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Review

Integrated Power and Thermal Management Systems for Civil Aircraft: Review, Challenges, and Future Opportunities

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Abstract: Projects related to green aviation designed to achieve fuel savings and emission reductions are increasingly being established in response to growing concerns over climate change. Within the aviation industry, there is a growing trend towards the electrification of aircraft, with more-electric aircraft (MEA) and all-electric aircraft (AEA) being proposed. However, increasing electrification causes challenges with conventional thermal management system (TMS) and power management system (PMS) designs in aircraft. As a result, the integrated power and thermal management system (IPTMS) has been developed for energy-optimised aircraft projects. This review paper aims to review recent IPTMS progress and explore potential design solutions for civil aircraft. Firstly, the paper reviews the IPTMS in electrified propulsion aircraft (EPA), presenting the architectures and challenges of the propulsion systems, the TMS cooling strategies, and the power management optimisation. Then, several research topics in IPTMS are reviewed in detail: architecture design, power management optimisation, modelling, and analysis method development. Through the review of state-of-the-art IPTMS research, the challenges and future opportunities and requirements of IPTMS design are discussed. Based on the discussions, two potential solutions for IPTMS to address the challenges of civil EPA are proposed, including the combination of architecture design and power management optimisation and the combination of modelling and analysis methods.

Keywords: integrated thermal and power management systems; thermal management systems; power management systems; more-electric aircraft; energy-optimised aircraft

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1. Introduction

Aircraft engines generate greenhouse gases, such as carbon dioxide (CO_2) and nitrogen oxides (NO_x) [1]. The aviation industry was responsible for about 3% of global CO_2 emissions in 2019, and the CO_2 emissions could increase 2.5 times from 2015 to 2050 without rapid technological advancements and stronger policies [2]. Global and regional organisations have focused on these challenges. The United Nations has stated goals to combat climate change [3]. In the USA, NASA proposed a strategic implementation plan to reduce NO_x emissions by 80%, fuel consumption by 80%, and noise by 42 dB by 2035 [4]. In Europe, the Advisory Council for Aeronautics Research in Europe (ACARE) has set targets under the 'Fly the Green Deal' initiative to reduce net CO_2 emissions by 55% compared to the 1990 baseline and to achieve net-zero CO_2 emissions by 2050 [5]. If an aircraft is more electric, it requires less carbon-based fuel, potentially resulting in less CO_2 and NO_x emissions, high efficiency and reliability, and less noise [6]. As a result, there is a growing trend toward the electrification of aircraft with the proposed more-electric aircraft (MEA) and all-electric aircraft (AEA).

In conventional aircraft, an engine provides four main types of power: (1) mechanical, (2) hydraulic, (3) pneumatic, and (4) electric. These types of power are used for critical components in conventional aircraft systems, including pumps (hydraulic/mechanical), actuation systems (pneumatic), environmental control systems (ECSs) (pneumatic), wing ice protection systems (WIPS) (pneumatic), and avionics (electric). The aim of MEA/AEA is to reduce and ultimately eliminate all but electric power in aircraft. The B787, a civil MEA, for the first time eliminates the use of bleed air, implementing electric power for WIPS instead of pneumatic [7,8]. However, its propulsive power is still not electric. In an AEA, not only is the power of aircraft systems electric, but the propulsive power is also provided by electrochemical energy units such as batteries and fuel cells. Compared to MEA, AEA have lower operating costs and no emissions because all forms of power are electric.

MEA/AEA have obvious advantages, but the increasing use of electric power also brings more challenges. For military aircraft, the use of electrified subsystems such as ECSs, avionics, weapons, and actuators, as well as associated heat losses, has risen substantially [9,10], dramatically increasing the demand for heat sinks [11]. However, the limited heat sinks in military aircraft result in technical obstacles for an aircraft's thermal management system (TMS). In civil aircraft, not only is more and more of the power of subsystems electric, but the propulsion of aircraft is also increasingly electrified, with a trend toward hybrid-electric aircraft (HEA) and AEA. This growing use of electric power in civil aircraft also causes thermal challenges for airframe materials and heat sink capacity. The highly electrified subsystems increase thermal requirements and result in challenges for the power management system (PMS). In an aircraft, the PMS needs to provide enough power for both cooling and critical electric components. Particularly for electrified propulsion aircraft (EPA), such as HEA and AEA, it is necessary to split the power to provide both cooling power and propulsive power. These complicated interactions between the TMS and PMS therefore imply that the development of energy management in only one energy domain (thermal or power) would make it hard to optimise energy consumptions for future MEA/AEA.

How to manage electric and thermal energies has become a critical question for researchers to minimise the challenges offsetting the benefits offered by EPA. As a result, a novel aircraft energy management approach was proposed, which is the integrated power and thermal management system (IPTMS). Many institutions, such as Honeywell, the European Space Agency, and the United States Air Force, have focused on energy-optimised aircraft projects and developed IPTMSs for advanced thermal energy design. The United Kingdom's Aerospace Technology Institute (ATI) has listed novel thermal management systems for EPA as their priority study strategy [12]. It is highly likely that an IPTMS is a big step toward MEA/AEA and will play a more important role in energy management for aircraft [13].

There are published papers that have reviewed relevant fields of TMSs or PMSs, but there are limited sources in the public domain on the integrated system of a PMS and TMS. The authors in [14] reviewed the growing challenges of TMSs for military and civil aircraft due to increasing electrification and discussed future opportunities and potential solutions based on a simple classification of TMS factors and research topics. This article primarily focuses on the TMS for conventional aircraft and did not explore more details of an IPTMS for civil electrical propulsion aircraft. In [15], the authors review the TMS developments for HEA. They focused on different TMS architectures for the key components in electrical propulsion system to investigate an optimised TMS architecture under different operating conditions. Furthermore, a comprehensive review of the TMS challenges for hybrid-electric aircraft is presented in [16]. They investigated the challenges and solutions for the TMS components and subsystems to identify the future opportunities at the component level. The authors in [17] reviewed the architectures, control system design, and energy management strategies for electric propulsion systems to reduce fuel burn and emissions and presented an overview of future trends in aviation electrification. While the authors presented a wide literature review of energy management strategies, they did not review the strategies for managing energy flows in thermal and power domains.

Previous research has explored thermal and power management for Electrical Propulsion Aircraft (EPA), yet a gap exists in the literature regarding various types of IPTMS research for potential solutions in civil EPA. This paper aims to address this gap by reviewing recent IPTMS progress and exploring potential design solutions for civil aircraft. The paper is organised as follows. Section 2 presents the IPTMS in EPA, introducing the architectures and challenges of EPA, TMS cooling strategies, and power management optimisation approaches. Section 3 focuses on the architecture design of an IPTMS in two domains: (1) an IPTMS with energy recovery and (2) an IPTMS with an advanced electrical propulsion system (EPS) and TMS. Section 4 describes the power management (PM) design of the IPTMS. Sections 5 and 6 present the modelling and analysis methods of the IPTMS. Section 7 discusses the challenges and future opportunities of IPTMS, suggesting the requirements for future IPTMS design. Finally, the conclusion is presented in Section 8.

2. Integrated Power and Thermal Management in Electrified Propulsion Aircraft

2.1. Integrated Power and Thermal Management System

Integrated Power and Thermal Management (IPTMS) is a system/approach to manage the energy flows in two domains: (1) electric and (2) thermal. In simple terms, it can be assumed as an integration of a TMS and PMS. When it plays the role of TMS, it rejects heat from heat sources to ensure that components operate at their operating temperatures to avoid degradation. On the other hand, when it contributes to power management (PM), it allocates and balances the power to minimise it while providing sufficient power to critical power loads for safety [18].

The IPTMS has been widely researched and has different labels in different papers, such as power and thermal management system (PTMS), electro-thermal management system, energy–thermal management system, etc. In this paper, IPTMS is selected as it implies an integrated system to manage electric and thermal energies.

2.2. Electrified Propulsion Aircraft

The definition of degree of hybridisation (DoH) developed by Isikveren et al. [19] helps to categorise the types of aircraft (shown in Table 1) as follows:

- DoH for power (H_P)
    - ○ $H_P = \frac{P_{motor}}{P_{tot}}$
    - ○ $P_{tot} = P_{motor} + P_{engine}$
- DoH for energy (H_E)
    - ○ $H_E = \frac{E_{bat}}{E_{tot}}$
    - ○ $E_{tot} = E_{battery} + E_{engine}$

where P_{motor} = power of motor, P_{engine} = power of engine, P_{tot} = aircraft total power, $E_{battery}$ = energy of battery, E_{engine} = energy of engine, and E_{tot} = aircraft total energy.

Table 1. Classification of aircraft.

Aircraft Type	DoH for Power	DoH for Energy
Conventional aircraft	0	0
Series HEA	1	<1
Turboelectric	>0	0
Parallel HEA	<1	<1
AEA	1	1

Based on the DoH, the aircraft propulsion system can be electrified using motors ($H_P > 1$) and without a battery (e.g., turboelectric aircraft). Figure 1 shows the simplified schematic of the propulsion system for EPA. Readers can refer to [20–23] for more information on electrified aircraft propulsion.

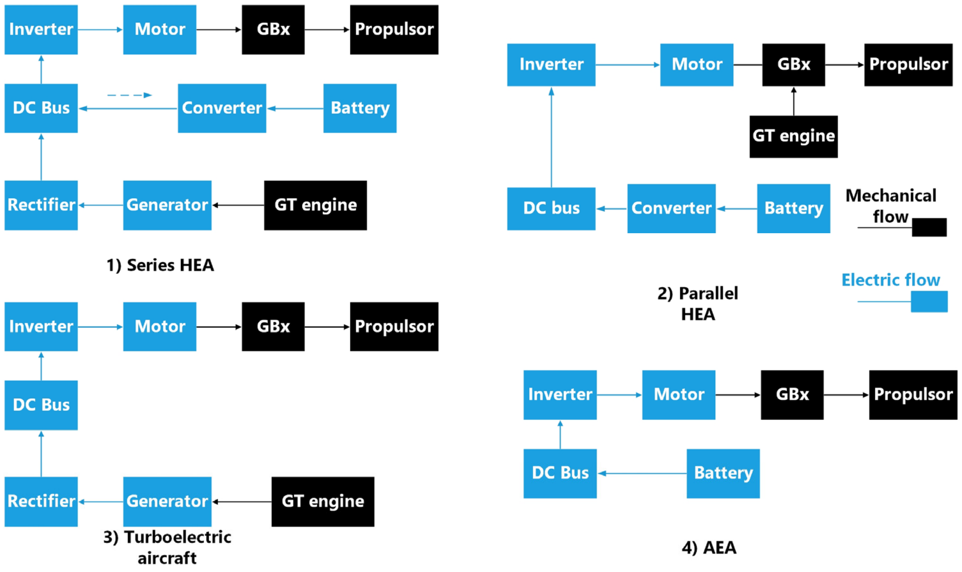

Figure 1. Simplified schematic of the propulsion system of EPA (adapted from [22]) (DC: direct current, GBx: power gearbox, and GT: gas turbine).

Generally, as Figure 1 shows, an electrical propulsion system (EPS) consists of electric machines (motors or generators), power distribution systems (DC or AC bus), and converters (rectifiers, inverters, or DC/DC converter). The motors have four main types of loss [24]: (1) ohmic losses, (2) core losses, (3) windage losses, and (4) other losses. The other losses are usually assumed to be constant as they are independent on the motor torque or rotational speed. Assuming the loss coefficients remain the same, the ohmic losses are dependent on the motor's torque, while the core losses and the windage losses are dependent on the motor's rotational speed. In this case, when the rotational speeds of the aircraft's propulsors are constant, the heat from the motors might not be reduced significantly even under low-power conditions, which increases the requirements of the TMS. Additionally, with the advancement of motor technology, motors are becoming smaller and lighter. However, a smaller size can limit the size of the motor's cold plate. Even though the efficiency of the motor may improve, under high-power conditions, the heat flux of the motor could increase, introducing challenges for the TMS. For the power distribution systems, the higher the system voltage, the less heat from the bus is generated. However, the higher system voltage might require a bigger size of battery or generator, which requires trade-off studies between the EPS and the TMS designs. Compared with other electrical components, the range of the operating temperature of the battery is narrower, usually within 15–45 °C [25]. While ensuring the battery temperature does not exceed the maximum temperature, an active temperature control might be required under low-temperature conditions to ensure the temperature is above the minimum temperature. Furthermore, the battery's state of charge should be above the minimum state of charge to prevent damage. Therefore, the IPTMS design should consider the power and thermal requirements of the battery.

For series and parallel HEA, the battery power output can be determined by determining the DoH, or by determining the power of the gas turbine engines. For example, the DoH for each flight phase is determined, and then the battery is sized. Alternatively, the maximum power output of the gas turbine engines is determined so that during the take-off flight segment, the supplementary power is provided by the battery. Additionally, at the end of the mission (i.e., during the descent or landing flight phase), the battery could also provide power, or it could be charged by the engine-driven generators to save energy. For AEA, all the power, such as for cooling, propulsion, emergency, etc., are provided by the battery. The battery is sized to ensure that the power requirements are satisfied, and it is necessary to ensure that the battery's state of charge is above its minimum state of charge to prevent damage. For turboelectric aircraft, the engines drive the generators to provide power. The power is distributed to several motors, which then provide propulsion. Similar to AEA, all the electric power comes from the turboelectric aircraft's turbogenerator which is the assembly of the engine and the generator. Additionally, the turbogenerator can also provide propulsive power through the gas turbine engine, so trade-off studies or optimisation strategies are required to balance the electric power and the propulsive power from the engines to minimise fuel consumption. Overall, to guarantee the green and sustainable nature of EPA, trade-off studies, optimisation strategies, implementation of high-efficiency electrical components, and so on are required. Additionally, battery power supply strategies can optimise energy use and maintain batteries, thereby extending battery life. The handling of expired batteries, such as through recycling or reuse, is related to battery technologies or relevant component-level studies, which are outside the scope of this paper.

2.3. Thermal Management System

In TMS, three key elements should be considered: heat acquisition, heat transport, and heat rejection [26]. TMS absorbs the heat from heat sources (heat acquisition) and then transfers the heat to coolants. Finally, through the coolants of cooling loops (heat transport), the heat is rejected to terminal heat sinks (heat rejection).

As discussed in Section 2.2, because of additive electric components, the considerations of TMS for conventional aircraft and electrical propulsion aircraft (EPA) are different. The TMS design of a conventional aircraft typically does not consider turbine blade cooling and relevant mechanisms [27]. Therefore, the heat loads considered by the TMS for a conventional aircraft include accessory gearboxes, engine gearboxes, engine-driven generators, bearings of shafts, oil pumps, etc., [27–29]. Compared with conventional aircraft, the additive heat loads of EPA involve converters (including inverters and rectifiers), batteries, electric bus/feeders, motors, and generators. These additive heat loads cause challenges for system weight, efficiency, power management, and thermal management.

Generally, there are three active TMS cooling strategies to transfer heat: (1) air cooling, (2) liquid cooling, and (3) vapour cycle system (VCS)/phase-change cooling. The most common method of cooling is air cooling, which is mature and widely used in civil aircraft [30]. Many coolants for liquid cooling have been studied, including the coolants that have been applied in aircraft such as fuel, oil, water/glycol mixture, polyalphaolephin (PAO), etc. [31], as well as coolants for potential application in aircraft such as supercritical carbon dioxide (sCO_2), therminol fluids, etc. [32–35]. Compared with air cooling and liquid cooling, the coolants of VCS cooling are two-phase. Because of the phase-change coolants, VCS cooling has better efficiency but is heavier and less commercially matured [36,37]. Active air cooling is usually the lightest, because it is open-loop and does not require heat exchangers, coolant pumps, and tanks. However, under high-heat-load conditions, the ram air drag, the weight, and the power due to the air-cooling fan could be considerable. In this case, air cooling is no longer suitable. In terms of liquid cooling, the IPTMS design should consider the coolant performance in thermal and power domains. When a water/glycol mixture is selected as the coolant, the use of propylene glycol can increase the freezing point of the coolant but can increase the viscosity of the coolant, which causes more cooling power for overcoming the pressure drop. Additionally, the IPTMS design should consider how different coolants impact the system weight, power requirements, and induced drag under high- and low-temperature conditions. As three active TMS cooling strategies have their pros and cons, the IPTMS design should compare their performance at the system level and obtain the optimal strategy.

The heat sinks for aircraft typically involve fuel and bleed/ram air. Using fuel as the terminal heat sink for an aircraft can improve its engine efficiency as the fuel is preheated. Additionally, unlike other coolants, the coolant of fuel does not require additive components (e.g., coolant pumps and tanks). However, one should be careful that the fuel is not overheated and that the flow rate of fuel is sufficient for heat transfer. This is why HEA usually use ram air as the terminal heat sink instead of fuel. The heat sink of air is low-cost, simple, and effective [33,35], but it induces drag [36,38].

Passive cooling can be implemented in a TMS. Compared with active cooling, passive cooling does not require any power for cooling. Generally, the passive cooling could include natural air convection, radiation, a heat acquisition technique [39,40], and aircraft skin heat exchangers [41–44]. Although natural air convection is less suitable for high-temperature heat loads [30,45], under low-temperature conditions, such as high-altitude, low-power, or cold-day conditions, the air's natural convection and radiation are potentially sufficient for cooling. The natural air convection and radiation are related to the volume of the component and the spacing between the heat sources. The bigger the component's volume, the larger the heat transfer area for natural air convection and radiation. At the same time, the bigger volume causes heavier weight and challenges in installation. In this case, it is necessary to assess the components' performance accurately to investigate the performance of natural air convection and radiation under the aircraft's operation conditions. Additionally, the design parameters, such as the design power of the motor and the design capacity of the battery, would also affect the passive cooling performance. These design parameters depend on the power requirements for propulsion and cooling, so the IPTMS design requires trade-off studies between component sizing and passive TMS performance. For HEA, the motors and generators are usually installed next to the gas turbine engines so that the natural air convection and radiation cannot be implemented for those components due to their limited spacing. Additionally, the battery might need active temperature control to ensure its temperature is above the minimum temperature to prevent damage. Therefore, the benefits of the natural air convection and radiation might have less positive impact. One of the challenges for skin heat exchanger applications is the heat transport from the heat sources to the heat sinks. If the coolant absorbs the heat and directly transfers the heat to the aircraft skin, this passive cooling method might consume more fuel than implementing a traditional active TMS [44]. The reason for this is that the pumps still actively operate to distribute the fluid, which requires more power, causing heavier pumps. This challenge leads to a need for an aircraft outer mould line cooling technique. In this case, the heat from the component is transferred to the outer mould line. The outer mould line distributes the heat to the skin heat exchanger, and the heat is finally rejected to the ambient air. To sufficiently cool the components, the outer mould line cooling could induce weight penalty.

2.4. Power Management Optimisation

Figure 2 shows a control architecture for EPA. The control for EPA is generally recognised as two levels: supervisory control and component control [46]. The EPA has a supervisory controller to manage the commands for the conventional and the electrified propulsion systems. Usually, in some papers, "control system design" or "controller design" refers to the component (lower)-level design, and the supervisor control approach refers to "power (energy) management strategy". In the IPTMS, based on the thermal requirements, the TMS components, such as the coolant pumps and the cooling fans, require power for cooling, which can be provided by the engine-driven generators or the battery. In the electrical propulsion system, the battery needs to provide power for the motors to drive propulsors. In this case, the supervisory controller should balance the energy flows, satisfying the power and thermal requirements, and obtain an optimal solution to minimise the energy consumption. Therefore, the power management optimisation strategies are researched for the supervisory controller.

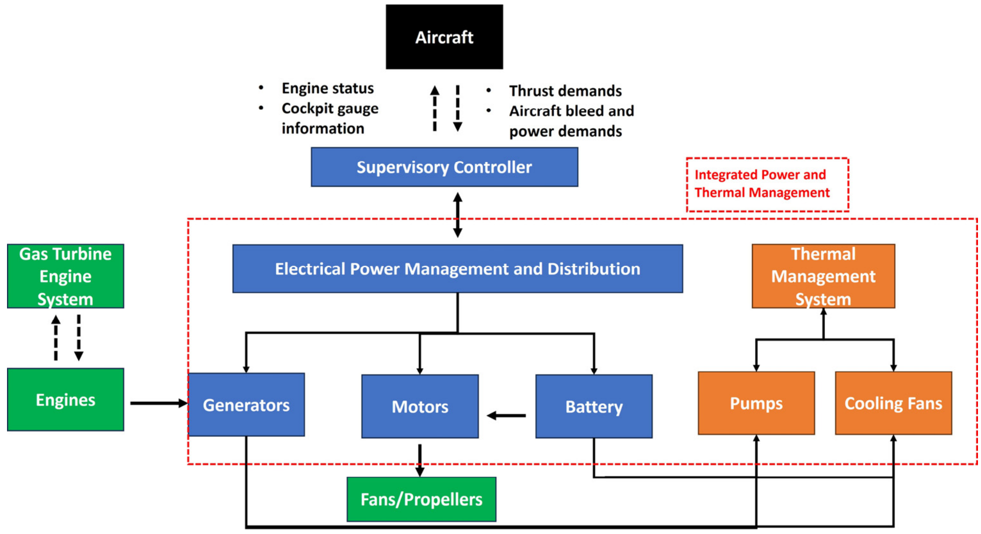

Figure 2. Control architecture for EPA, where the green blocks represent the engine system, blue blocks represent the power management system, and the orange blocks represent the thermal management system (adapted from [46]).

PM strategies have been studied widely for hybrid-electric ground-based vehicles (HEVs) and have been integrated with TMSs to manage energy flows at the vehicle level [47,48]. However, the general technologies developed for HEVs are not available for implementation in aircraft as aircraft have different considerations. Aircraft manage energy flows based on mission profiles. An aircraft mission has several segments in the following sequence: taxi-out, takeoff, climb, cruise, descent, landing, and taxi-in, and the propulsion requirements per mission segment (e.g., balancing thrust and drag) are different. In HEA, the PM strategy is more complicated, minimising fuel consumption with electric power, providing sufficient power for TMS and other electric components, and ensuring the state of charge (SOC) of the battery is above the minimum value to avoid damage [49].

PM strategies can be generally categorised into two types: causal and non-causal. Researchers apply non-causal ones when future conditions are known [50–53] and apply causal PM strategies for unknown-future conditions [54–58]. Both methods can be implemented for real-time applications, depending on if the mission profile is known beforehand or not. For aircraft, the decision of the type of PM strategy depends on the objective, optimising for the entire flight mission or a single moment. If the optimisation is non-causal, the overall fuel consumption is assessed and minimised. A non-causal cost function can be described by Equation (1). If the optimisation is causal, the fuel consumption for each time step is assessed and minimised. A causal cost function can be described by Equation (2).

$$\mathrm{J} = \int_{t_i}^{t_{end}} Wt_{fuel}(t_k)dt,\ t_k \in [t_i,\ t_{end}] \tag{1}$$

$$\mathrm{J} = W_{fuel}(t_k),\ t_k \in [t_i,\ t_{end}] \tag{2}$$

where J = objective function, t = time, t_i = initial time, t_{end} = end time, Wt_{fuel} = fuel weight, and W_{fuel} = fuel flow rate.

3. IPTMS Architecture Design

Generally, the IPTMS architecture design can be categorised into two approaches: (1) integrate different aircraft subsystems based on energy recovery theory, and (2) design advanced EPS and TMS architectures considering the interactions between the TMS and PMS.

3.1. IPTMS with Energy Recovery

With energy recovery, an IPTMS converts thermal energy to other secondary powers, such as mechanical power and electrical power. A simple IPTMS with energy recovery can be assumed as an integration of an APU (auxiliary power unit) and ECS (environmental control system), consisting of a compressor, a turbine, and a generator, as Figure 3 shows. In this kind of IPTMS, fluids (i.e., gas and coolant) expand within the turbine to achieve a low temperature for cooling. Through the expansion, the turbine output power can drive the compressor and the generator. Thereby, the IPTMS can have heat-cooling and power-generation functions.

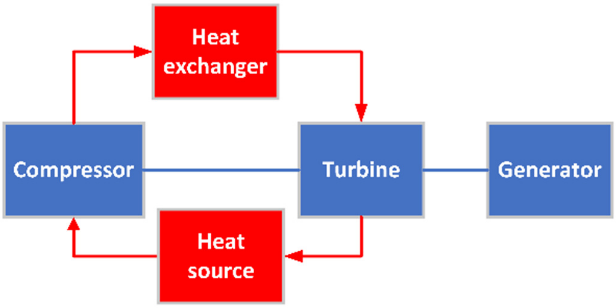

Figure 3. Simple IPTMS with energy recovery.

The IPTMS achieves ECS functions by implementing thermodynamic cycles, such as the Brayton cycle and Rankine cycle. The ECS with reversed Brayton cycle principle is used widely and has become commercially mature [37]. Generally, the working fluid of this type of ECS is air, resulting in low weight, high operating reliability, and low operating cost [59,60]. Compared with the ECS based on the Brayton cycle, the ECS based on reversed Rankine cycle can eliminate the use of bleed air. Additionally, it can have better efficiency, but it is heavier and less commercially matured [37].

A prominent example of IPTMS based on the Brayton cycle is the IPTMS developed by Honeywell [13,61]. This IPTMS integrates four conventional aircraft system functions: the auxiliary power unit (APU), emergency power unit (EPU), environmental control system (ECS), and thermal management system (TMS). The system has four operating modes: the Self-Start Mode, the Main-Engine Start, the Cooling Mode, and the Emergency Power Mode. The functions of these modes are as follows:

Self-Start Mode: In this mode, the battery initially provides power for the starter/generator of the IPTMS to drive the turbomachinery. When the shaft speed of the turbomachinery increases to an initial value, the IPTMS achieves self-sustaining operation and transitions to the Main-Engine Start Mode.

Main-Engine Start: In this mode, the system plays the role of APU. The IPTMS can provide power to start the main engine without the use of the aircraft battery.

Cooling Mode: In this mode, the IPTMS is powered by the bleed air from the main engine instead of the combustor of the IPMTS. The IPTMS plays the roles of roles of ECS and TMS, implementing active air cooling with a reversed Brayton cycle. The turbomachinery of the IPTMS functions similarly to a conventional air cycle machine, with the added capability of driving a generator to provide power, as Figure 3 shows. The IPTMS generates cooled air which not only serves the purpose of air conditioning but also aids in dissipating heat from avionics, flight-critical electronics, and oil.

Emergency Power Mode: When the main engine fails, the system transitions to the Emergency Power Mode. In this mode, the IPTMS plays the role of EPU, and is powered by the combustor of the IPTMS instead of the bleed air. The IPTMS-driven generator provides power for critical inflight electronics or for the main engine restart.

Based on this milestone set by the IPTMS of Honeywell, several studies have attempted to improve the IPTMS performance by reducing overall system weight, increasing energy conversion efficiency, and extracting more power. Dooley et al. [62,63] proposed a unit, named the Integrated Power and Cooling Unit, for the IPTMS. This unit simplifies the system by reducing the number of recirculation compressor components and limiting the use of bleed and ram air. Although this IPTMS design decreases the system's weight and volume and minimises the negative impact of bleed and ram air, it was found that the fluid efficiency of phase-change cooling and the recovery effectiveness are low. Abolmoali et al. [64] integrated a closed-loop air cycle system with an open-loop gas generator cycle to cool the gas turbine engine heat loads and provide sufficient power for auxiliary power loads. This IPTMS can provide up to 78.5% more power than the conventional power generation approach under sea-level static conditions. However, due to the impact of the flight altitude, the IPTMS cannot provide sufficient power for auxiliary power loads under other operation conditions and still requires supplementary power from the engine-driven generators. In [65], an IPTMS with a multi-mode Rankine cycle system was developed which was able to remove 10.7 kW from the coolant and satisfy the power requirements of the auxiliary systems (230 W at steady state). However, the response time of the heat transfer is slower than the power generation. Stoia et al. [66] designed an IPTMS for high-speed aircraft based on the Brayton cycle, using sCO_2 (supercritical carbon dioxide) as the coolant. This IPTMS can be recuperated (with the use of a recuperator) or non-recuperated. The recuperation depends on the ratio of heat transport to power required of the IPTMS. The IPTMS in [66] is recuperated and can provide power density greater than 3 kWe/L with up to 35% energy conversion efficiency. However, because of the recuperator, the weight and the volume of the IPTMS are significantly increased.

The IPTMS design with energy recovery is usually applied to military aircraft because it can save aircraft system weight and volume by integrating different subsystems. Compared with the conventional air cycle machine, although this type of IPTMS still needs additional power input to drive the compressor, its turbine can drive a generator to provide power, converting thermal energy to electric energy. Therefore, the power density and the energy conversion efficiency could be the key target parameters for the IPTMS design to obtain a smaller and lighter system which provides more electric power.

3.2. IPTMS with Advanced EPS and TMS

As discussed in Section 2.2, the heat loads of EPA are different from conventional aircraft, and because of the additive electric components, the TMS design for EPA faces more challenges, such as increased weight, induced drag, and TMS power use [39,67]. Therefore, the IPTMS architecture design for EPA should consider the interactions between the EPS and TMS architectures.

Kim et al. [68] proposed a sensitivity study of IPTMS for a Megawatt-class (MW-class) turboelectric aircraft. They investigated the impacts of advancements in power distribution systems and TMSs on the aircraft's performance and proposed three potential TMS architectures. They found that a 150-passenger MW-class turboelectric aircraft is infeasible at the current technological level due to the TMS challenges. In addition, they state that the advancements in TMSs are more urgently needed for the aircraft. Chapman et al. [69,70] proposed IPTMS architectures for different aircraft implementing advanced AC power systems. They developed a high-efficiency megawatt motor and a high-efficiency AC converter for the AC transmission of the aircraft EPS. Compared with the conventional DC transmission approach, the EPS with AC transmission reduces the conversion steps and the electric component weights. As a result, the TMS is redesigned to reduce the cooling loops. It was found that their IPTMS architecture design can significantly reduce overall system weight, drag, and power use. In [71], the IPTMS of a long-endurance unmanned HEA integrates the TMS with the propulsion system through a fuel loop. The fuel is reheated before burning in the combustor, rejecting the heat from the powertrain in order to increase the engine's thermal efficiency. Compared with the conventional propulsion system, the IPTMS can save 750 lb of fuel despite a 708 lb increase in the overall weight due to the electrification. Furthermore, Chapman et al. [44] presented an IPTMS design which implements an advanced EPS architecture with AC distribution system and a conventional TMS. It was found that this IPTMS design can achieve 2.5% reduction in fuel consumption. They also presented an Outer Mould Line (OML) cooling for the same advanced EPS architecture. Compared with the conventional TMS design, the IPTMS design with passive TMS can provide an additional 0.8% reduction in fuel burn. However, it results in an increase in TMS weight. Heersema et al. [42] presented a trade-off study to investigate the impact of the efficiencies of the electrical components on the OML-based passive TMS performance. It was found that, under the low-efficiency condition, the TMS weight is over twice as heavy as the weight at the normal-efficiency condition, and the required area for the installation of the passive TMS exceeds the area available. In [72], Coutinho et al. designed different TMS architectures for a hybrid-electric aircraft that implements either a ram air heat exchanger or a skin heat exchanger for liquid cooling and phase-change cooling. Through the comparison of different TMS architectures, it was found that for more significant improvements in minimising the negative impact of the TMS, the TMS design should be integrated with the EPS, considering different power and design needs. Additionally, the IPTMS design could further reduce fuel consumption when combined with other multidisciplinary analyses, such as those involving aerodynamics and aircraft structures.

The aim of the IPTMS design with advanced EPS and TMS is to minimise the challenges due to the electrical propulsion system, such as the additional weight, the required power for cooling, and the drag due to the use of ram air. The EPS design can affect the requirements of the TMS, while TMS design can similarly contribute to the power requirements. Therefore, trade-off studies are needed between the advancements in thermal and power domains, as the requirements for propulsion and TMSs, operating conditions, and architectures vary for different scales of aircraft. Additionally, the trade-off studies can assess the capability of an IPTMS under different operating conditions. When the power required for cooling constitutes a small proportion of the total power output, it is possible to reduce additional weight by using advanced TMS architectures, or to decrease TMS requirements by employing advanced EPS architectures. If the cooling power constitutes a big proportion of the total power output and affects the battery heat load significantly, it is necessary to manage the power supply strategies of the battery. Therefore, power management optimisation is needed.

4. IPTMS Power Management Optimisation

As presented in Section 2.4, an optimisation strategy for IPTMS can manage thermal and electric energy flows in the aircraft implementing suitable PM strategies. The optimisers aim to (1) reduce operational costs by minimising fuel consumption and battery usage, (2) achieve optimal operations for in-flight components, and (3) satisfy power and thermal demands in different flight conditions. Compared with the conventional optimisers for HEA that optimise power split, the IPTMS optimisers also consider the effect of temperature and auxiliary loads in the TMS. Due to increased electrification, there is a need to manage the power and thermal energies of additional electrical components. Additionally, some TMS components are electrified, such as electrical coolant pumps and cooling fans. These electric components require power supplies and generate heat loads in the aircraft. As a result, it is necessary to assess their performance and optimise their energy flows.

Dynamic programming (DP) is a non-causal power management (PM) strategy. It is highly versatile, enabling it to tackle a wide range of problems [73]. It has been applied for HEA [74–76], with findings indicating that DP can reduce operational costs and improve hydrogen fuel consumption for fuel-cell HEA [75]. Additionally, it also leverages flight scheduling and has nearly no accuracy losses when imitating mechanical operations [74]. However, DP has a disadvantage in computational speed. Pontryagin's Minimum Principle (PMP) is a causal PM strategy derived from DP through variational methods. It can convert the original global optimal problem to a local one [77]. This strategy has been widely studied for HEVs [78]. However, PMP has difficulty solving complex nonlinear problems [79], which presents a challenge for implementing PMP in HEA. Model Predictive Control

(MPC) is an online causal PM strategy. In MPC, the algorithm first predicts the future states based on the system model over a predictive horizon of length N at each sampling time. It then selects the optimal control law from the current time k to the time k + N through rolling optimisation. Once the optimising control law is chosen for the current time k, the results are output only for the time k, disregarding the rest, and the system state is updated. As a result, MPC is more sensitive to the aircraft's future performance. Therefore, while uncertainties in the prediction pose challenges to the robustness of MPC, it is less computationally demanding than DP [80].

Koeln et al. [81] proposed a hierarchical MPC approach for the IPTMS of a military aircraft. They design the IPTMS to provide power for auxiliary loads, emergency loads, and engine starts, while cooling electric components, such as AC/DC loads, advanced electrical equipment, batteries, generators, and inverters. They also assess the dynamic performance of the components with the graph-based approach developed in [82,83]. The MPC is three-level, where the upper level is for planning thermal and power demands, state predictions, and power shedding. The lower-level MPC provides optimal solutions for desired battery power and cooling mass flow rates when satisfying state constraints. The tracking-level MPC tracks the mass flow rates of pumps and fans and makes decisions for valves, inverters, batteries, and power loads. Compared with the baseline controller, the MPC has better performance in capability, safety, and efficiency. A hierarchical MPC approach is implemented for the IPTMS of a UAV in [84]. It was found that the fuel burn can be reduced by 16% with the MPC optimisation strategy compared to the baseline strategy, and the MPC is more reliable. Misley et al. [85] implemented PMP to optimise the performance of the rechargeable battery pack and the TMS for a parallel turboelectric aircraft. The battery is cooled by bleed air extracted from the engine, and it can provide power for propulsion. The optimisation aims to minimise the fuel consumption by controlling the power split (ratio of battery power to total propulsion power) and the cooling ratio (ratio of TMS power required to engine power), while the constraints are the battery temperature and state of charge. The results show that the computational time is reduced from 4 h to 2 min with PMP. However, the fuel consumptions are increased by about 2%.

Both military and civil aircraft need power management optimisation for IPTMS to obtain the optimal battery power supply strategy. When the battery provides required power for TMS and for other power consumers, such as avionics, motors, and anti-icing systems, there could be an optimal solution to manage power split between the battery and the engine-driven generators to minimise the energy consumption. The types of optimisation strategies depend on the requirements, such as computational speed, capability, and stability.

5. IPTMS Modelling

IPTMSs are highly integrated and interdisciplinary, making it beneficial for designers to access the components' performance in various forms, such as in terms of thermal and electrical energies. The models developed for an IPTMS can be used as analysis tools for researchers to investigate the interactions between different subsystems in order to obtain optimal solutions. To evaluate aircraft performance with an IPTMS, the tip-to-tail (T2T) models are developed, usually including the IPTMS, fuel thermal management system, engine system, and air vehicle system. In addition to the aircraft-level models for subsystems, the T2T models also involve component-level models for some critical components. With the integrated models, the T2T models provide a foundation for the aircraft's future optimisation. In some cases, the T2T models are designed for a certain type of aircraft, but the modelling methods are applicable to other aircraft types.

Wolff et al. [86] proposed a modelling and simulation process for IPTMS to maximise the aircraft's energy utilisation while minimising complexity. The component-level models involve electrical components such as the generator, feeders, and actuators. The integrated model has the capability to assess the transient behaviours of the subsystem and find the drivers of the system's performance to define the design points of the subsystems. Through testing, the researchers identified limitations with the assumptions of the design point of the energy storage unit.

Roberts et al. [87–89] developed a generic T2T model, including the subsystem of an air vehicle system, fuel thermal management system, IPTMS, engine system, and control system. They developed the model without proprietary data so that the tool is highly adaptable for different conceptual designs. To increase the model fidelity, they developed transient models for the integrated power package and TMS components (e.g., fuel and oil pumps and heat exchangers). The researchers found that the shortcomings in the TMS design can be detected through the assessment of the transient interactions between the subsystems, which could be neglected in conventional designs. In [90], the T2T model is adapted to a solid oxide fuel cell (SOFC) to analyse the impact of the SOFC at the aircraft level. It was found that the SOFC can improve the overall aircraft efficiency by a small percentage and can reduce the use of bleed air from the main engine. The T2T offers the capability of a trade-off study by evaluating the relationship between subsystems, but only the configuration of the IPTMS integrated with a SOFC is studied.

Due to the multidisciplinary interactions within the subsystems of the IPTMS, a T2T model is required for the IPTMS to assess its performance. A versatile model can be used by different design teams, reducing the operating cost of design. Additionally, the development of IPTMS modelling can contribute to the modular design of IPTMSs.

6. IPTMS Analysis Method

The IPTMS designs in the fields that are mentioned in the previous sections are mostly based on energy analysis relating to the first law of thermodynamics. The energy-based designs aim to minimise aircraft energy usage. However, in 1987, Szargut et al. [91] stated that energy analysis cannot detect most of the problems of thermodynamic imperfection. In 1999, Bejan [92] defined a concept, named “exergy”, to measure the quality of various types of energy. The exergy analysis is based on the second law of thermodynamics. A process can satisfy the first law, but compliance does not mean the process is feasible because entropy cannot decrease according to the second law. An exergy analysis is an optimal approach based on the objective functions of entropy generation. Design problems can be identified because aircraft inefficiency can be quantified using exergy analysis. Additionally, researchers can compare the performance of different subsystems with exergy analysis.

Tipton et al. [93] applied an exergy analysis to an IPTMS where the optimisation objectives were exergetic efficiency and total take-off weight. The entropy generated by the IPTMS subsystems is estimated and the total entropy generation of the overall system is found. In this research, the exergy approach can help with the design, but its results are similar to the results of the energy approach and its advantages in IPTMS design need to be validated further. Maser et al. [94] investigated the thermodynamic irreversibility for IPTMSs with exergy approach. They found that exergy optimisation can help to obtain absolute and consistent measurements for aircraft performance trade-off.

In addition to thermodynamic characteristic optimisation, IPTMS optimisation can also achieve light weight at the system level. Rong et al. [95] proposed a system-level analysis method to minimise the total fuel weight penalty for a simplified IPTMS with energy recovery. They adopted the equivalent mass method for analysis and compared the performance of three cooling strategies of the IPTMS. It was found that the optimal cooling strategies are different under different operating conditions.

The development of IPTMS analysis methods can contribute to the trade-off study of an IPTMS. The IPTMS analysis methods can be beneficial for engine cycle designs and lightweight system-level designs. Additionally, the IPTMS analysis methods require validation to ensure their stability.

7. Challenges and Future Opportunities

As presented in previous sections, IPTMSs have been studied widely in different research fields. Owing to increasing electrification, the design of aircraft systems requires a multidisciplinary approach. In this context, TMS designs necessitate integration with other aircraft systems [96], and current IPTMS designs require further enhancement to meet the requirements under various conditions [97]. As a result, it is necessary to discover the current challenges of IPTMSs and their future opportunities.

This section initially presents the challenges and future opportunities for the IPTMS research topics mentioned in Sections 3–6 and explores the potential solutions for civil electrical propulsion aircraft (EPA) based on these discussions.

Regarding the IPTMS architecture design with energy recovery, the system's high integration and multidisciplinary requirements add to its complexity. This complexity brings difficulties in terms of operating cost, reliability, and safety, and presents obstacles for various conceptual designs as well as control and power management system design. This IPTMS design is usually applied to military aircraft due to its ability to reduce overall weight and save volume for other subsystems, thus increasing the aircraft capability. Therefore, future research in this field should focus on integrating more functions into an IPTMS, while enhancing system stability and safety and developing feasible architectures for different aircraft conceptual designs.

As presented in Section 3.2, an IPTMS approach is integrating EPS and TMS architecture designs. It has been found that the advanced EPS architecture design can reduce the requirements of the TMS and ultimately reduce the TMS's overall weight, power, and drag due to ram air. In this research field, the heat loads are usually determined by the efficiency-based method. However, the power required varies across the whole flight mission, which means the current is different as well at different operating points, so the efficiencies of electric components will change. To assess the performance of components and investigate the interactions between the TMS and PMS more accurately, other component modelling methods should be adopted, such as the experiment-based method and the physics-based method. The IPTMSs in this research field are usually designed for HEA. In this case, it is difficult to avoid the use of ram air. Thus, the future research should focus on discovering approaches to minimise ram air usage.

The power management for an IPTMS manages the power and thermal energy flows at the aircraft level. However, its current stage still focuses on the conventional aircraft subsystem architecture. For example, in military aircraft, the power management optimisation is not based on the energy recovery architecture but focuses on the interactions between conventional aircraft subsystems. In civil aircraft, the power management mainly optimises battery performance. Usually, the battery has two power supply strategies: it provides propulsive power only, or provides propulsive power and all the cooling power of the propulsion system. However, there are limited papers that investigate the strategies of battery power supply. For example, the battery can satisfy the required propulsive power and provide from 10% or 20% to 100% of the TMS power needed for propulsion system cooling. Therefore, a potential solution is to design the power management strategies considering the power usage of the TMS to obtain the optimal battery power supply strategies across the aircraft's flight mission.

As presented in Sections 5 and 6, various researchers have developed methods or tools for IPTMSs at the aircraft level, involving modelling, optimisation, and analysis. Although these methods were designed for different power conditions, they need to be more versatile to accommodate other conditions, such as subsonic/supersonic conditions and different aircraft platforms. The integration of more subsystems and the multidisciplinary nature of these methods contribute to their complexity. Therefore, future work should focus on enhancing their versatility and addressing time-related issues (e.g., computational time or simulation time) due to the increasing complexity of design.

Based on the challenges and opportunities presented above, a summary list of requirements for future IPTMSs is as follows:

1. Enhanced system integration: future IPTMSs could benefit from higher levels of integration, not only with TMS and PMS but also with other aircraft subsystems.

2. Improved system stability and safety: as the complexity of IPTMSs increase, the importance of system stability and safety may also increase.
3. Minimisation of system weight and volume: for military and civil aircraft, future IPTMS research should investigate methods to minimise the system weight and volume.
4. Minimisation of cooling power and ram air usage: future research should explore approaches to minimise the use of ram air and the power usage of TMS.
5. Optimised power management strategies: Future IPTMS should consider the trade-off study between propulsive power and the power usage of TMS. This could lead to the development of optimal battery power supply strategies across the aircraft flight mission.
6. Investigation of IPTMS optimisation domain: For different operating conditions and different propulsion requirements, the impacts of the TMS and the PMS would be different. Future IPTMSs should investigate at the system level whether the optimisation of the IPTMS should be in the thermal domain or the power domain.
7. Versatility and stability of methods and tools: The methods and tools developed for an IPTMS at the aircraft level should be versatile enough to accommodate different power conditions, flight conditions (e.g., subsonic/supersonic, normal/cold-day/hot-day conditions), and different aircraft platforms. At the same time, the methods and tools should ensure their stability through validation.
8. Addressing time-related issues: with the increasing complexity of design, future work should focus on addressing time-related issues, such as computational time or simulation time.

For civil EPA, the electrified propulsion systems introduce more electrical components than those in military aircraft, thereby increasing the requirements for cooling and energy conservation. Although the IPTMS with energy recovery has the capability to handle cooling and power generation simultaneously, it is not suitable for civil EPA. This is due to this IPTMS typically using fuel as the coolant. While the fuel flow is sufficient for cooling the heat loads of military aircraft, it is inadequate for civil aircraft. Furthermore, the power generation of the IPTMS might not meet the power requirements of civil EPA, as they have more power consumers than military aircraft. In this case, the IPTMS with advanced EPS and TMS could be a feasible IPTMS solution for EPA. With an advanced EPS or TMS design, the thermal and power requirements can be reduced at the architecture level by minimising electric components and simplifying the TMS. Furthermore, an optimal battery power supply strategy can affect the capability of energy saving and the size of the battery, and the battery size then impacts thermal and power requirements. Additionally, the implementation of power management strategy can further optimise the IPTMS performance across the flight mission, reducing energy consumption. Therefore, a potential approach for an IPTMS to address the challenges of EPA is the combination of architecture design (IPTMS with advanced EPS and TMS) and power management optimisation.

Typically, the iteration of civil aircraft models tends to be faster than that of military aircraft. This is because manufacturers need to update their models based on market conditions to meet customer demands and pursue higher profits. Therefore, it is necessary to develop IPTMS platforms with high versatility for civil EPA. This necessitates research on the modelling methods of an IPTMS. The IPTMS platform needs to allow designers to assess the heat and power loads across the flight mission. Additionally, it should also be adaptable when designers decide to use different components. As a result, this platform can enable designers to implement a modular design for IPTMSs. In this context, the future trend in the development of IPTMS analysis methods should be at the system level. This will enable designers to conduct system-level trade-off studies and identify areas for improvement. Given the modular design capability of the platform, these changes can be made easily, thereby enhancing the overall performance of the aircraft in a convenient manner. In this context, the combination of modelling and analysis methods for an IPTMS could be another potential solution for EPA.

8. Conclusions

A comprehensive review on IPTMS in terms of several research areas has been presented to investigate the current challenges and future opportunities of IPTMSs for civil electrical propulsion aircraft (EPA). The current IPTMS research is classified into four research areas: (1) architecture design, (2) power management optimisation, (3) modelling, and (4) analysis method development. Based on the discussions on their challenges and future opportunities, a summary of requirements for future IPTMS design is demonstrated.

The future IPTMS for EPA should deal with the challenges due increasing electrification. Consequently, there are two potential solutions for the IPTMS for EPA:

1. The combination of architecture design (IPTMS with advanced EPS and TMS) and power management optimisation can reduce thermal and power requirements and energy consumption.
2. The combination of modelling and analysis methods can facilitate the implementation of modular designs and optimise the overall performance of the aircraft.

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Abbreviations

AC	Alternating Current
ACM	Air Cycle Machine
AEA	All-Electric Aircraft
APU	Auxiliary Power Unit
DC	Direct Current
DP	Dynamic Programming
ECS	Environmental Control System
EPA	Electrical Propulsion Aircraft
EPU	Emergency Power Unit
GBx	Gearbox
GT	Gas Turbine
HEA	Hybrid-Electric Aircraft
IPTMS	Integrated Power and Thermal Management System
MEA	More Electric Aircraft
MPC	Model Predictive Control
PAO	Polyalphaolephin
PM	Power Management
PMP	Pontryagin's Minimum Principle
PMS	Power Management System
SOC	State of Charge
T2T	Tip-to-Tail
TMS	Thermal Management System

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