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INTEGRATED HYBRID ENGINE CYCLE DESIGN AND POWER MANAGEMENT OPTIMIZATION

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ABSTRACT

A novel integrated gas turbine cycle design and power management optimization methodology for parallel hybrid electric propulsion architectures is presented in this paper. The gas turbine multi-point cycle design method is extended to turboprop and turbofan architectures, and several trade studies are performed initially at the cycle level. It is shown that the maximum degree of electrification is limited by the surge margin levels of the booster in the turbofan configuration.

An aircraft mission-level assessment is then performed using the integrated optimization method initially for an A320 Neo style aircraft case. The results indicate that the optimal cycle redesigned hybrid electric propulsion system (HEPS) favors take-off and climb power on-takes while optimal retrofit HEPS favor cruise power on-takes. It is shown that for current battery energy density (250 Wh/Kg), there is no fuel burn benefit. Furthermore, even for optimistic energy density values (750 Wh/kg) the maximum fuel burn benefit for a 500 nm mission is 5.5% and 4% for redesigned and retrofit HEPS, respectively. The power management strategies for HEPS configurations also differ based on gas turbine technology with improvement in gas turbine technology showing greater scope for electrification.

The method is then extended to ATR 72 style aircraft case, showing greater fuel burn benefits across the flight mission envelope. The power management strategies also change depending on the objective function, and optimum strategies are reported for direct operating cost or fuel burn. The retrofit case studies show a benefit in direct operating cost compared to redesigned case studies for ATR 72. Finally, a novel multi-mission approach is shown to highlight the overall fuel burn and direct operating cost benefit across the aircraft mission cluster.

NOMENCLATURE

LP	Low pressure
HP	High pressure
PEM	Proton exchange membrane
ANN	Artificial neural network
SMR	Short medium range
HEPS	Hybrid electric propulsion system
HPT	High pressure turbine
BPR	Bypass ratio
OPR	Overall pressure ratio
T40	Combustion outlet temperature
T30	Compressor outlet temperature
PMS	Power management strategy
GT	Gas turbine
EIS	Entry into service
DOC	Direct operating cost
OD	Off design
T41	Rotor Inlet temperature
NASA	National Aeronautics and Space Administration
LPC	Low pressure compressor
HPC	High pressure compressor
T/O	Take-off
TOC	Top of climb
tsfc	Thrust specific fuel consumption
D_T	Tip diameter

1. INTRODUCTION

Extensive work has been done by aerospace companies and academic institutions in the field of hybrid electric propulsion systems in the previous decade, as summarized in [1], [2], [3]. In recent years, the studies have narrowed down and focused on parallel hybrid electric configurations utilizing either lithium-based batteries [1], [6], [7], [9], [10], [11], [12], [13], [14], [24], aluminum-based batteries [4], [8] or PEM fuel cells [5], [15].

All these technologies have similar uncertainties when integrated into aircraft platforms. These include the impact on hybrid gas turbine cycle design, power management strategy, thermal management, aircraft design, airport operation and fleet-level performance. Most of these elements have been addressed individually in different publications.

The work from Lents et al. [10] provided the first approach to redesign parallel hybrid gas turbine cycle and showed a 6% potential mission fuel burn saving for a B737-class aircraft with motor power of 2.1 MW. Seitz [5] extended this and compared different locations of providing the electric power, concluding powering the LP shaft on the faster side of the gearbox being the best performing. Kang et al. [9] compared powering LP and HP shafts with the electric motor in a parallel arrangement and showed the LP compressor surge margin benefits on powering HP shaft. Similar conclusions of increase in LP compressor surge margin and transient benefits of electrification from powering HP shaft were shown by NASA [18], [19]. These studies didn't address the effect of energy and power optimization on the performance, nor its effect on the engine redesign.

Concerning the power and energy management strategy numerous studies are looking at its optimization. Trawick [16] compared different power management optimization methods to identify power ratios between motor and gas turbine along the mission and concluded that cruise is the most favored flight segment for electrification. Perullo et al. [17] utilized this method and showed an energy benefit of 15% across an aircraft fleet. Zhang et al. [11] [20] provided an energy management optimization method simultaneously comparing different motor powers, battery sizes, and power splits along the mission, showing a fuel burn reduction ranging from 8% to 45%, depending on battery energy density. The limitation of these studies is associated with the optimization of the energy management on a fixed "retrofit" gas turbine cycle without exploring the flexibility provided by electrification on the cycle design space.

Ghelani et al. [1] benchmarked and quantified the individual impact of gas turbine cycle redesign and power management optimization for parallel hybrid electric propulsion systems for different technology scenarios. The results indicate that to fully assess the potential benefits of electrification in performance, life and cost the cycle design should be directly coupled with the energy management optimization. This approach is essential to provide a realistic fuel burn and operating cost benefit from electrification considering all the constraints and system interdependencies.

An integrated approach to simultaneously design and optimize these systems across different aircraft classes is lacking in the current literature.

This method would allow answering the following research questions:

1. What is the optimal motor power and battery size for a given mission range to minimize fuel burn, energy consumption and direct operating cost?
2. How do power management strategies differ for cycle redesigned and retrofitted gas turbines and for different objective functions?
3. How do the fuel burn and direct operating cost benefits vary between different aircraft classes?
4. What maximum fuel burn and direct operating cost benefit can be obtained when considering all the constraints imposed by electrification on a realistic off-design mission cluster?
5. How does an integrated approach comprising all aspects related to the cycle redesign and energy management optimization change the outcome of the selection of propulsion system configuration and the expected benefit from electrification?

This paper answers the questions mentioned above for lithium-chemistry based batteries, but the method can be applied to alternative energy/power sources such as alternative batteries and fuel cells. It is envisioned that in the future, with the addition of thermal management models and transient operability assessment, the novel 'design and optimize in the loop' approach can eliminate most of the uncertainty around the application of parallel HEPS at conceptual level.

2. METHODOLOGY

An integrated aircraft-engine framework has been developed to assess parallel hybrid electric aircraft performance. The main elements of this framework include ORION (aircraft performance tool), 3-point gas turbine cycle design utilizing TURBOMATCH (engine performance tool), ATLAS (gas turbine weight estimation) and electrical system models. More information on each of these can be found in [1]. Some new elements have been added to this framework for the multi-mission optimization. These include ANN-based gas turbine cycle design and off design performance, direct operating cost calculations and multi-mission analysis.

2.1 ANN-based gas turbine cycle design and off-design performance

A feedforward ANN model is developed which predicts off-design performance of different redesigned hybrid engine cycles after selecting target core temperatures and fan diameter from the cycle trade study. The main aim of developing an ANN model was to reduce the computational cost of optimizing power management strategies on both design and off-design missions with simultaneous engine cycle design in the loop. A database of engine decks is developed by running the engine cycle models for various off-design flight conditions. The inputs and outputs of the training data can be summarized below:

$$(sfc, fuel\ flow, LP\ Shaft\ Power, Thrust, T41, T30) = f\begin{pmatrix} TO\ Ontake, ToC\ Ontake, Cruise\ Ontake, \\ Alt, Mach, LP\ Spool\ Speed, OD\ Ontake \end{pmatrix} \quad (1)$$

The ANN training model information is based on the data provided by Zhang et al [11]. The final errors across the whole dataset as compared to the baseline can be seen in Figure 1.

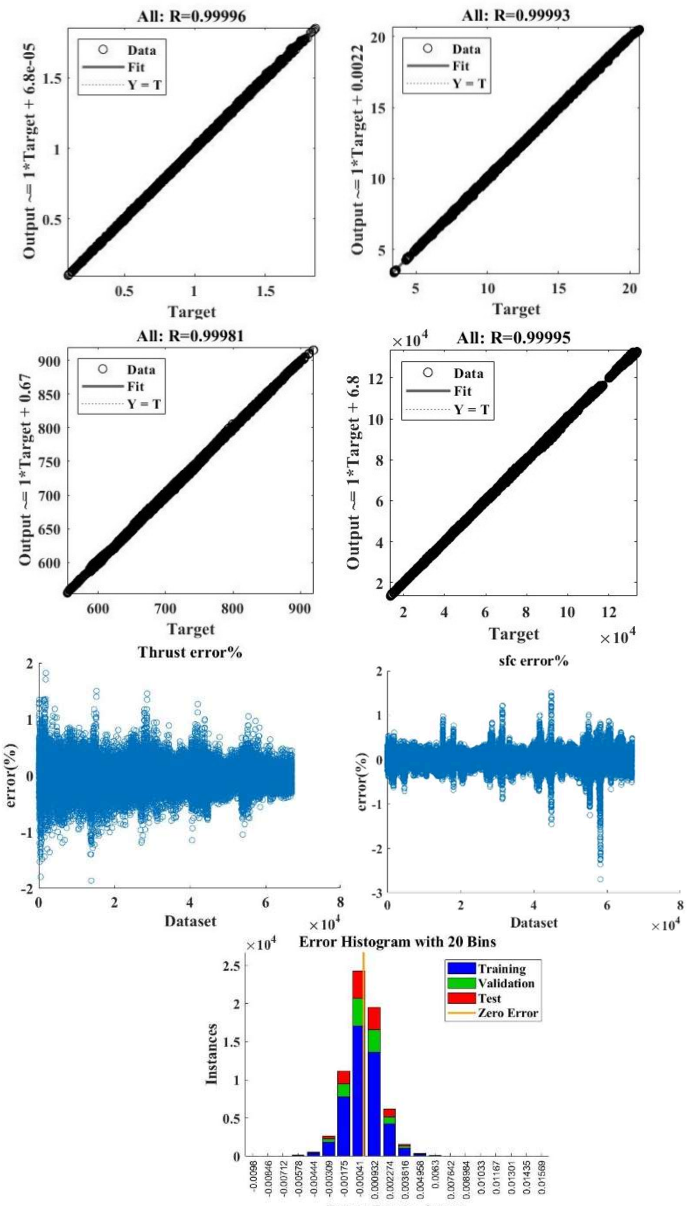

Figure 1 - ANN Fits for SMR test case

From the fit plots and error distributions, the fitted data matches well with the input data and the neural network can predict off-design performance of redesigned engine cycles within 2% relative error for specific fuel consumption across all flight phases.

2.2 Direct operating cost method & assumptions

In this section, the various inputs to estimate direct operating cost for both SMR and regional turboprop test cases are summarized. The direct operating cost module consists of engine maintenance cost, aircraft maintenance cost, fuel cost, aircraft acquisition cost, taxes, and insurance. For a hybrid-electric aircraft, the extra cost of battery replacement, battery charging cost and carbon tax is added. The maintenance cost of the HPT rotor module is calculated using HESTIA [21], [23], in which the number of cycles to failure are calculated using miner's law to account for temperature rating and time for different flight mission segments. The overall number of cycles to failure is the minimum of cycles calculated from failures by oxidation, fatigue, and creep. As given in [23], the HPT rotor module replacement sets the number of shop visits. The relation between engine maintenance cost and shop visits is taken from work of Mavris et al [26] for the SMR test case and from ATR Guide [25]. Cost assumptions for the battery replacement, battery charging, and life cycles is taken from [12], [24]. The final direct operating assumptions are summarized in Table 1.

Table 1- Direct operating cost assumptions

Battery charging cost ($/kWh)	0.15
Carbon tax ($/ton)	240
Battery cycles	500
Fuel price ($/kg)	1.6
Battery cost ($/kWh)	100
Total aircraft cycles (SMR)	60000
Cost per shop visit ($ mill)	2.1
Total aircraft cycles (Regional turboprop)	72000
SMR economic mission (nm)	500
Regional turboprop economic mission (nm)	300
Acquisition cost ($ mil) (Regional turboprop)	26
Acquisition cost ($ mil) (SMR)	108.4
Acquisition cost increment - hybrid variants	10%

2.3 Multi mission method

The method to identify the optimum propulsion system on combined design and off-design missions is described in this sub-section. A mission cluster is obtained for the aircraft test cases assessed from [22], which consists of airline data flown in North America. Based on the flight intensity in the mission cluster, off-design missions are selected. Both the redesigned and retrofit HEPS are designed for different mission ranges across the maximum payload line and then assessed at selected off-design missions. Power management is also optimized at the off-design missions keeping the same physical propulsion system size and energy. The flowchart is shown in the Figure 2.

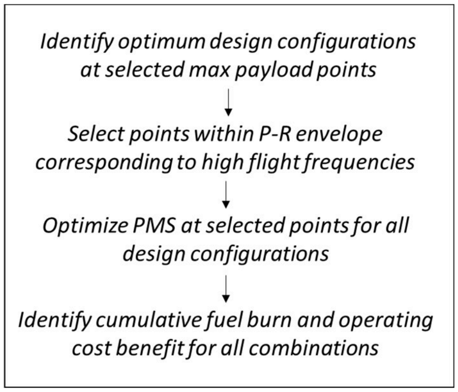

Figure 2 - Multi mission method

2.4 Overall framework

The overall framework utilized in this work is summarized in Figure 3. All the models are connected in an automatic loop with the main function being the genetic algorithm optimizer, calling other gas turbine ANN models, aircraft models, DOC, and electrical system models during a mission optimization run.

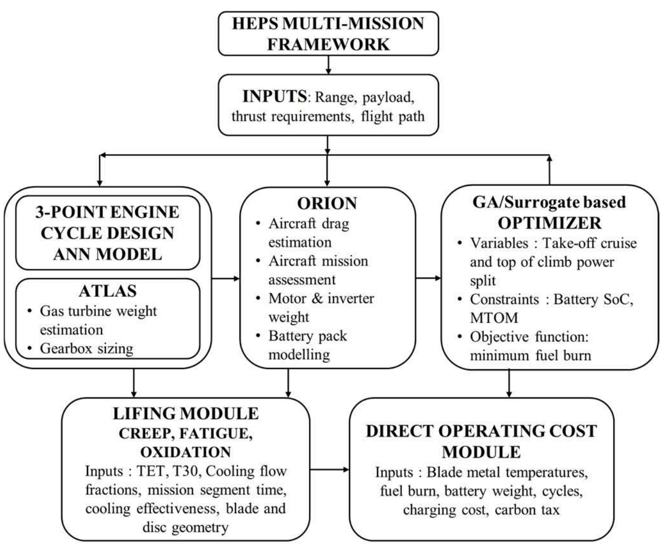

Figure 3- HEPS Framework

3. RESULTS AND DISCUSSION

Two aircraft test cases are considered – SMR (Short medium range) test case based on A320 Neo (180 pax, 3000 nm design range) and turboprop test case based on ATR 72 (70 pax, 850 nm design range).

3.1 Gas turbine cycle design

A 3-point cycle design approach [1] is followed to redesign the gas turbine thermodynamic cycles with electrification. The results and trends are described for both test cases.

3.1.1 SMR test case

For the SMR test case, both retrofit and redesigned gas turbine cycle information are computed based on two gas turbine technology levels – EIS 2010 and EIS 2035. The thrust requirements for the three design points are shown in Table 4.

Table 2 - EIS 2010 SMR gas turbine cycle data

Parameter	Baseline	Retrofit, delta		Redesigned, delta	
Cruise BPR	5.7	5.7	0	6.1	7%
Cruise tsfc (g/kN.s)	16.6	16.6	0	16.5	-0.8%
Cruise OPR	24.7	24.7	0	25.6	3.6%
Cruise T40 (K)	1288	1288	0	1342	54
T/O T40 (K)	1641	1584	-57	1641	0
T/O T30 (K)	860	852	-8	860	0
Cruise on-take (kW)	0	0	0	0	0
TOC on-take (kW)	0	600	600	600	600
T/O on-take (kW)	0	1500	1500	1500	1500
Fan D_T (m)	1.65	1.65	0	1.65	0

Table 3 - EIS 2035 SMR gas turbine cycle data

Parameter	Baseline	Retrofit, delta		Redesigned, delta	
Cruise BPR	15.8	15.8	0	17	7.6%
Cruise tsfc (g/kN.s)	13.2	13.2	0	13.1	-0.9%
Cruise OPR	39	39	0	40.5	3.8%
Cruise T40 (K)	1536	1536	0	1585	59
T/O T40 (K)	1890	1830	-60	1890	0
T/O T30 (K)	940	931	-9	940	0
Cruise on-take (kW)	0	0	0	0	0
TOC on-take (kW)	0	600	600	600	600
T/O on-take (kW)	0	1500	1500	1500	1500
Fan D_T (m)	1.98	1.98	0	1.98	0

Table 4- SMR thrust requirements

T/O Thrust (kN)	95
ToC Thrust (kN)	25
Cruise Thrust (kN)	18.8

The temperature reduction for the retrofit case and specific fuel consumption benefit for the redesigned case as compared to the baseline is shown in Table 3. Both the cases are shown with T/O power on-take of 1.5 MW on the LP shaft, corresponding to 7% degree of electrification. The degree of hybridization by power at T/O and ToC is the same (7%) [1]. The cycle-level benefit extracted from the EIS 2035 gas turbine is slightly higher than the EIS 2010 (Table 2) gas turbine, due to motor power being a greater fraction of LP shaft power [1].

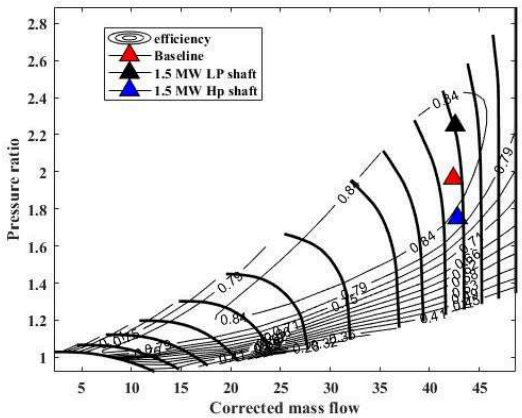

Figure 4 - EIS 2010 SMR retrofit booster operating points, top of climb

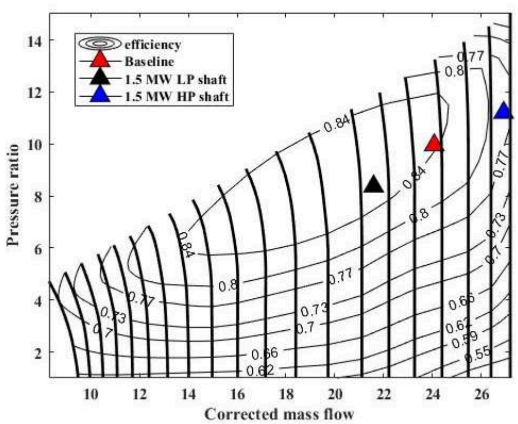

Figure 5 - EIS 2010 SMR retrofit HPC operating points, top of climb

The impact of providing electric power on-take on the LP & HP shaft at top of climb is shown in Figure 4 and Figure 5. Only the top of climb is presented as it is the sizing point for compressors. The surge margin for the booster reduces on increasing electrical power on the LP shaft due to the components rematching. The booster surge margin drops to 10% on application of 1.5 MW at top of climb (14% degree of hybridization). It should be noted that this would not occur if it were a 3-spool or turboprop configuration where the LPC and fan are driven by different turbines.

$$H_P = \frac{P_{motor}}{P_{shaft}} \quad (2)$$

To have 15% surge margin as a transient stack consistently during all 3 electrified flight segments, the percentage of hybridization on LP shaft (H_P) is restricted to 10%. This percentage can be increased either by opening the bleed-off valves or by powering the HP shaft. The first option is avoided so as not to detriment performance and the second to avoid HP shaft overspeed. There is potential for a combination of LP and HP power on-take to have best performance, this will be pursued in future work. In this study, LP shaft power on-takes are considered.

3.1.2 Regional turboprop test case

For the regional turboprop case study, for the case that the electric power train drives the power turbine, the degree of electrification is not limited by component operability but by the power/thrust ratios, compressor polytropic efficiency and thermal management requirements for peak heat loads. Snyder [21] suggested an equation for centrifugal compressor polytropic efficiency change with corrected exit mass flow. This relationship is used when assessing the hybrid cycle design space for the turboprop case. It can be seen from Figure 6 and Figure 7, that when the effect of resizing on compressor efficiency is considered the benefit in specific fuel consumption for redesigning for H_P =30% drops from 5.1% (Fig. 6) to 3.7% (Fig. 7). Beyond 30% H_P, the cruise temperatures will be very high and will dictate the core size hence, 30% H_P is a limit on redesigning the turboprop engine cycle, with take-off and climb hybridization. The gas turbine cycle data for 15% H_P is shown in Table 5.

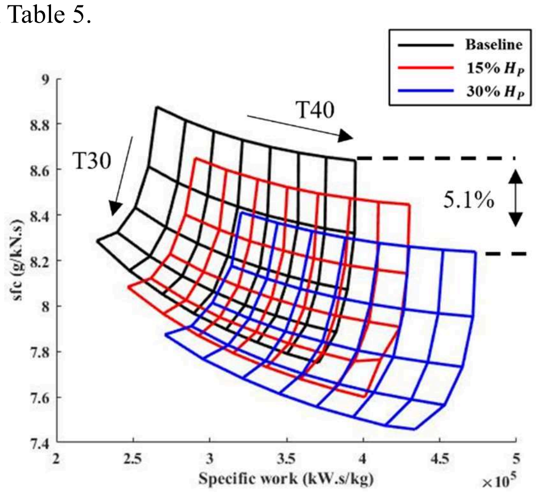

Figure 6 - Turboprop cycle design space without efficiency correction

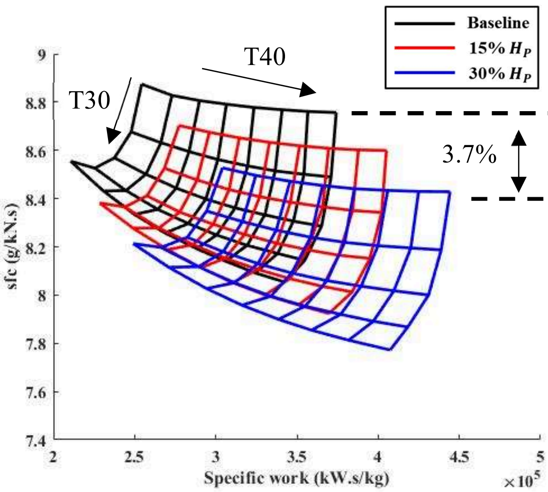

Figure 7 - Turboprop cycle design space with efficiency correction

Table 5 - Turboprop EIS 2035 gas turbine cycle data

Parameter	Baseline	Retrofit, delta		Redesigned, delta	
T/O core flow (kg/s)	5.6	5.27	-6%	4.9	-13%
Cruise tsfc (g/kN.s)	8.4	8.4	0	8.25	-1.7%
Cruise OPR	18	18	0	19.1	6.1%
Cruise T40 (K)	1298	1298	0	1357	59
T/O T40 (K)	1600	1537	-63	1600	0
T/O T30 (K)	780	760	-20	780	0
Cruise HP	0	0	0	0	0
T/O HP	0.15	0.15	0.15	0.15	0.15

3.2 Power management optimization and fuel burn benefit trends

The limits on electrification mentioned in the previous section, namely 10% DoH by power for the geared turbofan and 30% for the turboprop, are now applied at an aircraft mission level for both test cases.

Table 6 - Electrical powertrain assumptions [1]

Parameter	Current	2035
Motor Power density (kW/kg)	7	13
Inverter Power density (kW/kg)	11	19
Thermal Management Power density (kW/kg)	0.7	1.2
Battery Power density (kW/kg)	1.2	2

Optimized power management strategy trends and fuel burn benefits for both retrofit and redesigned gas turbines are presented. EIS 2035 estimations of the electrical powertrain power density are used in the simulations as summarized in Table 6[1].The trends in optimal power management strategies are presented first and then fuel burn benefits are presented. There are variations in power management distributions due to different thrust/power ratios across aircraft classes. But the global trends are similar for all aircraft classes hence are bunched together. The power management strategy trends are assessed for three different purposes:

1. To understand the difference in power management strategies between redesigned and retrofit gas turbines.
2. To understand the difference in power management strategy trends with change in gas turbine technology.
3. To understand the difference in power management strategies with different objective functions: direct operating cost, fuel burn or energy consumption.

3.2.1 PMS Variation with redesign/retrofit

First up, the optimal power management strategies are compared for the retrofit (Figure 8) and redesigned case (Figure 9) for the SMR test case. The three main factors which dictate the optimal PMS are the electrical powertrain added weight, the benefit gained from core re-sizing and the battery efficiency. It can be noticed that the redesigned case always favors a higher fraction of take-off and initial climb power on-takes as opposed to retrofit case. Take-off and initial climb power on-takes dictate the core size as shown in 2.1, hence the benefit coming from reduced specific consumption surpass the penalty due to higher electric powertrain weights and higher battery efficiency. In retrofit's case, the optimizer always tries to reduce discharge rates for the battery to have better efficiency and lower powertrain weights hence cruise is the favored flight segment.

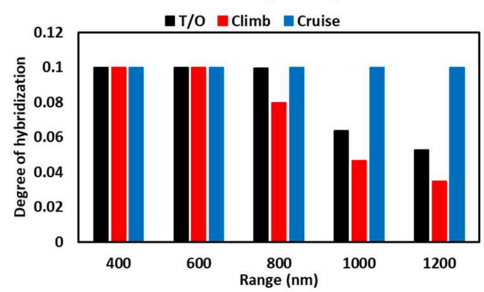

Figure 8 – SMR Optimal PMS EIS 2035 (retrofit)

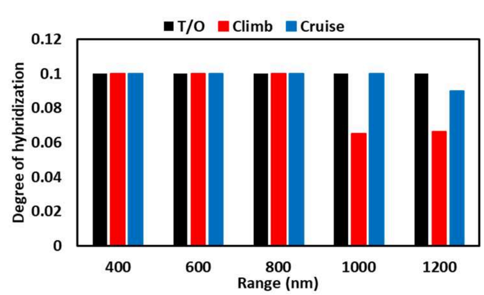

Figure 9 – SMR Optimal PMS EIS 2035 (redesigned)

3.2.2 PMS Variation with GT technology

The figures below show the optimal power management strategies for EIS 2010 gas turbine technology (Figure 10 & Figure 11). The degree of hybridization increases as we move from EIS 2010 to 2035. This is due to the reduction in LP shaft power, which in turn is driven by reduction in specific thrust and improvement in thermal efficiency. These findings are also backed by conclusions from [1].

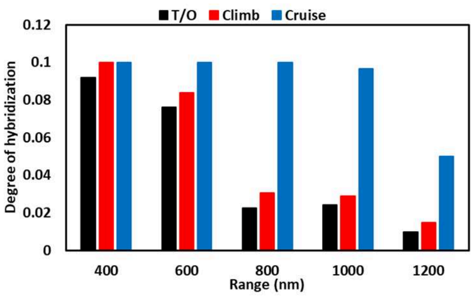

Figure 10 – SMR Optimal PMS EIS 2010 (retrofit)

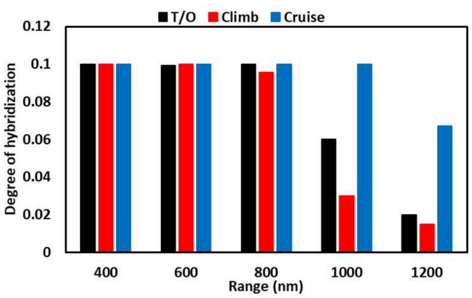

Figure 11 – SMR Optimal PMS EIS 2010 (redesigned)

3.2.3 PMS Variation with objective function

The PMS trends change for different objective functions. Minimizing direct operating cost and fuel burn is considered herein. for the regional turboprop test case. This is because there is no direct operating cost benefit for any hybrid SMR test case hence the optimizer always picks the non-hybrid baseline gas turbine as the best one.

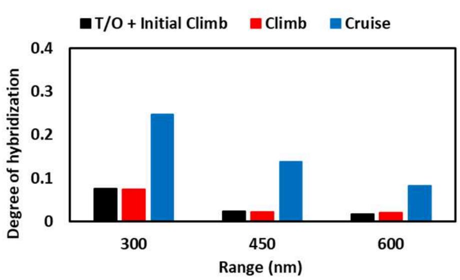

Figure 12 – Regional Optimal PMS (retrofit)

The trends are initially shown for the retrofit (Figure 12) and redesigned (Figure 13) cases optimized for fuel burn. The trends are like the SMR test case favoring even greater hybridization fraction at cruise for retrofit and take-off for redesign. This is due to the lower non-dimensional cruise to take-off thrust ratio for the turboprop platform. For the case of DOC minimization, the trend changes significantly, as seen in Figure 14. The retrofit case no longer favors cruise but take-off and climb. This is due to the importance of gas turbine maintenance and battery replacement cost. The optimizer tries to pick a small battery pack just enough to reduce the number of HP turbine replacement cycles (achieved by reduced take-off temperatures) and keep the battery replacement cost low.

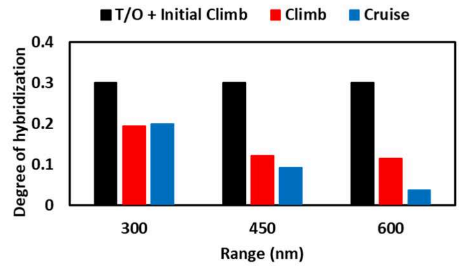

Figure 13 – Regional Optimal PMS (redesigned)

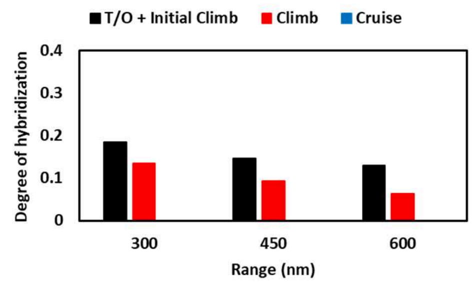

Figure 14 – Regional Optimal DOC PMS (retrofit)

3.2.4 Comparison of fuel burn benefit for the two aircraft platforms

In this section, the maximum potential percentage fuel burn benefit for the two aircraft platforms is shown (Figure 15).

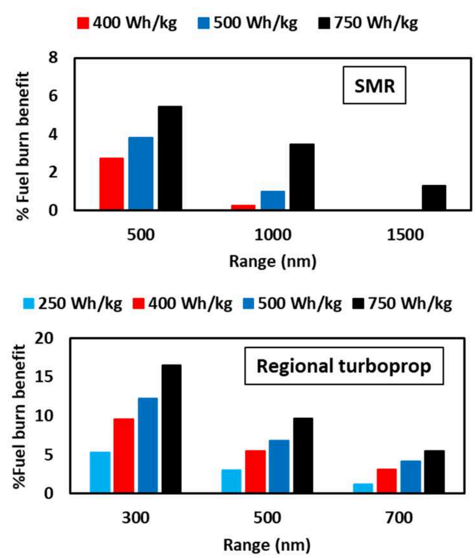

Figure 15 – Percentage fuel burn benefit for SMR and turboprop test case with varying battery energy densities

EIS 2035 gas turbine technology level is used for both platforms as it shows greater fuel burn benefit from electrification [1]. The benefit is calculated for 3 different design missions and for different battery technology level. Each case corresponds to a unique redesigned propulsion system. As seen from the results the application of electrification for the regional turboprop can offer substantial benefits, especially for short range missions, even for current and near future batteries technology. For the SMR case the benefit is marginal for missions longer than 500nm and no benefit is calculated for current technology level batteries.

3.3 Multi mission assessment

The multi-mission assessment method is now applied to the two aircraft test cases. This method allows the identification of the optimum single configuration that can address the requirements of the relevant platform. The multi-mission analysis is performed for both platforms and for both objective functions (fuel burn and DOC).

3.3.1 SMR test case

Off-design mission operation of two different design ranges of 400 nm and 600 nm is shown in the Figure 16 & Figure 17, respectively. The results shown correspond to the redesigned case with battery energy density of 750 Wh/kg, on a baseline aircraft design range of 3200 nm.

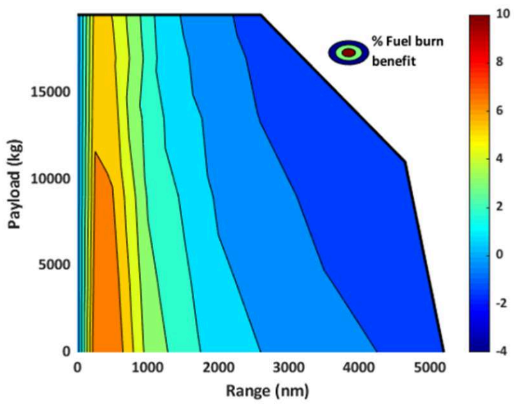

Figure 16 – SMR test case, 400 nm design range, redesign

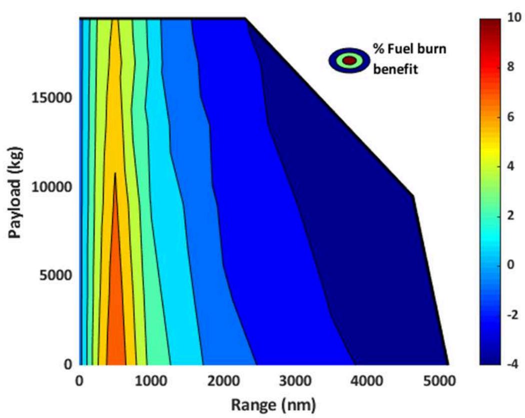

Figure 17 -SMR test case, 600 nm design range, redesign

First thing that can be noticed is the loss of payload-range capability when sizing the HEPS at a design range of 400 nm (Figure 16) and 600 nm (Figure 17). A HEPS design range of 600 nm has greater peaks of fuel burn benefit between 300-800 nm but beyond that it is worse. From this it can be concluded that because the fuel burn benefit is in single digit for the SMR test case, it is better to go with as small a battery pack as possible to have no or little fuel burn penalty on slightly longer ranges. This leads us to select the 400 nm design configuration over others, which on 500 nm economic mission translates to 5% fuel burn benefit. This is slightly lower than the fuel burn benefit of 5.5% obtained by the propulsion system that is designed for the 500 nm (Figure 15).

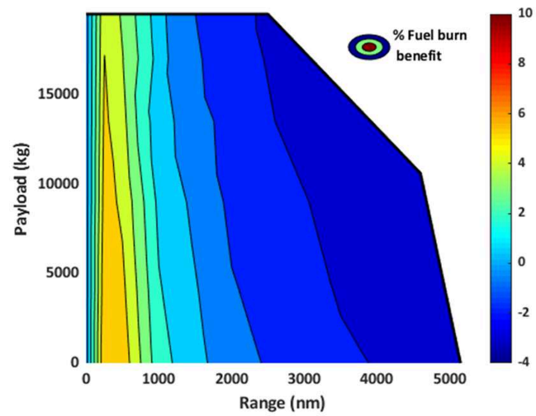

Figure 18 - SMR test case, 400 nm design range retrofit

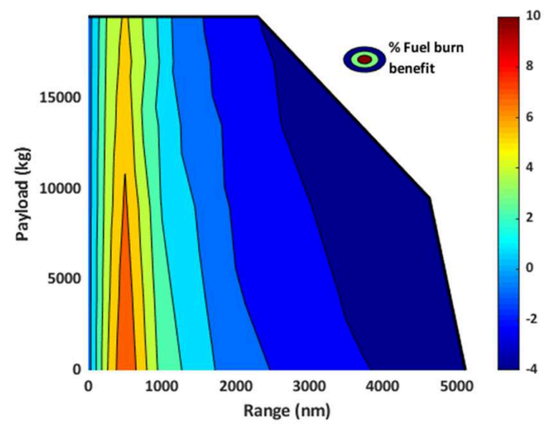

Figure 19 - SMR test case, 600 nm design range retrofit

Similar trends are also seen for the retrofitted case, where the HEPS design range of 400 nm (Figure 18) is again favorable against 600 nm (Figure 19) when a complete off-design operation is considered. The rest of the HEPS design ranges are performing much worse than both 400 and 600 nm, hence have not been shown here. Using the direct operating cost assumptions shown in Section 2.2, the direct operating cost was evaluated based on a 500 nm mission for all 3 cases; baseline, retrofit and redesigned. This is presented in Figure 20 for the selected design configurations. The retrofit case has a penalty in DOC of 3.6% relative to baseline while the redesigned case has a penalty of 4.4%. The retrofit case has a lower penalty due lower turbine entry temperature translating in lower engine maintenance cost.

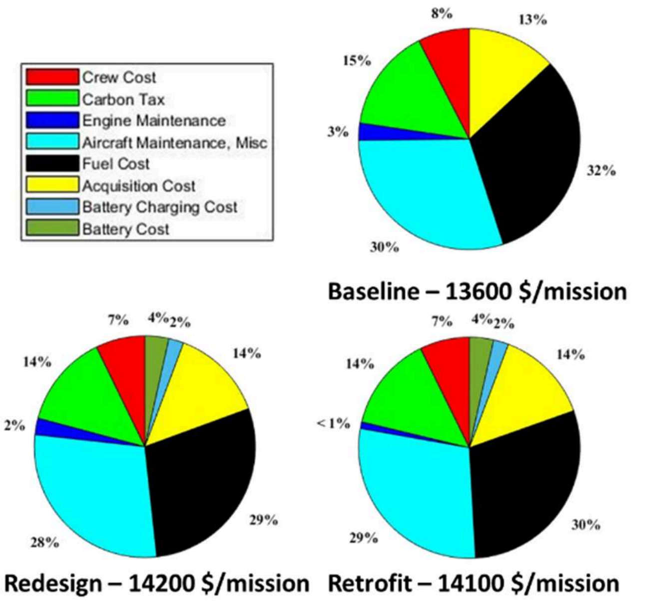

Figure 20 - Direct operating cost comparison, SMR

The retrofitted case has an average of 1.5% lower fuel benefit than the redesigned case across the mission spectrum (average difference between Figure 16 & Figure 18). Since both the retrofit and redesigned cases have a penalty in DOC relative to baseline, it is better to go for the redesigned case due to higher fuel burn benefit.

The two final conclusive scenarios are shown below.

- Scenario 1: Selecting a design range configuration of 400 nm, a cumulative percentage fuel burn benefit of 3% (Figure 21) can be obtained when assessed across selected OD missions (selected based on [22]). This is lower than the value of 4% on 500 nm economic mission.

Scenario 2: After seeing the distribution of OD mission points (seen in black), the batteries can be placed in cargo hold with reduced maximum payload capability. This will lead to lower landing gear and operating empty weight, translating in extra 0.6% fuel burn benefit (average difference between Figure 21 & Figure 22).

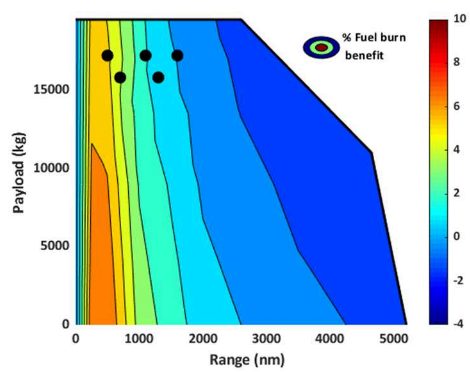

Figure 21 - Scenario 1

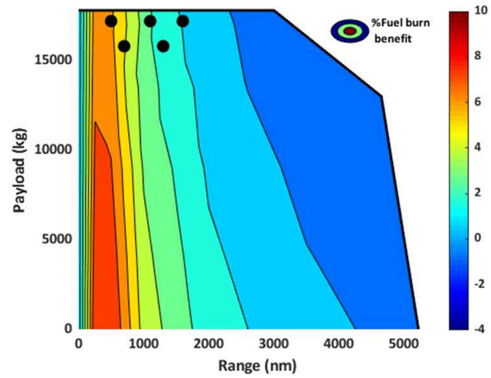

Figure 22 - Scenario 2

3.3.2 Regional turboprop test case

The multi-mission analysis was then performed for the regional turboprop test case on battery energy density of 500 Wh/kg, and the final set of scenarios is shown below.

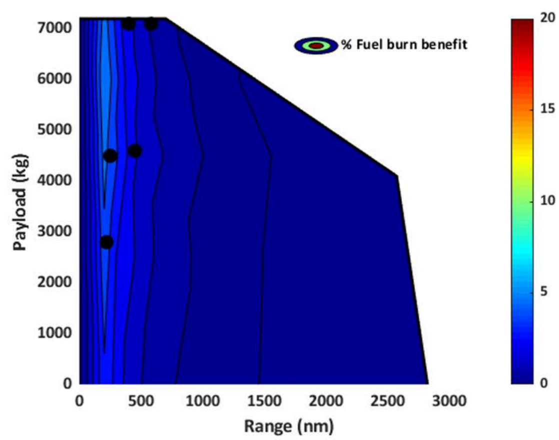

Figure 23 - Overall fuel burn benefit, regional turboprop, Scenario 1

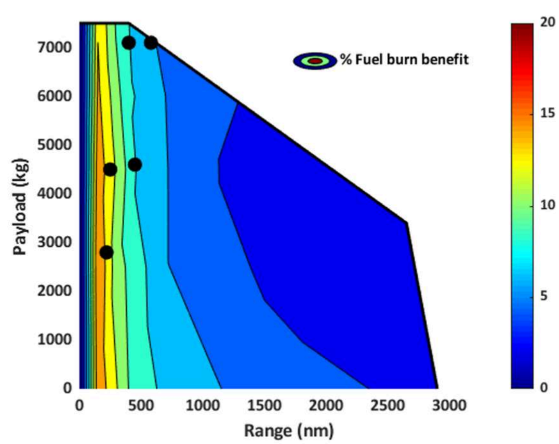

Figure 24 - Overall fuel burn benefit, regional turboprop, Scenario 2

Scenario 1: It was found that there is a direct operating cost benefit for the retrofit case as compared to the baseline case (performing with assumptions from Section 2.2). From the distribution of OD missions (black points in Figure 23), it is possible that small battery packs can be put in place of cargo baggage. This allows for minimal to no changes on both the aircraft and engine side. Hence, by selecting a design range configuration of 400 nm for the retrofitted case, a cumulative percentage fuel burn benefit of 3% (Figure 23) and direct operating cost benefit of 3% can be obtained.

Scenario 2: For the redesigned case, 300 nm design range was found to be the most beneficial in terms of fuel burn benefit. A cumulative average 10% fuel burn benefit (Figure 24) and 2% direct operating cost penalty can be obtained for this case as compared to the baseline non-hybrid.

3.4 Synthesis

In the previous subsections, three aspects of HEPS – gas turbine cycle design, optimal PMS and multi-mission assessment were covered for both test cases. In this section, a synthesis of those is provided and explicit trends between direct operating cost and fuel burn benefit are presented. For a fair comparison, a 500 Wh/kg of battery energy density is used for both platforms.

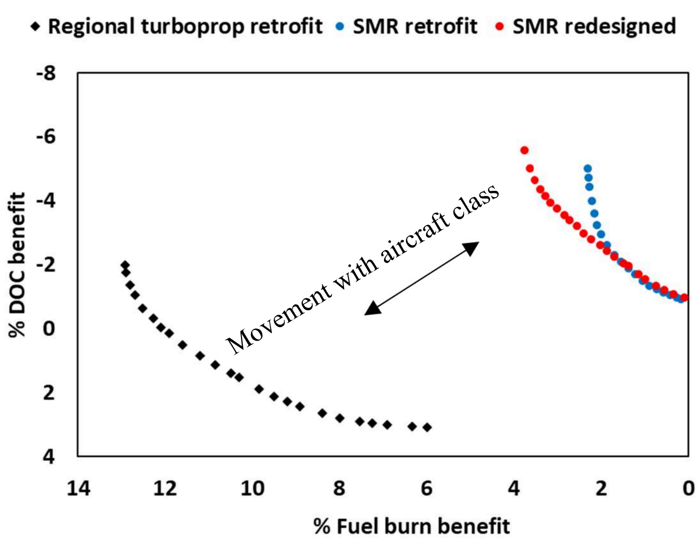

Figure 25 - %DOC vs %Fuel burn benefit pareto

Figure 25 summarizes all the trends for both aircraft classes. An explanation is now provided each of the trends:

1. In all 3 pareto fronts, the maximum fuel burn benefit is restricted by the maximum aircraft ramp weight limit and maximum degree of hybridization. On the other hand, the maximum DOC benefit is limited by the turbine replacement cycles and battery cycles.

2. Between redesigned and retrofit, the trade-off is primarily between significant fuel burn benefit and marginal DOC penalty as seen from the blue and red colored fronts in Figure 25. The difference between them is primarily dependent on the thrust ratios between T/O and cruise. The greater the normalized difference between the two flight points, the greater will be the benefit gained from redesigning the gas turbine.

3. When a direct comparison is made between the retrofit regional turboprop (black) and SMR (blue), it can be clearly seen that the regional turboprop is much more favorable than SMR test case. This difference can be attributed to the power to weight ratio of the aircraft, which in turn is driven by flight Mach number and engine specific thrust. The turboprop being the lowest possible specific thrust and flown at lower Mach will always be much more suitable for electrification. The fuel burn benefit becomes greater as the power to weight ratio of the aircraft reduces and hence, the electrification weight penalty reduces.

4. CONCLUSION

An integrated parallel hybrid engine cycle design, power management optimization and multi-mission analysis method is presented in this paper. Results for retrofit, and redesigned optimal HEPS architectures were presented firstly for different design ranges and then applying a multi-mission approach for identifying the optimum configuration for each platform. A trade-off between direct operating cost and fuel burn benefit has been identified for HEPS architectures depending on aircraft class. The major conclusions from this study can be summarized as follows:

- High battery energy density, low engine specific thrust, low flight Mach, and low normalized cruise T/O thrust ratios are driving factors for reduction in fuel burn for HEPS.
- SMR test case: Redesigned HEPS provides 5.5% fuel burn benefit on 500 nm mission range with 750 Wh/kg battery energy density.
- SMR test case: Performing a multi-mission assessment shows the optimal HEPS design range to be 400 nm and the expected cumulative fuel burn benefit to be 3%. This configuration has a DOC penalty of 4.4% relative to baseline.
- Regional turboprop test case: The same method shows 3% DOC benefit for retrofit HEPS and 10% fuel burn benefit for redesigned HEPS.
- Redesigned HEPS favours take-off and climb power on-takes while retrofit HEPS favours cruise power on-takes.
- Change in objective function from fuel burn to DOC, switches the PMS trends from powering cruise to powering T/O and climb.

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Integrated hybrid engine cycle design and power management optimization

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