight type, Norway, BAU vs Hydrogen development

In the regional, and short/medium, the emissions are noticeably lower in the "towards hydrogen development" scenario compared to the Business-as-Usual scenario. This suggests that the use of hydrogen can significantly reduce emissions for these types of flights. Moreover, the use of green hydrogen can reduce the emissions even further compared to its blue hydrogen counterpart. For the long-haul flights, "towards hydrogen development" keeps sustainable aviation fuels (SAFs) as the alternative and that's why emissions decrease but not as much as for the previous categories.

Emissions reductions observed in figure 8 correspond to a reduction in emissions for both regional and short/medium haul flights of 74% with the use of blue hydrogen and 97% with the use of green hydrogen. For long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario. For a country such as Norway, decarbonizing its shorter haul flights which include regional and shorter haul flights is a key, as it can be observed from the figure that is it were most of the emissions are currently being emitted.

3) *Scenario C: Towards electrification*

Figure 9 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Norway under three scenarios: Business as Usual and "Towards electrification" using two sources of electricity generation, Electricity from the countries' grid with its corresponding average emissions and electricity produced with renewable energy, in this case an average between hydropower and wind energy. Again, the flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional flight category, the emissions are noticeably lower in the "Towards electrification" scenario compared to the Business-as-Usual scenario. This suggests that the use of electric aircraft can significantly reduce emissions for these types of flights.

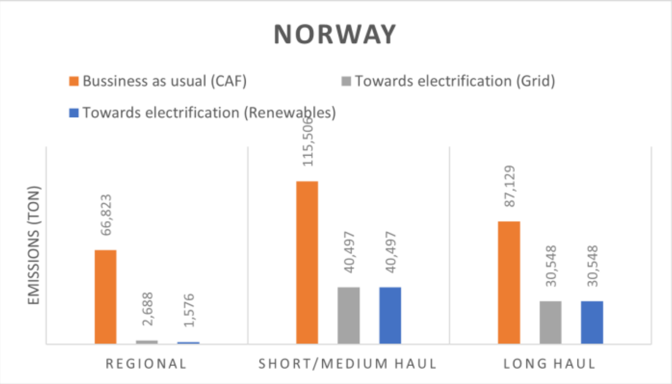

Figure 9. Emissions per flight type, Norway, BAU vs Electrification

Moreover, the reduction between the national countries grid with compared to 100% renewables is similar as the national grid in Norway and the Nordic countries is mostly based on renewables. For short/medium haul and long-haul flights the, "towards electrification" keeps sustainable aviation fuels (SAFs) as the alternative and that's why emissions decrease but not as much as for the previous categories.

Emissions reductions observed in figure 9 correspond to a reduction in emissions for regional of 96% with the use of electricity from the grid and 98% with the use of renewable energy. For short/medium haul and long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

D. *Case Study (3) Portugal*

In this last case study, the aviation sector of Portugal will be assessed with different decarbonization options in three scenarios. The first scenario is a pessimistic scenario in which sustainable aviation fuel replaces kerosene as the decarbonization energy carrier. Afterwards a second scenario will be assessed, the towards development of hydrogen scenario in which it is supposed that industry pushes into the development of hydrogen aircraft. In this both regional and short/medium haul flights are decarbonized using hydrogen as the energy carrier, and long-haul flights are decarbonized using sustainable aviation fuel. Last, the third scenario will be assessed, the towards electrification scenario in which it is assumed that electrification of regional aircraft is pushed. Here, short/medium, and long-haul flights are decarbonized with sustainable aviation fuel.

1) *Scenario A: pessimistic*

Figure 10 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in Portugal under two scenarios: Business as Usual and the Pessimistic scenario. The flights are categorized into three types: regional, short/medium haul, and long haul.

In the regional, short/medium, and long-haul categories, the emissions are noticeably lower in the Pessimistic scenario compared to the Business-as-Usual scenario. This suggests that the use of Sustainable Aviation Fuels (SAF) can significantly reduce emissions for these types of flights. This reduction in each of the three categories is 65% in life cycle emissions. While being able to use the same fleet of aircraft and same infrastructure in current airports.

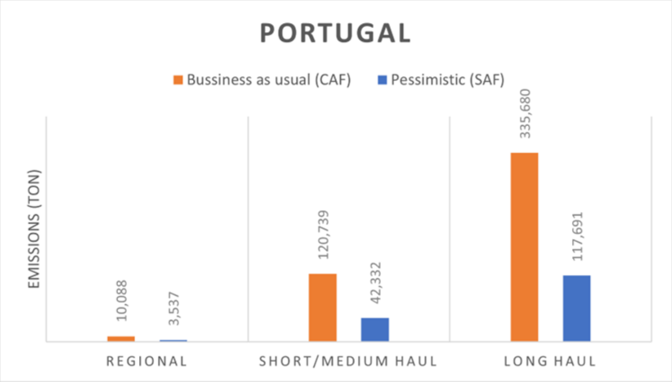

Figure 10. Emissions per flight type, Portugal, BAU vs pessimistic

2) *Scenario B: Towards hydrogen development*

Figure 11 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and "towards hydrogen development" using two sources of hydrogen, blue hydrogen produced using natural gas through steam methane reforming process and green hydrogen produced using renewable electricity through water electrolysis process. The flights are categorized into three types: regional, short/medium haul, and long haul.

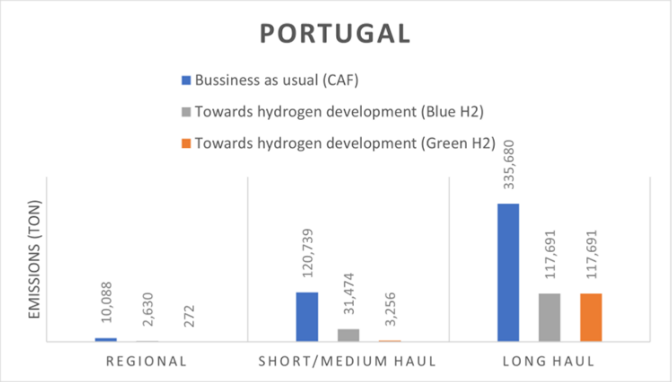

Figure 11. Emissions per flight type, Portugal, BAU vs Hydrogen development

In the regional, and short/medium, the emissions are noticeably lower in the "towards hydrogen development" scenario compared to the Business-as-Usual scenario. This suggests that the use of hydrogen can significantly reduce emissions for these types of flights. Moreover, the use of green hydrogen can reduce the emissions even further compared to its blue hydrogen counterpart. For the long-haul flights, "towards hydrogen development" keeps sustainable aviation fuels (SAFs) as the alternative and that's why emissions decrease but not as much as for the previous categories.

Emissions reductions observed in Figure 11 correspond to a reduction in emissions for both regional and short/medium haul flights of 74% with the use of blue hydrogen and 97% with the use of green hydrogen. For long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

3) Scenario C: Towards electrification

Figure 12 presents a comparison of CO_2 emissions equivalent in tons for different types of flights in the Netherlands under three scenarios: Business as Usual and "Towards electrification" using two sources of electricity generation, Electricity from the countries' grid with its corresponding average emissions and electricity produced with renewable energy, in this case an average between hydropower and wind energy. Again, the flights are categorized into three types: regional, short/medium haul, and long haul.

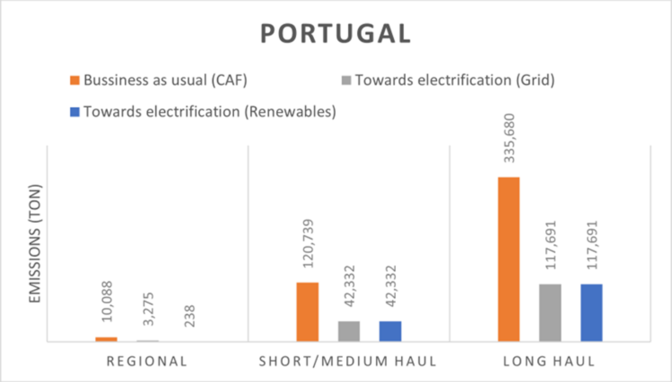

Figure 12. Emissions per flight type, Portugal, BAU vs Electrification.

In the regional flight category, the emissions are noticeably lower in the "Towards electrification" scenario compared to the Business-as-Usual scenario. This suggests that the use of electric aircraft can significantly reduce emissions for these types of flights. Moreover, the use of renewable energy can reduce emissions even further compared to using the national grid average, at least while this one is continuing its decarbonization journey. For short/medium haul and long-haul flights the, "towards electrification" keeps sustainable aviation fuels (SAFs) as the alternative and that's why emissions decrease but not as much as for the previous categories.

Emissions reductions observed in Figure 12 correspond to a reduction in emissions for regional of 68% with the use of electricity from the grid and 98% with the use of renewable energy. For short/medium haul and long-haul flights the use of Sustainable Aviation Fuels (SAF) reduces the emissions to 65% compared to BAU scenario.

IV. DISCUSSION

Final emission intensities are obtained dividing the total emissions by the total number of passengers and kilometers travelled and presented in Table 4. This table offers a comprehensive comparison of the emissions intensity in the aviation sector across three selected countries for the case studies: the Netherlands, Norway, and Portugal. It also summarizes several decarbonization options, including blue and green hydrogen, grid and renewable electrification, and sustainable aviation fuel (SAF).

From the table, it's evident that the regional flights have the highest emissions intensity in its aviation sector, while long haul flights have the lowest. This could be attributed to various factors such as the volume of air traffic, efficiency of aircraft, and load factors assumed. The emissions intensity notably decreases when decarbonization options are assessed in the scenarios. For regional flights the lowest emissions intensity is found using renewable energy or green hydrogen resulting in 5 g CO_2e/Pk. Next for the short-medium haul flights, the lowest emissions intensity is found using green hydrogen resulting in around 3 g CO_2e/Pk. Lastly, long haul flights were only evaluated using sustainable aviation fuels (SAF), decreasing the emission intensity to 30 g CO_2e/Pk.

Table 4. CO_2e emissions per passenger kilometre (Decarbonization options summary)

Countries	**Flight categories**	**Kerosene (gCO2e/Pk)**	**SAF (g CO2e/Pk)**	**Towards hydrogen development (Blue) (gCO2e/Pk)**	**Towards hydrogen development (Green) (gCO2e/Pk)**	**Towards electrification (Grid) (gCO2e/Pk)**	**Towards electrification (Renewable) (gCO2e/Pk)**
Netherlands	Regional	183.4	64.3	47.8	4.9	90.6	4.3
	Short/Medium haul	109.2	38.3	28.5	2.9	38.3	38.3
	Long haul	94.2	33.0	33.0	33.0	33.0	33.0
Norway	Regional	189.3	66.4	49.3	5.1	7.6	4.5
	Short/Medium haul	108.2	37.9	28.2	2.9	37.9	37.9
	Long haul	86.9	30.5	30.5	30.5	30.5	30.5
Portugal	Regional	190.6	66.8	49.7	5.1	61.9	4.5
	Short/Medium haul	97.3	34.1	25.4	2.6	34.1	34.1
	Long haul	87.1	30.6	30.6	30.6	30.6	30.6

V. CONCLUSIONS

In the present work, one of the several pathways to achieve the so deserved decarbonization and guilt-free flying is explored, here in the substitution of current jet fuel, with more sustainable alternatives such as drop-in Sustainable aviation fuels (SAF), hydrogen and direct electrification with batteries. Through a comprehensive emissions inventory made following European emissions reporting methods and a later well-to-wheel (wake) emissions analysis in which GHG emissions avoidance is compared to the baseline considering the assumptions and limitations. Lastly, a comparison of the current production capacity installed of these more sustainable alternatives versus the amount needed to replace this energy requirement, on a high-level basis.

While Sustainable Aviation Fuel (SAF) is a leading development for decarbonization in the aviation industry. Other research areas include alternative energy sources such as hydrogen and electric power [17]. The presented analysis of the different decarbonization options has given rise to different paths for each of the flight types, each with a different level of GHG emissions avoidance.

From the perspective of sustainable aviation fuels (SAF) as a decarbonization vector, different production methods and feedstock have a different emission factor which could compromise the sustainability of the fuel. Current production levels are low worldwide, with Europe and the United States leading with policies and mandates which are investing heavily into increasing the production of sustainable aviation fuel from both biological and non-biological feedstock. From the current work comparison, SAF is the best and only solution as of now to help reduce the emissions of long-haul flights, with an average emission avoidance of 65%. For the other flight types, regional and short-medium haul flights, the use of hydrogen and electrification wins in emissions avoidance but might take longer to be deployed according to recent technology advancements and hydrogen/energy production.

From the perspective of hydrogen as a decarbonization vector, again different production methods have a different emission factor which could compromise the sustainability of the fuel. From the current work comparison, the highest GHG emissions avoidance were obtained when green hydrogen was used. Emissions avoidance for the moderate case were blue hydrogen with a high CCS usage and moderate methane emissions was found to be ten times higher emissions than its green hydrogen counterpart but still resulting in GHG overall emissions avoidance compared to baseline with jet fuel or the use of sustainable aviation fuel as decarbonization vector.

Lastly, from the perspective of electrification and the use of batteries as a decarbonization vector, emissions are highly connected to how electricity is produced and could compromise the overall sustainability of the option. From the current work comparison, the highest GHG emission avoidance was obtained when electrification was achieved with renewable energy, in this case from wind and hydropower energy. Emissions avoidance for the moderate case where electricity is used from the grid resulted in different emission intensities depending on the current state of decarbonization of the grid. Having the highest emission intensity when using electricity from the grid in the Netherlands with a share of renewable energy in the grid of 33% and an emission intensity of 90.55 gCO_2e/Pk, next Portugal with a share of renewable energy in the grid of 62% and an emission intensity of 61.9 gCO_2e/Pk, and with the lowest emission intensity Norway with a share of renewable energy in the grid of 99% and an emission intensity of 7.61 gCO_2e/Pk.

Ultimately, this research presents contributions towards the important task of decarbonizing the aviation sector by providing a high-level overview of the studied decarbonization vectors and their GHG emissions avoidance contributions to policy makers, researchers and to the public. An effective strategy for decarbonizing the aviation sector hinges on the thoughtful selection of alternative energy vectors such as SAF, hydrogen and electricity, and their respective power systems combinations. This approach should be a combination of all different options were better suitability and should not be only limited to the change of energy vector or technology but should also come together with policies to a sustainable decarbonization of the aviation sector for the whole society.

VI. REFERENCES

[1] B. Graver, K. Zhang, and D. Rutherford, "CO 2 emissions from commercial aviation, 2018," 2018.

[2] Shell and Deloitte, "DECARBONISING AVIATION: CLEARED FOR TAKE-OFF 1 IN COLL ABOR ATION WITH Decarbonising Aviation: CLEARED FOR TAKE-OFF Industry Perspectives DECARBONISING AVIATION: CLEARED FOR TAKE-OFF 2," 2021. [Online]. Available: www.shell.com/DecarbonisingAviation

[3] ATI, "ATI SUSTAINABILITY MODEL Technologies Fleet Usage Aircraft development End of life ATI whole aircraft models Net CO_2 (NO x) (H_2O) (Noise) Figure 1-Schematic of ATI's sustainability model," 2022.

[4] EASA, "European policy." Accessed: Oct. 28, 2023. [Online]. Available: https://www.easa.europa.eu/eco/eaer/topics/introduction/european-policy

[5] EASA, "Current landscape and future of SAF industry." Accessed: Oct. 16, 2023. [Online]. Available: https://www.easa.europa.eu/eco/eaer/topics/sustainable-aviation-fuels/current-landscape-future-saf-industry

[6] DNV, "An evaluation of emerging hydrogen value chains," 2018.

[7] European Environment Agency., *EMEP/EEA air pollutant emission inventory guidebook 2019 : technical guidance to prepare national emission inventories.* 2019.

[8] EEA, "1-a-3-a-aviation," 2019.

[9] "Fuels - Higher and Lower Calorific Values." Accessed: Oct. 24, 2023. [Online]. Available: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

[10] "CORSIA SUPPORTING DOCUMENT CORSIA Eligible Fuels-Life Cycle Assessment Methodology".

[11] C. Bauer *et al.*, "On the climate impacts of blue hydrogen production," 2022, doi: 10.1039/d1se01508g.

[12] S. Nicholson and G. Heath, "Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update Life Cycle Assessment of Energy Systems," 2012, Accessed: Oct. 24, 2023. [Online]. Available: https://data.nrel.gov/submissions/171

[13] "Carbon intensity of electricity, 2000 to 2022." Accessed: Oct. 24, 2023. [Online]. Available: https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table&country=~PRT

[14] F. Asher, "Aircraft Engine Design Fuel efficiency vs. Noise".

[15] Zeroavia, "The Hydrogen-Electric Cessna Grand Caravan."

[16] Heart Aerospace, "ES-30." Accessed: Oct. 16, 2023. [Online]. Available: https://heartaerospace.com/es-30/

[17] FAA, "United States 2021 Aviation Climate Action Plan," 2021.