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Towards energy self-sufficiency for a regional airport thanks to local production of new energy carriers

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ABSTRACT

The transition from fossil fuels to sustainable energy sources is an important challenge for current aviation industries. One of the critical questions in this transition is how much electricity is needed to accommodate future air transport demand and how to supply it. The answer depends on the type of energy carriers, their production process, and the source of the electricity. This paper provides a methodology to estimate the annual required electricity to produce energy carriers (particularly electrofuel and liquid hydrogen) with a given energy production process for an airport. The methodology also computes the surface of solar panels and/or the number of wind turbines needed to produce the annual electricity, which shows the possibility of energy self-sufficiency within the region around an airport. We apply the methodology to the Carcassonne Airport located in the Aude department, France, where sustainable energy sources are easily accessible. The result shows that 112 GWh and 138 GWh of electricity will be required when all the airplanes departing and landing at the airport in 2022 are replaced with electrofuel and liquid hydrogen-powered airplanes, respectively. 49 ha of solar panels or 21 onshore wind turbines are necessary to supply the required electricity in the case of electrofuel. 61 ha of solar panels or 25 onshore wind turbines are necessary to supply the required electricity in the case of liquid hydrogen. This corresponds to 1% to 3% of the electricity production of the Aude department in 2030, which implies that energy self-sufficiency of the airport is feasible. The methodology is also applied to all French airports in 2016. The total electricity required at the national level and per airport is assessed. This methodology can contribute to the elaboration of national and local energy strategies for aviation.

Introduction

Air transport has been mostly relying on a single energy carrier: kerosene, a fossil fuel. The combustion of kerosene generates greenhouse gases, such as CO₂, water vapour, soot, sulphate, and NO_x [18]. These gases from air transport correspond to around 3% of global greenhouse gas emissions [18, 13]. Reducing fuel consumption (fossil kerosene) per passenger and per kilometer is one way to reduce adverse gas emissions. According to the Civil Aeronautics Research Council [10], however, fuel consumption per passenger kilometer has already decreased by five times since 1960 which is due to improvements in engine and on-board system technologies and lighter aircraft with optimized aerodynamics [10]. Most new engines introduced are more efficient in terms of reducing fuel consumption and consequent CO₂ emissions, but their energy sources still rely on fossil fuel [33], which has limitations in reducing emissions. To overcome such limitations and reduce aviation's climate impact, most current research focuses on the employment of low-carbon energy carriers, improvements to operations (e.g., trajectory optimization and air traffic management) and infrastructure, and transition of engine technology (e.g., implementing new low-carbon propulsion technologies) [23, 7, 38, 6, 36, 28, 2]. Among them, we investigate the employment of low-carbon energy carriers, particularly electrofuels and liquid hydrogen. The importance of these energy carriers in the reduction of aviation emissions has been highlighted in many literature articles [15, 27]. For example, "Scenario 2: aggressive sustainable fuel deployment," proposed by ATAG, shows that sustainable aviation fuel, including electrofuel, can contribute 75% of aviation emissions reduction by 2050 [2]. Assessing the impact of changes in airplanes' energy carriers should be holistic, from energy generation to energy use. Another alternative to reduce aviation emissions is to use liquid hydrogen (LH₂) as a fuel [15, 27]. To do so, we

consider an airport's energy consumption. Airports play a vital role in the air transport industry value chain, acting as the interface point between the air and surface transport modes [4]. Airport energy consumption can be broken down into two parts:

1. Energy consumption due to airport operations [9, 29, 3]. In other words, the energy used to power airport infrastructures (buildings and airport equipment). This represents approximately 3% of the total energy consumption of the civil aviation industry [19].
2. Energy consumption due to flight operations [39, 40, 5]. In 2018, jet fuel costs accounted for about 24% of airlines' operating costs *.

In this study, we focus only on the latter by looking into information about the flights and the number of passengers. Particularly, the effect of introducing the "low-carbon" fleet, either electrofuel or liquid hydrogen (LH₂) burning airplanes, is considered. The energy required, which corresponds to the energy consumption, for a "low-carbon" fleet is estimated. A mixed fleet made of both electrofuel and LH₂ is not considered. The feasibility of the airport's energetic self-sufficiency is also assessed by investigating an inventory of local (in the department) renewable energy resources.

The paper is organized as follows: First, we present the general methodology for estimating the annual required electricity to produce energy carriers with a given energy production process for an airport. We then apply the method to the specific case of Carcassonne airport. Finally, we showcase the past energy demand of most French airports and discuss their self-sufficiency potential.

1.0 Method

Let us answer the following question: what energy and surface area budget does a regional airport need to satisfy air transport demand? The approach used to answer this question is as follows: firstly assessing the air transport demand, secondly quantifying energy demand and finally quantifying electricity demand.

1.1 Assessing the air transport demand

In this work, the OAG (Official Airway Guide) database is used. The database contains all scheduled flights per year, aircraft type (IATA code), number of seats offered N_{pax} , origin and destination (OD pairs) and flight frequency F on each OD pairs per year. The database is filtered to include only commercial passenger flights. We assume that 100% of the seats offered are occupied. In this way, the database gives us air travel demand for a given OD pairs. Annual air travel demand for an OD pairs is defined as the annual number of passengers on each route. The number of passengers is determined by flight frequency and the aircraft seats offered on each route.

1.2 Quantifying energy demand

First we evaluate the required on-board energy : The total energy $E_{mission}$ necessary to fulfill a given mission takes into account taxiing, take-off, climb, cruise, descent and reserves of

* <https://www.iata.org/contentassets/c81222d96c9a4e0bb4ff6ced0126f0bb/iata-annual-review-2019.pdf>

energy in case of delay or diversion. The reserves are not included in the fuel consumption.

$$E_{mission} = E_{flight}(TOW, L/D, SFC, V, d) \quad \dots (1)$$

with TOW the take-off weight, L/D the lift over drag ratio, V the cruise speed, d the flight distance. For a given airplane, with a given number of passenger, the TOW depends on the flight distance, the Operational Empty Weight (OEW) and the mass of fuel needed to fly this distance. For electrofuel airplanes, the OEW will remain the same as for fossil-fuel airplanes. But for liquid hydrogen airplanes, a new design is needed to host the hydrogen tank. This design is performed thanks to the Generic Airplane Model (GAM) [37]. This aircraft design tool is based on statistical regressions to rapidly obtain an estimate of the main mass and consumption characteristics of thermal aircraft burning kerosene, methane or hydrogen, or even battery- or fuel-cell-powered electric aircraft. For aircraft sizing, the GAM needs some information about each aircraft (see Table 1). The following assumptions have been made to size the aircraft:

- for electrofuel aircraft: each electrofuel based aircraft will have the same fuel consumption as a fossil-fuel based aircraft.
- for liquid hydrogen aircraft: we assume that airplanes will have the same design mission, only the energy carrier is different.

Power system	Design mission
energy type	Aircraft category
engine count	N_{pax}
engine type	cruise speed
thruster type	design range
bpr (for turbofan engine only)	cruise altitude

Table 1

Inputs for GAM design procedure. bpr stands for ByPass Ratio.

Finally, the energy consumption at the airport level will depend on the destinations, flight frequency and aircraft type.

$$E_{airport, on-board} = \sum_{i \in destinations} \sum_{j \in aircraft.type} E_{mission}(TOW_j, L/D_j, SFC_j, V_j, d_i) \quad \dots (2)$$

1.2.1 Electrofuel

Electrofuels are synthetic fuels using the CO_2 captured from the atmosphere or from source (at plant outlets) as feedstock. This captured CO_2 is combined with hydrogen to produce synthetic fuel. It can be produced via the methanol or Fischer-Tropsch pathway [26, 21]. This fuel has properties similar to those of fossil kerosene. As such, its use does not require any major changes to the configuration of the aircraft or engine, or to the energy storage and distribution infrastructure [23]. In this paper the CO_2 is assumed to be captured from atmosphere (Direct Air Capture) and only the Fischer Tropsch pathway is considered to produce electrofuel. We choose the approach of Soler and Schmidt [30] to model this process, but with changes in the heat production model from electricity to a heat pump model with a ratio of

thermal power to electrical power of 4. Electrofuel production process could be split into the following sequences [22, 16]

1. Capture of CO₂ from the atmosphere or concentrated source
2. Hydrogen production via water electrolysis.
3. The Reverse Water Gas Shift (RWGS) process. This process converts CO₂ and hydrogen into carbon monoxide and water
4. Fischer-Tropsch synthesis, a catalytic reactions that transform the syngas (gaseous mixture of carbon monoxide and hydrogen) into a synthetic crude with very long carbon chain.
5. Hydroprocessing process consisting of several petroleum reactions (hydrotreating, hydrocracking, hydro- isomerisation) that purify the syncrude from heteroatoms (O, N, S...), break down the large hydrocarbon molecules of the waxy product into the desired electro fuel carbon length chain and finally isomerize the different molecules to improve their low temperature properties. These different petroleum operations are done under a hydrogen-rich environment, high pressure and high temperature.

It is assumed in this article that the electrofuel is not blended with the fossil fuel. Pure electrofuel have almost zero sulfur and aromatics [8]. The absence of aromatics has both advantages and disadvantages. The major advantage of aromatic free fuels is that they are cleaner burning fuels with, generally, lower particulates remaining after combustion (no sulphur dioxide (SO₂) and sulphuric acid (H₂SO₄)) compared to those from the conventional jet fuel [34]. However, this could pose problems of compatibility with engine materials [34].

1.2.2 Liquid hydrogen (LH₂)

Hydrogen is one of the solutions that could replace fossil-based kerosene if produced sustainably, i.e. using decarbonized energy. Hydrogen offers several advantages. In fact, using hydrogen as fuel for aircraft produces no CO₂ emissions in flight. In addition, hydrogen contains around 2.8 times more energy than kerosene per mass unit [20] but the energy/volume ratio of LH₂ is more than 4 times lower than that of kerosene if the container is included in the estimate [11]. However, the widespread use of hydrogen poses a number of problems.

- Safety problem. Hydrogen is about 14 times lighter than air. So when it spills out, it diffuses rapidly [27]. What's more, hydrogen's auto-ignition temperature is considerably higher than that of kerosene. Its flammability range is 4-76%, compared with 1.4-7.6% for kerosene [24, 14]. So, if the concentration of hydrogen in air is higher than 4% and lower than 76%, a fire can occur. Note that the hydrogen flame is invisible and the gas is odorless. This makes leak detection and fire-fighting difficult. Therefore, to reduce the evaporation rate of hydrogen, it is necessary to have hydrogen tanks that comply with safety standards, particularly in terms of insulation [27]. Hydrogen can be stored in two forms: compressed at 700 bar or liquefied at -253C. Storage in liquid form requires less volume than storage in compressed form for the same mass quantity. The gravimetric index of the compressed hydrogen tank at 700 Bar (0.05 kg/kg) is much lower than that of the LH₂ tank (0.4 kg/kg). As a result, compressed hydrogen tanks are heavier than liquid hydrogen tanks.

- NO_x emission problem. Hydrogen combustion in today's aircraft engines favors an undesirable rise in temperature during the combustion process. This results in excessive NO_x emissions, as NO_x is produced during high-temperature combustion. Thus, the use of LH_2 in conventional kerosene engines requires a redesign of the combustion chambers to achieve optimum efficiency [25, 27].

Electrolyser efficiency (%)	Specific liquefaction energy (kWh_{elec}/kg_{LH_2})	Hydrogen energy density (MJ/kg)
66.5	10	120

Table 2

Assumptions for liquid hydrogen production modelling [12, 24, 31, 17, 32, 1]

1.3 Electricity demand

For a given amount of on-board energy, the production of the energy carrier (electrofuel, biofuel, liquid hydrogen) consumes electricity. In the following we investigate two approaches :

- The first approach evaluates the solar photovoltaic surface area or the number of onshore wind turbines that would enable a self-sufficient airport electricity production. In such a case, the airport would have the possibility to source its energy off grid, which would of course reduce transmission loss but also make it independent of energy market price and imponderable.
- The second approach is to compare the airport's energy requirements (electricity) with green electricity production (i.e. production from renewable resources) in the department or territory where the airport is located.

The first case study proposed takes the Carcassonne airport as case study. We will determine the energy needs of Carcassonne airport. Next, we will assess the local resources of the Aude department in terms of electricity production. Finally, we will evaluate different scenarios for making the airport self-sufficient, considering electro-fuel and liquid hydrogen as energy carriers.

2.0 Case study 1: Carcassonne airport

Carcassonne airport is located in the department of Aude in France and covers an area of 110 ha. The airport handles international and domestic non-scheduled commercial flights. Traffic averages 23,606 aircraft movements a year, for 326,375 passengers [†]. Between 2013 and 2022 Carcassonne airport was connected to nineteen airports (see Table 3)

2.1 Carcassonne airport's energy need

At present, Carcassonne's aircraft fleet is powered by fossil fuels. The objective of this section is to replace Carcassonne's fleet of aircraft with a fleet using decarbonized energy. To do

[†] <https://www.aeroport.fr/view-statistiques/carcassonne-sud-de-france> consulted in february 2024

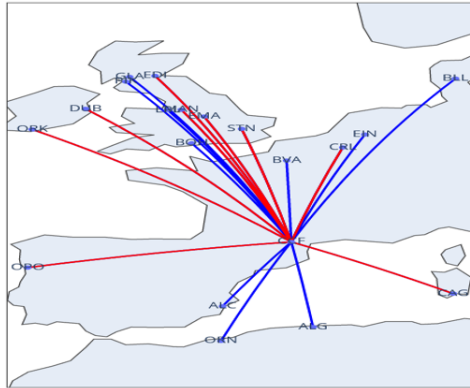


Figure 1. Carcassonne network in 2022 (blue) and all routes since 2013 (red and blue)

Airport	IATA	distance d (km)	Aircraft IATA code	$PK_{max}/1000$
Cork	ORK	1252	738, 73H	9702
Liverpool John Lennon	LPL	1188	738, 73H	24474
Londres-Stansted	STN	977	738, 73H	64305
Dublin	DUB	1297	738, 73H	38731
Francisco Sá-Carneiro	OPO	927	738, 73H	18396
Charleroi Bruxelles-Sud	CRL	821	738, 73H	56326
East Midlands	EMA	1101	738, 73H	23514
Alicante-Elche	ALC	597	AT7, CR2, CR9, CRK	529
Glasgow	GLA	1487	738, 73H	16862
Oran	ORN	879	320, 319	10073
Alger-Houari Boumédiène	ALG	727	320	1221
Manchester	MAN	1176	73H	28672
Edimbourg	EDI	1473	73H	21158
Eindhoven	EIN	945	738, 73H	15181
Billund	BLL	1476	738	18969
Bournemouth	BOH	896	738	11007
Paris-Beauvais	BVA	694	738	17314
Glasgow-Prestwick	PIK	1453	738	17301
Cagliari-Elmas	CAG	713	73H	6873

Table 3

Airport connected to Carcassonne airport between 2013 and 2022 (source: OAG database). "PK_{max}" represents the maximum number of passenger kilometers between 2013 and 2022.

that, two scenarios are considered. The first scenario involves using a fleet of aircraft powered solely by electrofuels to meet two different air transport demands. The second scenario involves doing the same thing, but considering a fleet of aircraft powered by liquid hydrogen. The first demand (actual demand) is based on Carcassonne traffic in 2022. The second demand (anticipated demand) is based on Carcassonne traffic between 2013 and 2022. It is assumed that all routes between 2013 and 2022 are active (see Table 3). This demand is

therefore estimated from the maximum frequency of flights on each route observed between 2013 and 2022. To assess global on-board energy consumption from Carcassonne, GAM tool was used to size the Carcassonne fleet using either electrofuel or liquid hydrogen. To do that, GAM need some inputs to size each aircraft in Carcassonne fleet (see Table 4)

Aircraft	737-800 Winglets	737-800	A320neo	A319-100	ATR 72-201/-202	CRJ 200	CRJ900	CRJ1000
Aircraft IATA code	73H	738	320	319	AT7	CR2	CR9	CRK
Energy type	kerosene or liquid hydrogen							
Engine count	2							
Engine type	turbofan				turbopropeller	turbofan		
Thruster type	fan				propeller	fan		
bpr	5.1	5.3	12.5	5.9	-	6.2	5	5
Category	short-medium				regional		short-medium	
N_{pax}	160	189	165	156	66	50	90	100
Cruise speed	0.78	0.79	0.78	0.78	513	0.74	0.78	0.78
Design range (km)	5400	5665	5800	6000	1426	3150	2800	
Cruise altitude (ft)	35000				20000	35000		

Table 4
Model GAM inputs for the Carcassonne aircraft fleet

2.1.1 Use of electrofuel

Table 5 indicates the amount of fuel required to fuel all aircraft to a given destination per year. Net fuel consumption (including reserves) at Carcassonne has decreased between 2013 and 2019. The Covid crisis severely affected traffic in 2020. In 2022, traffic has not fully recovered. The overall trend shows a decline in traffic. It's not clear what traffic will be like in the future. In 2022, we estimate fuel consumption at 3,401 tonnes, corresponding to 40.62 GWh of on-board energy. Fuel consumption at Carcassonne airport for anticipated demand amounts to 7173 tonnes of fuel, corresponding to 86.68 GWh of on-board energy. This estimate of fuel consumption is valid for both fossil kerosene and synthetic fuel (biofuel or electrofuel). As a result, the airport would consume around twice as much fuel as in 2022.

Year	2013	2014	2015	2016	2017	2018-2022
ORK	185.08	157.99	117.36	111.43	408.57	
LPL	451.84	469.05	466.46	102.27	-	-
STN	1025.88	1094.52	1080.23	1012.75	1095.22	2995.35
DUB	760.02	736.70	720.72	669.39	665.13	2481.44
OPO	234.56	203.52	220.77	198.41	258.25	1032.99
CRL	1127.34	1034.17	1091.93	1008.77	969.10	3094.33
EMA	453.98	413.80	377.65	363.43	341.40	822.3
ALC	-	-	7.44	10.59	-	-
GLA	-	-	317.61	295.44	300.28	227.63
ORN	-	-	4.91	177.97	117.58	-
ALG	-	-	-	21.65	-	-
MAN	-	-	-	362.44	498.84	1773.2
EDI	-	-	-	-	81.61	31185.69
EIN	270.12	298.18	91.21	-	-	-
BLL	357.46	336.44	-	-	-	-
BOH	217.67	207.62	-	-	-	-
BVA	355.84	-	-	-	-	-
PIK	326.35	305.63	-	-	-	-
CAG	-	-	-	-	-	128.19
Fuel	5766.15	5257.64	4496.30	4334.55	4434.72	14149.75

Table 5

Aircraft fuel consumption (tons) per route and per year in Carcassonne Airport using kerosene.

2.1.2 Use of liquid hydrogen

Table 6 shows the amount of liquid hydrogen that would have been needed to fuel aircraft with a passenger capacity and range equivalent to the aircraft in Table 4, powered by internal combustion engines running on liquid hydrogen. The mass of liquid hydrogen consumed Table 6 is less than the mass of kerosene Table 5, due to the higher energy density of hydrogen. However, on-board energy consumption is higher in the case of hydrogen. In 2022, for example, kerosene consumption was estimated at 3,400 tonnes (40 GWh of on-board energy), whereas hydrogen consumption would have been 2,300 tonnes (76 GWh). For anticipated

demand, liquid hydrogen consumption would be 5059.80 tonnes. The liquid hydrogen tank was sized with a gravimetric index of 0.4, which is a rather optimistic value. The value of the gravimetric index has the potential to reduce or increase the amount of on-board liquid hydrogen [37] for a given mission.

Year	2013	2014	2015	2016	2017	2018-2022
ORK	125.76	107.35	79.75	75.49	276.82	
LPL	306.87	318.56	316.75	69.26	-	-
STN	694.97	741.47	731.72	684.17	739.88	2023.54
DUB	516.56	500.71	489.80	453.62	450.73	1681.58
OPO	158.76	137.75	149.42	133.92	174.31	697.24
CRL	761.14	698.24	737.15	679.27	652.55	2083.60
EMA	308.08	280.81	256.27	245.92	231.02	556.43
ALC	-	-	3.75	6.24	-	-
GLA	-	-	215.99	200.31	203.59	154.33
ORN	-	-	2.86	103.17	75.15	-
ALG	-	-	-	12.46	-	-
MAN	-	-	-	245.42	231.02	1200.71
EDI	-	-	-	-	55.33	803.88
EIN	182.89	201.89	61.75	-	-	-
BLL	243.09	228.80	-	-	-	-
BOH	147.23	140.43	-	-	-	-
BVA	239.24	-	-	-	-	-
PIK	221.93	207.84	-	-	-	-
CAG	-	-	-	-	-	86.02
<i>LH₂</i>	3906.53	3563.85	3045.24	2909.27	2993.06	9564,19

Table 6
Aircraft liquid hydrogen (tons) consumption per route and per year in Carcassonne Airport.

2.2 Energy self-sufficiency scenarios

Electric power is needed to produce electrofuels and liquid hydrogen. The electricity demand is summarized in Table 7. In this section, we assess the feasibility of locally generating the

Demand	Actual	Anticipated
Electrofuel (tons)	3401.12	7173.39
Electricity input for efuel production (GWh)	111.49	214.95
<i>LH₂</i> (tonnes)	2299.04	5059.80
Electricity input for <i>LH₂</i> production (GWh)	138.11	303.97

Table 7
Electricity supply for electrofuel production via Fischer Tropsch or liquid hydrogen via electrolysis.

electricity needed to produce fuel or hydrogen. The first approach compares the electricity

needs of Carcassonne airport with the electricity production of the Aude department, while the second estimates the amount of photovoltaic cells or onshore wind turbines needed on or near Carcassonne airport to produce its own electricity.

2.2.1 Assessment of energy resources in the Aude department

The Aude department is located in the south of France. In 2021, the Aude department's electricity consumption reached approximately 2145GWh with 58% of this electricity produced on its territory, i.e. 1245GWh. This energy was made up of 75% wind power, 20% photovoltaic, 4% hydro and 1% bioenergy. In 2022, there were 7,577 electricity generation sites in the Aude département, including 7,471 photovoltaic sites, 53 wind farms, 47 hydroelectric plants and 2 bioenergy. A total of 1,525 GWh of electrical energy was generated, compared with consumption of 2,222 GWh plants[‡]. The main objective in this section is to estimate electricity production in Aude department in 2030. To do this, we consider two scenarios:

- The **trend scenario** considers the electricity production units that are already being built or which construction is very likely to start.
- The **optimistic scenario** takes into account the trend scenario with additional projects which are still uncertain. For more explanations see appendix A

Year	2022	2030	
Scenario	-	Trend	Optimistic
Solar	387.60	3607.85	3820.32
Wind turbine	921.03	2481.76	4638.20
Hydroelectric	215	215	258
Total	1523.63	6304.61	8716.52
Electric consumption	2222.62	2889.41	
Energy surplus	-	3415.2	5827.11

Table 8
Electricity production in Aude department (GWh)

Estimates of electricity consumption in 2030 (see Table 8) have been calculated on the basis of an excess consumption of around 30% compared with 2022. This increase takes into account the affordability of electric means of transport (car, bicycle, etc.). The difference between the energy produced and the energy consumed is called the energy surplus.

ES^a represent the ratio between electricity input and the energy surplus of Aude department in the case trend scenario. ES^b represent the ratio between electricity input and the energy surplus of Aude department in the case optimistic scenario.

Table 9 shows:

- In the case of a fleet of electrofuel-powered aircraft, the electricity requirements also represent 3.3% (actual demand) to 6.3% (anticipated demand) of the surplus energy produced in the Aude department in the trend scenario

[‡] <https://openservices.enedis.fr/bilan-de-mon-territoire>

	Electricity input (GWh)	ES ^a	ES ^b
Actual demand (electrofuel)	111.49	3.3%	2%
Anticipated demand (electrofuel)	214.95	6.3%	3.7%
Actual demand (LH ₂)	138.11	4%	2.4%
Anticipated demand (LH ₂)	303.97	10%	5.2%

Table 9

Comparison of Carcassonne airport's electricity needs with the surplus energy produced in the Aude region for a fleet of electrofuel aircraft.

- In the case of a fleet of liquid hydrogen-powered aircraft, the amount of electricity required by the airport represents between 4% (actual demand) and 10% (anticipated demand) of the energy surplus in the Trend case, and between 2.4% (actual demand) and 5.2% (anticipated demand) in the Optimistic case.

It should be noted that the electricity requirement for liquid hydrogen production is only 24% higher than for electrofuel, although the on-board energy for liquid hydrogen aircraft has been estimated to be twice as high. This is because the hydrogen liquefaction process is energy-intensive ($15 \searrow 10 kWh/kg LH_2$) [31]. Krasae-in *et al.* present a review of the development of large-scale hydrogen liquefaction processes worldwide from 1898 to 2009. This review highlights studies on reducing electricity consumption for hydrogen liquefaction. We could reach $5 kWh/kg LH_2$. Electrofuel production is also less efficient (around 37%, taking into account the direct capture of CO₂ from the air and hydrogen production [26], see 1.2.1).

2.2.2 Self-generation of electricity at Carcassonne airport

In this section the surface area of solar panels or the number of wind turbines is assessed needed to self-generate electricity to meet the fuel demand. The efficiency of photovoltaic panels is 15% and the nominal power of onshore wind turbines is 3MW. We consider the load factor (ratio of yearly averaged output power versus nominal output power) is 0.146 for photovoltaic panel and 0.224 for onshore wind turbine. This value are the actual load factor in Carcassonne. Table 10 shows the surface area of photovoltaic panels or the number of

	Electricity input (GWh)	PV surface (ha)	Onshore wind turbines
Actual demand (electrofuel)	111.49	49	21
Anticipated demand (electrofuel)	214.95	94	39
Actual demand (LH ₂)	138.11	61	25
Anticipated demand (LH ₂)	303.97	133	55

Table 10

Self-generation of electricity at Carcassonne airport (PV : photovoltaic panel)

onshore wind turbines for different scenarios. Given that, whatever the air transport demand

considered, the electricity requirement for liquid hydrogen production is higher than that for electrofuel, the area of solar panels required is greater. The same applies to the number of onshore wind turbines. The surface area of photovoltaic panels varies from 49 ha to 133 ha ($1 \text{ ha} = 10^4 \text{ m}^2$), whatever the energy vector and air transport demand considered. For example, if we consider current demand, a fleet powered by electrofuel would require almost half (49ha) the total surface area of Carcassonne airport (110 ha) This first approach shows that producing locally the electricity for small regional airports is not out of reach.

3.0 Case study 2: Energy self-sufficiency scenario for French regional airports

In this section, we use the air transportation request from the OAG database of 2016. After eliminating the demand for cargo and business aircraft, we quantified fuel demands for all airports operating in France in 2016. The total quantity of fuel at national level in 2016 is estimated to reach 4.64 Mt. To produce this mass of electrofuel, it would require 124 TWh of electricity.

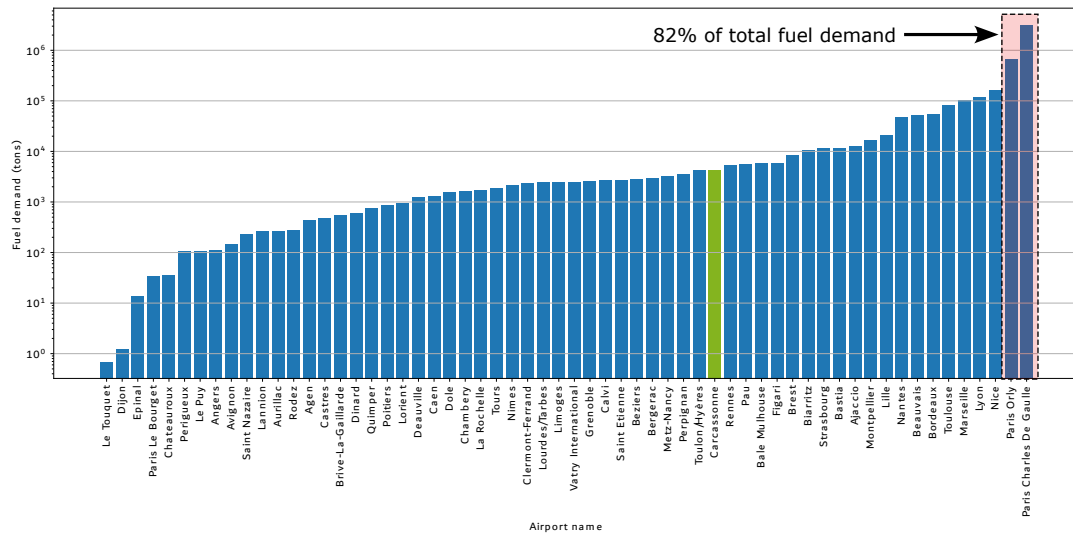


Figure 2. Fuel requirements for France's operational airports in 2016 (passenger transport only), the total is 4.64 Mt of fuel.

Fig. 2 shows the different airport groups. The first group are the major hubs, such as Paris Charles de Gaulle and Orly airports. These airports are major fuel consumers : they represent 82% of the total fuel consumption. After them, comes the second group which includes major regional airports such as Marseille, Toulouse, Nice, Lyon, Bordeaux, Beauvais and Nantes. The last group includes smaller regional airports. Among the small regional airports all those whose annual fuel consumption is less than or equal to that of Carcassonne airport (see Fig. 2) represent 1.2% of the total fuel consumption in 2016. Notice that, the small regional airport represent more than 50% of all operating airport in 2016. We've evaluated the number of onshore wind turbines and the surface area of photovoltaic panels required by small regional

airports to meet their electrofuel needs (see Fig. 3). To make these calculations, we considered the same load factor for all airports : the french average. Of course a more realistic analysis should take into account the variability of local load factor depending on regional weather conditions.

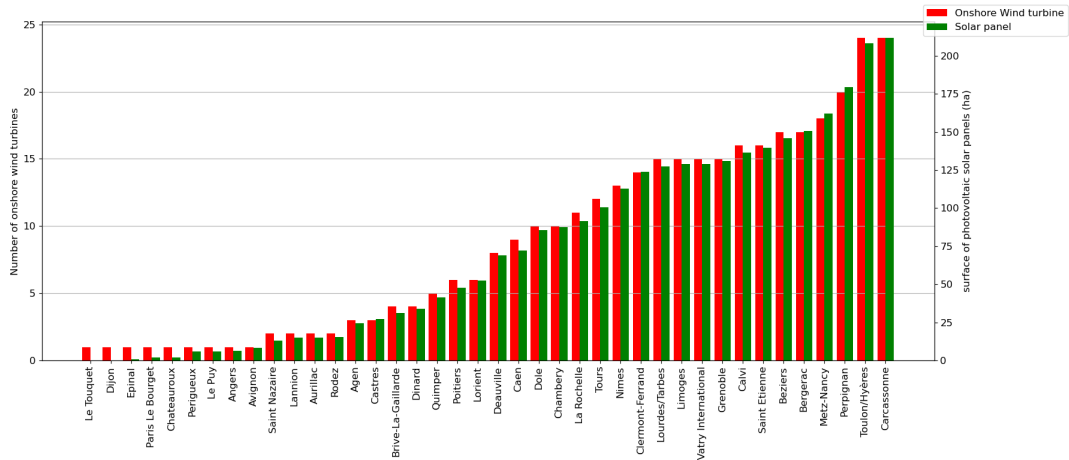


Figure 3. Estimated surface area of photovoltaic panels and number of wind turbines for small regional airport. A national averaged load factor is used, no local weather variability is taken into account.

Conclusion

This paper introduced a methodology to compute the required electricity to produce electrofuel and liquid hydrogen at the scale of a regional airport. The methodology is divided into three stages:

- Assessing the air transport demand for a given airport.
- Defining a fleet of airplanes with low-carbon energy carriers. We considered a fleet composed of only electrofuel airplanes or only liquid hydrogen airplanes to satisfy air transport demand at airport.
- Computing the required electricity for producing low-carbon energy carriers for new aircraft fleet and analyzing it by considering the local renewable energy resources.

The methodology was applied to the case of Carcassonne airport, located in the department of Aude in France where the weather conditions around are favorable to renewable energy. To meet the air transport demand in 2022 with a fleet powered by electrofuel, the airport would need 111 GWh of electricity. This corresponds to 3% of the energy surplus (difference between electricity production and consumption) in the Aude department by 2030 for a trend scenario, which requires 49 ha or 21 ha of area for solar panels or wind turbines. This implies that reaching energy self-sufficiency is realistic for Carcassonne airport.

For other small regional airports, the methodology should be improved to take into account local weather conditions such as solar irradiance and wind.

For larger airports, a specific study for each airport will probably be necessary to assess the feasibility of local energy production, depending on the local weather, energy demand, and available space around the airport.

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Appendix

A.0 Wind turbine energy

The Aude department is one of the windiest in France, with 300 to 350 windy days a year. Two-thirds of the territory enjoys frequent winds of between 6 and 9 m/s, largely due to the relief to the north and south, which forms a corridor into which the Marin winds (winds from the sea) and the Cers (winds from the land) flow. In 2022, its 53 wind farms had a total capacity of 465.4 MW according to the french electricity network manager (Enedis[§]). The department's objective is to double wind power production by 2030 according to[¶], under certain assumptions:

1. Replacement of existing onshore wind turbines with new-generation turbines with 4 times more power than those installed 20 years ago. In 2017, the Aude department had 265 wind turbines with an overall capacity of 387MW. As the lifespan of a wind turbine is 20 years, 143 wind turbines (installed in 2010) will have to be replaced by new turbines with an average output of 2 MW by 2030. This would represent an additional capacity of 196 MW, bringing the total capacity of wind turbines to 583 MW by 2030 [35].
2. Installation of new offshore wind turbines. According to the recent news^{||}, two 30 MW pilot sites will be built : one in the east (Leucate) and one in the south-east of the Aude department (Gruissan) during 2023.
In addition to these two pilot parks, according to the website^{**}, a large-scale park could be planned off the coast of Aude, in the Mediterranean. This project involves a 250 MW floating wind farm with a 500 MW extension. Commissioning is scheduled for 2031. The extension of the offshore wind farm will be taken into account in the optimistic scenario.

In 2022, according to Enedis^{††} the load factor onshore wind power in the Aude department was 0.224. We assume that the load factor remains the same in 2030. According to France's electricity transmission network^{‡‡}, the load factor for offshore wind power at Saint-Nazaire

[§] <https://openservices.enedis.fr/bilan-de-mon-territoire>

[¶] <https://www.aude.fr/construire-un-nouveau-mix-energetique>

^{||} <https://france3-regions.francetvinfo.fr/occitanie/aude/carcassonne/aude-jean-castex-en-visite-a-port-la-nouvelle-pour-l-eolien-en-mediterranee-2496679.html>

^{**} <https://www.revolution-energetique.com/futurs-parcs-eoliens-flottants-en-mediterranee-voici-leur-emplacement-exact/>

^{††} <https://openservices.enedis.fr/bilan-de-mon-territoire>

^{‡‡} bilan électrique 2022 RTE + EDF Renouvelables

over the wind farm period from 12/2022 to 01/2023 was 0.492, thus we assume the same factor for offshore wind power in the Aude department. Electricity production in 2030 through wind power in the trend and optimistic scenarios can be summarized in Table 11

Scenario	Trend	Optimistic
Electricity production(GWh)	2481.76	4638.20

Table 11

Forecast electricity production from wind turbine in 2030

B.0 Photovoltaic energy

In 2022, according to Enedis openservices, the solar photovoltaic capacity in the Aude department represented 322.3 MW, or 25.4% of its electricity production. One of the objectives of the Aude department set in 2015 was to increase installed rooftop capacity tenfold (between 2018 and 2030), by increasing the efficiency of modules already installed and prioritizing new installations on large industrial, commercial and agricultural rooftops. In 2017, photovoltaic energy production stood at 178 GWh. A study of theoretical photovoltaic potential by building type, carried out in 2017 in the Aude region, estimates that overall photovoltaic energy production would be :

1. 3607.85 GWh from 2030 onwards, assuming that all existing single-family homes, buildings, parking lot urns, large rooftops and crop and leisure centers in 2017 were equipped with photovoltaic panels between 2018 and 2030. It is also assumed that photovoltaic power plants will be installed only once between now and 2030 [35]. This is trend scenario (see Table 12)
2. 3820.32 GWh from 2030, assuming the previous hypothesis and considering the installation of new single-family homes, buildings, large rooftops and crop and leisure centers between 2018 and 2030 [35]. This is optimistic scenario (see Table 12)

Scenario	Trend scenario	Optimistic
Electricity production(GWh)	3607.85	3820.32

Table 12

Forecast electricity production from photovoltaic panels in 2030

C.0 Hydro-electric energy

In 2022, according to Enedis openservices, Aude's hydropower fleet had a capacity of 132.9 MW and produced 215 GWh of electricity. In the trend scenario, we will assume that electricity production remains unchanged in 2030 (see Table 13). In the optimistic scenario, we assume that the hydropower plant will be rehabilitated. Rehabilitating a power plant enables an increase in power output, which means an increase in electricity production. Let's assume a refurbishment operation leading to a 20% increase in the plant's rated capacity in 2030. This would increase electricity production to 258 GWh (see Table 13).

Scenario	Trend scenario	Optimistic
Electricity production(GWh)	215	258

Table 13**Forecast electricity production from hydroelectric power plants in 2030****References**

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