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Comprehensive Thermal Engine Modeling for Techno-Economic Aircraft Hybrid Electric Evaluation

INCOSE WSRC · 2025

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PUBLICATION DATE

July, 2026

SUBMISSION #

20

INCOSE PUBLICATIONS

COMPREHENSIVE THERMAL ENGINE MODELING FOR TECHNO-ECONOMIC AIRCRAFT HYBRID ELECTRIC EVALUATION

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Abstract

Proper techno-economic evaluation of hybrid electric powertrain commercial aircraft necessitates a holistic thermal engine model that captures the various behaviors contributing to the output of the overall study. This model needs to encompass not just the typical size, weight, and power characteristics, but also critical factors such as cost and reliability. This paper provides an overview of these essential characteristics and examines how their usage under actual application conditions can impact the results. By integrating these diverse aspects, the evaluation offers a comprehensive understanding of the performance and economic feasibility of hybrid electric powertrains in commercial aviation, thereby supporting informed decision-making and strategic planning for future technological advancements.

Keywords

Hybrid electric, engine modeling, techno-economic.

Introduction

Aviation has long been an area where worldwide forces and technology innovations have come together to drive fundamental changes within the industry. Some have argued that we are now in the "Third Era of Aviation" – the first being the original piston engine aircraft, the second being gas turbine powered aircraft, and the third being the introduction of Electrification to aircraft propulsion (Machinery Market, 2019).

There are several forces that are driving the innovation of this new era. The trends of population growth/urbanization and increased focus on sustainability and environmental issues have resulted in new and increasing demands on the aviation sector. Continuing commercial pressures on airlines cause challenges to airline profitability and motivation to provide affordable air service in many areas, particularly in the absence of government incentives and/or mandates.

The first major force is the growth in world population which, along with increasing affluence, result in the continuing growth of travel demand and aviation. World population has doubled in the last 50 years, with most of this growth (at least in absolute terms) occurring in Asia. Much of this growth has occurred in urban areas. While annual population growth rate has slowed in recent years, it has maintained at 1-2% for much of the latter 20th and early 21st centuries (Roser, Ritchie, & Ortiz-Ospina, 2019).

The growth rate of air travel, however, has exceeded that of the population at large. Air travel has grown at an annual rate of 4-5% over the last 25 years, and it is expected to continue at almost this rate for at least the next 25 (Graver, 2022), with Airbus predicting a large commercial aircraft sector growth rate of approximately 4.4% (Shulz, 2018). If you only focus on the regional aircraft market, ATR (ATR, 2022) projects an annual traffic growth rate of approximately 4.9%, greater than the overall commercial airline market.

This increased air traffic, however, comes at an environmental price, which is related to the second trend of environmental sustainability. While carbon emissions due to aviation have held steady at approximately 2.5% of overall carbon emissions worldwide, the absolute level of aviation carbon emissions has steadily increased and now stands at approximately 1 billion tons/year (Ritchie, 2020; DLR, 2020). This is despite an average yearly increase in aircraft fleet fuel efficiency of 1.3% in the years between 1960 and 2014 (Kharina, 2015). This carbon footprint has become more of a social issue in recent years, and "flight shaming" threatens to impact future airline growth, most pointedly in European and North American markets (Timperley, 2019).

The last trend driving change is the commercial pressure on airlines, impacting on the routes that they can profitably serve. Currently, 0.6% of US airports support over 70% of US domestic air travel (Antcliff & Borer, 2021), resulting in large numbers of locations that are not being served to their full potential. The number of US regional domestic routes has decreased by more than 30% since the year 2000 (ATR, 2022). The airline industry is intensely competitive, with very small (sometimes negative) margins between revenue and cost (Saxon & Weber, 2013).

In combination, these trends illustrate that aviation needs to become bigger (in terms of greater seat-km per year), cleaner (in terms of absolute greenhouse gases despite rising seat-km), and more economically attractive (in terms of $ per seat-km). This is a substantial, complex technological/economic problem that needs to be addressed through the application of advanced systems engineering approaches.

Background

A variety of aviation groups have studied these trends, and presented industry with a series of challenges, particularly around carbon emissions. Various stakeholders have started programs aimed at mitigating aviation's climate change impact, such as ACARE's Flightpath 2050 (European Com-mission, 2011). Comparable actions have been announced by IATA (IATA, 2009), ICAO (ICAO, 2016), and NASA (Drake, 2012), committing the commercial aviation industry to the ambitious goal of achieving "net-zero' carbon emissions by the year 2050 (van der Sman, 2021). One of these groups, the Air Transport Action Group (ATAG), has published a widely cited study (ATAG, 2021) of projected aviation carbon emissions with no changes, as well as anticipated effects from various technology and operational improvements as illustrated in Figure 1.

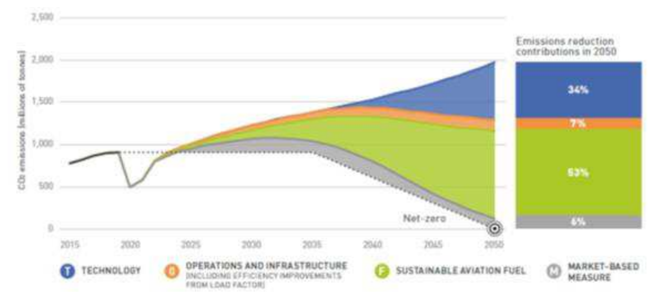

Figure 1. ATAG Carbon Emissions Projections (ATAG, 2021)

Hybrid electric aircraft have been widely studied as one of the referenced technology advancements, with the promise of significant reduction in fuel burn, energy consumption and CO_2 emissions compared to a conventional aircraft. The studies and methodologies presented to date (Bradley & Droney, 2015; Cinar, et al., 2018, 2019; Antcliff, et al., 2016; Fornaro, et al., 2022; Plötner, et al., 2022; Hoelzen, et. al., 2018; Scholz, et al., 2021; Kavvalos, et al., 2021; Ribeiro, et al., 2021; Spierling & Lents, 2019), however, are not amenable to the regional aircraft de-sign/optimization/commercialization problem that would enable the future implementation of commercially viable sustainable aviation. Previous work has focused on pure aerodynamic performance, assessing attributes such as range, speed, climb rate, fuel burn, etc., has been performed for vehicles (either grossly smaller or larger) outside of the range of interest, or has only considered fuel and battery costs in their cost assessments. These attributes are important to determine gross technical viability of a given configuration, but do not address the economic attractiveness of a particular solution relative to existing legacy regional aircraft, which is of primary importance to the ultimate customer for this technology, the regional commercial airlines. This shortcoming highlights the need for a broader techno-economic analysis methodology to capture ultimate airline customer value.

Overall Techno-Economic Modeling Approach

The operating economics of commercial airline operations are complex and consist of multiple cost elements. Direct Operating Costs (DOC) as illustrated in Figure 2 is comprised of Cash Operating Costs (COC) which are expenses related to daily aircraft operation, and Cost of Ownership (COO) which accounts for the financial obligation of aircraft ownership or leasing.

Figure 2. Direct Operating Cost Elements

An example Direct Operating Cost (DOC) breakdown of a typical regional airline is also shown as Figure 3 below (Harish, et al., 2016).

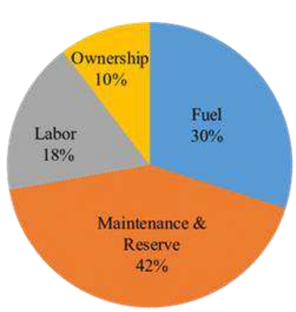

Figure 3. Typical Regional Aircraft Cost Breakdown

As this figure illustrates, fuel, crew, and maintenance costs are the largest cost drivers for daily operations. Fuel costs (either jet fuel or electricity) will be influenced by the amount of energy consumed on a given flight, and the relative costs of each energy type. Crew costs will be impacted by flight speeds and refueling/recharging times (how many flights can be completed in each crew shift) if those turn times increase beyond legacy aircraft. Maintenance costs will be driven by part/repair costs, reliability, and need for scheduled maintenance. Ownership costs will be impacted by the initial purchase price of the aircraft and its expected useful life. The remaining costs are largely independent of propulsion system configuration and can be considered as constant in this research activity.

The flowchart presented in Figure 4 illustrates the analysis framework used to determine quantitative measures for each of these elements of the DOC (illustrated in the orange boxes), as well as lifecycle emissions (gold box) since that is an important metric for some airline customers, as well as the broader society. As you can see on the left, data (blue boxes) is needed for the aircraft/powertrain, the usage profile of the aircraft, and the infrastructure capabilities of the applicable airports. Intermediate values are illustrated in the green boxes. The configuration of the aircraft and powertrain determine product cost and the associated COO. The aircraft and powertrain performance characteristics are combined to “fly the mission” and determine the resulting power demands, energy usage, and operating conditions, which impact energy costs, emissions, and component life/maintenance needs. Airport infrastructure impacts aircraft turnaround time and overall aircraft utilization (productivity).

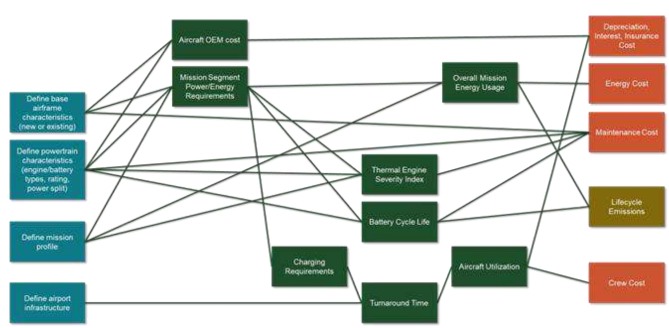

Figure 4. Techno-Economic Evaluation Flowchart with Dependencies

As airframers consider options for either new aircraft or the upgrade/retrofit of existing aircraft, the powertrain configuration will be one of the key points of evaluation. A diagram of a generic hybrid electric powertrain is illustrated in Figure 5. Note that this diagram illustrates a parallel hybrid configuration where multiple shaft power sources are combined to drive a single propellor. A similar configuration exists with individual propellors for each shaft power source, which still is comparable from a functional viewpoint. While each aircraft will not include all these elements, this illustration serves as a superset of the catalog of components that must be addressed to build an appropriate evaluation library.

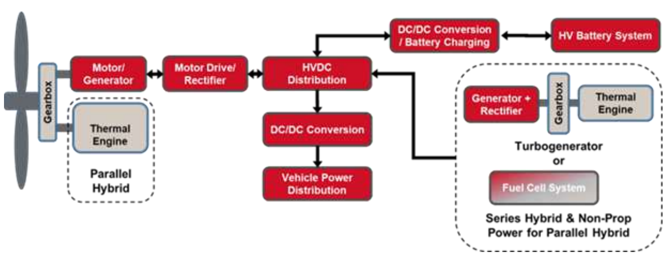

Figure 5. Generic Hybrid Powertrain Configuration

To properly include the powertrain in the higher-level overall evaluation structure, it is necessary to determine and characterize important hybrid electric configuration elements through empirical and physics-based models. Optimizing the system will require an understanding of how physical and performance characteristics of the key elements change as configurations and power ratings as modified as a part of that higher level optimization.

Thermal Engine Models

It is apparent that fuel burning thermal engines will form the heart of hybrid electric aircraft powertrain systems, and that being able to provide models for this engine type is a key to a successful aircraft level optimization methodology.

Modern turboprop aircraft in the 30-50 seat class have traditionally used gas turbine engines in the 1800-2800 SHP sea level static power range (Pratt & Whitney, 2024). For purposes of this work, the aperture was widened to include other engine types that, although they were previously discounted, may bring advantage when used in a hybrid electric configuration. Aircraft internal combustion engines may be either intermittent combustion (piston or rotary) or continuous (gas turbine types). Gas turbines generally exhibit higher specific power (particularly at sea level) but have higher specific fuel consumption (less efficient) as shown in Figure 6 below.

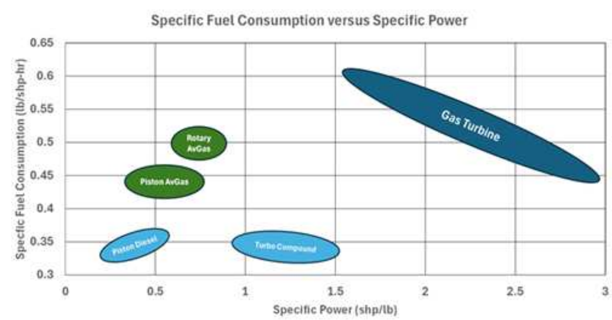

Figure 6. Comparative Performance of Various Aircraft Engine Types

The engine models created for this work include gas turbines and turbocompounded engines, as these engine types were both believed to have the performance needed by the applicable regional aircraft.

Gas Turbines

The gas turbine used for this modeling was the Pratt & Whitney Canada PW100 family. This is the most common engine used in this class of aircraft. Over its 40-year history, there have been 30 PW100 engine models certified, and 9,000 engines built to date. Today, there are close to 3,000 PW100-powered aircraft in service with over 600 operators in 128 countries and these engines have logged approximately 200 million flight hours (RTX, 2024). An external view of this engine is provided in Figure 7.

Figure 7. P&WC 100 Gas Turbine

Additionally, information was modelled for the PWC PT6 family of engines. More than 64,000 PT6 engines have been produced since its introduction in 1963, and it powers over 155 different aviation applications, with 500 million flying hours (Pratt & Whitney, 2023). This engine is slightly too small for this size regional aircraft, with a power rating up to 1,900 SHP (Pratt & Whitney, 2024), but it was modelled in case a variant of parallel hybrid could use an engine of that power class. This engine family includes three variants – "small", "medium" and "large". An external view of this engine is provided in Figure 8.

Figure 8. P&WC PT6 Gas Turbine

Specific Power. The specific power of a thermal engine is defined as the Takeoff Power at Sea Level Static (SLS) operating conditions divided by the engine mass. Depending on the particular engine design, the takeoff power limit could be due to either thermodynamic limits of the engine cycle, or mechanical limits of the propellor gearbox or airframe mounting structure. Pertinent details of a variety of PT6 and PW100 engines are included as Figure 9 below (Meier, 2021; Pratt & Whitney, 2024).

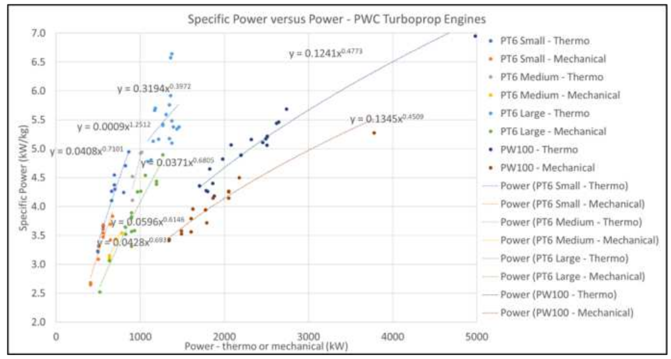

Figure 9. Specific Power versus SLS Power Rating

Thermal Efficiency. The second major thermal engine characteristic is its thermal efficiency. Engine datasheets typically express this characteristic as Brake Specific Fuel Consumption (BCFC), which is a measure of fuel mass consumed per unit power per unit time (kg/kW-hr). This parameter for operating at SLS ratings is provided in Figure 10 below and illustrated strong dependence on engine power rating (Meier, 2021).

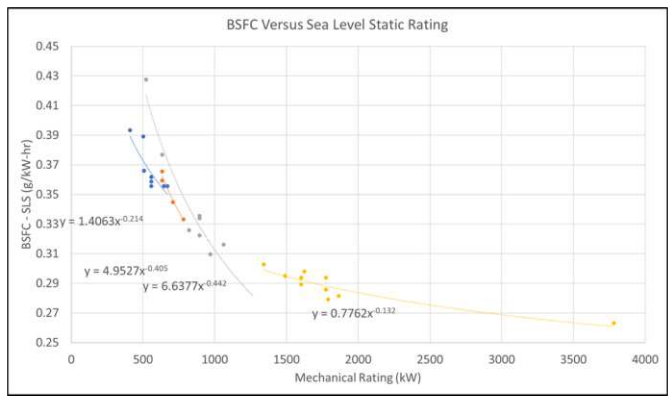

Figure 10. Brake Specific Fuel Consumption versus SLS Rating

Engine thermal efficiency, however, changes as the engine is operated at power ratings other than 100% power. As seen in Figure 11 below, thermal efficiency worsens as the engine is operated at less than 100% power levels (ATR, 2001).

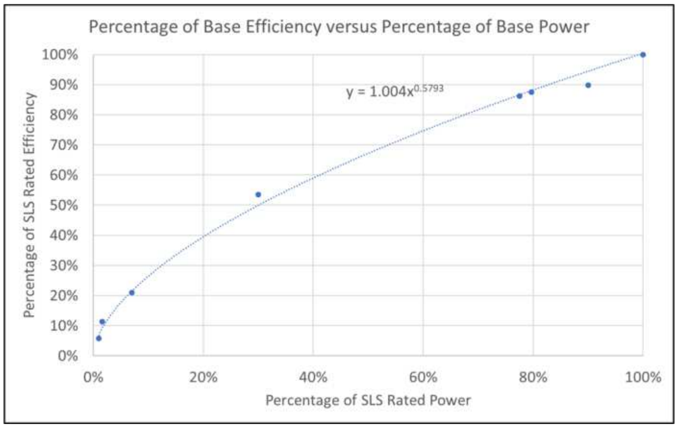

Figure 11. Thermal Efficiency at Varying Power Levels

Available Power During Flight. As the operating altitude increases, the air density decreases. Since the gas turbine engines of this power class operate with fixed geometry, this air density decrease results in reduced engine power. The density used for this altitude lapse calculation is the total stagnation air density, accounting for pressure, temperature, and aircraft speed effects. Additionally, consideration must be made for the varying operating conditions (takeoff, climb, cruise) and how that impacts the available engine power.

These considerations result in an available power equation (1) of the following form:

Power (Cl,Cr)=Power (SLS Thermo)*Derate (Cl,Cr)* 〚(ρ (Cl,Cr)/ρ (SLS))^(Density derate)〛^ (1)

PWC engine power charts from the ATR42-500 Flight Crew Operating Manual (Avions de Transport Regional, 1998) were used to determine the coefficients for this equation with the following results:

Table 1. Engine De-Rate / Lapse Rate Coefficients

Parameter	Value
Derate (Cl) - climb	0.92
Derate (Cr) - cruise	0.84
Density derate exponent	0.885

Product Cost. A key product attribute for any economic based analysis is the cost of the product. Data was collected from a wide number of sources (Forecast International, 2023; CFM International, 2017; Sasso, 2011; GE, n.d.) to understand how engine cost varies as a function of engine size (which impacts both material quantity and mechanical complexity).

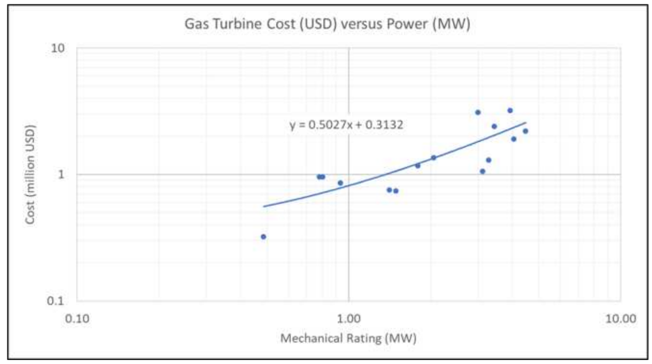

Figure 12. Gas Turbine Cost versus Power Rating

Maintenance Costs. Gas turbine engines have a maintenance schedule that is based on a combination of fixed hours/cycles (life limited parts) or on-condition monitoring (exhaust temperature margin or oil/bearing debris). For the PW120 engine family most used on mid-sized regional turboprops, the major maintenance events are hot section inspections (HSI), which occur roughly every 5,000 engine flight cycles, and overhauls, which occur every 15,000 cycles. Additionally, there is also typically one other shop visit for unscheduled maintenance within that 15,000-cycle interval (Aircraft Commerce, 2006). Collectively, the total cost of the material and labor or these maintenance actions is roughly equal to the initial purchase price of a new engine (Standard Aero, 2024), so that is the base value that is assumed for economic modeling, which is then further modified by the severity factor discussed in more detail in the next section. Equation (2) illustrates this relationship.

Cost (maintenance,per hr,modified)=Cost (maintenance,per hr,base)*Severity Factor (2)

Severity Factor. The durability of a gas turbine engine is strongly impacted by how the operator uses the engines. A gas turbine has many life drivers, which may be temperature based or cycle based. With this concept, the maintenance costs are estimated for a baseline operating case (typically 10% thrust derate, 2 hr flight cycle) and then those maintenance costs are ratioed up or down based on the actual expected usage. Most publicly available severity curves are based on turbofan engines instead of turboprop, but the failure mechanisms and behaviors were assumed to be the same between engine types (Ackert, 2010; Seemann, et al., 2011; Hanumanthan, 2009; Chiles, 2011). These sources were consolidated to create a generic surface fit for severity index based on thrust derate and flight length as shown in Figure 13. The equation related to that surface fit is given as:

Severity Factor=3.86+5.00x-2.53y+7.06x^2+0.73y^2-1.87xy+7.14x^3-0.072y^3+0.21xy^2-1.16x^2y (3)

where x = thrust derate

y = flight length (hrs)

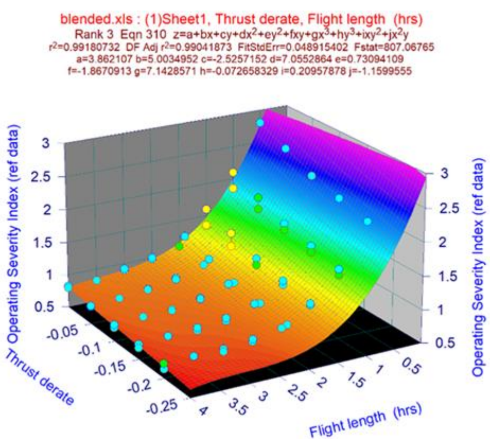

Figure 13. Gas Turbine Operating Severity Curve

Turbo-compounded Engines

A compounded engine is an arrangement that combines two or more power producing units into a single integrated power plant. As has been applied to aircraft engines, this takes the form of a com-bination of an internal combustion engine (either reciprocating or rotary) with a compressor/turbine (turbo) assembly. This arrangement combines the airflow capacity and light-weight pressure rise features of a gas turbine with the highly efficient, although heavier, diesel. A schematic diagram of this engine concept is illustrated in Figure 14 below (Aviation Week, 1954).

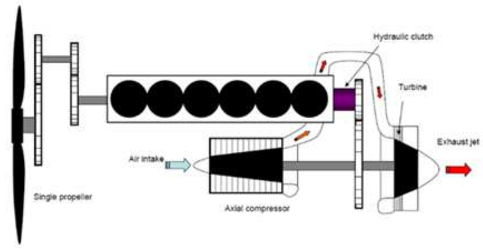

Figure 14. Turbo Compound Engine Schematic

A key feature of this approach, as compared to a traditional turbocharged engine, is that the com-pressor/turbine assembly is mechanically coupled to the internal combustion engine, allowing excess mechanical power that is harvested by the turbine to contribute to the total mechanical power output of the overall powerplant. While the exact power ratios vary slightly between designs and operating conditions, the internal combustion engine provides 70-80% of the total shaft power, while the compressor/turbine provides the remaining 20-30% (Aviation Week, 1954).

Turbocompounded engines were first researched during World War 2 as a potential method to increase the power levels and efficiency of piston engine aircraft. At that time, the Wright Aeronautical Division of Curtiss-Wright in the United States and D. Napier & Son Limited in the United Kingdom were leaders in this technology (Aviation Week, 1954; Curtiss-Wright Corporation, 1956). Tur-bo-compounded engines saw both military and commercial usage in the 1950's but became obsolete with the increased performance of gas turbine based powerplants, coupled with the low cost of fuel at the time and the drive toward faster speeds. Turbocompounded technology stagnated while gas turbines flourished, although in recent years, interest has revived in this type of powerplant due to its superior fuel efficiency.

<u>Wright Turbo-Cyclone 18R-3350-TC Radial Engine</u>

The most commercially successful example of a Turbocompounded engine has been the Wright Turbo-Cyclone 18R-3350-TC. Studies began on this engine in 1942, resulting in a demonstration engine in 1946, and entering series production in 1950 (Curtiss-Wright Corporation, 1956). Throughout its

10-year production history, approximately 16,000 of these engines were produced in various models for both military and commercial use (Kuhns, n.d.). This engine was an 18-cylinder radial piston engine configuration, displacing 3,350 cubic inches (54.9 L), and used three power recovery turbines, each being fed by 6 cylinders (National Air and Space Museum, n.d.; Wiegand & Eichberg, 1954). The overall engine can be seen in Figure 15 below.

Figure 15. Wright Turbo-Cyclone 18R-3350-TC Radial Engine

Napier Nomad 2

A different approach to turbocompounding was pursued by D. Napier and Son Limited in the United Kingdom. This engine was based on a two-stroke diesel cycle, with the engine having a horizontally opposed cylinder configuration. While this engine only reached the flight demonstration stage and never entered production, it was considered the most fuel-efficient aircraft engine ever built and the peak of piston engine development (Gunston, 1954; Sammons & Chatterton, 1955). This engine was a 12-cylinder horizontally opposed piston engine configuration, displacing 2,505 cubic inches (41.1 L), and used a single power recovery turbine (Gunston, 1954). Both external and cutaway views of the engine can be seen in Figure 16 below.

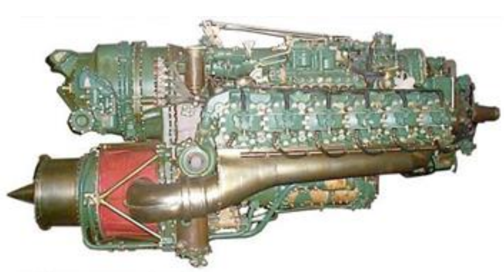

Figure 16. Napier Nomad 2

Modern Study Engines

In the early 1980's, the oil crisis and subsequent rise in jet fuel prices reinvigorated interest in more fuel-efficient aircraft engine technologies. NASA sponsored design investigations with the Garrett Turbine Engine Company as well as Teledyne Continental Motors for engines in the 1,000 to 2,000 horsepower class. These engines are both piston diesel cycles, with displacements between 200 and 800 cubic inches (Bobula, 1986; Bromers, 1981). Drawings of the Garrett concept engine is provided as Figure 17 below.

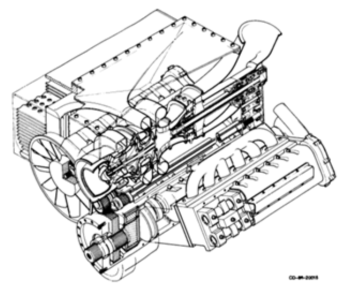

Figure 17. Garrett Turbocompound Concepts

High level performance data was gathered for each of the referenced engines and plotted as Figure 18 below. The more modern study engines show both Specific Power and Brake Specific Fuel Consumption (BSCF) that is superior to the engines from the 1950's, although whether that is due to better materials and analytical methods or estimates prior to potential development weight growth is un-known.

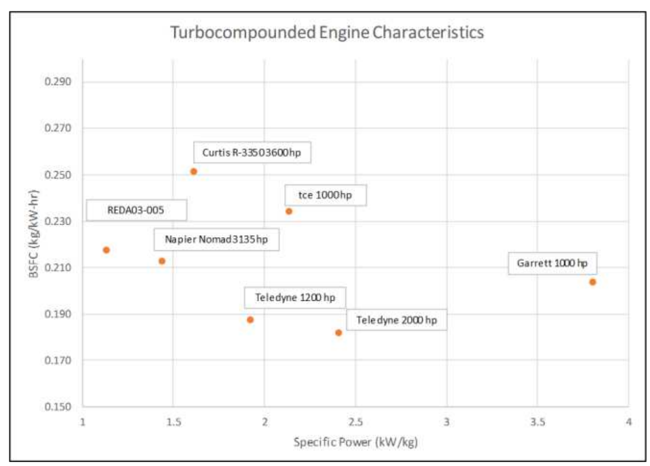

Figure 18. Turbocompound Engine Characteristics

The following sections address the model characteristics for the turbocompounded engine for a variety of measures of interest.

Specific Power. The specific power of the Turbocompounded engine as a function of takeoff power is illustrated in Figure 19 below. These data are for standard day, sea level static operating conditions. The specific power is significantly less than a gas turbine of comparable takeoff power rating, but difference in the lapse rate behavior with altitude (discusses below) results in both engine types having comparable specific power at cruising altitudes.

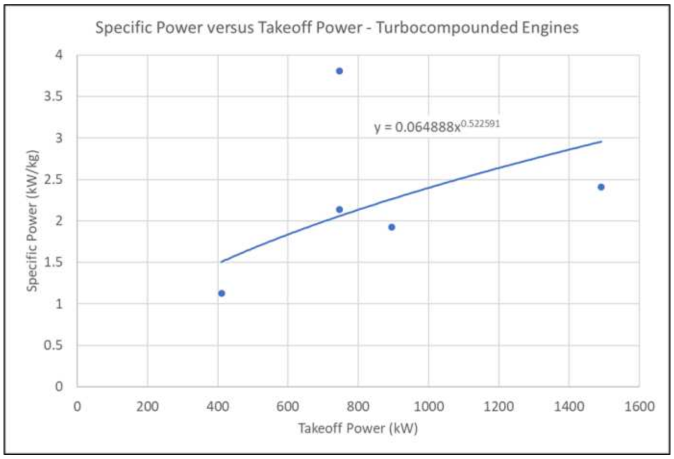

Figure 19. Turbocompounded Engine Specific Power vs Takeoff Power

Altitude Power Lapse. The previous data for a traditional gas turbine engine revealed that the engine power decreased with increasing altitude. The turbocompounded engine, however, does not reveal this same behavior, due to the ability to independently control the speed of the compressor/turbine with the variable ratio transmission. This results in a constant manifold pressure to the internal combustion engine that is independent of altitude, resulting in a constant power level. This behavior is illustrated in the power curve for a Napier Nomad (Gunston, 1954) as shown in Figure 20. Limitations of antiquated control systems resulted in a slight increase in available power with altitude, but for purposes of this analysis the behavior was assumed to be altitude independent.

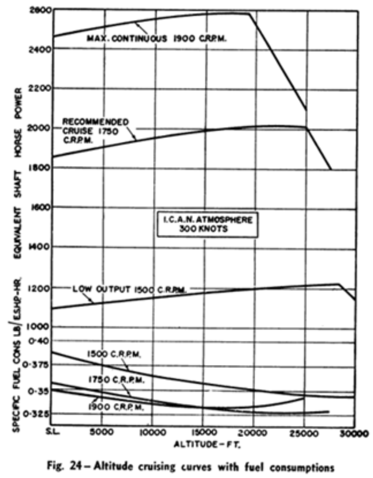

Figure 20. Turbocompounded Engine Power and BSCF vs Altitude

Thermal Efficiency. A low BSFC compared to small gas turbine engines is a known advantage of the turbocompounded engine cycle. The rated power thermal efficiency versus takeoff power levels is provided as Figure 21.

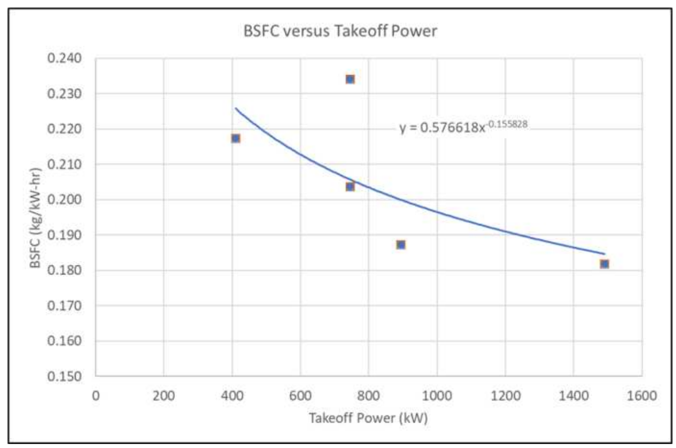

Figure 21. Rated Power BSCF vs Takeoff Power

As the engine operates at part throttle condition, however, the thermal efficiency drops, with slightly different behaviors at sea level versus at altitude. This behavior is provided as Figure 22.

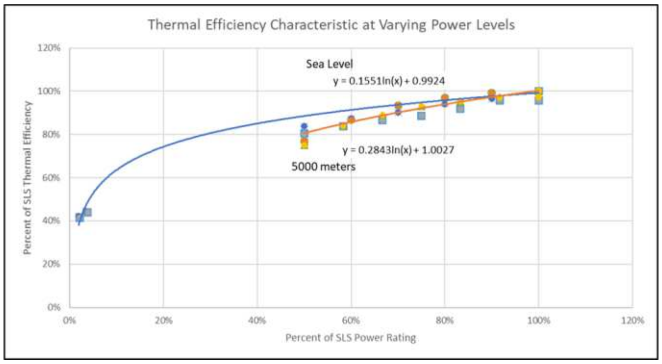

Figure 22. Thermal Efficiency at Varying Power Levels

Product Cost. Production costs of high power turbocompounded engines are difficult to determine since the only high-volume example (Wright 3350) was last produced in the 1950's. In 1957, the production cost of this engine was $88,000 (approximately $997,000 in 2025 dollars) (Kuhns, n.d.).

To provide a more modern comparison of costs for this engine type, a survey was performed on a variety of lower powered aircraft turbocharged diesel engines from manufacturers such as Lycoming (Air Power Inc., n.d.) and Raikhlin Aircraft Engine Developments (RED Aircraft) (AVweb, 2019). The resulting relationship between engine cost and takeoff power is provided in Figure 23.

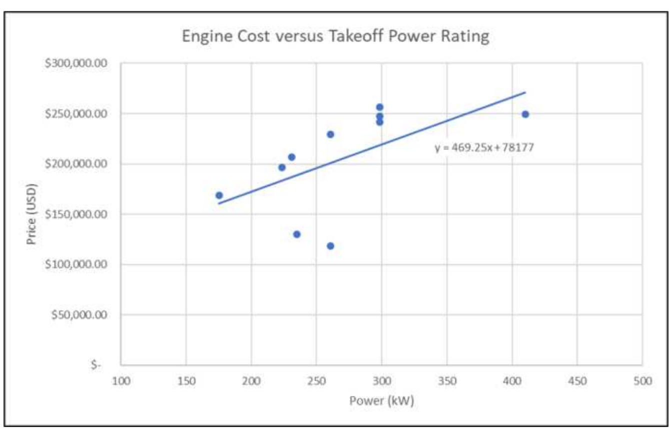

Figure 23. Turbocompounded Engine Cost versus Takeoff Power

Maintenance Costs. The Wright Turbo-Cyclone 18R-3350-TC engine achieved time between overhauls of approximately 4,000 hours in commercial airline service (Curtiss-Wright Corporation, 1956). Aviation piston engines accrue a maintenance cost (including overhaul costs) of approximately 2/3 the cost of a new engine over that 4,000-hour service interval (Air Power Inc., n.d.). This base hourly maintenance cost is also modified per the applicable severity factor that was earlier described as Equation (2).

Severity Factor. Since engines variants of this type were either in commercial service 75 years ago in the case of the Wright or were never put into commercial service in the case of the others, an extensive modern basis for predicting the severity factor for this engine type is not available. However, these engines are expected to follow that same general behavior as gas turbines, so for purposes of this study, the same ratio approach (eq. 2) and equation (eq. 3) were used.

Example Use Case

These thermal engine characteristics were used as a part of study comparing a ATR42 aircraft using both conventional and hybrid electric options. The conventional aircraft used the existing PW 127 gas turbine, while the hybrid aircraft used a combination of a turbocompounded engine plus a parallel battery fed electric powertrain. Results of this study for a 300 nm (555km) mission are provided in Table 2 below:

Table 2. 300 nm ATR42 Mission Study

Parameter	Gas Turbine	TurboCompound Hybrid
Mission Length (km)	555	555
OEW minus powertrain (kg)	10300	10300
Complete Powertrain Weight (including battery) (kg)	954	2412
Fuel Engine (kg)	954	945
Takeoff Weight (kg)	17953	18590
Thermal Engine Thermo Rating (kW)	2457	1300
Thermal Engine Mechanical Rating (kW)	1790	1300
Electric Motor Rating (kW)		650
Installed Battery Energy (kW-hr)		250
Battery Chemistry		NMC811
Fuel Type	Jet A	Jet A
Operating Country	China	China
Average Thrust De-rate	-20%	-10%
Battery Depth of Discharge - normal		68%
Battery Depth of Discharge - reserve		68%
Total Fuel (kg)	956.3	490.3
Total Electricity (kW-hr)	0.0	169.1
Mission Energy Cost (USD)	$726.79	$387.31
New Aircraft Cost (USD)	$21,370,195	$19,967,584
New Complete Powertrain Cost (including battery)	$3,096,718	$1,694,107
New Fuel Engine Cost	$3,096,668	$1,376,534
Mission Fuel Engines Only DMC (USD)	$411	$416
Mission Powertrain DMC (USD)	$411	$499
Full Aircraft DOC per Block Hour (USD)	$2,746	$2,478
Costs per Available Seat Kilometer	$0.124	$0.112
Emissions per Available Seat Kilometer (kg)	0.1423	0.0767

The configuration differences and resulting attributes between the conventional and hybrid aircraft are significant. The hybrid configuration uses a thermal engine approximately 2/3 the power rating of the baseline gas turbine powered aircraft, but that smaller engine is almost the same mass as the larger gas turbine. In addition, the added electrical motors and battery add significant powertrain mass to the aircraft. This results in the hybrid aircraft being at the aircraft MTOW limit when only carrying sufficient fuel for a 300 nm mission (plus necessary reserves) with a full passenger load, while the conventional aircraft still has weight margin for additional fuel and longer range while maintaining full passenger count capability.

Performance, however, shows a clear advantage to the hybrid propulsion system. Jet A consumption is almost halved, while overall energy consumption drops by almost 30%. Overall CO_2 emissions, including those created through electricity generation and battery manufacture, drop by 45%. Aircraft acquisition costs are lower for the hybrid configuration, primarily due to the significantly lower costs of the turbocompound engine compared to the gas turbine, while direct maintenance costs increase due to lower engine lives and required battery replacements. Overall Direct Operating Costs per Block Hour are approximately 10% lower for the hybrid configuration when all factors are considered.

Conclusions

In conclusion, this paper provides a comprehensive structure and specific numeric values essential for modeling turboprop engines within higher-level aircraft techno-economic analyses. Unlike traditional engine models that primarily emphasize specific power and efficiency, this approach includes a methodology to quantify the impact of varying thermal engine operating conditions—introduced by different hybrid configurations—on engine life and maintenance costs. It addresses the characteristics of both gas turbine and turbocompounded piston engine configurations. As the aviation industry progresses towards sustainability, these holistic analyses become crucial for harnessing the full potential of hybrid electric aircraft, supporting the industry's strategic planning and decision-making processes. The use case example provides a concrete illustration of how the various characteristics of the thermal engine types result in widely varying results for the numerous parameters of interest.

Recommendations

A key assumption of this work is that electrification of the thermal engine results solely in the resizing of the engine, without altering the thermodynamic cycle or internal configuration. This assumption may limit the model's ability to capture additional performance improvements achievable through hybridization. Modern engines are required to function across a broad spectrum of steady state and transient conditions, necessitating compromises in parameters such as surge margins, internal clearances, and cooling strategies. Employing electric augmentation in specific operating areas could enable further optimization of the engine for enhanced overall mission performance. These optimizations could translate into either improved fuel efficiency or reduced maintenance costs. En-gaging more deeply with turbine engine designers would provide better insights into the feasibility and potential scale of these performance enhancements.

Acknowledgements

The authors would like to thank Colorado State University and Collins Aerospace for providing inspiration for the research problem statement, and support for the execution and presentation of this work.

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