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ASSESSMENT OF THE PURPOSEFULNESS OF APPLYING FLEXIBLE SOLAR MODULES FOR LARGE COMMERCIAL AIRCRAFT

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Today we live in a diminishing world due to effective ways of transport, especially aviation. One of the most recent and important issues of our life and scientific research has become the negative climate change – partially due to aviation emission. The “More Electrical Aircraft” has been a term recently created. The ideology of this concept is to power onboard aircraft devices by electrical energy as much as possible. Applying new kind of electrical onboard energy sources (excluding these coming from traditional engines), there is a potential possibility to reduce fuel consumption. Such new electrical energy sources need to respond to some criteria, the most important one of which is that the energy density of the new electrical energy source must be as close as possible, or even greater than the energy density of the traditional fuel aircraft, taking into consideration the efficiency of traditional onboard energy generators. The achievement of this criterion makes the applicability of these new electrical energy sources justifiable. Covering the upper part of the aircraft fuselage oriented to solar radiations by flexible photovoltaic modules creates the possibility to obtain a new onboard electrical energy source. The new energy source is characterised by the fact that its energy production depends on the solar exposition time. Taking into account mass of the photovoltaic installation (in this study for B787) and power generated by these modules, the interrupted flight time needed to achieve the energy density criterion, explained above, has been estimated. Taking into account the current technological possibilities and strongly optimised flight conditions, this time is about 29 hours. Commercial aircraft do not exhibit such long flight duration, which makes the application of accessible flexible photovoltaic modules to passenger aircraft unsuitable.

1. Introduction

Modern aviation is a part of worldwide pro ecological technological reorganisation. A vast number of projects and assessments related to reduction of the negative impact of aircraft on both local and global natural environment has been already undertaken, and several advantages, threats and challenges were indicated. Importantly, many of them focused only on a relatively narrow range of applications or technologies, limiting the results to an analysed case only, resulting in difficulties in direct knowledge transfer between general and commercial aviation. One of the most perspective solution dedicated to future “green” aviation is photovoltaic technology. Very popular in stationary applications, it gradually boosts now in transport industry as well, including bikes, cars, boats (i.e. vehicles made by the PWr Solar Boat Team [1]) and, importantly, aircraft (i.e. Solar Impulse 2 [2]). No direct atmospheric emission, typical for modern jet and piston engines [3], controlled by more and more international organisations and legislators, seems to be a vital benefit of PV implementation within the aircraft.

An implementation of PV units within fuselage, wings, elevators or stabilisers might be justified in terms of fuel savings and reduction of CO_2, CO, NO_x, soot and particulate matter emissions from aircraft propulsion. Energy yield from PV technologies does not result in direct emissions of the abovementioned pollutants and leads to reduction of quantity of kerosene that need to be burned in order to supply all electric devices. According to [3], burning of 1 kg of kerosene in a modern turbofan engine results in average emission of 3.15 kg of CO_2, 11.1 g of NO_x, 0.93 g of SO_2, 0.74 g of CO, 0.15 g of hydrocarbons and 0.04 g of particulate matter. It is crucial to add that the average fuel consumption per seat of B787-800 is 2.3-2.8 kg per 100 km.

Photovoltaic panels are more and more often used, and their efficiency still increases. The most popular aspect of the photovoltaic panels is that they are flat stiff plates whose shape can be tailored. For a few years, the photovoltaic panel has met an impressive development and became flexible. This aspect of the flexible photovoltaic panel is suitable for its use in complexly shaped devices. In this paper, the flexible photovoltaic module will be treated in the context of its applicability in large size aircraft.

Actually, when analyzing a solar aircraft, the photovoltaic panels are considered as power sources used to extend the flight range by charging onboard batteries powering an electrical engine (Mauro Solar Riser [4]) or to power the low power drive (Solar Impulse 2 [2]). In the first case, the solar power is used as a range extender, but the solar energy does not permit the aircraft to perform a whole solar flight. In the second case, the solar energy source is enough to power the whole aircraft but the low power of the aircraft drive eliminates this solution from cargo or passenger aircraft. In both cases, the proposed solutions could not permit a cargo aircraft to fly. This the reason why in this paper the solar energy source will be used as an additional power source next to the traditional engine generator (powered by kerosene) in order to save a part of the fuel – it is the “More Electric Aircraft”.

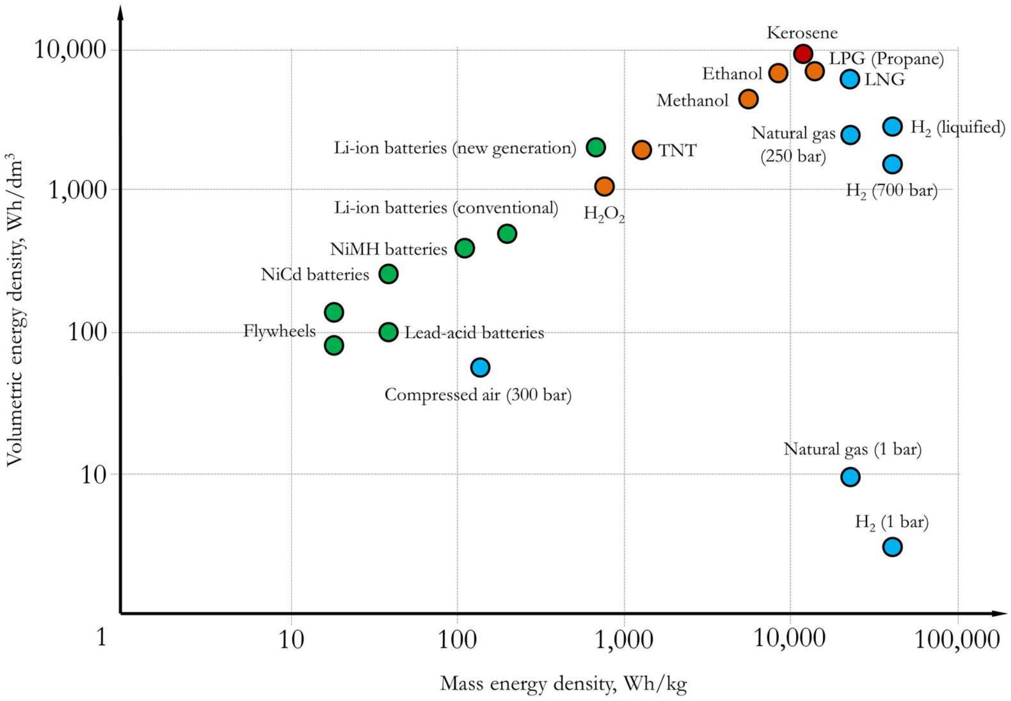

Fig. 1. Volumetric and mass energy density of selected energy carriers (own elaboration)

The implementation of PV technologies in aviation seems to be vital due to increasing interests in “more-electric” aviation systems. In a conventional airplane, electrical systems, supplies flight deck displays, flight control, in-flight electrical consumption are powered by engines via generators (these machines convert mechanical power engine shafts to electric power), while many actuators and subsystems use pneumatic and hydraulic systems to work properly. Interestingly, by removing high-energy air receivers and replacing them by electric equivalents, many advantages might be obtained (more thrust from the engine, smaller engines, better fuel efficiency, lower maintenance costs, saved weight of the subsystems). This fact has been applied in the 787 Dreamliner, which uses more electricity and less pneumatics to power airplane systems (engine start system – extra APU batteries, wing ice protection, selected actuators) and, therefore, its energy economy is clearly distinguishable in modern high-capacity civil aviation sector [5].

A classical aircraft needs enough lift in order to fly. This lift is generated by wings which interact with the air. The generated lift is dependent on the air flow velocity around the wing and on the angle of attack of the wing. When more lift is needed, the flight velocity and the angle of attack (or both) need to be increased. When the velocity and/or angle of attack are increased, the drag of the aircraft is also increased. The drag force is compensated by the aircraft drive systems engines. When the engine needs to generate more thrust, the fuel consumption is also increased. From the above reason, it may be concluded that when the aircraft mass increases, the fuel consumption also grows. This is the reason for which when designing an aircraft, the chosen materials need to be selected so as to maintain its functioning with the lowest possible mass. It is the same when selecting the fuel: there is a need to have high energy with the smallest mass – this criterion is described by energy density. When selecting a fuel to empower the aircraft, the energy density of its fuel needs to be as high as possible. At the same time, there is a need to take into account the importance of aircraft safety – gaseous fuels, like hydrogen, natural gas, etc. are avoided. Basing on these criteria, and according to the information delivered by figure 1, kerosene is the most suitable fuel for aircraft applications. In calculations presented in the next part of this paper, photovoltaic panels energy density will be compared to kerosene energy density.

However, more-electric systems on a plane means more electric demands. For example, the B787-800 has six generators (two in each engine and two in the auxiliary power unit), four AC buses, 17 small electrical substations and both main (located in the forward equipment bay) and APU (located in the aft electrical equipment bay) batteries (Li-Ion, 32 V DC) – including additional layers of redundancy for continued safe operation. With proper optimisation of all electrical devices, generators and connections need to be harnessed in order to achieve fuels savings (electricity is still generated using engines). Additional sources of electrical power seem to be an interesting option to boost fuel savings within all modern planes.

The aim of this paper is to assess whether the use of flexible photovoltaic panels on a passenger aircraft (B787) will provide an efficient, highly-energy-densed onboard source of energy and, if possible, to what extent.

2. Assumptions for calculations

In the next part, calculations of the energy density of the optimal flexible solar modules and the Jet-A fuel will be compared (in the context of electrical power generated onboard the aircraft for the electrical devices). In aviation, the energy sources which are used onboard need to present high energy density. The Jet-A fuel energy density depends on the engine efficiency only (from fuel to electrical energy). The energy density of solar modules depends on many parameters (altitude, solar module efficiency, shape of the irradiated surface, time, etc.). To perform an analysis, there is a need to take into consideration an exemplary aircraft model. A comparison of energy density of the solar module and fuel will enable one to establish travel duration after which the energy density of the solar modules becomes higher than that of Jet-A fuel. The travel duration is the minimum flight time in order to take advantages of applying the solar modules. Additionally, the power generated by the solar modules must will be calculated to compare it to the onboard electrical power demand. The calculations are made on the following assumptions:

- Boeing 787 (Dreamliner) aircraft is taken into consideration,
- flexible solar modules are applied to the higher surface of the hull, wings and horizontal tails,
- solar radiations are perpendicular to the projected surfaces of the aircraft (in order to establish the most optimal energy generation coming from the flexible solar modules),
- the aircraft performs a flight with constant pitch and during daylight (the aircraft pursuits the sun).

3. Calculations

The radiation intensity available at the atmospheric frontier E_s is equal to 1367 W/m^2 [6]. Flisom is a company producing flexible solar modules, even used for aeronautical and space applications. This is a kind of photovoltaic panel being flexible and light [7]. According to operational parameters revealed by the mentioned producer, their flexible solar modules, called eFilm, are able to generate about $P_{js} = 140\,\mathrm{W/m^2}$ in space applications. According to the above data, it is proposed to estimate the efficiency of the mentioned solar modules η_{FSM} in aerospace conditions, as presented in by equation (3.1)

$$\eta_{FSM} = \frac{P_{js}}{E_s} = \frac{140\frac{\mathrm{W}}{\mathrm{m}^2}}{1367\frac{\mathrm{W}}{\mathrm{m}^2}} = 10.2\% \tag{3.1}$$

The Boeing 787 (Dreamliner) has a ceiling established at 13.1 km [8]. According to the data given in figure 2 [9], the solar irradiance E at this altitude is equal to 1320 W/m^2.

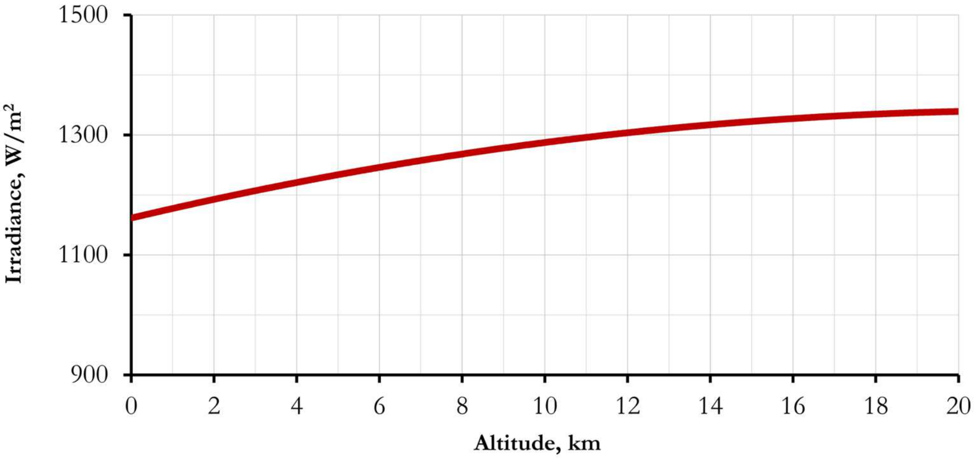

Fig. 2. Available solar irradiance in function of altitude (own elaboration on the basis of [9])

Taking into consideration the efficiency of the applied solar module, accessible solar irradiance intensity at the ceiling of the B787, and assuming no changes in the solar modules efficiency, it is possible to estimate the maximum surface power generated by the solar module P, see equation (3.2)

$$P_{13.1} = E_{13.1}\eta_{FSM} = 1320\frac{\mathrm{W}}{\mathrm{m}^2}\cdot 10.2\% = 134.6\frac{\mathrm{W}}{\mathrm{m}^2} \tag{3.2}$$

Is this analysis, it is supposed that the aircraft is covered by flexible solar modules, as described above. The solar modules are applied on the higher part of the hull, both wings and on the horizontal tail. The draft of the B787 available at [10] has been copied into the AutoCad software [11]. This software enables one to draft contours of the hull, wings and the horizontal tail. The draft is a projection of the aircraft, viewed from above. The surface of this projection is representative for electric energy generation. It is supposed that the solar radiation is perpendicular to the projected surface of the aircraft. The draft was introduced into the software at the scale of 1:1 (figure 3a). The energy generation representative surface is about $626.3\,\mathrm{m}^2$ (A_{proj}).

The wings and horizontal tail are approximately planar, so their projected surfaces correspond approximately to the real surfaces. As the hull has a cylindrical shape, the real surface is greater than the projected surface. In order to estimate the real surface of the hull, the hull was created in the Solid Edge software [11] (figure 3b). The hull surface was added to the wings and horizontal tail (established in AutoCad) in order to calculate the real surface of the solar modules. It was estimated that the real surface of the solar module was equal to $780.0\,\mathrm{m}^2$ (A_{real}).

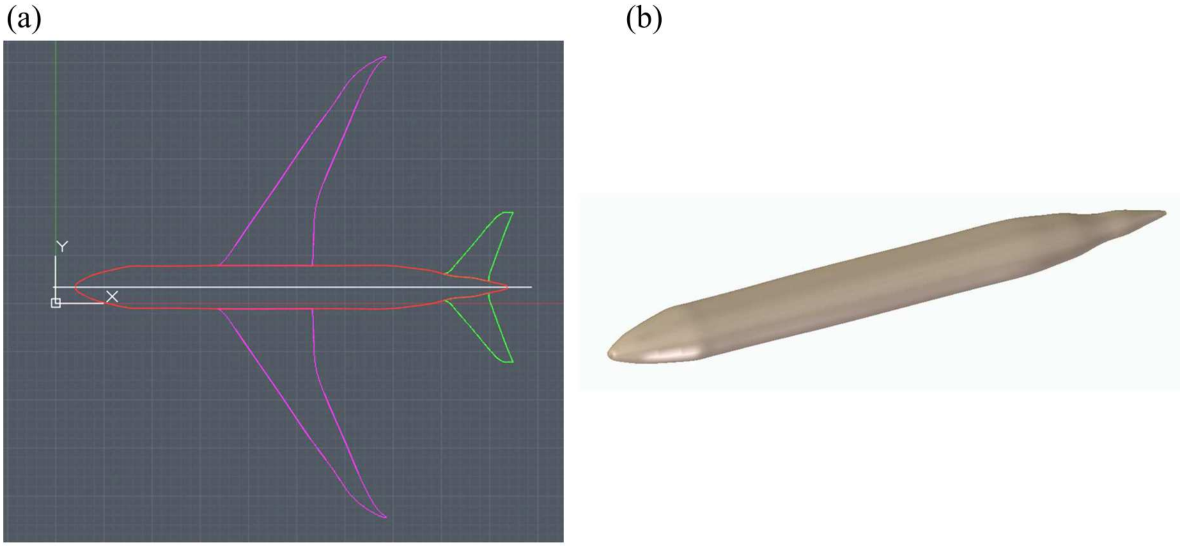

Fig. 3. View of the draft used to estimate the representative surface for electric energy generation of the B787 aircraft (a) and a simplified 3D model of the B787 hull (b)

According to the projected surface of the flexible solar modules and to the maximum value of the generated surface power at the B787 ceiling, it is possible to calculate the maximum power generated by all flexible solar modules fixed on the higher surface of the aircraft (N_{FSM}), see equation (3.3)

$$N_{FSM} = P_{13.1}A_{proj} = 134.6\,\frac{\mathrm{W}}{\mathrm{m}^2}\cdot 626.3\,\mathrm{m}^2 = 83\,300\,\mathrm{W} \tag{3.3}$$

According to the solar module manufacturer, it is possible to obtain its specific weight m_j equal to 0.06-0.5 $\mathrm{kg/m}^2$ [12]. In the next calculation, see (3.4), the mass of solar modules was estimated for the specific weight $0.5\,\mathrm{kg/m}^2$

$$m_{FSM} = m_j A_{real} = \frac{1}{2}\,\frac{\mathrm{kg}^2}{\mathrm{m}}\cdot 780\,\mathrm{m}^2 = 390\,\mathrm{kg} \tag{3.4}$$

Taking into consideration the estimated values of the maximum power generation by the solar system and its weight, formula (3.5) for the energy density W_u was established in function of time t (here in hours). As the solar radiation is free of weight, the mass of solar modules was taken into consideration in calculations

$$W_{uFSM} = \frac{N_{FSM}}{m_{FSM}}t = \frac{83\,300\,\mathrm{W}}{390\,\mathrm{kg}}\,t = 216.15\,\frac{\mathrm{W}}{\mathrm{kg}}\,t \tag{3.5}$$

The energy density for flexible solar modules was established taking into consideration the solar irradiation, aircraft pitch, solar module efficiency, aircraft surfaces and time of the flight (at the given altitude).

The lower heating value (LHV) of the Jet-A fuel is about 43 MJ/kg. According to [13], the efficiency of conversion of chemical energy into electric one η_c in B787 is equal to 53%. These two parameters enabled determination according to formula (3.6) the energy density of the fuel in terms of the electric energy yield. The weight of the engine was not taken into consideration, because the engine is usual a part of the aircraft without which an autonomous flight would not be possible

$$W_{uJET-A} = LHV_{JET-A}\,\eta_c = 43\,\frac{\mathrm{MJ}}{\mathrm{kg}} \cdot 0.53 = 22.79\,\frac{\mathrm{MJ}}{\mathrm{kg}} \tag{3.6}$$

In aviation, the energy sources used need to be characterized by high energy density. In the above calculations, the solar module (for optimal flight conditions) and Jet-A fuel energy density were established in terms of electric power generation onboard the B787 aircraft. In figure 4, the energy density of both technologies are presented.

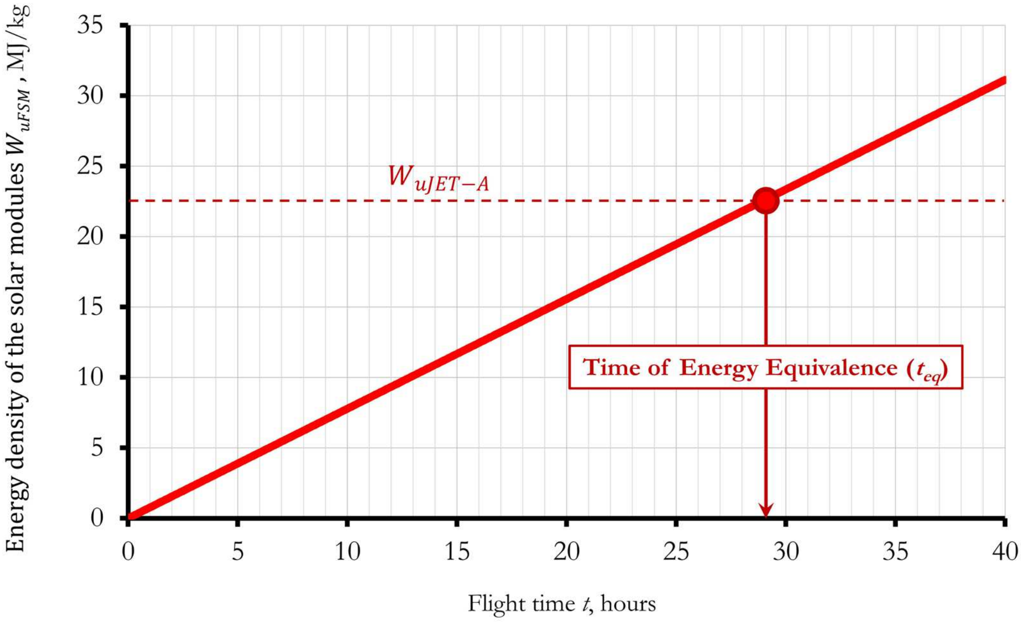

Fig. 4. Flexible solar modules (for optimal flight conditions of B787) and Jet-A fuel energy density in function of flight duration for $m_j = 0.5\,\mathrm{kg/m^3}$

Above figure 5 shows that the travel duration after which the solar modules energy density becomes higher that of the Jet-A fuel is approximately equal to 29 hours.

4. Results and discussion

The presented calculations proved that for most optimal irradiation conditions of the B787 aircraft covered by flexible solar modules, their energy density overcomes the Jet-A fuel energy density after about 29 hours of flight. It must be noticed however that the actual record of continuous flight of a passenger aircraft is equal to 18 hours [14]. This record was established by the B787. This directly means that the use of flexible solar modules for a commercial aircraft is not yet beneficial from the energetical point of view.

The analysis also showed that the solar modules maximum electrical power generation is about 84 kW. Onboard the B787, the engines generators produce 944 kW [13]. It means that about 8.9% of onboard energy could be generated by the solar modules. And for their use to be more advantageous than the use of Jet-A fuel, the travel duration should be equal or greater than 29 hours.

It must be underlined that the duration of 29 hours is established for most optimal radiation and flight conditions. Taking into consideration that these flight conditions could not be accomplished in a real commercial flight (various destinations, flight by night, starting and landing, etc.), the durations over 29 hours could never be met (this minimum flight duration could be expanded even to infinity). It means that the solar modules applied to commercial flight seem not to be desirable yet.

Complementary hypothetical studies were performed to visualize the impact of the solar modules efficiency and their surface weight on the travel time needed to equalize their energy density with the one for the classical aircraft fuel (taking into consideration the efficiency of electric generators). In figures 5, 6 and 7, graphs are presented to establish the minimum travel time to equalize t_{eq} the mass energy density between the solar modules and the classic aircraft fuel in function of the solar modules efficiency and their surface weight.

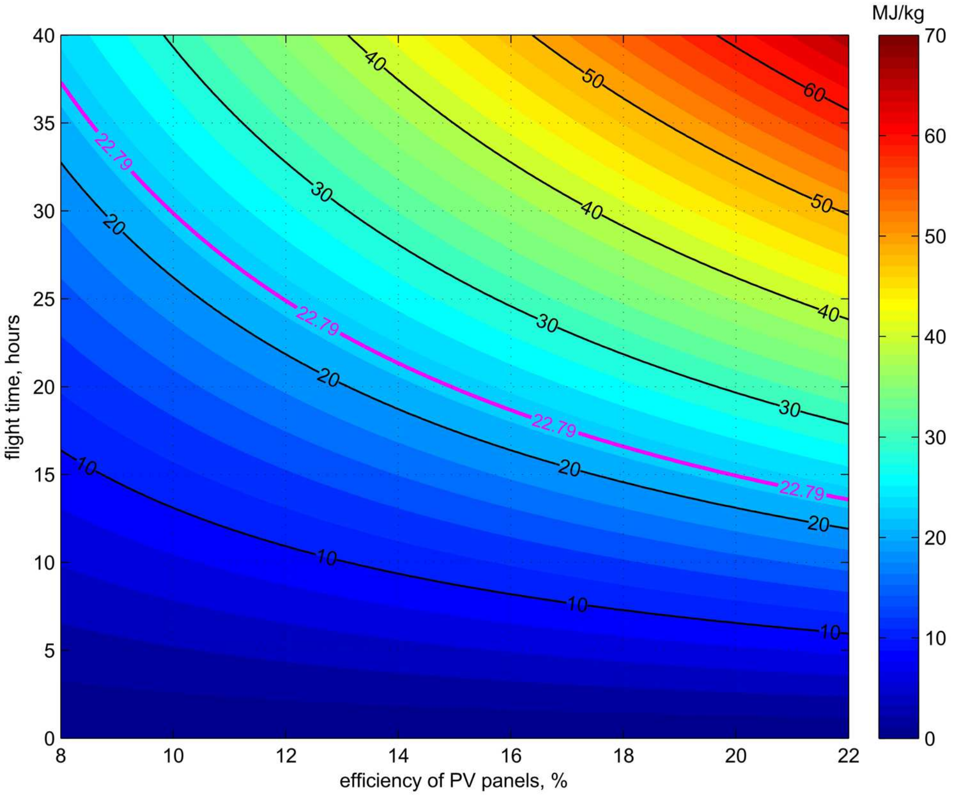

Fig. 5. Mass energy density of a PV system in function of efficiency of flexible solar modules (for a surface weight of 0.5 kg/m^2) and flight time

According to figure 5, for the surface weight of the solar module equal to 0.5 kg/m^2 (as in the exemplary calculation of this paper), when the efficiency is multiplied by 2 compared to the calculation sample (from 10% to 20%), the equivalent travel time is divided by 2 (passing from about 30 hours to about 15 hours). Then, according to figure 7, when the surface weight is decreased to 0.06 kg/m^2 (from 0.5 kg/m^2), with an efficiency of 10% (as in the calculation sample), the equivalence travel time is reduced to 4 hours (starting from 30 hours). In both

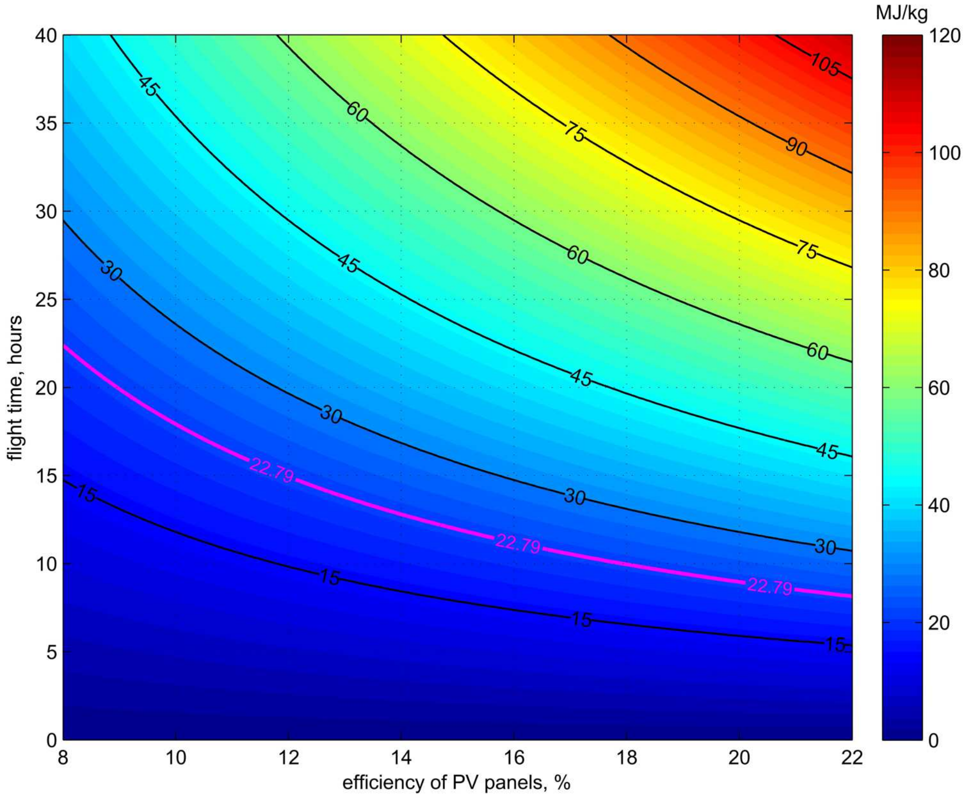

Fig. 6. Mass energy density of a PV system in function of efficiency of flexible solar modules (for a surface weight of 0.3 kg/m^2) and flight time

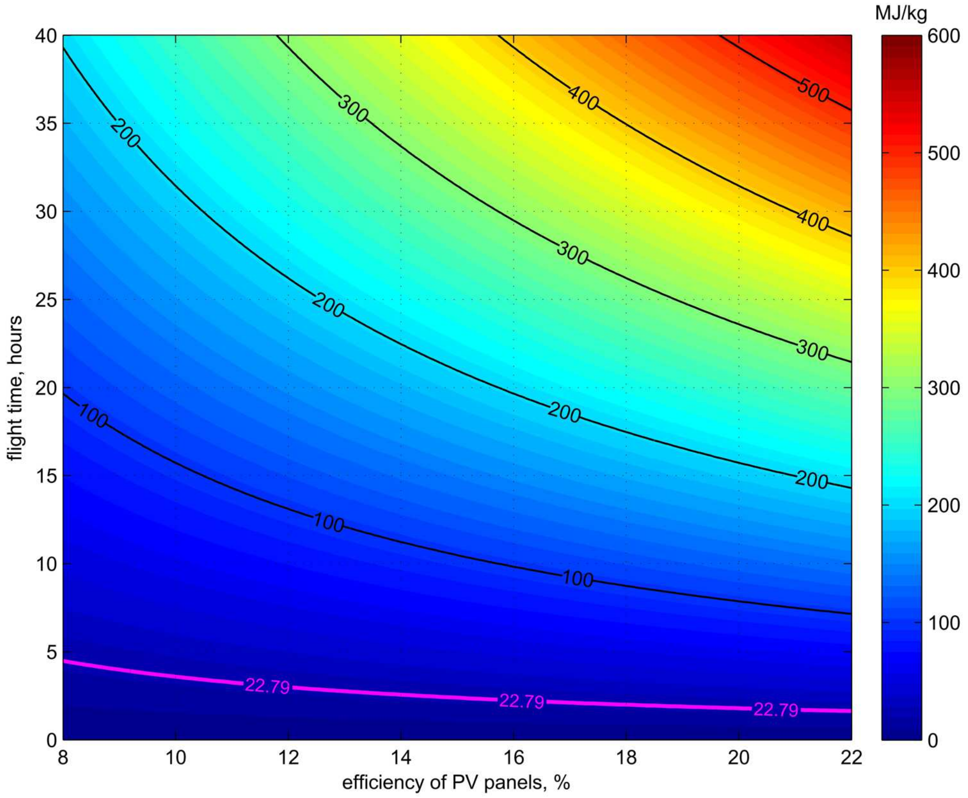

Fig. 7. Mass energy density of a PV system in function of efficiency of flexible solar modules (for a surface weight of 0.06 kg/m^2) and flight time

examples, the equivalent travel time could be exploitable in aircraft operation (in optimized flight conditions). According to the next graphs, it is important to notice that the equivalent travel time is decreasing when the solar module efficiency grows and their surface weight goes down. These additional studies underline the need for researches on efficiency and surface weight of flexible solar modules to make them suitable for aircraft operations in the future.

5. Conclusions

This study estimates the value of energy density of flexible solar modules on the example of the Boeing 787 ("Dreamliner") aircraft (commercial – cargo applications). The calculations were performed for the most advantageous conditions of solar irradiation (perpendicular to the aircraft, viewed from the above and for a flight performed by day) and established flight conditions. The maximum value of energy density requires flight duration (in these utopic conditions) by at least of 29 hours. Then the solar modules are more advantageous than the use of Jet-A fuel (for onboard electricity generation). The calculated duration could be much more longer in real flight conditions. Additionally, as commercial flights are not usually overcoming this minimum duration of 29 hours, the application of flexible solar panels for this kind of aircraft would not be suitable. However, when optimised toward more efficient or less specific surface mass, it seems to become an option for aircraft applications in the future, including international or continental flights.

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Ocena celowości zastosowania giętkich modułów słonecznych na duże samoloty komercyjne

Żyjemy obecnie w świecie „pomniejszającym się” dzięki coraz efektowniejszym środkom transportu, między innymi przez coraz powszechniejsze wykorzystanie lotnictwa. Istotną dziedziną naszego życia oraz prowadzonych prac naukowo-badawczych stał się przy tym zmieniający się klimat, m.in. z racji rosnących emisji zanieczyszczeń (m.in. CO_2, NO_x, pyłów, SO_2, CO) z sektora lotnictwa. Jedną z odpowiedzi na zachodzące w ostatnich latach zmiany stała się idea „samolotów bardziej elektrycznych” (ang. MEAs – More Electric Aircraft). Jej filarem jest zasilanie energią elektryczną (najlepiej przy tym nie pochodzącą z generatorów sprzężonych ze spalinowymi silnikami lotniczymi czy też z baterii ładowanych energią pochodzącą z wysokoemisyjnych technologii energetycznych) jak największej liczby odbiorników pokładowych, w tym także dzięki równoczesnemu wykorzystaniu dodatkowych skojarzonych z płatowcem źródeł elektryczności. Wykorzystując dodatkowe, najlepiej ściśle związane z OZE (odnawialnymi źródłami energii) układy energetyczne, istnieje bowiem możliwość ograniczenia ilości zużywanego paliwa oraz np. zmniejszenia bezpośredniego śladu węglowego towarzyszącego eksploatacji samolotów. Niemniej każde nowe źródło energii elektrycznej musi przy tym spełniać pewną liczbę kryteriów technologicznych, ekonomicznych, ekologicznych czy też logistycznych. Przykładowo, aby takie przedsięwzięcie było efektywne, gęstość (masowa, objętościowa) energii skupionej w źródle powinna być jak najwyższa i – o ile to możliwe – przewyższać gęstość energii elektrycznej pochodzącej z paliwa lotniczego. Spełnienie tego kryterium uzasadnia bowiem ewentualną rezygnację z wykorzystania części składowanego na pokładzie paliwa na rzecz nowego źródła energii elektrycznej. W niniejszej pracy oszacowano zasadność pokrycia części dużego samolotu giętkimi panelami fotowoltaicznymi stanowiącymi alternatywne wobec konwencjonalnych generatorów pokładowych źródło energii elektrycznej na pokładzie oraz ustalono czasy lotu, przy których staje się ono atrakcyjne energetycznie. Uwzględniając masę modułów fotowoltaicznych możliwych do wykorzystania w obrębie analizowanego samolotu (wybrano B787) oraz dostępną moc generowaną przez te moduły, wyliczone zostały czasy lotu (bez międzylądowania), dla których uzyskana gęstość energii elektrycznej dzięki panelom fotowoltaicznym równa się gęstości energii elektrycznej pochodzącej ze spalania paliwa lotniczego (z uwzględnieniem sprawności tradycyjnych agregatów prądotwórczych). Zakładając masę jednostkową paneli równą ok. $0{,}5\,\mathrm{kg/m^3}$ oraz sprawność modułów na poziomie ok. 10%, w mocno wyidealizowanych warunkach lotu, czas ten wynosi 29 godzin (co znacznie przekracza obecnie obowiązujące rekordy długości lotu samolotów pasażerskich). Wykazano jednak, iż wraz z rozwojem technologii fotowoltaicznych (podwyższeniem ich sprawności i obniżeniem masy jednostkowej) w niedalekiej przyszłości może on ulec skróceniu nawet poniżej 5 godzin. Daje to podstawy do uznania tej grupy technologii za perspektywiczne w kontekście rozwoju pokładowych systemów elektroenergetycznych także w skali dużych samolotów pasażerskich.