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The use of hybrid propulsion systems in the last decade has increased enormously due to main concerns about environment and energy cost. In this regard, hybrid series systems for small and MALE UAVs have proved better performance, due to its basic control, low cost and electrical system lower weight contribution. These platforms usually are envisioned for technification of the monitoring processes, where it is required a low CO2 footprint, whilst maintaining good performance. This study carries out a parametric modelling of a UAV using a series hybrid propulsion system, using as case of study the monitoring of biodiversity in the Galapagos Islands. The design space for the propulsion system is carried out using semi-empirical and parametric approaches. A constrain analysis coupled with a weight estimation tool is used to determine hybridization points, which feed the engine bench marking analysis module. From this analysis an optimal propulsion configuration with a hybridization degree of 46% is found. The endurance defined by the application and UAV capabilities provides five hours of flight time, whilst maintaining a MTOW lower than 160 [Kg] and a wingspan of 5.9 [m], these two latter parameters are used as figure of merit, since they help for UAV transport and storing.

I. Nomenclature

AR	=	Aspect Ratio
BWB	=	Blended Wing Body
EM	=	Electric Motor
H_C	=	Cruise altitude
HP	=	Hybrid point
ICE	=	Internal Combustion Engine
M_{BATT}	=	Batteries mass
M_{BWB}	=	Mass of Blended Wing Body
M_{EM}	=	Electric motor mass
M_{GEN}	=	Generator mass
M_{ICE}	=	Internal combustion engine mass
M_{LG}	=	Mass of Landing gear
$MTOM$	=	Maximum take-off mass
n_{load}	=	Ultimate load factor
P_{EM}	=	Power electric motor
P_{ICE}	=	Power internal combustion engine
P/W	=	Power to weight ratio
ROC	=	Rate of climb
SFC	=	Specific fuel consumption
STO	=	Take-off runaway

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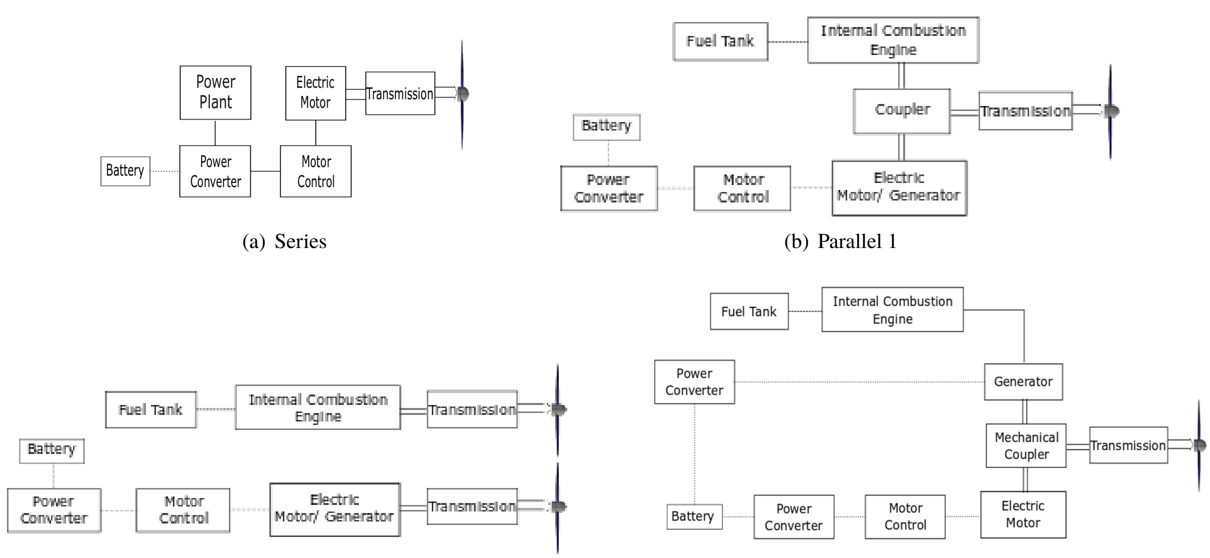
S_W	=	Wing reference Area
UAV	=	Unmanned Aerial Vehicle
V_C	=	Cruise Speed
V_S	=	Stall Speed
W/S	=	Wing loading

II. Introduction

In the last decade, Unmanned Aerial Vehicles (UAV) have become an important tool for different civilian uses, such as: ecosystem monitoring, marine patterns surveillance, search-rescue missions [1, 2], among others. In the monitoring of marine ecosystem, UAVs present many synergies with the work of conservation agencies and hence their implementation has a lot of potential for data collection, which is vital to tackle multiple problems such as: over-exploitation, pollution, climate change, induction of invasive species, etc; that put at risk their existence and conservation [3, 4].

Electric propulsion UAVs have emerged as good option for monitoring, since they are able to reduce carbon emissions and produce low noise. Nevertheless, the low specific power of batteries limits UAV endurance and payload. In order to tackle this problem hybrid systems have been envisioned as a solution, where the advantages of combustion propulsion systems (high energy density) are combined with the low pollution footprint of electrical driven UAVs [5]. Hybrid systems can be classified into three basic categories [6–8]:

- Series: The ICE works as a motor-generator which provides power to the electric propulsion system, while the EM is connected to the propeller. In this configuration the ICE does not contribute to the thrust required for the propulsion, which simplify its control. [9, 10] (See figure 1 (a)).
- Parallel: This option adds the ICE and EM torque to produce thrust, and depending how the power from both sources is managed can be obtained different configurations. This gives some flexibility for design and presents synergies with distributed propulsion concepts (figure 1 (b) and figure 1 (c) show possible configurations). However, the problem with this configuration is the need of more complex controllers to enable their operation [9, 10].
- Series-Parallel: These systems include the features of both series and parallel configurations. It implements an additional power converter which allow the ICE to charge the batteries during operation [6, 10] (See figure 1 (d)).



(a) Series (b) Parallel 1 (c) Parallel 2 (d) Series-Parallel

Fig. 1 Hybrid electric configurations

From these three configurations, the series architecture offer better features for the ecosystem monitoring application, as it provides: control simplicity, lower specific fuel consumption, good operation at lower flight speeds[11] compared with the parallel configuration. Some the benefits aforementioned are result of the ICE operating at its optimum conditions, regardless of the operational regime [12]. In the case of distributed propulsion, series configurations present flexibility, since once the mechanical energy is transformed to electrical one, this later can be easily managed to drive the EMs without affecting the ICE performance [13–15].

Over the last years, several studies of design methods for series hybrid aircraft have been developed. In 2012, Green [16] developed an analysis of turboelectric propulsion systems using distributed propulsion with conventional electric machines. the study shown that it is possible to use conventional electric technology to operate an aircraft but the associated weight and inefficiencies appear to outweigh the potential benefits for large airplanes. Two years later, Friedrich and Robertson published a research [11] to expose the challenges in sizing hybrid propulsion systems and size a parallel and a series configurations using a commercial air frame using simulations and analysis tools in Matlab and X-Plane. This study shows that the hybrid systems shows better performance with a degree of hybridization of 46% in series and 60% in parallel configurations. The same year Merical et.al. [15] design a series hybrid propulsion system for small unmanned aircraft using gasoline spark-ignition engine and heavy fuel spark ignition engine, which shows that using heavy fuel enhance the endurance by 18.5% compared to gasoline. Hence, Cipolla and Oliviero [17] presented a simulation tool to analyze series hybrid aircraft performance for a mission profile. This tool comprises a flight simulator, flight planner and performance module. The performance is evaluated changing mission parameters such as: range, cruise altitude and cruise speed. In 2018, Finger and Braun [6] developed an algorithm capable to size series and parallel hybrid-electric light aircraft through an innovative point and mission performance analysis, which employs the power to weight ratio and wing loading comparison approach to determine the minimal gross weight related to the optimal degree of hybridization in order to increase aircraft performance. Other approach to assess performance is given by Ravishankar and Chakravarthy [18], who developed a range equation for series hybrid electric systems. The equation calculate the range for each degree of hybridization by considering the change of fuel and engine masses and keeping the total take-off mass as constant. However, this approach requires an aircraft configuration defined. Hence, this work uses the approach from Finger [6], since this approach starts from the conceptual design stage, where several configurations can be tested. Even though, several studies have been done about hybrid propulsion systems, there is hardly no information about the effect of using a 2 stroke and 4 stroke commercial internal combustion engines at an early design stage.

Only a few prototypes of aircraft with series hybrid electric propulsion systems have been made. Developed by Diamond Aircraft, Siemens, Austro Engine and EADS the DA36 Estar 1 and 2 are The two-seater motor glider that used series configuration to investigate the potential of hybrid configurations in mid-scale aircraft. The first one used a 70[kW] electric motor from Siemens and a small Wankel engine of 30[kW]. Meanwhile, the second one used 30 [kW] Wankel ICE, 65 [kW] EM. The second version provides an increase in range and endurance and a reduction of 100 [Kg] against the first version. Both airplanes use a fixed wing configuration with 16 [m] wing span and two passengers capacity [19, 20].

The present study focuses on the conceptual design of a hybrid propulsion series system for mid-scale UAV to monitor Galapagos Islands. The UAV was designed to operate between 120 to 2000 m.a.s.l. and a cruise velocity of 35 m/s maximum. For this aim, the study uses a constraint analysis coupled with a weight estimation tool to determine the design and hybridization points. The weight estimation tool uses a benchmarking analysis of two and four strokes engines to size the ICE. At the end two different configurations using commercial two and four stroke engines that fulfill the mission requirements are determined.

III. Methodology

The aim of this research is to establish the preliminary design of a series hybrid propulsion system to perform missions at Galapagos islands. To achieve this, parametric and semi-empirical tools are coupled and used to determine optimal hybrid propulsion system configurations based on top design requirements. The requirements were established by gathering data from previews researches of the ecosystem of Galapagos islands and its problems.

A. Design requirements: Mission analysis

Galapagos islands has one of the most beautiful and biodiversity ecosystems in the word. Its unique environment allowed these islands to be part of the UNESCO list of the Natural World Heritage in 1978, but it was not until 1986 when the sea next to the Galapagos Islands was protected. Besides all the efforts done to secure the area, in 2007 Galapagos islands were added to the World Heritage sites in danger list [21]. The Galapagos islands harbor unique wildlife and flora are highly vulnerable. This has made authorities to declare that 97% of the territory must be protected. The total area of coverage represents around 133 000 square kilometers. At present, Galapagos islands suffer from species invasions, modification of natural habitats, illegal fishing, besides other problems related to tourism [22, 23]. Therefore, the necessity of a eco-friendly monitoring system which can cover a significant area of the Galapagos islands is visible. In this context, UAVs with hybrid propulsion system offer an increase in the range and endurance over those with electric propulsion system. Also, this kind of UAVs can reduce the fuel consumption which reduces the pollute emissions regarding UAVs with conventional propulsion systems [9, 24, 25].

The uniqueness of Galapagos ecosystem set some requirements to proceed with the conceptual design phase. On figure 2 is shown the illegal fishing zones in the Galapagos protected area, which are considered to set the flight plan. The table 1 presents the amount of each critical fishing areas in Galapagos. The area considered for the study was the S4, because of its proximity to the Isabel island, where the UAV can be easily deployed.Based on this area and UAV average flying speeds, the endurance required should be within three and five hours. Since the space is reduced in the Islands the runaway must not exceed the 150 meters [26–28].

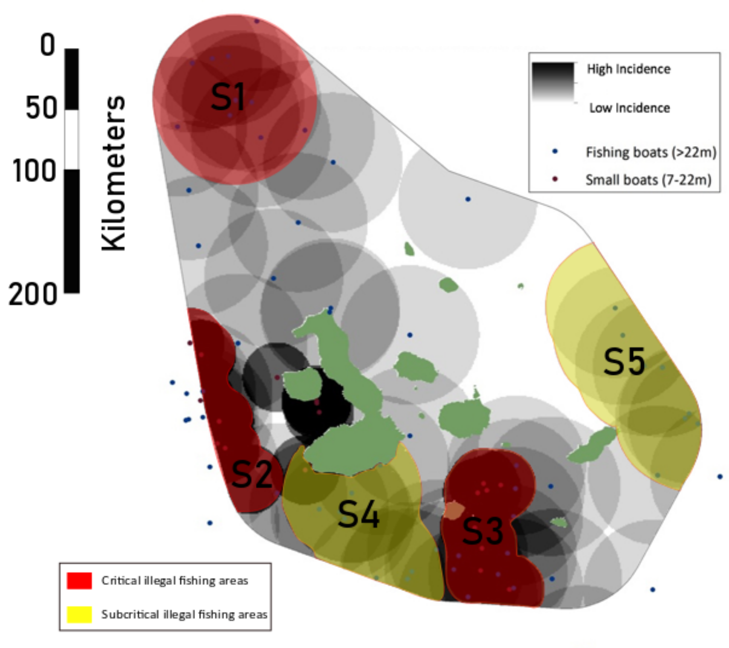


Fig. 2 Illegal Fishing at Galapagos Islands.

The mission also considered the endemic birds behavior that live on the islands, such as blue-footed boobies, red-footed boobies, masked boobies, brown pelicans, red-billed tropicbirds, waved albatross, storm-petrels, audubon's shearwaters, among others. These coastal and marine birds which live in the Galapagos need to fish to secure their survival. Galapagos's birds flight about 30 meters above the sea when they fish. Meanwhile they usually fly between 100-120 meters above the sea level. Only when they migrate, they fly between 6000-7000 m.a.s.l.. Hence, considering the latter, the cruise altitude of the designed UAV was set between 120-2000 m.a.s.l. [26, 28]. The upper limit of altitude is set based on the resolution of the imagery and radar specifications [29]. Cruise speed range is defined in function of current technology in hybrid systems and payload limitations. Table 2 shows the mission operating requirements.

Table 1 Critical Fishing Areas in Galapagos islands

Area	Dimension [Km^2]
S1	14027.71
S2	5208.86
S3	8458.83
S4	9037.83
S5	12604.18

Table 2 Mission operating requirements

Parameter	Min. Value	Max. Value
Cruise altitude [m]	200	2000
Take-off runaway [m]	110	150
Endurance [hours]	3	4
Cruise speed [m/s]	20	40

1. Payload

In this study the payload includes the on-board electronic and surveillance equipment. Therefore the payload components will collect the specific data during the UAV flight. The payload has been divided in three subsystems: Communication, sensors and data. The table 3 shows the equipment required for the monitoring mission [29–41]. Using this information the payload was set as 40[kg].

Table 3 Final Payload

Communication System	Weight [Kg]	Range [Km]*	Speed Max [m/s]
Cameras	2,6	2	22
Gimbals	2,2	-	-
LiDar	2,3	0,2	22
Antennas	4,81	5	-
GPS/GNSS	0,185	-	100
Sensors System	Weight [Kg]	Range [Km]*	Speen Max [m/s]
Wind sensors	0,38	4	75 m/s
Laser	0,115	16,385	-
Inertial Navigation	0,98	-	-
Radar	18	2**	-
Data system	Weight [Kg]	Capacity [Gb]	
Autopilots	1,2	32	
Datalink	0,5	128	
Total weight [Kg]	**33,27**		

* Range of measured data. Not maximum altitude of operation.
** Range of altitude. Five kilometers range around.

B. Framework of analysis

The methodology uses a conceptual design tool coupled with a bench marking analysis of two and four strokes engines. The former, involves the constrain analysis coupled with a weight estimation tool to define design space, hybridization points and possible configurations, as shows the road map presented in Figure 5. The last part use the data from the conceptual design to select the engine and to determine the engine and its performance through semi-empirical correlations and analysis of the commercial motors. Through these two tools a preliminary propulsion system design is established to assess the performance of the hybrid cycle.

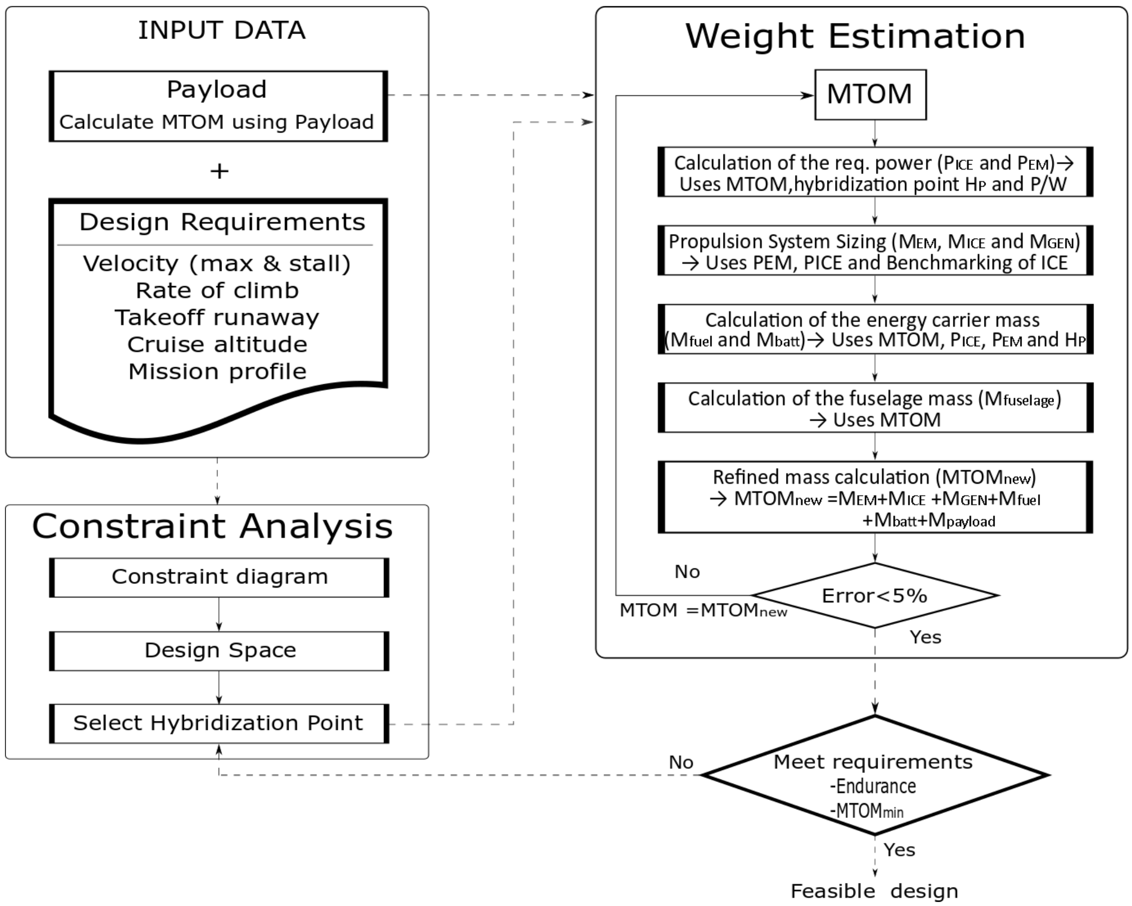
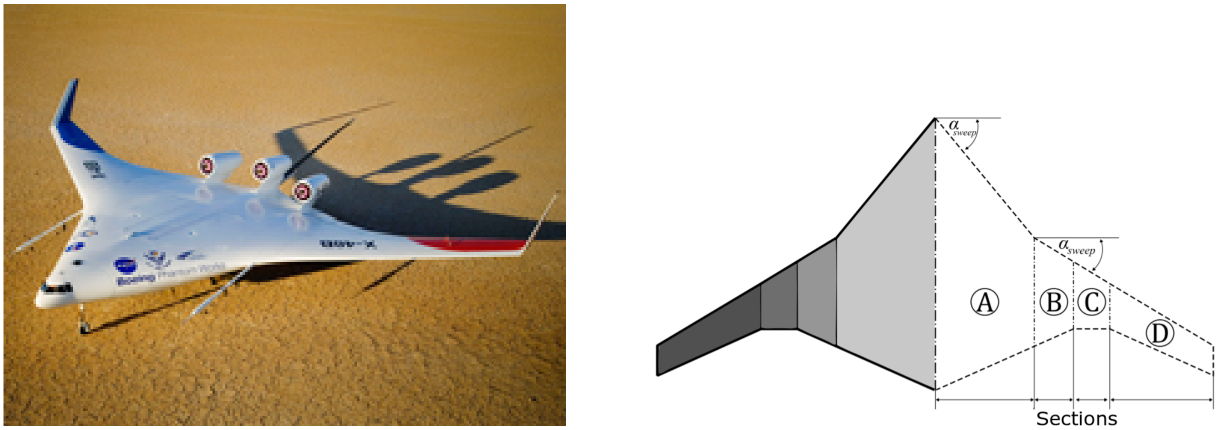


Fig. 3 Design Methodology.

The fuselage consider in this study is a blended wing body (BWB) base on the Boeing X48 model (See fig. 4). The research group have presented a few research articles using this model as its base (Ref. [42, 43]). Table 4 presents the specifications of the Boeing X-48.

Table 4 Boeing X-48 specifications

Parameter	Value
Wing span	6.22 [m]
Wing area	9.34[m^2]
Max. speed	60 [m/s]
Ceiling	3000 [m]



(a) Boeing's sub-scale X-48B [44] (b) Scheme Boeing X-48

Fig. 4 BOEING X48

1. Conceptual design of the hybrid-electric UAV

The aim of this stage is obtain preliminary hybrid configurations using parametric models and the top level UAV requirements. In order to achieve this, a constraint analysis was performed to define the design space. Then, different hybridization points were calculated to start the preliminary sizing of the propulsion system using the weight estimation module. Afterwards, the most suitable configurations that fulfill with the design requirements and initial mass estimation are presented.

Constraint Analysis In order for analyzing the design space with regards to the power-to-weight ratio (P/W) and wing-loading (W/S) a matching diagram of the different flight constraints was developed. For this purpose, the top design requirements as stall speed (Vs), cruise speed (Vc), cruise altitude (Hc), rate of climb (ROC), take-off runaway (STO) and some aerodynamic parameters were set and considered as constrains for the present analysis (Table 5). The study only considered three flight stages for the constraint analysis, the take-off, rate of climb and the cruise (See figure 5).

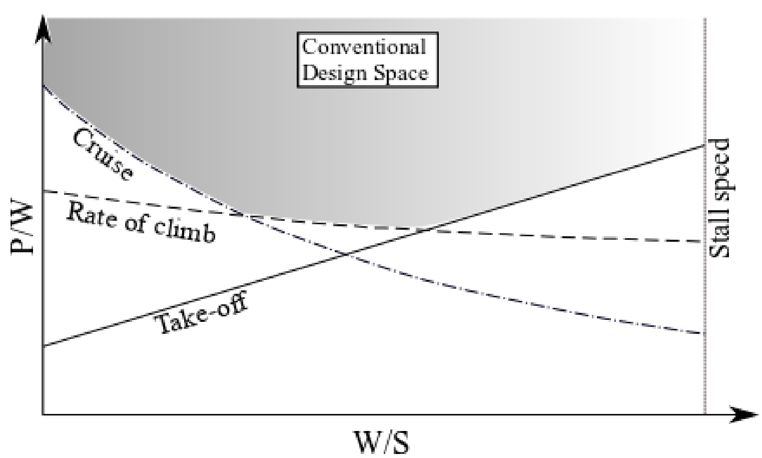


Fig. 5 Conceptual Design Methodology: Constrain analysis.

Degree of Hybridization For hybrid series propulsion systems, the EM generates all the power or thrust require by the UAV. The ICE only provides energy to the EM. In the study the Degree of hybridization (Hybridization point) used is define as the ratio of the installed conventional propulsion system, in this case the max power of the ICE, and the

Table 5 General Data and Top Level Requirements

Requirements		Aerodynamics	
Stall Speed [m/s]	15	Efficiency Factor, e	0.8
Cruise Speed [m/s]	35	CL_{max}	1.6332
Max. Cruise Altitude [m]	2000	CDo	0.0154
Rate of Climb [m/s]	4.5	Aspect Ratio, AR	4.15
Take-off Runway [m]	110		

installed electric propulsion system, referring to the max power of the EM, as introduced by Eq.1.

$$H_P = \frac{P_{ICE,max}}{P_{EM,max}} \tag{1}$$

As is shown in the figure 6 of the matching diagram the HP indicates the hybridization point which represents how much P/W the ICE supplies of the total P/W require. The rest of the P/W to fulfill the requirements of each flight stage is supplied by the battery pack. An UAV designed at this P/W and W/S combination will overcome all the constraints at the lowest weight and power possible at the W/S propose.

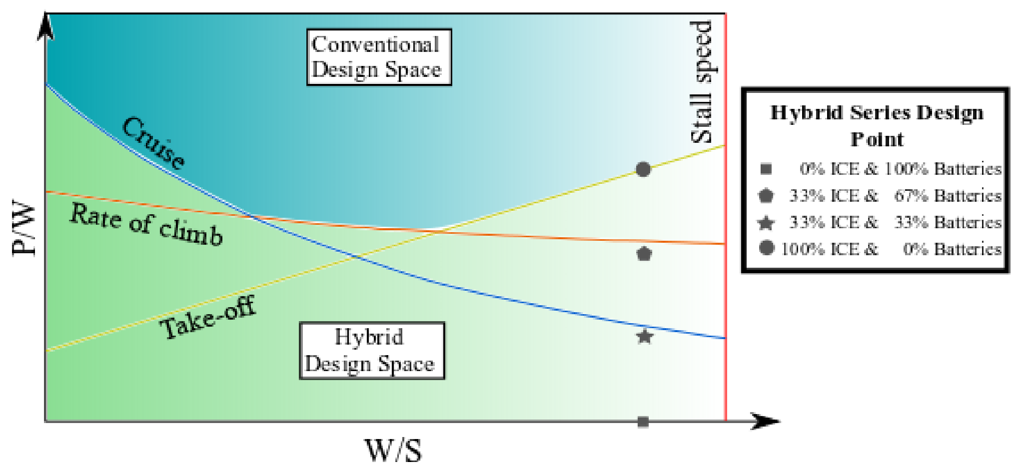


Fig. 6 Conceptual Design Methodology: Series hybrid Constrain analysis.

2. Preliminary weight analysis of the hybrid-electric UAV

Series hybrid propulsion systems are conformed by a power plant, a power converter, a battery pack, a motor controller and an electric motor as shows the figure 1.a. For this study the component selection and their technical features are set accounting on reducing costs and mass, whilst maintaining a good performance.

Electric motor This study considers a brushless out-runner DC electric motor to size the propulsion system, considering they are more efficient and lighter than brushed motors. Also, out runners motors allow to generate a bigger torque with low RPM which avoids the use of a gearbox unlike in-runners motors [45]. The EM is sized using a semi-empirical model presented by Cirigliano in Eq.2 [46].

$$M_{EM} = a + b \cdot P^c \tag{2}$$

Where,

M_{EM} : EM mass [Kg]

P : Output EM power require [KW]
a, b and c : Are coefficients of the power-weight fitting curves. With the value of -2.354, 1.609, 0.6693 respectively

Battery package The electric module do not only control the flight mission and the energy supply but also sets the thrust split in the series configurations, hence it is necessary to size the battery pack [47, 48]. There are a number of rechargeable batteries and the most commonly used types are Li-Po, Li-ion, LiFePO4, NiCd, and NiMH. The principal constrain using batteries is its low energy density, which is around 200 Wh/Kg for commercial batteries [49]. Comparing the fuel energy density with the batteries energy density, the first one allows to reach a longer endurance or larger range while reducing the weight of the UAV energy carrier. Thus, implementing series hybrid systems let the the battery pack reduce its size and increase the endurance of the aircraft which is an important parameter for performing the mission established [10]. The study uses the correlations of Li-Po batteries and the mass is calculated by Eq.3 presented in the Ref. [50].

$$M_{Cell} = A \cdot C_{cell}^{B} \tag{3}$$

Where,
M_{Cell} : Cell mass[g]
C_{Cell} : Cell capacity [Ah]
A and B : Are regression coefficients for unitary cell weight. With the value of 0.0446 and 0.9273 respectively.

The mass is calculated by estimate the number of cells of the battery pack in parallel and series battery configurations. A 27 series arrange which provides a 100[V] was set for the study. The capacity of the cells use is 2600[mAh] and the energy density is 175 Wh/kg.

3. Sizing of the power plant converter

In this case the power plant comprises an ICE coupled with a generator (alternator). This configuration was selected for its power conversion efficiency and lower volume compare of solar power. In this area, the different ICE have been widely used in aviation due to their long endurance operation and high power or thrust generated per fuel mass consumption [46, 51]. Nowadays, various types of engines like piston-prop, turboshaft, turboprop, turbofan, turbojet and ramjet, are manufactured and employed in aircraft [51, 52]. The study considered the piston-prop engines owing to its easy purchase, low maintenance costs, easy assembly and low cost.

ICE performance As is known the performance of an ICE decrease while the operation altitude increase. The Gagg and Ferrar equation (eq. 4) describes the engine's power fall-off as a function of density and is used for engines driving a constant-speed propeller. The equation was used in the analysis to obtain more accurate results. [53, 54].

$$P_{alt} = P_{sl} \cdot (1.13 \cdot \sigma - 0.13) \tag{4}$$

Where,
P_{alt} : Power at operating altitude.
P_{sl} : Power at sea level.
σ : Air density rate ($\sigma \leq 1$)

Weight assessment(Benchmarking analysis) The study considered a power plant integrating a Otto's cycle ICE of 2 or 4 strokes with a generator. These types of ICE have high power density, low weight, low costs,compact dimensions, high efficiency as well as a great reliability which are the key factors in designing and sizing power plants [55]. The study aims to compare these two types of ICE applied in series hybrid propulsion systems. The model use to size the propulsion system is based on a semi-empirical model presented in Ref. [50] as show Eq.5.

$$M_{ICE} = A \cdot P^{B} \tag{5}$$

Where,
M_{ICE} : ICE mass[Kg]

Table 6 Weight of ICE engines, regression coefficients.

	A	B	R^2	n
Two stroke	0.0003	1.0530	0.8959	114
Four stroke	0.0013	0.8952	0.9300	113

P : Output ICE power require [W]
A and B : Are regression coefficients of ICE engines weight

The ICE is selected from the data base using power required from the hybrid point. The data base consist of 114 two stroke engines and 113 four stroke engines from different manufacturers. At the end, the selected ICE will be used to calculate the performance of the hybrid propulsion system. In addition, the fuel mass is calculated using the specific fuel consumption. From the data base the average SFC for two strokes engines is 400 [g/KWh] and for four strokes engines is 300[g/KWh].

Generator The model selected to size the generator is the same as the electric motor but it is sized using the power required by the ICE. It was considered a brushless out runner DC electric motor. This model was selected because there are little information about alternators which could be used for aircraft.

4. Mission energy consumption schedule

In series configurations the energy is provided by two sources : power plant (ICE) and battery pack. The ICE operates at the max efficiency point during all flight phases. The battery pack is only use in flight phases where the ICE can not secure enough energy to support the propulsion system demand. Energy demands can arise from aerodynamic drag, acceleration (kinetic energy), altitude change (potential energy). The energy demand in each flight phase was calculated using Eq.6. The study does not consider the energy demand of Taxi phase.

$$\Delta E = \underbrace{\frac{m \cdot g \cdot v}{\frac{L}{D}} \cdot \Delta t}_{\Delta E_{Aero.Drag}} + \underbrace{\frac{m \cdot \Delta v^2}{2}}_{\Delta E_{Kinetic}} + \underbrace{m \cdot g \cdot RoC \cdot \Delta t}_{\Delta E_{Potential}} \tag{6}$$

IV. Results and Discussion

In this section three different series hybrid configurations are studied. The configurations are defined to fulfil the Galapagos monitoring mission requirements for applications flying at different altitudes (120 m, 600 m, 2000 m) .

A. Constraint Analysis

Figure 7.a. shows the design space for the three different operation altitudes. In this figure the design points for each configuration are depicted. The cruise velocity for each configuration is set for the case of minimum drag and corresponds to 31, 32 and 35 [m/s] for 120, 600 and 2000 meters respectively. The effect of the operating conditions and constraints for V_s, V_c, ROC and S_{TO} are shown in this figure. Regarding the mission in the Galapagos islands the takeoff runaway is limited to 110[m] to suit current runways in the Islands. In this diagram, it is observed how the three design points vary and the effect of the operating altitude in the wing and power loading. From this diagram is clear that the constrain of 110 m for runway sets some of the design conditions.

Since the weight increment is an important design feature in hybrid systems, the mass distribution is included in the constrain analysis. Figure 8 shows the constraint analysis coupled with the mass assessment for the three different operation altitudes assuming a mission endurance of five hours (based on the endurance requirement for the monitoring missions) using a two stroke engine. Each figure plots the optimal design and hybrid point, which are selected by minimizing the MTOM in the mass analysis, then the hybrid point sets the ICE. The configurations selected are presented in table 7. As expected for configurations operating at higher altitudes the weight increases due to higher power demand during the climb phase, higher hybridization degree and higher operation speed. Analysing figure 8, it can be observed that the hybrid point is located near the cruise constraint, which provides the lowest mass contribution, hence, in these cases the ICE is sized for cruise condition and the battery bank assists during takeoff and climb phases.

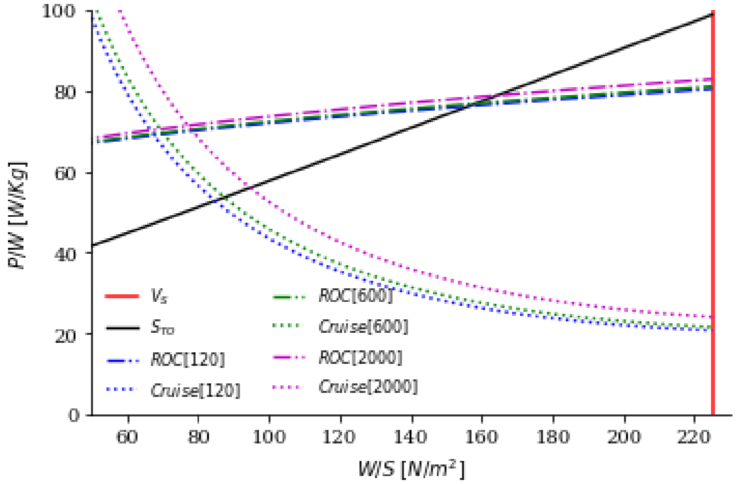
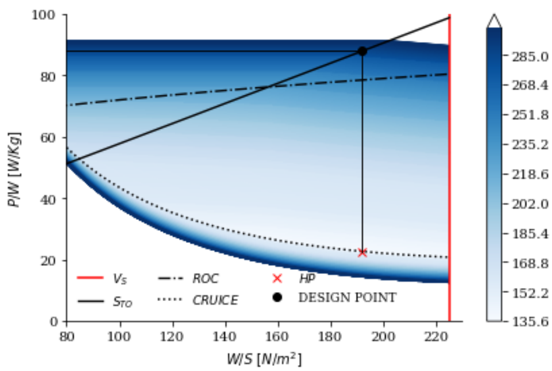
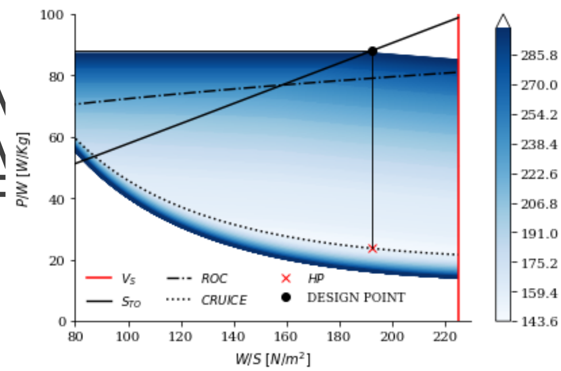


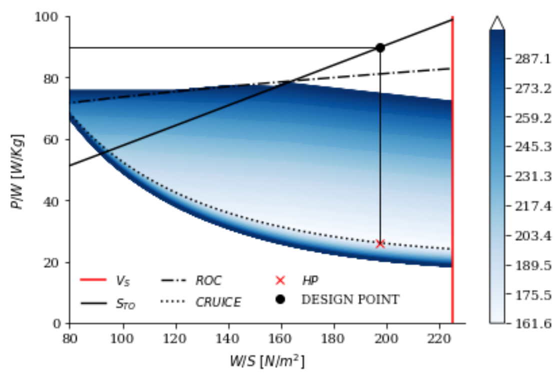
Fig. 7 Constraint Analysis Results



(a) 120 m cruise



(b) 600 m cruise



(c) 2000 m cruise

Fig. 8 Series hybrid Analysis

Since a main parameter to set the potential implementations of hybrid UAVs for monitoring is their endurance, figure 9 indicates the optimal aircraft configurations against endurance. The analysis shows that the weight and power loading

Table 7 Results - Five hours cruise mission and 2 stroke engine.

Configurations		120 [m]	600 [m]	2000 [m]
Wing loading	W/S[N/m2]	188.368	192.196	195.574
Power Loading	P/W [W/Kg]	86.676	87.934	89.044
Hyb. Point	Hp[%]	26.546	26.952	29.610
MTOM	[Kg]	133.377	141.405	160.638
Power ICE	PICE[KW]	3.155	3.639	5.286
Mass ICE	MICE[kg]	1.451	1.686	2.498
Mass Gener.	MGEN[kg]	1.438	1.835	3.087
Mass Fuel	Mfuel[kg]	6.401	7.469	11.214
Power EM	PEM[KW]	11.731	12.641	14.247
Mass EM	MEM[kg]	7.199	7.720	8.616
Mass Batt.	Mbatt[kg]	2.883	4.378	8.613
wing area	S[m2]	6.946	7.218	8.058
Wing Span	b[m]	5.369	5.473	5.783

increases as the demanded endurance increases. The increment of the design point implies an increment in weight and an increment in power demanded. Hence, the fuel mass and the battery pack increase to fulfill the energy demand.

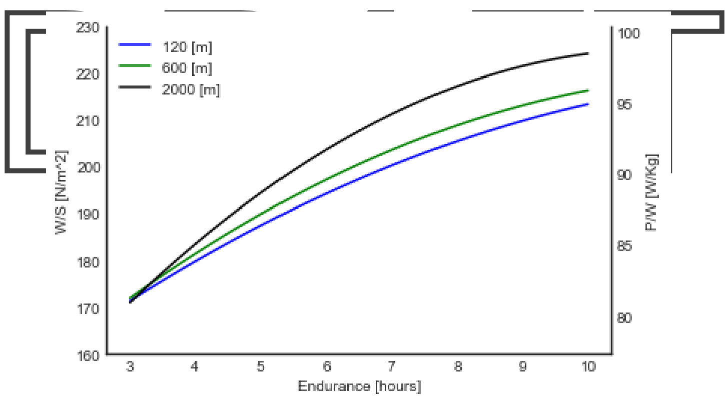


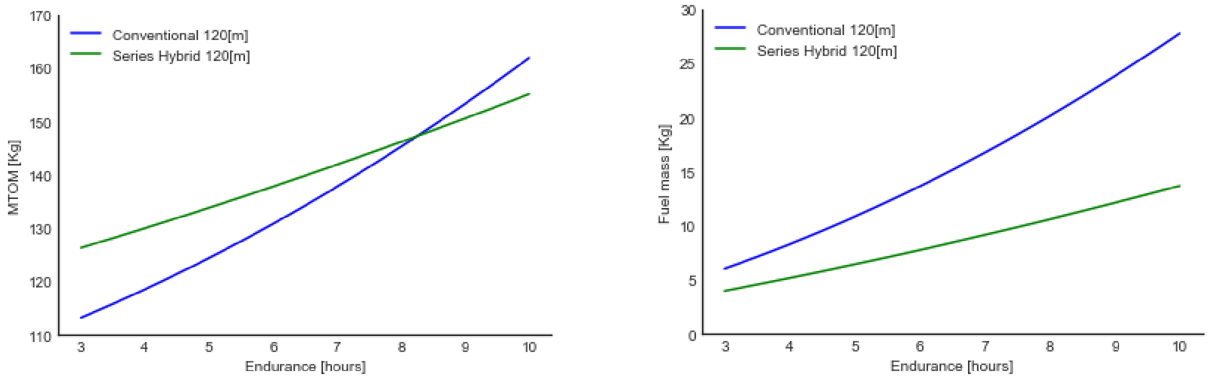
Fig. 9 Wing loading and power loading vs Endurance.

B. Hybrid series configurations

This section presents potential propulsion system configurations based on the endurance demanded for monitoring missions.

1. Cycle performance

Figures 10 a) and b) present the variation of MTOM and fuel mass against endurance, comparing the conventional (fuel driven) and Series hybrid configurations. As observed, for shorter endurance (less than 8 hours at 120[m]) the MTOM for the conventional case is lower, which is related to the EM, battery pack and generator required by the series hybrid propulsion system. Regarding fuel consumption, conventional case use more fuel than the series hybrid case, for instance for the five hours endurance the fuel mass required is almost the half as the required in the conventional case. This diagram motivates the use of hybrid system for long endurance UAVs. Despite, the MTOM increment when using series hybrid configurations, the lower fuel consumption motivates the use of hybrid systems for long endurance mission, since this will represent fuel savings and hence lower pollution. For the cases at higher altitudes the UAV performance trends are similar for MTOM and fuel mass, with the difference that the cross between conventional and hybrid in the MTOM occurs at 9.5 hours for 600 [m] with around 35% fuel saving at endurance of five hours and at 14.5hours for 2000 [m] with around 16% fuel saving at endurance of five hours.

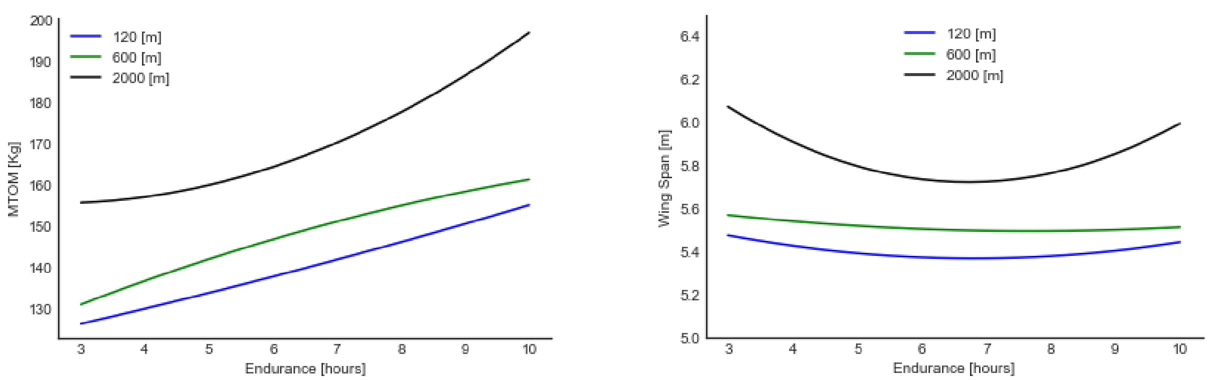


(a) MTOM vs Endurance

(b) Fuel mass vs Endurance

Fig. 10 Comparison between Series Hybrid and Conventional propulsion configurations 600[m]

Figure 11 show MTOM for the different configurations and the wing span required. As expected the MTOM increases anlagously to other studies for hybrid systems [56]. Also the MTOM is higher while the operation altitude increases which is produced for the weight contribution of the propulsion power plant, specifically the battery bank which is larger as they need to assist for climbing at higher altitudes. The wingspan shows an optimum endurance at 6.5 hours, which is due to a combination of MTOM and wing loading trends. The wing span is directly proportional to MTOM and inversely proportional to wing span. As the endurance increase both increase, the MTOM increment is exponential while the WS increment is parabolic. Regarding long endurance, the wing loading reach its limit (Stall speed constraint) but the MTOM continues increasing which implies the increment of the wing span proportional to MTOM increment.



(a) MTOM vs Endurance

(b) Wing span vs Endurance

Fig. 11 Aircraft configurations for different endurance

In order to assess how the UAV hybrid configurations will change when different battery packs are used, figure 12 plots the MTOM versus endurance for different battery specific capacity for 600[m], additionally the weight contribution of the battery pack is depicted. As observed the MTOM decreases while the specific energy of the battery increases. Nevertheless, the case of battery capacity of 1000 [Wh/kg] is too optimistic and based on studies depends on technology development achievable by 2028 [57, 58]. It is important to mention that in the present design as aforementioned the battery pack only assists during take-off and climb, hence their use remains for the cases studied was found that neither of them use the battery pack during cruise. This behaviour could be explain by analysing the method used. The method focuses in obtain the minimum MTOM for the different configurations in the design space. For the study case the specific energy of the battery was set as 175 [Wh/Kg]

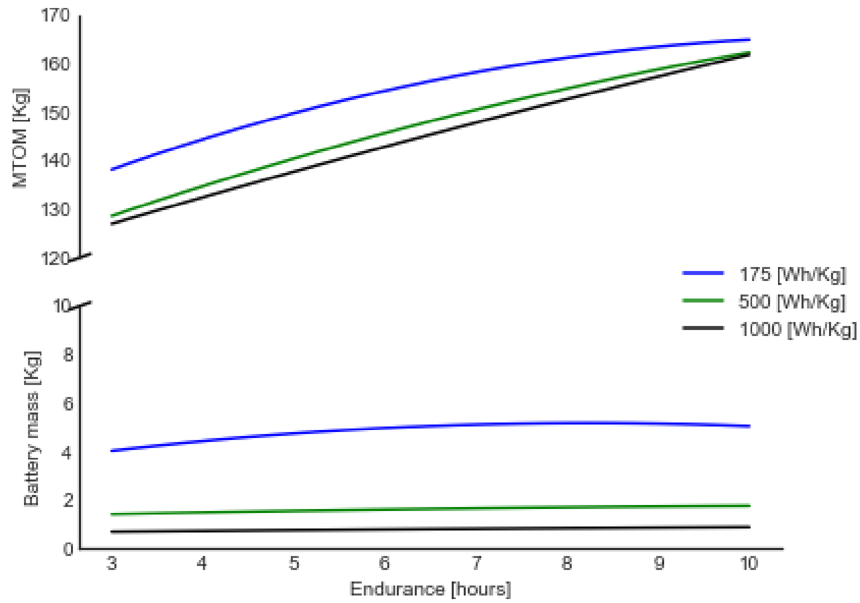


Fig. 12 MTOM vs Endurance for different battery specific capacity.

2. Benchmarking Analysis for the ICE

In this section two different conceptual designs of UAVs for a mission in the Galapagos islands are presented. The mission presented focused on a monitoring area of 4026[km^2] at 35 [m/s], which corresponds to a required range of 498.65 [Km]. Based on this mission a comparison using different power plants for the ICE is carried out based on the payload required for monitoring (table 3).

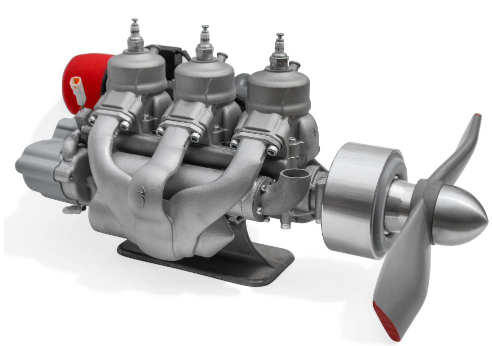
The design was performed by setting the design requirements, as follows: cruise velocity of 35[m/s], operation altitude of 2000[m], endurance= 5[hours], runway take-off-landing of 110 [m]. Table 8 exhibits the results comparing series hybrid and conventional configurations using two and four strokes. Regarding the two stroke configurations, the series hybrid case is 23.64% heavier than conventional case. Despite the MTOM increment, the fuel mass required in the series hybrid case is 2.20% lower than the conventional one. Concerning the four stroke configurations, the MTOM increment is 27.61% , whilst the fuel reduction is 4.10%. These results show as better power plant the four stroke configuration. Although the techno-economic assessment of these alternatives is beyond the scope of the present work, it is known the best performance of four strokes engines when operation time is higher, since the periods for maintenance are longer in comparison with two strokes, making operative costs lower. Nevertheless, the investment cost of a two stroke engine for this aviation sector is between 15% and 30% lower and hence this alternative is still a good option depending on the monitoring application (endurance). Figure 13 presents the ICEs selected from the benchmarking analysis for each series hybrid case.

The degree of hybridization is 41.80% for two strokes and 46.00% for two strokes four strokes. Concerning the MTOM, both configurations have hardly any differences. The gap between both configurations is due to the components integrating the propulsion system. Regarding the electric part, the main difference is the power of the EM due to the two stroke configuration higher design point (EM power 6.5% higher). Comparing the ICEs, the two stroke ICE is 3.23% lighter than the four stroke ICE. Despite ICE mass, the fuel require by two stroke case is 29.03% higher than four stroke case. Thus, the four stroke configuration yields a better performance by reducing the fuel consumption on the proposed mission. It is important to mention that in this case of study the benchmarking analysis just involves the operation characteristics of the ICEs without involving the acquisition and maintenance cost of the engines. Figure 13

Table 8 Results - Conceptual Design.

Configurations		2 stroke		4 stroke	
		Convent.	S. Hyb.	Convent.	S. Hyb.
Cruise time	t [hours]	5	5	5	5
Wing loading	W/S[N/m2]	164.496	197.601	164.496	180.936
Power Loading	P/W [W/Kg]	78.835	89.711	78.835	84.234
Hyb. Point	Hp[%]	-	41.801	-	46.003
MTOM	[Kg]	130.197	160.975	124.094	158.355
Power ICE	PICE[KW]	10.332	6.000	9.853	6.200
Mass ICE	MICE[kg]	5.059	3.650	4.886	4.500
Mass Gener.	MGEN[kg]	-	3.594	-	3.732
Mass Fuel	Mfuel[kg]	13.340	13.046	10.543	10.110
Power EM	PEM[KW]	-	14.354	-	13.477
Mass EM	MEM[kg]	-	8.674	-	8.190
Mass Batt.	Mbatt[kg]	-	5.402	-	5.212
wing area	S[m2]	7.764	7.992	7.401	8.586
Wing Span	b[m]	5.677	5.759	5.542	5.969

shows the ICEs selected from the benchmarking analysis for two and four strokes hybrid configurations.



(a) 2 Stroke engine A99 UAV EFI [59]

(b) 4 Stroke engine ROTO 130 FSi AL [60]

Fig. 13 Engine models suitable for hybrid systems

V. Conclusions

A series hybrid propulsion system implemented in a UAV designed for monitoring in the Galapagos islands is modelled at conceptual and preliminary phases. The conceptual model uses the constrain analysis adapted for hybrid systems and the preliminary propulsion sizing is based on semi-empirical models coupling parametric and benchmarking analysis. From the performance assessment of this propulsion system is observed that the system proposed can achieve a fuel consumption reduction of 2.20% for the 2 stroke engine configuration, compared to a baseline fuel based platform. For the case of the 4 stroke engine the fuel reduction arises to 4.10%. The aforementioned results encourage further study for hybrid systems, where more robust models can be implemented to account for aircraft level variables.

Furthermore, the current work assumed that the battery pack will assist only in power demanding conditions, and hence the battery pack influence is not large when analysing the UAV performance for different endurance.

To summarize the present work highlights the suitability of using hybrid series systems for propulsion of long endurance UAVs used in monitoring.

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