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Descriptive analysis of viability of fuel saving in commercial aircraft through the application of photovoltaic cells

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ABSTRACT

This paper presents the analysis of the technical feasibility to use a photovoltaic system to supply the electrical demand on two referential commercial aircraft, Airbus A340–300 and Cessna Conquest 441. The methodology approach comprises a process given by the selection of the photovoltaic technology, the calculation of the available solar radiation, the determination of the electrical demand, the layout definition of solar cells, the photovoltaic system capacity calculation, the estimation of the photovoltaic system weight, the estimation of fuel savings for photovoltaic system equipped aircrafts, and finally, the extrapolation of results to other aircrafts. The study concludes that the use of photovoltaic technology to supply power to the aircraft electrical system can result viable from the point of view of operational profitability, generating savings in fuel consumption. These fuel savings depend on the type of aircraft, the flying route and schedules of operation.

Contents

1. Introduction

The aeronautic industry is usually seen at the forefront of technological change; however, photovoltaic technology has had a shy presence in the aviation industry. Nowadays, there is a growing interest on alternative energy sources applied to

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Nomenclature

AWP average Weight Passenger [kg]
E_B battery energy storage capacity [W h]
Epc_o percentage of engine power in cruise condition of aircraft without PV system [%]
Epc_{pv} percentage of engine power in cruise condition of aircraft with PV system [%]
E_S fuel consumed to supply power to electrical system [kg]
E_{TD} total energy demand for the design configuration [W h]
EWo empty weight of aircraft without PV system [kg]
$EWpv$ empty weight of aircraft with PV system [kg]
f_D battery depth discharge factor [%]
f_{SL} system loss factor [dimensionless]
FCo_{AL} fuel consumed from start of the approximation until end of mission by the aircraft without PV system [kg]
FCo_{CL} fuel consumed at climb phase by the aircraft without PV system [kg]
$FCo_{\Delta tCR}$ fuel consumed from the apron until start cruise by the aircraft without PV system [kg]
$FCo_{\Delta ti}$ fuel consumed in the stage i of the cruise phase by the aircraft without PV system [kg]
$FCo_{\Delta ti+1}$ fuel consumed from start approach until park on apron by the aircraft without PV system [kg]
FCo_{TO} fuel consumed at takeoff phase by the aircraft without PV system [kg]
FCo_{TX} fuel consumed at taxi phase by the aircraft without PV system [kg]
$FCpv_{CL}$ fuel consumed at climb phase by the aircraft with PV system [kg]
$FCpv_{\Delta tCR}$ fuel consumed from the apron until start cruise by the aircraft with PV system [kg]
$FCpv_{\Delta ti}$ fuel consumed in the stage i of the cruise phase by the aircraft with PV system [kg]
$FCpv_{\Delta ti+1}$ fuel consumed from start approach until park on apron by the aircraft with PV system [kg]
$FCpv_{TO}$ fuel consumed at takeoff phase by the aircraft with PV system [kg]
$FCpv_{TX}$ fuel consumed at taxi phase by the aircraft with PV system [kg]
$FOBo_{CR}$ fuel on board at start of the cruise phase by the aircraft without PV system [kg]
$FOBo_{to}$ fuel required for the mission by the aircraft without PV system [kg]
$FOBo_{ti}$ fuel on board at time i of the cruise phase by the aircraft without PV system [kg]
$FOBo_{ti-1}$ fuel on board at time i-1 of the cruise phase by the aircraft without PV system [kg]
$FOBo_{ti+1}$ fuel on board on the aircraft without PV system at end of mission [kg]
$FOBpv_{CR}$ fuel on board at start of the cruise phase by the aircraft with PV system [kg]
$FOBpv_{to}$ fuel required for the mission by the aircraft with PV system [kg]
$FOBpv_{ti}$ fuel on board at time i of the cruise phase by the aircraft with PV system [kg]
$FOBpv_{ti-1}$ fuel on board at time i-1 of the cruise phase by the aircraft with PV system [kg]
$FOBpv_{ti+1}$ fuel on board on the aircraft with PV system at end of mission [kg]
K_{ps} percentage of power demand supplied [%]
M_B mass of the batteries [kg]
M_C mass of the photovoltaic module [kg]
m_{dc} mass density of photovoltaic panels [kg/m^2]
M_{PVS} total mass of the PV system [kg]
$MTOW$ maximum takeoff weight [kg]
η_C power transformation efficiency of cells [%]
η_D battery discharge efficiency [%]
n_L battery load efficiency [%]
n_{ST} number of starts generator [dimensionless]
ρ_B energy density of battery [W h/kg]
P_D total power demanded by the aircraft electrical system for the design point [W]
P_{DB} power demanded by the system to load the battery [W]
P_{PVS} power generation of the photovoltaic system [W]
PAX number of passengers [dimensionless]
PC_{CF} continuous electrical loads in cruise flight [W]
PC_{NL} continuous electrical loads with night lights [W]
PI_{CF} intermittent electrical loads in cruise flight [W]
PI_{COMM} intermittent electrical loads of communications [W]
PI_G starter-generator intermittent electrical loads [W]
PLo payload of aircraft without PV system [kg]
$PLpv$ payload of aircraft with PV system [kg]
PSH peak sun hour [W h/m^2]
PT total electrical power required per hour of operation [W]
R_{TW} ratio maximum power plant thrust to maximum take-off weight [kgf/kg]
s_{fc} specific fuel consumption [kg/kgf h]
S_I irradiated surface [m^2]
t_{ALB} available hours of radiation to load the battery [h]
t_{BO} hours of battery operation [h]
t_{CR} final time of phase climb [h]
t_{DL} initial time of phase approach [h]
T_{max} maximum power plant thrust [kgf]
t_{SG} generator starting time [h]
t_{TF} flight total time [h]
Z fuel adjustment at apron [kg]
WTo_{CR} total mass of the aircraft without PV system at start of the cruise phase [kg]
WTo_{DL} total weight of the aircraft without PV system at end of cruise phase [kg]
WTo_{to} total mass on apron of the aircraft without PV system [kg]
WTo_{ti} total weight of the aircraft without PV system at end of stage i of the cruise phase [kg]
WTo_{ti-1} total weight of the aircraft without PV system at end of stage i-1 of the cruise phase [kg]
WTo_{ti+1} total weight of the aircraft without PV system at end of mission [kg]
$WTpv_{CR}$ total mass of the aircraft with PV system at start of the cruise phase [kg]
$WTpv_{DL}$ total weight of the aircraft with PV system at end of cruise phase [kg]
$WTpv_{to}$ total mass on apron of the aircraft with PV system [kg]
$WTpv_{ti}$ total weight of the aircraft with PV system at end of stage i of the cruise phase [kg]
$WTpv_{ti-1}$ total weight of the aircraft with PV system at end of stage i-1 of the cruise phase [kg]
$WTpv_{ti+1}$ total weight of the aircraft with PV system at end of mission [kg]
Δt_i time between the stage i and the stage i-1 of the cruise phase [h]

Δt_{i+1}	time from start approach until park on apron [h]	$\Delta PAXpv$	penalization in passengers transported due to the installation of the PV system, pax
Δt_{CR}	time from mission start to cruise start [h]		

aeronautics, due to the potential fossil fuel shortage [1], the need to decrease the fuel demand [2–4], the development of "More Electrical Aircrafts" (MEA) [5–7] and the climate change. This interest can be seen, regarding the Photovoltaic (PV) Technology, in projects such as the Sunseeker and Solar Impulse. The Sunseeker I that was built between 1986 and 1989 and made its maiden flight in 1990. The Sunseeker Duo first flew in 2013 [8]. Ross [9] presented the progress of the Solar Impulse in 2008; one of the most ambitious projects of solar aviation and [10] presented the characteristics and aims of the Solar Impulse II up to June 2014. The Solar Impulse II started on March 2015 its challenge of going around the world [11].

The PV technology in aviation took its first step in 1974 with the project Sunrise I. Since then many other developments have been done, which are documented by [12–18]. Nevertheless the methodologies, models and studies available in the literature were focused on unmanned and experimental aircrafts [18–25]. Other projects deal with "High Altitude Long Endurance" (HALE) UAVs [26–34]. In recent years there have been done developments on airships, with the resurgence of these vehicles as a viable alternative of multipurpose platforms [35,36]. Several models and studies regarding the application of PV technology to airships were developed by [37–43]. These models can be extrapolated to the analysis of non-stratospheric aircrafts, such as radiation models [41], thermal behavior of the solar panels models [42], design and management of hybrid systems models, among others.

Although prior studies have addressed with more or less rigor the factors that affect the viability of the system, there have not been found studies in the literature about the feasibility to apply this technology in commercial aircrafts.

Studies such as [17–19] present design methodologies for solar powered aircraft for different applications. In [18] the influence of aircraft scale and its interaction with aspects of the photovoltaic system, aerodynamics, structure, power plant, among others, are studied. In that research it can also be found a list of manned and unmanned aircraft designs that have been developed. In [25] a genetic algorithm to adjust the dimensions and cruising speed of a UAV, departing from the preliminary design to the optimization of the energy consumption, has been developed.

Other studies [27,44,45] have analyzed a large number of airfoils for solar powered aircraft. Romeo et al. [27] have evaluated and optimized several wing plans. The blended wing body concept has also been studied as one of the best alternatives due to the availability of a large surface for the cells installation. Chen and Bernal [44] have analyzed 200 airfoils and characterized the best four options studied. On the other hand, in [32–34] the flight paths optimization for unlimited duration flights (HALE) are studied.

The MEA pose a challenge in the aircraft electrical system design, as explained in [6]. Some researchers show interest in hybrid systems [37,38,46–51]. James et al. [37] propose the use of a combined system of photovoltaic cells and fuel cells. Choi et al. [38] refer to the possibility of using other options such as advanced systems thermoelectric energy conversion (ATE) and nano materials solar energy collection, designed by NASA Langley Research Center. They show an approach to calculate the solar energy incident on the airship. With that calculation it is possible to maximize the energy produced per unit area, concluding that the area available is more than enough for supplying energy to the airship devices (propulsion, microwave beaming, laser power beam, housekeeping, radar surveillance, whose demand is 3,6 MW). So this study concluded that photovoltaic technology is the best choice in this case. Sun [50] proposes the use of hybrid power system for reuse the energy converted into heat by the photovoltaic cells. A particular study is the one developed by Li et al. [42], in which the thermal characteristics of the photovoltaic system are analyzed. On the same work it has been developed a thermodynamic model to obtain the temperature profile in three dimensions and the power output of the system, considering the effects of the altitude, time of year and wind speed. These studies highlight some of the many parameters that must be taken into account to apply complementary and hybrid systems.

The alternative of using complementary and hybrid systems has also been analyzed for UAVs, as in the case of [24,52–54]. Wickenheiser et al. [24] propose the implementation of a hybrid system consisting of microwave and photovoltaic cells. In [52] the design of a Radio Control airplane that combines photovoltaic cells, batteries and internal combustion engines is shown. The aim of this project is to double the autonomy of the drone. In pursue of an emissions free aviation, fuel cells are considered by [55–57] as the best option for general aviation future aircrafts. Aktas [53] presents the selection of the technology for use in general aviation aircraft. Lapeña et al. [56] have shown the details of the first manned flight propelled by Boeing fuel cells , and in Romeo [57] the progress of the ENFICA-FC project is presented.

The other key branch of these studies consisted in analyzing the current state of commercial aviation and its tendency regarding fuel economy. In this aspect Liscouët-Hanke [58] develops a methodology for the analysis and simulation of systems interaction and performance for conventional aircrafts and MEA. The works in [59,60] studied the relationship between the APU, environmental cost and economy of their use, proposing alternatives to reduce fuel consumption. In the same way, related to the importance of fuel consumption reduction, in [2] the reduction of aircraft fuel consumption and emissions is presented, considering the designs from the 50's to the present. The result found is that fuel reduction has been approximately 70% per seat in that period. It also states the target for the next generation of aircrafts, which is to reduce present values by 10–15%. The publications [61,62] deal with the analysis of reducing fuel consumption at the aircraft operating point. Schilling [62] presents an algorithm for calculating aircraft fuel consumption.

On other hand, the energy density of the batteries are the biggest obstacle for the alternatives applications to the fossil fuels as shown in [63]. It is expected that the energy density be doubled in the next decade [64]. Lithium–air batteries would achieve density energy about 3000 Wh/kg [63,65]. The company Excellatron Solid State LLC has announced developments for aeronautics industry with several possibilities for application in alternative systems [66], as the project CleanSky Joint Technology Initiative [67,68].

Batteries of lithium ion have begun to be used in recent years in commercial aircrafts such as B787 and A340. This new technology has presented some issues as occurred in the B787 in early 2013 [69], and although some preventive measures have been applied, it is necessary to continue working on the batteries safety and control [70,71].

Different authors have analyzed solar cells [72–80]. In [73–78] it is shown the evaluation of the life cycle of PV cells, related to investment and environmental costs. These works include third generation cells, presenting these cells as an alternative to reduce those costs in contrast to the first and second generation of cells. They state, however, that maintenance costs are expected to continue to be high; likewise it is necessary to further investigate this technology. In [77] a variation of GaAs cells with a single union is presented. Such a change would greatly increase their efficiency. Finally, in [78] attention is focused on NF3 (nitrogen trifluoride), on aspects to take into account during cells manufacturing process, and the need to act proactively in front to the increasing PV cells production, process in which NF3 is used, (an important greenhouse gas).

The advances in photovoltaic technology show that it is possible to approach to the cells efficiency theoretical limits, as shown for cells first generation [81–83]. A major challenge is to diminish the production cost as it is indicated in [84,85], using thin film cells. The third generation cells have a higher efficiency than its predecessors. They historically have been used in the aerospace industry, but currently the researches are focused on their use in terrestrial applications and its profitability [84].

Radiation models abound in the literature, especially the study of radiation patterns in specific areas in [86]. Different models are analyzed and classified according to its accuracy. Regarding non-stationary system models, Colozza [87] has developed a methodology for sun radiation estimation over a surface, considering several factors. This study also refers to the optimization of cells efficiency, taking into account characteristics of its application, particularly cells cooling. This aspect is also addressed in [14] for the particular case of the Pathfinder. The cooling of the cells is a fundamental aspect; [88] shows that one of the major factors is the cell temperature: when the operating temperature increases the efficiency of the cells decreases.

Within this context in this paper an analysis of the feasibility of implementing the PV technology in commercial aircrafts is presented, focusing in what extent the photovoltaic technology can be used to supply energy to the electrical system of the aircraft, and if its application produces savings in fuel consumption.

For this purpose, the PV technology state of the art is boarded in first instance, both its current status and their background and goals. This study section determined the available technology for use in commercial aviation, and the possibilities in the medium and long term, as well as the breakthroughs that occurred in this type of technology every year.

Then a survey of the state of the aviation industry allowed highlighting different parameters for the selection of individual cases to apply photovoltaic technology. The reference parameter adopted to evaluate the aircraft electric energy consumption was the APU power.

In the following stages the incident radiation over two selected reference aircrafts in various operational scenarios has been calculated. Afterwards the characteristics of the electrical system of the two aircrafts analyzed have been determined, together with the determination of the available surface for the cells and the weight of the photovoltaic system. Then the general methodology for determining fuel savings using the photovoltaic system has been developed. These fuel savings for the two selected aircrafts operational scenarios have been calculated. Finally the results obtained from the analysis have been extrapolated to other aircrafts.

2. Data and methodology

The methodology followed consists of the selection of a technological model for the photovoltaic system applied to aircrafts, the determination of the power generated by a given operational model, a power demand estimation for the same operational model, and expected consequences that derive from the system implementation.

2.1. Photovoltaic system model

The photovoltaic cells adopted in the current model are the so called cells of third generation, considered to be most efficient cells commercially available. The parameters adopted associated to them were: power transformation efficiency, η_C, of 43.5% [80,81,89,90] and mass density of photovoltaic panels, m_{dc}, of 1.76 kg/m^2 [91]. The system loss factor, f_{SL}, adopted is 1.2. As above mentioned, when the operating temperature increases the efficiency of the cells decreases [92,93]. This thermal behavior of PV cells is positive for solar aircrafts, due to the operating temperature. It is also possible the cooling of the PV cells, then increasing its efficiency above the values provided by the industry, which are for the standard test conditions (25 °C, AM1.5D, 50 W/cm^2). Even so in order to be conservative in the present work the efficiency used corresponds to the standard test condition [80,81].

The selected batteries for the photovoltaic system are commercial lithium ion, which have an energy density, ρ_B, of 400 W h/kg [13,23,94], a battery depth discharge factor, f_D, 85%, a discharge efficiency, η_D, 99.9% and a battery load efficiency, n_L, 99.9% [95].

The photovoltaic system consists of 4 main elements: inverter, regulator, batteries and photovoltaic module (cells, frame, protective surface). It is considered that inverters and regulators are already present in standard aircraft, while batteries and solar cells are incorporated.

The solar cells arrangement developed was based on different criteria depending on the type of aircraft considered. The first aircraft selected was the Airbus A340–300. For this aircraft two solar cells arrangements were selected, which are shown in Fig. 1. For the first one, the solar cells are distributed on the surface of the wings and the horizontal stabilizer of the aircraft. For the second the surface of upper half of aircraft body is incorporated to the first arrangement.

The second aircraft selected was the Cessna Conquest 441. Five cells configurations were considered, which are shown in Fig. 2. They include cells on different surfaces: wings, horizontal stabilizer, and body.

2.2. Available radiation/analyzed scenarios

Colozza [87] introduced an estimation method to estimate photovoltaic electricity production, which is adopted. This method was used in this study to demonstrate the sensitivity of the system for different operation conditions (day of the year, direction of flight, among others), and to determine the available radiation for the different scenarios.

The scenarios analyzed consider two days of the year: the ones of major radiation in the northern hemisphere, June 21st, and of major radiation in the southern hemisphere, December 21st. For these two days the following cases were evaluated:

1) Flight from Ezeiza Airport to Madrid Airport.
2) Flight from Madrid Airport to Ezeiza Airport.
3) Aircraft parked in Madrid Airport.
4) Aircraft parked in Ezeiza Airport.
5) Aircraft parked in Jujuy Airport, in northern Argentina.
6) Aircraft parked in Rosario Airport, in central Argentina.
7) Aircraft parked in Rio Grande Airport, in southern Argentina.

The cases 1–4 were evaluated for the aircraft Airbus A340–300, while the scenerios 5–7 were analyzed for the Cessna Conquest 441. Each of the scenarios was evaluated for the two days mentioned.

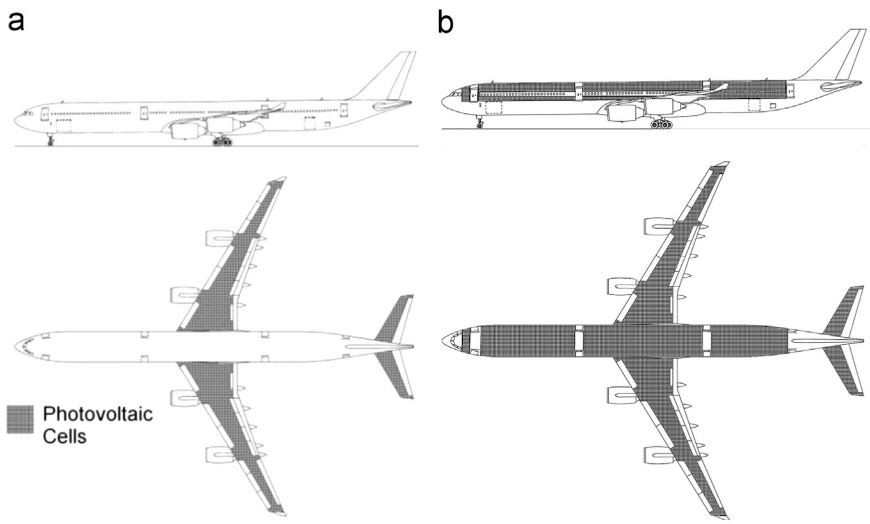

Fig. 1. A340–300 cell arrangement alternatives: (a) configuration 1, (b) configuration 2. The shadowed areas show the solar cells distribution on the aircraft. Source: made from http://www.the-blueprints.com/.

To calculate the incident radiation over the aircraft the following parameters were considered: the shape of the irradiated body, the day of year, the time of day, the latitude, the direction of flight, the flight altitude and the type of cells.

Two flight routes were adopted for the A340–300 that join Ezeiza and Madrid airports. The first one was an approximation of a currently used route and the second was a hypothetical route. The purpose was to consider a flight of maximum duration (aircraft maximum range). The scenario Ezeiza–Madrid and Madrid–Ezeiza real navigation path has a flight duration of 12 h at cruising speed. The alternative route involves a flight duration of 15 h. The departure times are identical in both cases: departure from Madrid at 10:00 a.m. local time and departure from Ezeiza at 7:00 a.m. local time.

For the Cessna Conquest 441 the operational scenarios were considered to be in the Argentine territory: south, center and north of the country. The missions considered were: maximum range with minimal payload, maximum range with maximum payload and 24 h operation (it was assumed three flights of maximum range with minimum payload).

2.3. Electrical power generation

The electrical power capacity estimations were done following the Peak Sun Hour (PSH) criteria, which is supported by the fact that power is generated and accumulated by the aircraft photovoltaic system, depending on aircraft electrical power demand, along its operative profile. The value 4 PSH is adopted for all the cases analyzed as a conservative value according to Colozza's method.

The power generation of the photovoltaic system, P_{PVS}, is calculated by

$$P_{PVS} = PSH\ S_I n_c f_{SL}^{-1}, \tag{1}$$

where S_I is the irradiated surface. Therefore, the percentage of power demand supplied, K_{ps}, is

$$K_{ps} = P_{PVS} P_D^{-1}\ 100\%, \tag{2}$$

where P_D is the total power demanded by the aircraft electrical system for the design point.

The total mass of the PV system is given by

$$M_{PVS} = M_B + M_C, \tag{3}$$

where M_C is the mass of the photovoltaic module, given by $M_C = m_{dc}\ S_I$, and M_B is the mass of the batteries, obtained by $M_B = E_B\ \rho_B^{-1}$.

An amount of energy that could be stored in the batteries, depends on the criteria adopted. This parameter, E_B, is given by $E_B = PT\ t_{BO}\ f_D^{-1}\ n_D^{-1}$,

where t_{BO} is the amount of hours of battery operation (number of hours to supply the electrical system from the batteries) and PT is the electrical power required per hour of operation.

Therefore, the mass of the batteries is obtained from:

$$M_B = PT\ t_{BO} \rho_B^{-1} f_D^{-1} n_D^{-1}. \tag{4}$$

2.4. Electrical demand

The electrical demand for both Airbus A340–300 and Cessna Conquest 441 was estimated. Airbus A340–300 specifications were taken from the aircraft flight crew operating manual. The cases analyzed are shown in Table 1.

Electrical demand for the Cessna Conquest 441 was also estimated from its manuals, which divide the electrical loads (28 VCC) into two groups: continuous electrical loads (PC) and intermittent electrical loads (PI). For the estimation of the electrical demand it was assumed that the continuous loads are supplied constantly throughout all flight phases, while the intermittent loads are supplied 5 minutes per flight hour for all loads that comprise this category, with the exception of the electrical loads of communication (10 min for every hour flight). The photovoltaic system does not consider the electrical loads of the ice protection equipment. The battery system associated with the PV system is considered as an electrical load in the sizing of the photovoltaic system. The number of starts (n_{ST}) considered was one for single flight operation and three for 24 h of operation.

Therefore, in general, the total energy demand for the design configuration, E_{TD}, is given by

$$E_{TD} = PT\ t_{TF} + P_{DB} t_{ALB} + PI_G t_{SG} n_{ST}, \tag{5}$$

Where PI_G is the starter-generator intermittent electrical loads , t_{TF}, t_{ALB} and t_{SG} are flight total time, the available hours of radiation to load the battery and generator starting time (30 s), respectively. PT is the total electrical power (load) per hour of flight (operation) and this given by:

$$PT = PC_{CF} + PC_{NL} + PI_{CF} 5\ \text{min}\ /60\ \text{min}\ + PI_{COMM} 10\ \text{min}\ /60\ \text{min}\ , \tag{6}$$

where PC_{CF} and PC_{NL} are the continuous electrical loads in cruise flight and in night light, respectively, and, PI_{CF} and PI_{COMM} are the

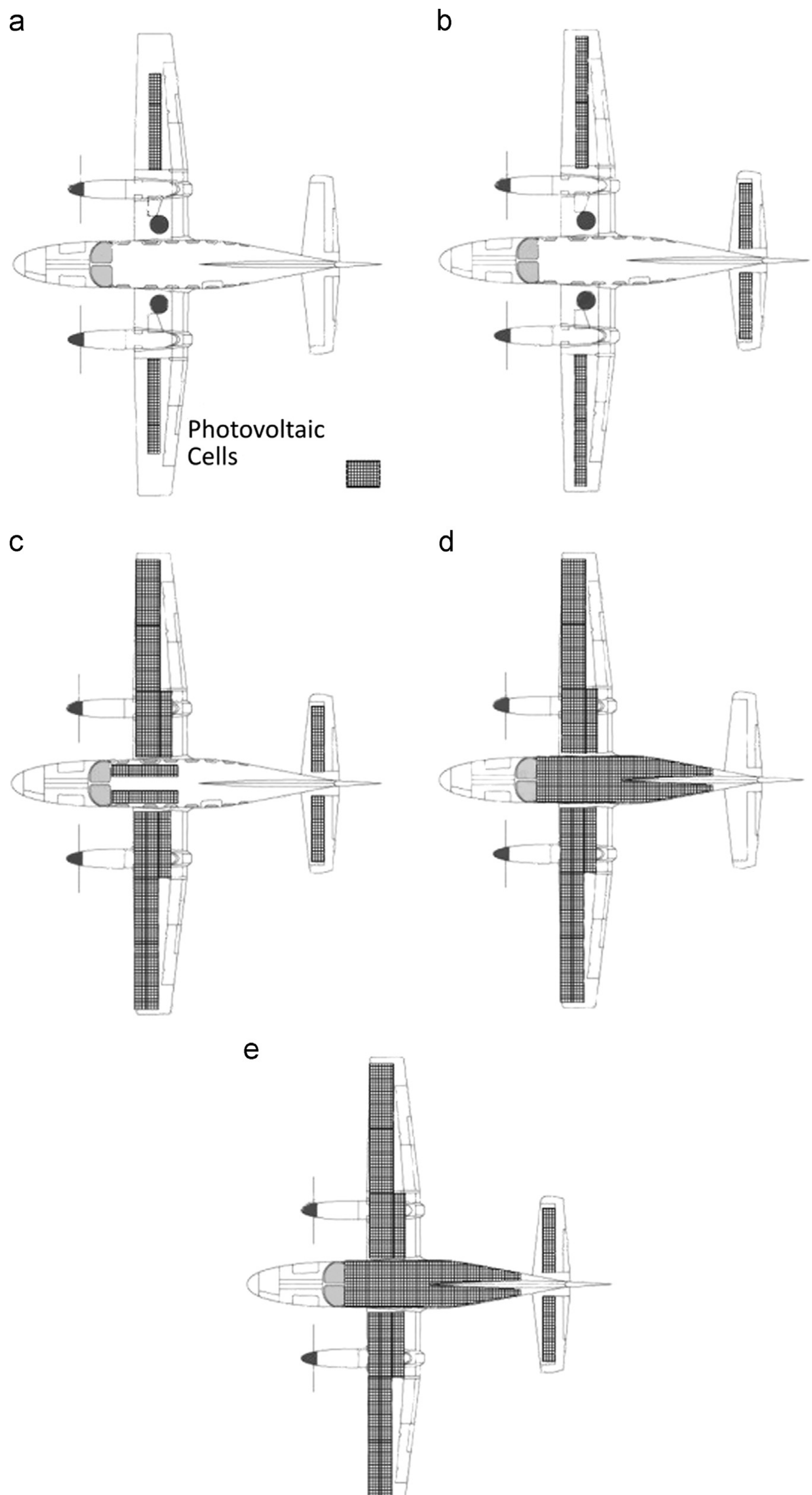

Fig. 2. Cessna Conquest 441 cell arrangement alternatives: (a) configuration 1, (b) configuration 2, (c) configuration 3, (d) configuration 4 and (e) configuration 5. The shadowed areas show the solar cells distribution on the aircraft. Source: made from http://www.the-blueprints.com/.

Table 1
Configuration of electric system and electric demand per flight phase for the A340–300.

Condition	Operational phase	Phase time, min	Delivered power, kV A	Electric demand, kV A h
Ground operation (only APU)	Operation in platform	84	92	129.0
Ground operation (APU+GEN)	Taxi, takeoff and landing	20	125.3	42.0
Abnormal operation (failure of one generator)	Climb, cruise and approach	720	109.5	1314.0
Ground operation (APU+GEN)	Taxi, takeoff and landing	20	125.3	42.0
Total electric power demanded				1526.0

Table 2
Calculations performed regarding fuel consumption and fuel saved.

	Step	Without PV system	With PV system
Apron, taxi, takeoff and climb	Total weight for the aircraft on the apron ($t=0$ s)	$WTo_{t0}=EW+PL+FOBo_{t0}$	$WTpv_{t0}=EW_{pv}+PL_{pv}+FOBpv_{t0}$
	Aircraft empty weight and payload	$PL=PAX{\bullet}AWP$	$EW_{pv}=EW+M_{pvs}$ and $PL_{pv}=(PAX-\Delta PAX_{pv}){\bullet}AWP$ In this study it is assumed $\Delta PAX_{pv}=0$
	Fuel required for the mission	$FOBo_{t0}$	$FOBpv_{t0}=FOBo_{t0}-E_S+Z$
	Fuel consumed to supply the electrical system		$E_S=s_{fc}{\bullet}(Epc_o-Epc_{pv}){\bullet}T_{max}{\bullet}t_{TF}$ Where, $Epc_{pv}=2\%{\bullet}Epc_o{\bullet}K_{ps}$
	Fuel on board at the start of the cruise phase	$FOBo_{CR}=FOBo_{t0}-Fco_{CL}-Fco_{TO}-Fco_{TX}$	$FOBpv_{CR}=FOBpv_{t0}-Fco_{TX}-Fco_{TO}-Fco_{CL}-s_{fc}\,{\bullet}R_{TW}{\bullet}(WTpv_{to}-Wto_{t0}){\bullet}Epc_{pv}{\bullet}\Delta t_{CR}$
	Fuel consumed from the apron until start cruise	$Fco_{\Delta tCR}=FOBo_{t0}-FOBo_{CR}$	$FCpv_{\Delta tCR}=FOBpv_{t0}-FOBpv_{CR}$
	Total weight of the aircraft at start of the cruise phase	$Wto_{CR}=Wto_{t0}-Fco_{\Delta tCR}$	$WTpv_{CR}=WTpv_{t0}-FCpv_{\Delta tCR}$
Cruise	Fuel on board at stage i of the cruise phase	$FOBo_{ti}=FOBo_{ti-1}-s_{fc}{\bullet}R_{TW}{\bullet}Wto_{ti-1}{\bullet}Epc_o{\bullet}\Delta t_i$	$FOBpv_{ti}=FOBpv_{ti-1}-s_{fc}{\bullet}R_{TW}{\bullet}WTpv_{ti-1}{\bullet}Epc_{pv}{\bullet}\Delta t_i$
	Fuel consumed in the stage i of the cruise phase	$Fco_{\Delta ti}=FOBo_{ti-1}-FOBo_{ti}$	$FCpv_{\Delta ti}=FOBpv_{ti-1}-FOBpv_{ti}$
	Total weight of the aircraft at stage i of the cruise phase	$Wto_{ti}=Wto_{ti-1}-Fco_{\Delta ti}$	$WTpv_{ti}=WTpv_{ti-1}-FCpv_{\Delta ti}$
Approach, landing, taxi and apron	Total weight of the aircraft at finishing the mission	$Wto_{i+1}=Wto_{tDL}-Fco_{\Delta ti+1}$	$WTpv_{i+1}=WTpv_{tDL}-FCpv_{\Delta ti+1}$
	Fuel consumed from start approach until parked on apron	$Fco_{\Delta ti+1}=FOBo_{ti}-FOBo_{ti+1}$	$FCpv_{\Delta ti+1}=FOBpv_{ti}-FOBpv_{ti+1}$
	Fuel on board at finishing mission	$FOBo_{ti+1}=FOBo_{ti}-Fco_{AL}$	$FOBpv_{ti+1}=FOBpv_{ti}-Fco_{AL}-s_{fc}{\bullet}R_{TW}{\bullet}(WTpv_{ti}-Wto_{ti}){\bullet}Epc_{pv}{\bullet}\Delta_{ti+1}$
	Total fuel saved	$\sum_I (Fco_i-FCpv_i)$	

where *EW* is the empty weight of aircraft, *PL* is the Payload, *FOB* is the fuel on board, *PAX* is the number of passengers on board, *AWP* is the average passenger weight, ΔPAX_{pv} is the penalization in passengers transported due to the installation of the PV system, *FC* is the fuel consumption, s_{fc} is specific fuel consumption, *T* is thrust of the aircraft power plants, *Epc* is Percentage of Engine Power in used Cruise.
R_{TW} is Thrust to Weight ratio, given by $T_{max}/MTOW$ and *Z* is the fuel adjustment at apron ($t=0$ s) to obtain the same amount of fuel reserve at the end of the flight for both configurations, and it is determined by an iterative calculation. According to the mission, it can take positive or negative values.

intermittent electrical loads in cruise flight and for communications, respectively.

The power demanded by the system for loading the battery, P_{DB}, is

$$P_{DB}=E_B n_L^{-1} t_{ALB}^{-1}, \tag{7}$$

where η_L is the battery load efficiency. E_B is the energy stored, which is given by:

$$E_B=t_{BO} PT\, f_D^{-1} n_D^{-1}, \tag{8}$$

where t_{BO} is the hours of battery operation, f_D is the depth discharge factor and η_D is the discharge efficiency of the batteries.

2.5. Fuel consumption

The fuel consumption of an aircraft equipped with a photovoltaic system and a standard aircraft were compared for the operational scenarios mentioned. The following assumptions were considered:

- The specific fuel consumption, sfc, is constant along the entire flight.
- The Thrust to Weight ratio, *RTW*, remains constant throughout the flight mission and it is equal to the maximum thrust (*T*max) to the maximum takeoff weight (MTOW) ratio.
- The power extracted from the engines, for cruise flight condition without photovoltaic system, Epc_O, is 80% of the total power available.
- The power extracted from the engines to supply 100% of the electrical system consumption is 1.6% of the maximum power [96].
- The duration of the mission phases corresponding to taxi, takeoff, climb, approach and landing, are defined for the case of the A340–300, as indicated in reference LTO cycle of ICAO, annex 16 vol. II [97]. For the Cessna Conquest 441 it was taken from [98] as the average duration of the LTO cycle in general aviation.

Table 2 shows the calculations performed to obtain the fuel saved by the aircraft equipped with the PV system for the entire flight, for the calculations, the phases apron, taxi, takeoff and climb were considered together as only one phase. For cruise phase, parameters are calculated for each time fraction: from the $t_{i-1}=t_{CR}$ (final time of phase climb) until $t_i=t_{DL}$ (initial time of phase approach), dividing the total cruise phase according to the desired accuracy. The phases approach, landing and taxi, until the mission end are considered together as only one phase.

2.6. Application of PV technology to other aircrafts

Comparative analysis for the this analysis aims to be a basic comparison of the relative potential of introducing the PV technology to other aircrafts.

The analysis is based in the comparison of the parameters and indicators identified in the study for two reference aircrafts: A340–300 (for large, medium and regional jets) and Cessna Conquest 441 (for business jets and general aviation).

The parameters identified for the comparison are: electrical power generation, electrical demand, electrical power generation to electrical demand ratio, and percentage of increased empty weight due to the installation of the PV system.

The electrical power generation was calculated as shown in 2.3, taking for large, medium and regional jets, the available irradiated surface corresponding to the configurations 1 (cells distributed on the surface of the wings and the horizontal stabilizer of the aircraft) and 2 (is equal to the first one, incorporating the surface of upper half of aircraft body). For business jets and general aviation aircrafts, the available irradiated surface was the required to supply the 100% of electrical demand. In both cases the radiation was considered equal to 4 PSH.

The electrical demand for large, medium and regional aircrafts was considered as the 85% of APU electrical power. This hypothesis is based on the analysis of the A340–300 and is endorsed by the FAR-25, which indicates that the APU should be capable of supplying all the electrical demand of the airplane.

The electrical demand for business jets and general aviation aircrafts was considered as the electrical demand in standard operation condition (without energy supply to the anti-ice system, optional systems and abnormally loads). This demand is equal to the 15% of the maximum capacity of the electrical system, which is obtained from the airplane datasheet.

The electrical power generation to electrical demand ratio was calculated for the scenarios: flight of maximum autonomy and 12 h of continue operation by day.

The percentage of increased empty weight by installing the PV system for business jets and general aviation aircrafts is calculated as shown in 2.3. The hypothesis adopted was that the batteries weight corresponds to the required to operate a time equivalent to maximum autonomy of the aircraft.

3. Results

3.1. Analysis for the Airbus A340–300

According to the methodology presented in II.B, the calculated radiation for the A340–300 in the different scenarios, gives the following results.

- Scenario 1, 12 h flight: the total radiation per day varies between 4300 and 9800 W/m^2, depending on day of the year.
- Scenario 2, 15 h flight: the total radiation per day varies between 5850 and 11,900 W/m^2, depending on day of the year.
- Scenario 3, Aircraft on the apron: the total radiation per day varies between 2150 and 8860 W/m^2, depending on day of the year.

Fig. 3 shows the available radiation on the solar cells for different scenarios, given by day of the year, site and operation. In Fig. 3 when the day number is mentioned followed by the airport code, it means that the aircraft was parked on that airport during the day solar hours. On the other hand, when the operation, the day number and the hours of flight are mentioned, then the aircraft receives solar radiation on ground before departure and then during the flight.

Considering the above results it was assumed for the different calculations 4 PSH as the available average radiation, because it was considered as an average conservative value. The design condition to dimension the PV system for the A340–300 was a 14 h flight with the electrical demand shown in Table 1.

The implementation of the PV system in the above configurations carries an increased empty weight of the aircraft, which is shown in Table 3.

Then the fuel saved by implementing the PV system was calculated, according to the methodology presented in II.E. The results obtained are shown in Figs. 4 and 5.

It can be seen that implementing the photovoltaic system on the A340–300 allows a reduction on fuel consumption of 252 kg (20 kg per flight hour) and 594 kg (46 kg per flight hour) for a flight mission range of 11,112 km, for configurations 1 and 2, respectively. As the range departs from the design point, the fuel consumption reduction decreases, reaching zero at 1800 km. For shorter ranges there is an increment in fuel consumption due to the PV system introduction (more fuel is required to transport the weight of the PV system).

The reduction in fuel consumption for the case of a flight range of 11100 km is 0.30% of the total fuel consumed for configuration 1 and 0.71% for configuration 2.

3.1.1. Comparison with other large, medium and regional jets aircrafts

Fig. 6 shows the electrical demand supplied by the PV systems for 12 h of aircraft continuous operation, for different aircraft, taking the A340–300 as a reference. For the same aircrafts

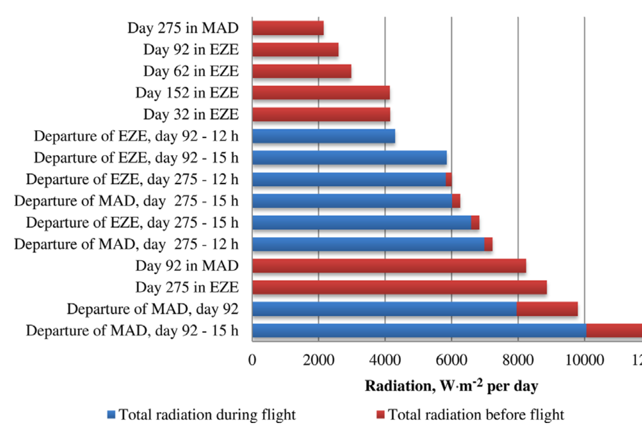

Fig. 3. Radiation on the solar cells for different scenarios in the A340–300, day 92 (June 21st) and day 275 (December 21st).

Table 3
Weight composition of the PV system and increased empty weight of the aircraft (A340–300).

Component	Configuration 1		Configuration 2	
	Mass, kg	PV system weight/ EW, %	Mass, kg	PV system weight/ EW, %
Solar cells	794		1794	
Battery	490		1135	
Total weight of system	1284	1	2929	2.3

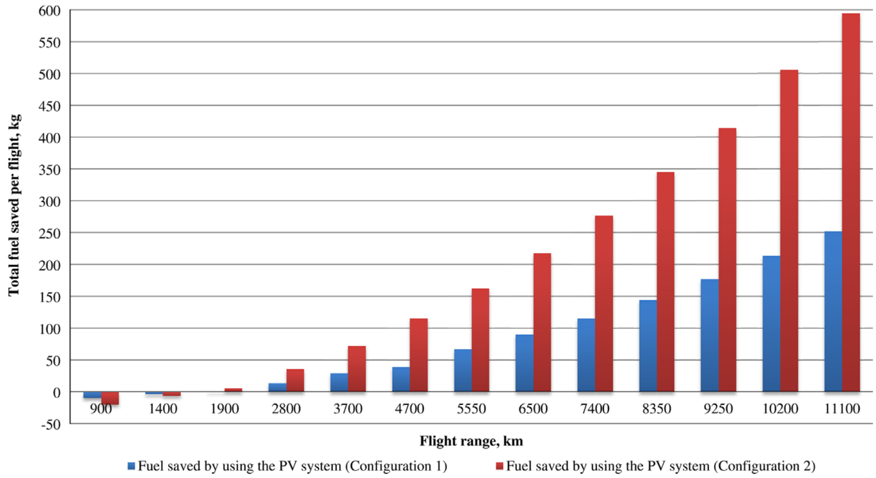

Fig. 4. Total fuel saved by type of flight and PV system configuration for the A340–300.

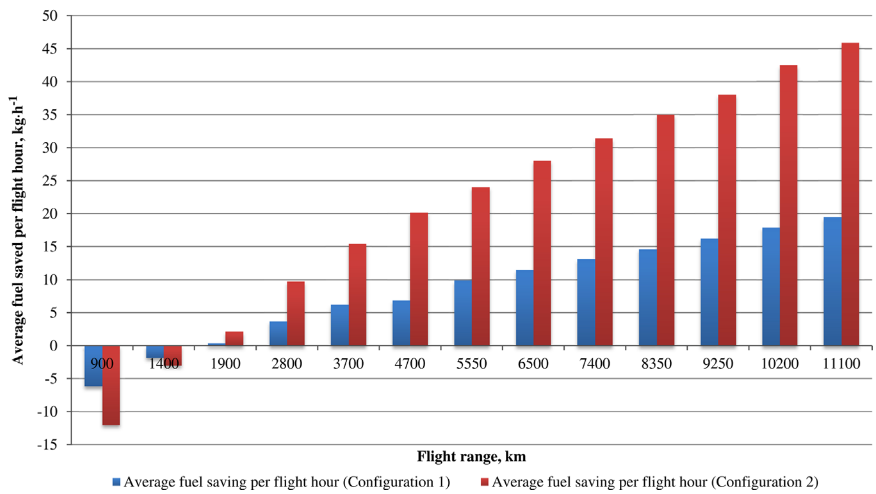

Fig. 5. Average fuel saved per flight hour by type of flight and PV system configuration for the A340–300.

Fig. 7 shows the electrical demand supplied by the PV systems for their maximum autonomy flight. For all the cases it was taken 4 PSH as available radiation.

The same analysis was done for the configuration 2 (see Fig. 8 and Fig. 9).

3.2. Analysis for the Cessna Conquest 441

According to the methodology presented in II.B, the calculated radiation for the Cessna Conquest 441 in the different scenarios, gives the following results.

- Southern of the Argentine territory: the total radiation per day varies between 580 and 8450 W/m^2, depending on day of the year.
- Center of the Argentine territory: the total radiation per day varies between 2900 and 8850 W/m^2, depending on day of the year.
- Northern of the Argentine territory: the total radiation per day varies between 4100 and 8600 W/m^2, depending on day of the year.

Fig. 10 shows the available radiation on the solar cells for different scenarios, given by day of the year, site and operation. In all cases it was considered that the aircraft was parked on the airport during the day solar hours.

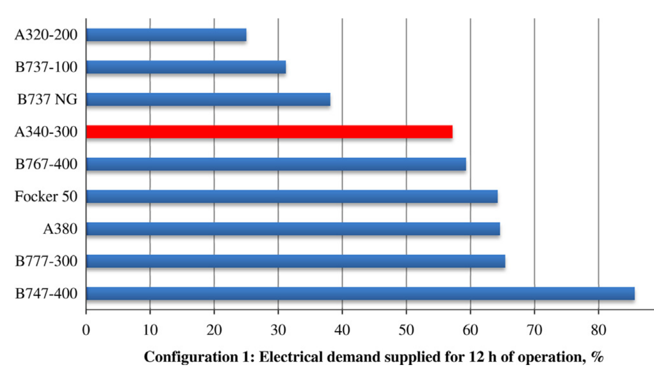

Fig. 6. Percentage of electrical demand supplied by the PV system for 12 h of aircraft continuous operation, configuration 1 cells arrangement for different aircrafts.

To analyze the Cessna Conquest, seven cases were considered, conformed by 5 types of cells configurations (according to the flight type) and availability or storage unavailability (battery), and in all cases it was assumed that the electrical demand is standard. The application of the methodology for calculating the electrical demand of the Cessna Conquest 441, allowed to obtain, for the different scenarios, the values shown in Table 4, which are for the standard operating conditions approximately 15% of the maximum capacity of the electrical system.

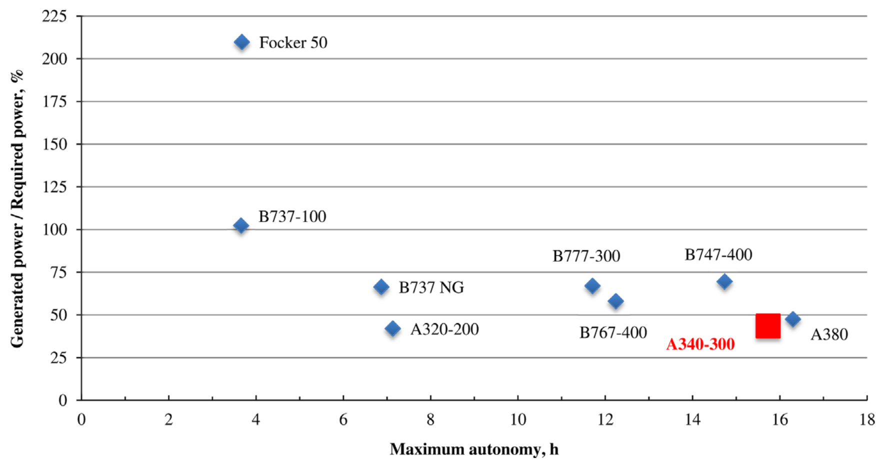

Fig. 7. Percentage of electrical demand supplied by the PV system for maximum autonomy flight, configuration 1 cells arrangement for different aircrafts.

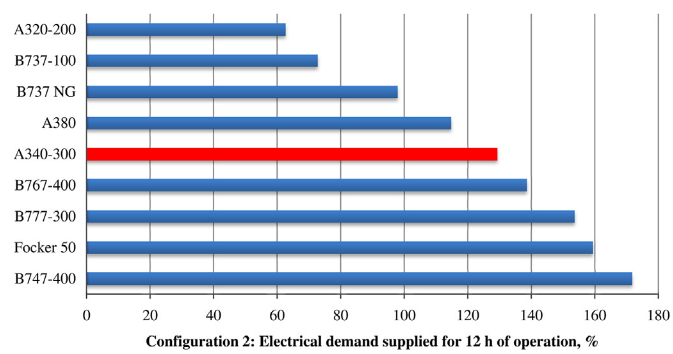

Fig. 8. Percentage of electrical demand supplied by the PV system for 12 h of aircraft continuous operation, configuration 2 cells arrangement for different aircrafts.

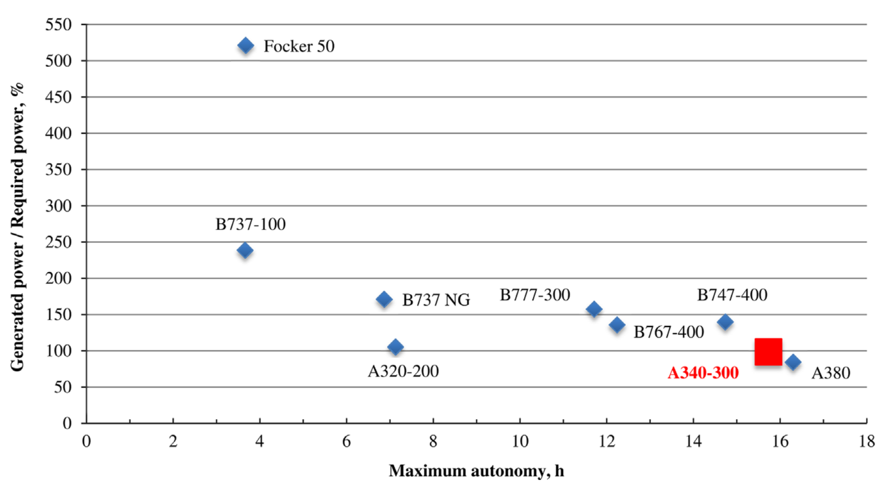

Fig. 9. Percentage of electrical demand supplied by the PV system maximum autonomy flight, configuration 2 cells arrangement for different aircrafts.

The implementation of the PV system in the previous cases involves the following increase of the empty weight of the aircraft (Table 5).

In this aircraft the photovoltaic system implementation would give the following reductions in fuel consumption (see Fig. 11).

- Flight with maximum payload and 100% electrical energy storing capacity: reduction in consumption of 5.7 kg, 0.88% of total consumption.
- Flight with maximum payload and without electrical energy storing capacity: reduction in consumption of 9.1 kg, 1.4% of total consumption.
- Maximum range flight and 100% electrical energy storing capacity: reduction in consumption of 3.2 kg, 0.22% of total consumption.
- Maximum range flight and without electrical energy storing capacity: reduction in consumption of 22.8 kg, 1.58% of total consumption.

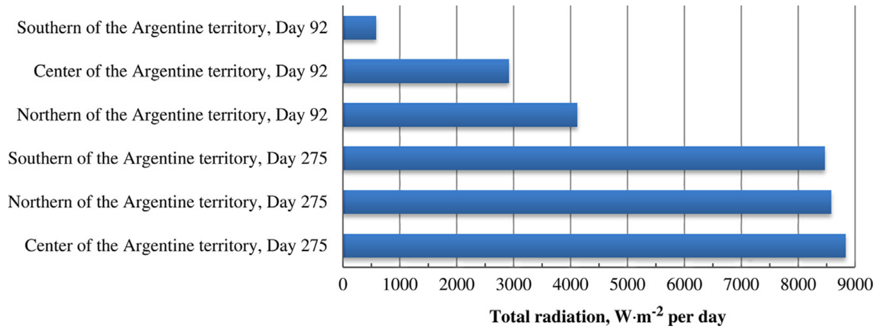

Fig. 10. Radiation on the solar cells for different scenarios in the Cessna Conquest 441, day 92 (June 21st) and day 275 (December 21st).

Table 4
Cases analyzed for the Cessna Conquest 441, according to the PV system configuration, flight types and electrical demand.

Case	Cells configurations[a]	Battery	Flight types	Flight hours per day	Electrical demand per flight, kV A h	Observations
1	1	No	Flight with maximum payload, maximum takeoff weight and standard electrical demand[b]	4.1	7.2	
2	1	Yes	Ditto cases 1	4.1	7.2	[c]
3	2	No	Maximum flight range with maximum takeoff weight and standard electrical demand[e]	8.5	14.9	
4	2	Yes	Ditto cases 3	8.5	14.9	[c]
5	3	Yes	24 h of operation per day and standard electrical demand[b]	24	44.3	[e]
6	4	Yes	Ditto cases 5, plus system anti-ice operating 24 h	24	75.2	[d]
7	5	Yes	Ditto cases 6, plus optional equipment operating 24 h	24	79.2	[d]

[a] See cells configuration in the Fig. 2.
[b] Without energy supplied to the anti-ice system, optional systems, abnormally loads.
[c] When having energy storage capacity, two flights per day could be done in high radiation hours (summer) or flight in nighttime using the energy stored during the day (at the airport in low radiation hours, and at the airport or flight in times high radiation).
[d] This case is cited to highlight the increase in electrical demand, to consider one configuration operative with additional loads.
[e] Using the energy stored in the batteries to operate for 14 of the 24 h.

Table 5
Weight composition of the PV system and increased empty weight of aircraft (Cessna Conquest 441).

Case	Mass of cells, kg	Mass of batteries, kg	Total system mass, kg	PV system weight/ EW, %
1	9	n/a	9	0.3
2	9	24	33	1.3
3	17.5	n/a	17.5	0.7
4	17.5	46.5	64	2.5
5	52	86	138	5.4

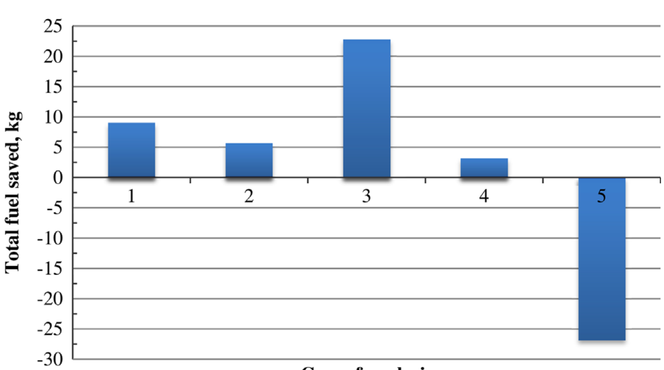

Fig. 11. Total fuel saved per type of flight according to the PV system configuration, for the cases indicated in Table 4.

– 24 h flight, operating 14 h with the energy stored in the batteries: the consumption rises to 26.8 kg by flight of maximum range, that is, it generates an increase in fuel consumption of 1.86%.

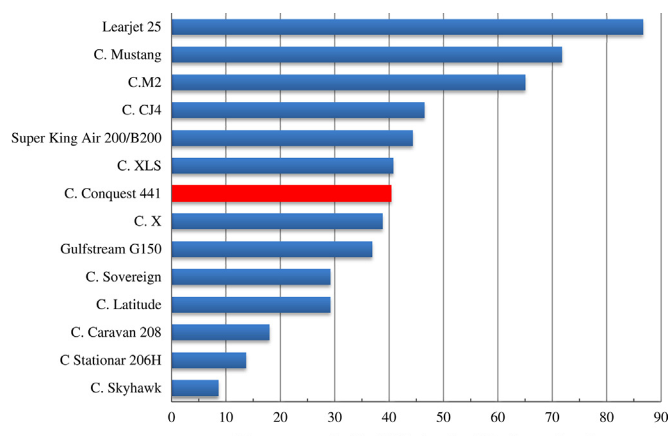

Fig. 12. Surface required by the PV system for condition of 12 h of operation per day, assuming 4 PSH, for different aircrafts.

From the analysis performed, it can be seen that the implementation of the photovoltaic system on the Cessna 441 could even allow to the aircraft to operate 17.5 h during the high solar radiation season and, 8.5 h when the radiation is low in Argentina, in both cases supplying 100% of the electrical demand and generating savings in fuel consumption.

In this aircrafts type deploying the photovoltaic cells only to 15% of the wings area is enough to supply 100% of the electricity demand for a flight with maximum payload and MTOW. For the case of two maximum range flights in a day, in the high solar radiation season, it would be required to install photovoltaic cells over the 30% of the wings area. On the other hand for the case of 24 h of operation it would be required a surface covered with cells equivalent to 88% of wing area. Finally considering the ice protection system and optional devices, all the available surface of the aircraft (configuration 4 and 5) should have installed the photovoltaic cells to supply 100% of the energy required.

3.2.1. Comparison with other business jets and general aviation aircrafts

To compare the feasibility of implementing the photovoltaic system on other aircrafts, the guidelines shown in Section 2.6 were applied. The results obtained from the analysis of capacity and demand of the electrical system are comparable, since both the geometrical characteristics as electrical demand does not vary strongly in this type of aircraft.

In Figs. 12 and 13 it can be seen (for 12 h of operation per day on all aircrafts) that the Cessna Conquest 441 is the 7th aircraft with the largest restrictions for applying the PV system, from the point of view of the required surface, and the 4th with greatest restrictions regarding empty weight increase of the aircraft.

If we consider only the operation of the aircraft during a single flight of maximum autonomy, the Cessna Conquest 441 is the most restricted in required surface and empty weight increase, as show in Figs. 14 and 15, where the ID. Airplanes are 1) C. Caravan 208, 2) C. X, 3) C Stationar 206H, 4) Super King Air 200/B200, 5) C. XLS, 6) C. Sovereign, 7) C. Skyhawk, 8) C.M2, 9) C. Latitude, 10) C. Mustang, 11) C. CJ4, 12) Learjet 25, 13) Gulfstream G150, 14) C. Conquest 441.

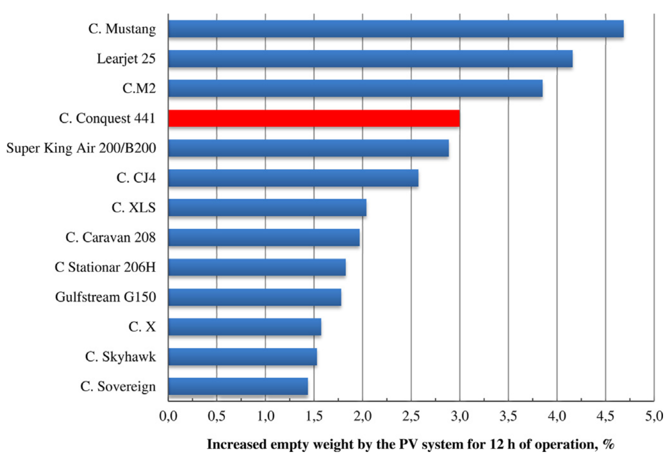

Fig. 13. Increased empty weight by installing the PV system for condition of 12 h of operation per day, assuming 4 PSH, for different aircrafts.

4. Summary and conclusions

In this work, the feasibility of implementing photovoltaic technology to supply the electrical demand of aircrafts has been studied by a defined methodology, which comprises: the selection of the photovoltaic technology, the calculation of available radiation, the estimation of electrical demand, the layout of solar cells, the PV system capacity calculation, the determination of the photovoltaic system weight, the calculation of fuel savings for PV system equipped aircrafts, and finally the extrapolation of results to the other aircrafts. It is worth to mention that this works deals only with the operational feasibility of the PV system, and not regarding the investment costs and certification feasibility.

Given the characteristics of electrical demand in the commercial aircraft, third-generation multijunction photovoltaic cells have been chosen. They currently have an efficiency of 43.5%, promising to achieve up to 60; an efficiency of 45% has been used for the calculations.

The batteries proposed to implement the photovoltaic system correspond to Lithium-ion, with capacity 400 W h/kg.

The methodology to determine the available solar radiation showed a strong influence on the type of mission, navigation path and day of the year, and a second order influence on the aircraft geometry and on its orientation to the sun.

The calculation of the PV system capacity was realized for an average radiation of 4 PSH. This value was considered representative and conservative for the operations considered.

Regarding aircraft electrical demand an almost linear relationship with its dimensions can be observed. This fact allows extrapolating the results obtained from the analysis of the A340–300 to other jet aircrafts (large, medium and regional jets).

The feasibility of applying a photovoltaic system on a commercial aircraft such as the A340–300 is dependent on each particular operational case: flying hours per day, schedules of operation and especially of the constancy of these variables. In the case of A340–300 covering the flight Buenos Aires–Madrid and Madrid–Buenos Aires, doing one flight per day, the fuel savings per year could be 169,300 kg, equivalent to the fuel required by the A340–300 for two flights between Buenos Aires and Madrid.

The implementation of photovoltaic system in business jets and general aviation aircrafts as the Cessna Conquest 441 is technically feasible; a reduction in fuel consumption could be achieved.

The implementation of a photovoltaic system on an aircraft involves an empty weight increase, which can be translated into a penalty of any of the following aspects: reduction in payload, reduction in the flight range, and reduction in fuel economy. The alternatives of penalizing the payload or range are not considered as a viable option, so the focus was pointed on savings in fuel consumption.

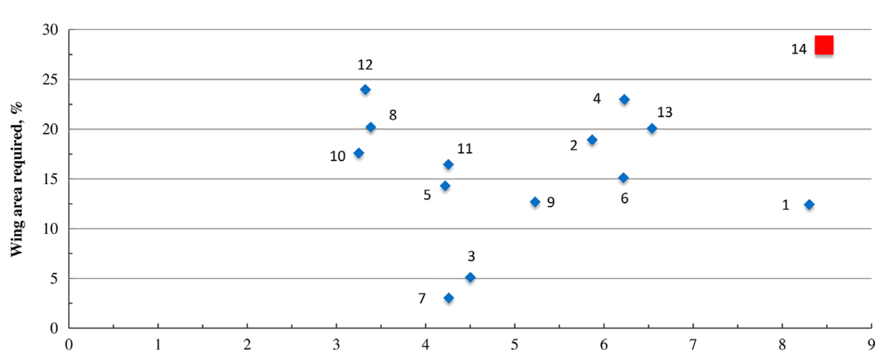

Fig. 14. Surface required by the PV system a maximum autonomy flight per day, assuming 4 PSH, for different aircrafts.

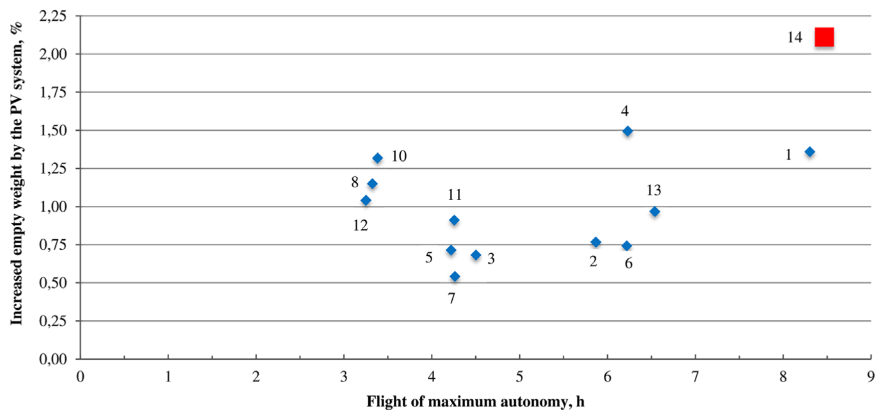

Fig. 15. Increased empty weight by install the PV system for a maximum autonomy flight per day, assuming 4 PSH, for different aircrafts.

Conceptual designs of next generation of commercial aircraft, such as the BWB (Blend Wide Body), have geometric characteristics that would allow higher efficiencies in the implementation of PV systems than for current aircrafts. Likewise, the advancement in technology of solar cells and batteries is really noticeable from year to year, so the application of photovoltaic technology in commercial aircrafts may be perceived as a viable alternative in the near future.

The photovoltaic system implementation finds it greatest obstacle in the storage capacity of the batteries, as this leads to a significant increase of weight of the aircraft. For the A340-300 it is unfeasible to have a storage capacity of 100% of the energy captured in a day of 4 PSH, so it was limited to 25% of the electrical demand. Then the stored energy can supply only 100% of the demand required by no more than 3.5 h.

Regarding the supply of the electrical demand, the results show that a PV system with cells on the aircraft wings supplies 45% of the aircraft electrical demand, while if the aircraft has additional cells on the fuselage, the PV system would be able to supply 100% of the aircraft electrical demand.

The aircrafts of shorter range (regional aircrafts) exhibit greater viability to supply electrical demand for the case of only one flight of maximum range per day. If the aircrafts operate the same number of hours per day, the viability of the PV system is higher in the aircrafts of large and medium range than for short range aircrafts. For this criterion the A340–300 is situated in an intermediate case.

For the case of the Cessna Conquest 441 and similar aircrafts it is feasible to storage 100% of the energy generated by the PV system, however, in such a way this system performance regarding fuel consumption reduction is not optimized.

Regarding future work, this analysis could be extended to other aircrafts and operational scenarios. Other aspect could be the management of the airlines operations to obtain the maximum fuel reduction with their PV aircraft fleet.

Furthermore, the feasibility analysis could consider the use of PV system batteries combined to the aircraft batteries to reduce weight.

Finally, other aspect that has not been considered is the study certification process for these types of aircrafts that could be included in future work.

Acknowledgments

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