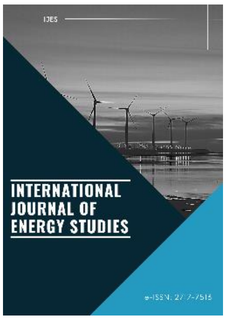
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article

Int J Energy Studies 2023; 8(3): 385-399

DOI: 10.58559/ijes.1312169

Received : 09 July 2023

Revised : 28 July 2023

Accepted : 04 Aug 2023

Investigation of hybrid-electric propulsion system applied on Cessna 172S aircraft

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Highlights

- The effects of aircraft electrification on fuel economy, flight cost and emission values were examined.
- The hybrid electric propulsion system was conceptually designed for the Cessna 172S.
- The hybrid-electric configuration achieved an average fuel savings of 13.1%, cost savings of 12.3% and CO_2 emission reductions of 6.0 kg per hour compared to conventional flights.

You can cite this article as: Ata I, Akgül B. Investigation of hybrid-electric propulsion system applied on Cessna 172S aircraft. Int J Energy Studies 2023; 8(3): 385-399.

ABSTRACT

In this study, hybrid-electric propulsion systems, which have become a focal point in aviation in recent years, were addressed. In order to see the effects of hybrid-electric propulsion systems on fuel consumption, greenhouse gas emissions and flight costs, five different flight times (60, 90, 120, 150, 180 min) and five different cruise altitudes (1200, 1800, 2400, 3000, 3600 m) were compared with conventional flights. The widely used Cessna 172S aircraft was taken as a reference for the conceptual applications in the study. As a result of the study, the hybrid-electric propulsion system achieved the highest fuel and cost savings of 15.1% and 14.2%, respectively, for 120 minutes flight time and 2400 m altitude, while the lowest fuel and cost savings of 9.7% and 9.1% were achieved for 60 minutes flight time and 1200 m cruise altitude. The highest CO_2 reduction was 6.86 kg per hour for 120 minutes and 1200 m altitude flight, while the lowest CO_2 reduction was 4.47 kg for 180 minutes and 3600 m altitude flight. It has been determined that flights with hybrid-electric configuration have advantages over conventional flights.

Keywords: Hybrid-electric aircraft, Conceptual desing, Fuel consumption, Electrified propolsion

1. INTRODUCTION

Throughout almost all of modern aviation history, fossil fuels have been used. Due to this fossil fuel usage, emissions have increased, and many countries in the world have become dependent on other countries with fossil fuel resources. Electrified aviation has become a very important issue for energy independence and reducing emissions, especially, especially considering the advancements made in electrified systems in the automotive sector over the years, which have proven themselves. Since electrification has gained significant success in the automotive industry, the aviation sector has also begun adopting electrified systems. Various programs and targets have been set to make aviation more sustainable and determine a clear path for its future. Most significant programs of those are ACARE SRIA, Flightpath 2050 and NASA ERA. In Flightpath 2050 program the targets are 75% reduction in CO_2 emissions, 90% reduction in NO_X, 65% reduction in noise pollutions in comparison to reference airplane in 2000 [1]. In NASA ERA program 80% reduction in NO_X, and 60% reduction in fuel consumption are main targets [2]. Until today, researches about SAFs (Sustainable Aviation Fuels) have significant roles for aviation's future, with developments in electrical systems the main focus of aviation's future become electrification.

For aircraft electrification, there are four main concepts: MEA (More Electric Aircraft), AEA (All Electric Aircraft), HEA (Hybrid Electric Aircraft), TeA (Turbo-electric Aircraft). In MEA concept, the fundamental concept is to replace inefficient and complex mechanical, pneumatical and hydraulic systems which requires more maintenance with electrical systems. The goal is to get benefits from simple structured high efficiency electrical systems which have lower weights and requires lower maintenance efforts. Therefore, fuel consumption is reduced. In AEA concept propulsion power is provided from energy stored in batteries. Due to absence of fuel consumption GHG emissions are not occurred in flight. In AEA concept, there is no fuel combustion and combustion engine, therefore noise and temperature level are lower compared to conventional aircrafts [3]. On the other hand, with the current technology level AEA applications are limited to Unmanned Aerial Vehicles (UAV) and light aircrafts for today. TeA is the concept that based on conversion of fossil fuels energy into mechanical power, and then electrical power to get propulsion. Due to high energy density of fossil fuels, TeA concept does not have the disadvantage of batteries mass, on the other hand flight emissions still exist because of the fossil fuels [4]. HEA is the concept that have at least two different energy sources which contribute to propulsion. For HEA propulsion systems, various elements can be used, therefore different configurations can be obtained. In parallel HEAs both conventional and electrical systems can generate propulsive power directly. In parallel HEA systems lower weight is an advantage, but complex control is required. In series HEA systems, power generated in conventional engine is converted to electrical power through generator and then finally converted into propulsion. In series systems conventional engine can be set to run at optimum point, on the other hand generator requirement and mechanical – electrical conversion brings efficiency losses [3,5,6].

Friedrich and Robertson evaluated hybrid-electric aircraft concept and compare current models. The study evaluated the SOUL microlight aircraft, which had an 8 kW internal combustion engine and a 12 kW electric motor, for a conceptual 1-hour flight mission. The study found that fuel consumption could be reduced by up to 50% for flights shorter than 1 hour. Based on this calculation, a 10% savings in fuel consumption for commercial aircraft could be achieved [6]. Koruyucu designed a hybrid-electric propulsion system for general purpose helicopter and obtained 3.91% reduction in CO_2 emissions at 3000 m altitude and 6% hybridization degree [7]. Hoelzen et al. evaluated operation strategies of a hybrid-electric aircraft. In the paper, reduced carbon footprint through battery usage, specific energy level that energy storage devices have and importance of appropriate battery selection for flight mission were main focuses. The most important result in the work was 22% reduction in emissions were achieved with 25% increase in cost at 66% hybridization degree. CO_2 emissions reduction up to 5% was possible without cost increase. According to the study, it was found that hybrid-electric aircraft were cost competitive fo ranges up to 350 nm [8].

Righi designed a hybrid-electric propulsion system with fuel cells and batteries and showed that the system was capable to power a Cessna 172R for flight [9]. Hepperle evaluated aircraft electrification and focused its different aspects than that of automotive sector. Elements of aircraft electrification were explained and consumed energy values were found for each stage in simplified flight profile of a regional aircraft. Important result of the work was by using batteries with 1500 Wh/kg specific energy capacity the payload level as same as conventional aircraft was reachable [10]. Vratny and Hornung evaluated sizing considerations of electric aircraft. In the paper, A320 aircraft with 1000 nm range was chosen as reference for year 2035. For the same mission discrete parallel hybrid-electric aircraft was 34% heavier than standard A320 and batteries made 16% of total mass, and also 56% increase in weight of propulsion system were the important aspects of the work. As a result of the work, it was seen that fuel consumption was decreased by 8.5% while total required energy was increased 9.2% [11].

Iwanizki et al. evaluated short range hybrid-electric aircraft conceptual design and created flow chart for hybrid-electric aircraft design. Two flight missions were chosen as reference 2500 nm range 17 tons payload capacity and 800 nm range 13.6 tons payload; and as a result of study 10% hybridization degree became optimum point with 2% of fuel consumption decrease [12]. Pornet presented design methods for narrow body hybrid-electric aircrafts in his study. It was obviously seen that aircrafts fuel consumption, weight and efficiency were affected in negative way because of increase in range required heavier batteries. By using batteries with 1500 Wh/kg specific energy capacity in the aircraft that have 180 passengers, 16% fuel saving was achieved for 900 nm range and 20% fuel saving were achieved for 1100 nm range [13]. Voskuijl et al. designed a hybrid-electric turboprop regional aircraft. As a result of the study 28% reduction in fuel consumption was achieved in 1528 km range aircraft with 70 passengers when 34% of propulsion power come from electric which was supplied by 1000 Wh/kg specific energy batteries [14]. Mariani evaluated electric propulsion's emissions in his work. In the work main focus was to compare a hybrid-electrical powertrain and a conventional propulsion system which was based on an internal combustion engine. As a result of the work hybrid-electric aircraft performed 80% reduction in pollutant emissions [15]. Donateo and Spedicato evaluated fuel economy of hybrid electric flight. In the work battery specifications and engine working points' effects on fuel economy were discussed. The work was performed under assumption of constant power-level flight conditions with on-off strategy. As a result of the work, improvement up to 12% in fuel consumption was achieved [16]. Van Bogaert evaluated fuel consumption of a hybrid-electric regional aircraft using batteries which had 1000 Wh/kg of specific energy. On the chosen design point which had 14% higher MTOM, 28% fuel weight reduction was achieved compared to the reference aircraft [17].
In this study, a conceptual design of a Cessna 172S aircraft equipped with a hybrid propulsion system was carried out, and the fuel savings, flight costs, and emission reductions of the aircraft were examined for different flight times and altitudes. For this purpose, calculations were made for five different flight times and five different flight altitudes, and the data for conventional flights were compared with those for hybrid flights.

2. MATERIAL AND METHOD

In this paper, a hybrid electric propulsion system configuration was designed in order to see the effects of aircraft electrification with regards to fuel economy, flight cost and emissions. In the hybrid-electric configuration battery, pmad, electric motor and motor controller elements were added to conventional propulsion system of Cessna 172S, it was assumed that the elements used were added by removing seats of the aircraft other than pilot seat, therefore power requirement from original design was not changed and also by removing passengers enough capacity is available for electrical elements. In the electrical propulsion configuration elements; battery pack which weighs 162 kg and capable to store 35.1 kWh energy [18]; an electric motor which generates 15 kW maximum continuous power and weighs 5.2 kg [19]; a motor controller which weighs 1.18 kg and can regulate up to 33 kW continuous power [20], pmad manages power and energy and regulates and optimizes energy flow according to flight phase, were used. The Cessna 172S aircraft was chosen as the reference aircraft for the conceptual application due to its widespread use, easy accessibility to data, and relatively small size, which made it a suitable starting point for electrification studies. The technical data of the Cessna 172S aircraft was given in the Table 1.

Table 1. Technical data of Cessna 172S [21]

Length	8.3 m
Height	2.7 m
Wing span	11 m
Maximum take-off weight	1157 kg
Maximum payload	405.96 kg
Maximum speed	230 kmh
Maximum range	1185 km

During the conceptual application of the hybrid-electrical propulsion system configuration, the aircraft's maximum take-off weight was not exceeded, so the power requirements from the design did not change. The main idea behind the conceptual application of hybrid-electrical propulsion system in this paper was to operation of electric motor at maximum continuous power for propulsion as a support system to conventional propulsion system, relieving the internal combustion engine duty. As a result, the purpose of fuel saving was accomplished. The schematical representation of the hybrid-electric propulsion system was shown in Figure 1.

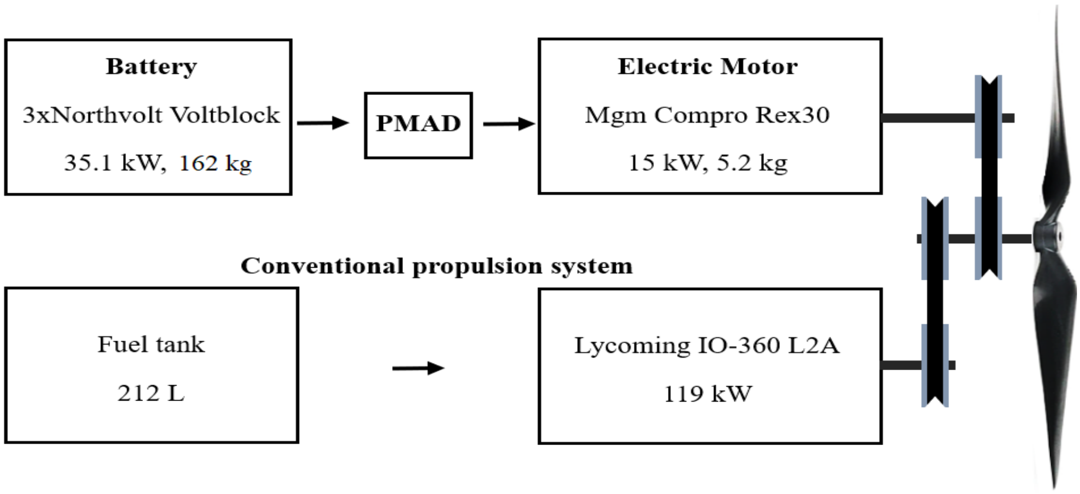

Figure 1. Schematical representation of the hybrid-electric propulsion system

In the conceptual hybrid-electric propulsion system, the total weight added to aircraft was 168.38 kg, weight changes due to pmad elements, cabling and removed seats were ignored. For the conceptual application, there were two main sources of energy to power the aircraft, Avgas 100LL and electric from batteries. In order to compare emissions between conventional and hybrid flight, emission values of energy sources were found.

The engine used in the Cessna 172S aircraft is the Lycoming IO-360-L2A. This engine is an air-cooled, 4-cylinder engine. The aircraft's propeller is a two-bladed, fixed-pitch McCauley 1A170E/JHA7660 propeller. Additionally, the approved fuels for use in the aircraft are Avgas 100 and Avgas 100LL, and the two fuel tanks can store a total of 212 liters of fuel [21]. In the conceptual application of the hybrid electric propulsion system conducted in this study, Avgas 100LL and electrical energy were used as energy sources. In terms of their cost and emission values:

Emissions produced from the combustion of Avgas 100LL [22];

$$1\ kg\ Avgas100LL + O_2 + 2kgCO_2 + 1.2kgH_2O + 1kgCO + 1.5x10^{-2}kgHC + 5x10^{-3}kgNO_x + 0.8x10^{-3}kgP_b \quad (1)$$

In the study, it was assumed that mains electricity was used to charge the battery in the hybrid electric propulsion system and Avgas100 LL price was assumed to be 3 euro/liter for cost comparison. In order to make emission and cost comparison emission values and price of mains electricity per kWh were found. The mains electricity emissions per kWh was calculated as 0.455 kg CO_2, 5.59x10^{-6} kg CH_4, 8.88x10^{-6} kg N_2O and the invoice price was 0.71 TL [23-25].

The hybridization degree is the ratio of electric motor power to total installed power and it is a parameter that enables comparison of electrification in terms of fuel savings, emissions and costs.

$$H_p = P_{EM}/P_t \quad (2)$$

Considering that the electric motor produces 15 kW and Lycoming IO-360 L2A engine produces 119 kW of continuous power, therefore the hybridization degree of the hybrid-electric propulsion configuration in this paper was 11.19%.

In this study, in order to see the effects of electrification conceptual reference flight missions were determined. In the conceptual flight missions five cruising altitudes and five flight duration; the flights consist of three basic phases take off – climb, cruise, descent – landing, and it was assumed that the flights start with a maximum take-off weight from a sea level. In the conceptual flights conventional engine operated at 2400 rpm during take-off – climb and cruise phases and operated at 1800 rpm during descent – landing phase.

Table 2. Flight times and altitudes

Mission parameter	Mission levels				
	1	2	3	4	5
Flight times (min)	60	90	120	150	180
Cruise altitudes (m)	1200	1800	2400	3000	3600

In conceptual flights, in order to reach cruise altitude, the take off – climb times and energy requirements were differed. For 1200 m cruising altitude, the take-off-climbing and descending-landing phases were 12 minutes in total, while for 1800 m the phases time lasted 20 minutes, for 2400 m these phases took 28 minutes, for 3000 m 40 minutes and for 3600 m 56 minutes. The power-fuel consumption graph for the Lycoming IO-360 L2A engine, which was the engine of the Cessna 172S aircraft, was used to determine the fuel consumption values based on power [26]. The interpolated power-fuel consumption graph for the Lycoming IO-360 L2A engine was provided in Figure 2.

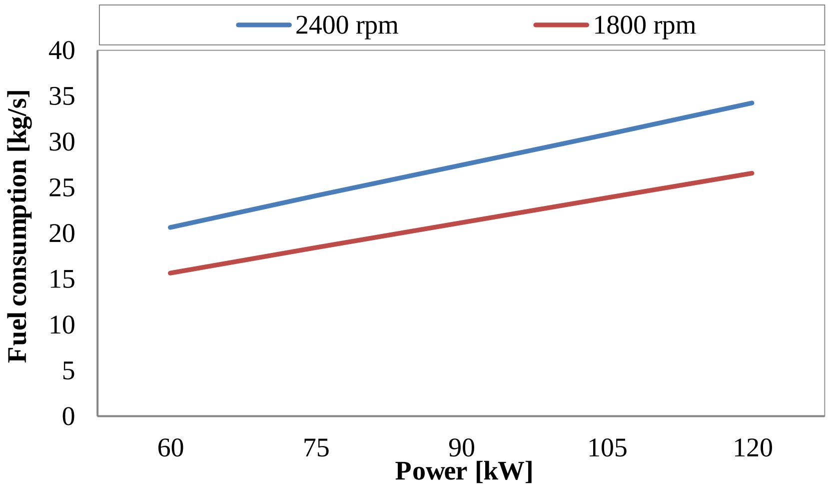

Figure 2. The power-fuel consumption graph for the Lycoming IO-360 L2A engine, [26]

The obtained power-fuel consumption graph was shown in Figure 2. The power-fuel consumption equation where $\dot{m}$ is the fuel flow rate consumed in [kg/h] and P is the power in [kW],

for 2400 rpm,

$$\dot{m} = 0.23 \times P + 6.79 \tag{3}$$

For 1800 rpm,

$$\dot{m} = 0.18 \times P + 4.72 \tag{4}$$

3. RESULT AND DISCUSSION

The fuel consumption, cost and CO_2 values that obtained for five different flight times and five different cruise altitudes were compared between conventional and hybrid-electric propulsion systems. The variation of fuel economy with flight time was shown in Figure 3. As the Figure 3 was examined, the fuel-saving values varied between 14.2%, 14.4%, 14.5%, 11.6%, and 9.7% at a cruise altitude of 1200 m, whereas they changed between 12.6%, 13.9%, 14.6%, 12.1%, and 10.3% at a cruise altitude of 3600 m for flight times of 60, 90, 120, 150, and 180 minutes, respectively. When the values were analyzed for the 1800 m cruise altitude, fuel savings were 14.3% in a 60 minute flight, 14.7% in a 90 minute flight, 14.9% in a 120 minute flight, 11.8% in a 150 minute flight, and 10.0% in a 180 minute flight. It is clearly seen from Figure 3 that, the highest fuel saving value of 15.1% was achieved at a cruising altitude of 2400 m and a flight time of 120 minutes. Especially in flights up to 120 minutes, fuel saving values increased with flight time. However, after 120 minutes, it is observed that the fuel saving values decreased with the increasing flight time due to the limited energy stored in the electrical system.

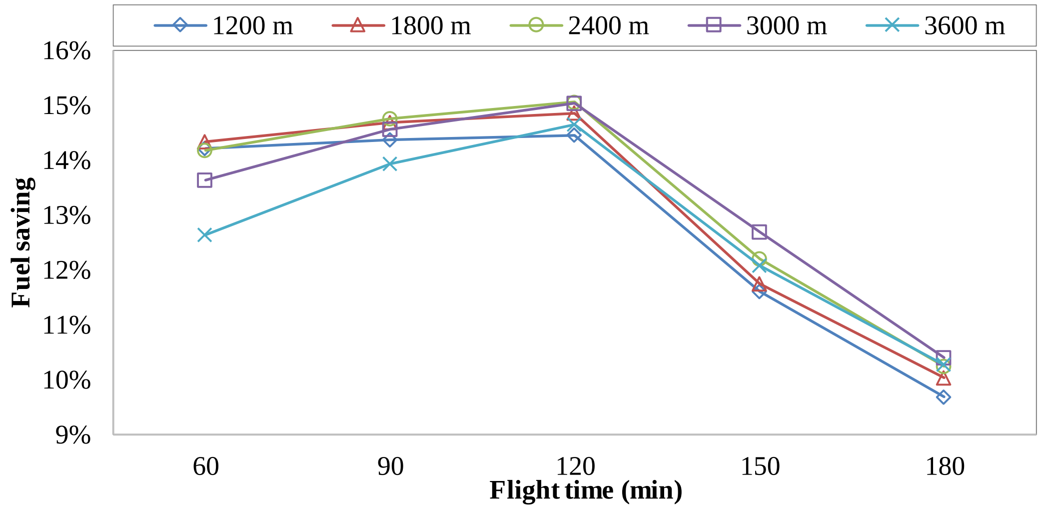

Figure 3. Flight times versus fuel saving for all flights

The variations of fuel savings with the flight cruise altitudes were illustrated in Figure 4. As shown in Figure 4, fuel saving values increase up to 2400 m, and particularly, the values remain similar for altitues of 2400 m and 3000 m. However, fuel savings decrease for a cruise altitude of 3600 m. As the Figure 4 was examined, it is seen that the best fuel saving values occured with a 120 minute flight time were 14.5% for 1200 m, 14.9% for 1800 m, 15.1% for 2400 m, 15.0% for 3000 m, and 14.6% for 3600 m cruise altitudes. The lowest fuel saving values occured with a 180 minute flight time were 9.7% for 1200 m, 10.0% for 1800 m, 10.2% for 2400 m, 10.4% for 3000 m, and 10,3% for 3600 m cruise altitudes, respectively. When the results were examined, the fuel saving values increased up to 2400 m, as the power required for the flight was low and percentage of energy provided by the electrical propulsion system was higher in total energy required for the flight. Technically, higher cruise altitudes require less power; however, more power is required to reach higher altitudes. Therefore, especially during the take off – climb phase, the contribution of the electrical system is limited compare to other flight phases, resulting in lower fuel saving values.

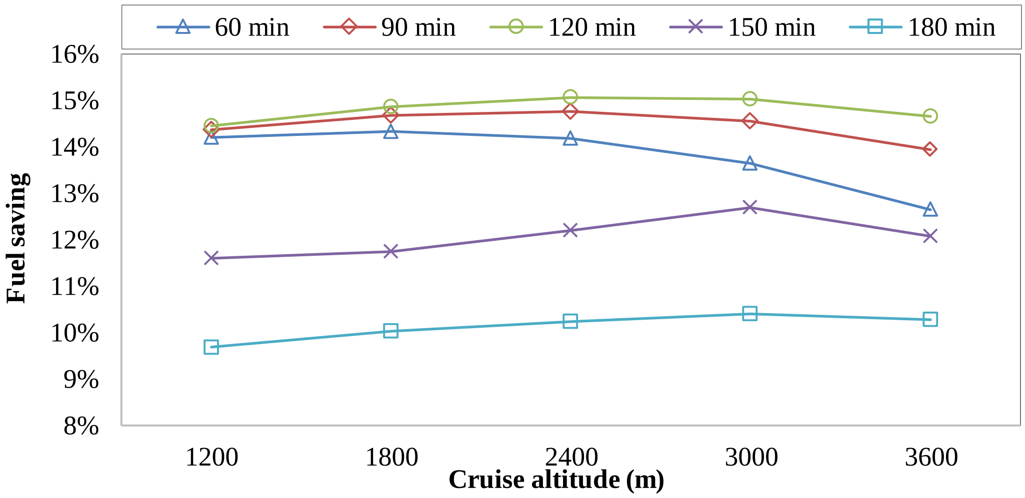

Figure 4. Cruise altitudes versus fuel saving for all flights

Due to decarbonization, which has becomes an important issue recently, reducing CO_2 emissions has become one of the main topics for energy sector. Therefore, in this work CO_2 emissions of conventional and hybrid-electric flights were compared. The variations of emitted CO_2 by flights with different cruise altitudes were given in Figure 5. When Figure 5 was examined it was seen that decrease in CO_2 emissions were similar for the same flight time, and the decrease in CO_2 decreased with altitude. For the 60 minute flight time, the CO2 reduction values decreased from 6.78 kg per hour to 6.24 kg per hour, representing a decrease of 8.6% as the cruise altitude increased from 1200 m to 3600 m. Evaluating the flight time from 60 minutes to 180 minutes, CO_2 reduction values decreased by 47.9% for 1200 m, 46.3% for 1800 m, 44.9% for 2400 m, 42.0% for 3000 m and 39.7% for 3600 m, respectively. The highest CO_2 reduction was obtained with 6.86 kg per hour for 120 minutes flight time and 1200 m altitude, while the lowest CO_2 reduction was obtained with 4.47 kg per hour for 180 minutes flight time and 3600 m altitude. Since the lowest take-off-climb and descent-landing phases (in terms of time and power requirement) for all flight missions were realized at 1200 m cruise altitude, the highest CO_2 reduction value was obtained for this altitude.

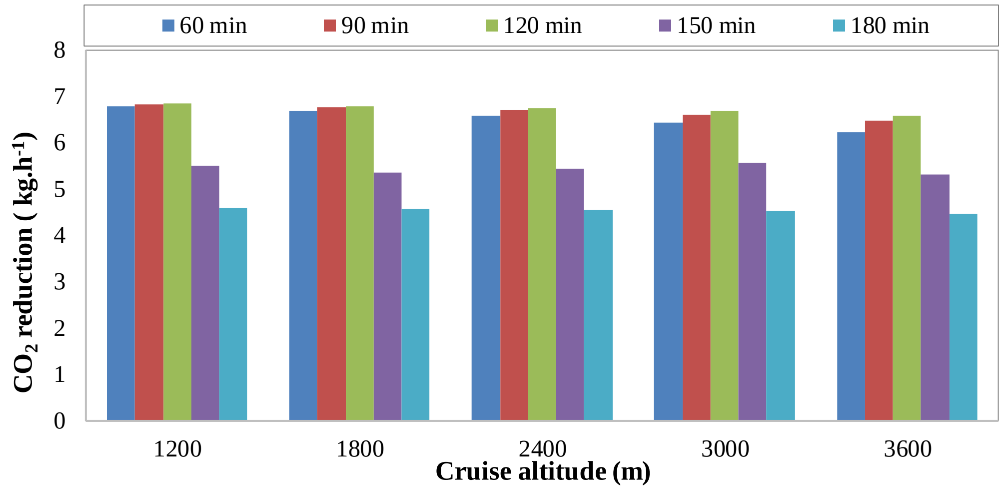

Figure 5. Variation of CO_2 reduction with cruise altitudes for all flights

Variation of cost savings with flight time for all fligts is shown in Figure 6. For the 1200 m cruise altitude, the cost savings values varied between 13.4%, 13.5%, 13.6%, 10.9% and 9.7% for 60, 90, 120, 150 and 180 minutes of flights, respectively. The highest cost savings was 14.2% for 120 minutes flihgt time and 2400 m, while the lowest cost savings was 9.1% for 180 minutes flight time and 1200 m cruise altitude. When these values are explained, it can be seen that with increasing flight time, cruise phases share in total flight time increased and since cruise phase required less power, therefore role of electrical system in propulsion was increased and this situation directly affected the cost saving values due to relatively low price of electricity compare to Avgas 100LL.

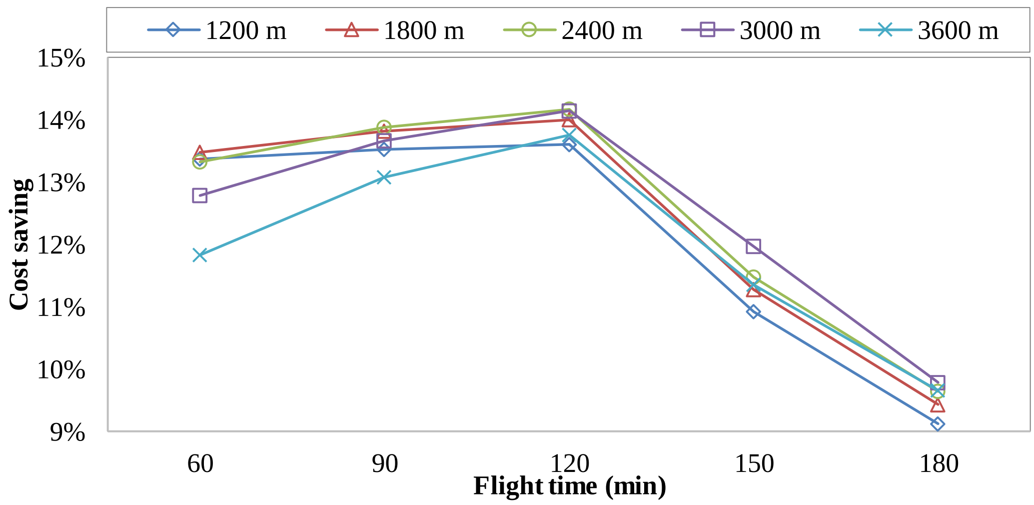

Figure 6. Variation of cost saving with flight time for all flights

4. COMPARISON WITH LITERATURE

In this study, a conceptual comparison between conventional and hybrid-electric propulsion systems was conducted to examine the effects of electrification in aviation. Since the aviation electrification is relatively new issue, there are no wide range of study and works, but when similar works were considered, it was possible to do a comparison between works. Even if the compared works were different than each other, the comparison was made to see electrification effects. The comparisons were summarized in Table 3.

Table 3. Comparison with previous studies

Studies	Fuel saving	CO_2 reduction	Cost saving
Pornet [13]	16.0%	-	-
Vratny [11]	8.5%	-	-
Voskuijl [14]	28.0%	-	-
Koruyucu [7]	3.91%	1.19 kg	-
Friedrich ve Robertson [6]	10.0%	-	-
Present study	13.1%	6.0 kgh^{-1}	12.3%

In order to compare the results of this work with others, the arithmetic average of the fuel saving, CO_2 reduction and cost saving results of all flight scenarios were taken. The obtained results were 13.1% for fuel saving, 6.0 kg per hour for CO_2 reduction and 12.3% for cost savings. If these results were compared with the results that obtained in other works, it was seen that the results were reasonable.

3. CONCLUSION

In this work, conceptual hybrid-electric propulsion systems were applied to the Cessna 172S aircraft with the current technology level in order to assess effects of electrification on fuel consumption, greenhouse gas emission and flight cost. The results obtained in the work are briefly as follows;

- The results of twenty-five flights showed that hybrid-electric flights achieved an average of 13.1% fuel savings, 6.0 kg per hour reduction in CO_2 emissions, and 12.3% cost savings compared to conventional flights.
- The highest fuel saving was achieved at 120 minutes flight time and 2400 m cruising altitude as 15.1%, while the lowest 9.7% was obtained for 180 minutes and 1200 m cruising altitude.

- The lowest cost saving, which is 9.1%, was achieved in a 180 min flight with a cruise altitude of 1200 m.
- The highest cost saving is achieved as 14.2% in the flights that 120 min and 2400 m cruise altitude.
- The highest CO_2 reduction was obtained with 6.86 kg per hour for a 120 minutes flight at 1200 m altitude, while the lowest CO_2 reduction was obtained with 4.47 kg per hour for a 180 minutes flight at a 3600 m altitude.
- The advantages of electrification remain limited in cases that required high power such as take off and climb.

NOMENCLATURE

O_2	Oxygen
CH_4	Methane
CO	Carbonmonoxyde
CO_2	Carbondioxyde
H_p	Hybridization degree
HC	Hydrocarbons
H_2O	Dihydrogenoxide (water)
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
nm	Nautical mile
P_b	Lead
P_{EM}	Electric motor power, kW
pmad	power management and distribution
P_t	Total installed power, kW

ACKNOWLEDGMENT

This research did not receive any specific grant from funding agencies in public or not-for-profit sectors.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Ismail Ata: Analyzed the results of the experiment and wrote the manuscript.

Burak Akgül: Performed the experiment and analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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