ESTIMATION OF MISSION FUEL SAVINGS POTENTIAL USING THERMOELECTRIC RECUPERATION IN AERO-ENGINES

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ABSTRACT

The reduction of fuel consumption represents a major challenge on the way to an environmentally friendly air transport system. Thermoelectric generators (TEG) can offer a robust solution for direct conversion of lost heat from an aero-engine to electricity, reducing the fuel burn fraction of engine offtake and thereby required mission fuel. The overarching goal of the TERA-project (Thermoelectric Energy Recuperation for Aviation) within Germany's fifth Aeronautical Research Program (LuFo-V) is thus to evaluate the potentials of TEG on engine and aircraft level. To that effect, integration between the hot section of the engine and the cooler bypass flow is considered to quantify achievable output power.
Fundamentally, two aspects determine the success of the concept: Firstly, the gravimetric power density of the TEG, which depends on thermoelectric material properties and thermal conditions, determines whether a break-even performance can be reached. Beyond break-even, mission fuel is saved. Secondly, the total generated power, limited by the TEG size and available area, determines the overall fuel savings potential.
In this contribution, a trade-study approach is presented. In order to evaluate the fuel savings potentials, an aircraft with entry-into-service in 2035 was defined and sized for future requirements as a baseline. Mission fuel is calculated as function of TEG power and weight of the TEG system. Two models are used: a simple model based on the Breguet range equation considering cruise phase only, and a more elaborate mission-based model, in which the aircraft is sized according to engine offtake and weight modifications. Results are presented for design and off-design missions and collated to expected TEG performance. From the trade studies, break-even power density is determined, and the fuel savings potential evaluated. Preliminary studies, based on a TEG integrated into the engine nozzle, indicate a fuel savings potential of one tenth of a percent.

KEYWORDS: *Aero-engine, Energy Recuperation, Fuel Savings, Thermoelectric Generator, Waste Heat Recovery*

NOMENCLATURE

ACARE - Advisory Council for Aviation Research and Innovation in Europe
APD - Aircraft Preliminary Design
ECS - Environmental Control System
EIS - Entry Into Service
FHV - Fuel Heating Value
ICAO - International Civil Aviation Organization
ISA - International Standard Atmosphere

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KCAS - Knots Calibrated Airspeed
L/D - Lift-to-Drag ratio
MLW - Maximum Landing Weight
(M)TOW – (Maximum) Take-Off Weight
OEW - Operating Empty Weight
PAX - Passengers
p - Power density
P - Power
$\dot{Q}$ - Heat flux
RANS - Reynolds-averaged Navier–Stokes equations
RF - Reserve Fuel
R - Resistance
s - Range
SFC - Specific Fuel Consumption
SL - Sea Level
SRIA - Strategic Research and Innovation Agenda
T - Absolute temperature
TEG - Thermoelectric Generator
TERA - Thermoelectric Energy Recuperation for Aviation
TOC - Top-Of-Climb
v - Airspeed
ZFW - Zero Fuel Weight
ZT - Thermoelectric Figure-of-Merit
S - Seebeck coefficient

η - Efficiency
κ - Thermal conductivity
σ - Electrical conductivity

Superscripts
Gen - Generator
tr - Transmission

Subscripts
0 - Reference
Gen - Generator
A - Area-specific
C - Cold-side
g - Gravimetric
h - Hot-side
L - Load
P - Propulsive
th - Thermal
tr - Transmission

1 INTRODUCTION

It is well-known that the fuel efficiency of transport aircraft and especially the propulsive efficiency of jet engines have improved remarkably since the beginning of the jet age [1]. Major contributors toward the achieved efficiency potentials of aero-engines come from advancements in materials, engine sizing, overall pressure ratio, burn temperature, mechanics, aerodynamics, and control. There are numerous approaches to exploit untapped potentials – e.g., considering optimized engine-airframe integration, distributed propulsion concepts, or electrification and hybridization. However, it seems clear that the stated goals of EU ACARE Flightpath 2050 [2] of a 75% decrease in fuel consumption require a strong and combined effort of optimizing both technological and operational potentials, and that a need for near-term solutions is evident. As it is becoming increasingly difficult to further improve fuel burn of conventional aero-engines, different avenues have already been explored, including thermodynamic recuperation concepts. These concepts typically require bulky components, such as heat exchangers for efficient operation, adding weight and drag to the engines, so that the achievable potentials must be carefully evaluated.

In this contribution, another possibility is explored. As a fraction of fuel burn is used for electricity generation, the direct generation of electric energy from waste heat in the exhaust gas flow is an attractive option to improve the thrust-specific fuel consumption of aero-engines. As thermoelectric modules generate electrical energy from heat directly via the Seebeck effect, thermoelectric generators (TEG) may in principle be placed downstream the burn chamber between core and bypass flow and relieve, or even replace, the mechanical generators, thus reducing mechanical shaft load. Thermoelectric modules are flat, solid-state devices, promising favorable integration opportunities and a low maintenance requirement.

Therefore, in this contribution we present results of the TERA-project (Thermoelectric Energy Recuperation for Aviation) within Germany's fifth Aeronautical Research Program (LuFo-V), in which the potentials of TEG in aero-engines are explored [3]. To this end, a future, 180 PAX class airliner with entry-into-service 2035 was defined as a reference aircraft model to evaluate the fuel savings potentials of TEG integration on the basis of a) a Breguet-based performance estimation and b) mission performance modeling of an optimized aircraft in the Pacelab APD modeling environment [4]. The design aircraft, performance metrics and TEG integration are discussed in the following sections, before the presentation of methods and results.

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1.1 Design Aircraft

An EIS 2035 aircraft and corresponding engine was sized according to generator offtake requirement and mass of additional systems (i.e. TEG and ancillary devices, such as power converters). The design aircraft has a range of $2850\ \mathrm{NM}$ with 180 PAX at a design cruise speed and altitude of $\mathrm{M}0.76$ and $35\ \mathrm{kft}$, respectively. The aircraft mission requirements are defined in Table 1 below, assuming an A320neo-successor with entry-into-service 2035.

Table 1: Aircraft mission requirements

Requirement	**Target value**
PAX @ 102kg	180
Range	2850 NM
Design Mach number	$\geq$ 0.76
Cruise altitude	35,000 ft
Take-off field length @ ISA, SL	2100 m
Approach speed (V_{APP}) @ ISA, SL, MLW	<140 KCAS
ICAO Code C Annex 14	Wingspan < 36m
SRIA goal 2035: CO_2 reduction vs. 2000	-60%
SRIA goal 2035: NO_X reduction vs. 2000	-84%
SRIA goal 2035: Noise emission reduction	-11dB

The baseline for TEG evaluation produced reference aircraft parameters given in Table 2. MTOW is approximately 10% lower compared to a similar aircraft of today, emanating from assumed technological advances.

Table 2: Reference aircraft parameters

Parameter	**Value**
MTOW / MLW / OEW	70,075 kg / 58,544 kg / 38,487 kg
Wing loading	645 kg/m²
Thrust-to-weight	0.33
Wingspan	36.5
Wing aspect ratio	12
Block-fuel Design / 1000 NM / 500 NM Mission	10,793 kg / 3,807 kg / 2,046 kg

1.1 Performance metrics

Two fundamental metrics define the viability of thermoelectric waste heat harvesting in aero-engines: firstly, a gravimetric power density limit is imposed on the TEG system (i.e., the weight-specific electrical power output with regard to TEG system weight), and secondly, the area-specific power density of the TEG, which defines the overall output power according to available integration space. The gravimetric power density doesn't compete directly with that of a conventional generator system, and it may in fact be lower compared to electromechanical devices. However, gravimetric power density is related to the fuel-savings potential at reduced mechanical offtake, due to reduced SFC: in the simplest case, fuel mass can be traded with TEG mass at fixed take-off weight, while retaining mission performance. The ratio of compensated electrical power (i.e., TEG output power) and fuel mass can then be used to define a break-even condition on the gravimetric power density, such that the aircraft achieves its design range. Beyond the break-even, the area available for waste-heat harvesting defines the overall harvestable energy and thus overall fuel-savings potential.
In this contribution, we perform a sensitivity analysis in this way, in which actual performance figures of TEG (or possibly other alternative energy systems) may then be placed to perform a first evaluation of technological viability.

1.2 Thermoelectric Generator Integration

The energy conversion efficiency of thermoelectric devices is governed by electrical and thermal properties, which is condensed in the figure-of-merit

$$\mathrm{ZT} = \frac{\sigma S^2}{\kappa} T, \tag{1}$$

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with specific electrical conductivity σ, thermal conductance κ, and the Seebeck coefficient S which relates the temperature difference to an induced voltage. Therefore, thermoelectric materials should have good electrical, but low thermal conductivity. The temperature-averaged ZT can be used to estimate the efficiency of TEGs (in power generation mode) [6]

$$\eta_{\mathrm{TEG}} = \frac{\sqrt{1+\mathrm{ZT}}-1}{\sqrt{1+\mathrm{ZT}}+T_{\mathrm{c}}/T_{\mathrm{h}}}\eta_{\mathrm{carnot}} \,. \tag{2}$$

In Figure 1, (left), the temperature distribution in a cross-section of the design-engine is shown in cruise condition. In the core stream at the nozzle, temperatures reach $623\,\mathrm{K}$ while the temperature is around $238\,\mathrm{K}$ in the bypass. Directly at the nozzle surface, the temperature difference reduces to 614 and $342\,\mathrm{K}$ (center of the nozzle length), while the TEG itself sees a temperature difference of 501 and $350\,\mathrm{K}$, respectively[1].

Conversion efficiency as function of effective ZT is shown in Figure 1 (center). Here, TEG hot- and cold-side temperatures of $T_{\mathrm{h}} = 501\,\mathrm{K}$ and $T_{\mathrm{c}} = 350\,\mathrm{K}$ were used, according to above-mentioned values, with the bulk of the temperature drop occurring in the boundary layer.

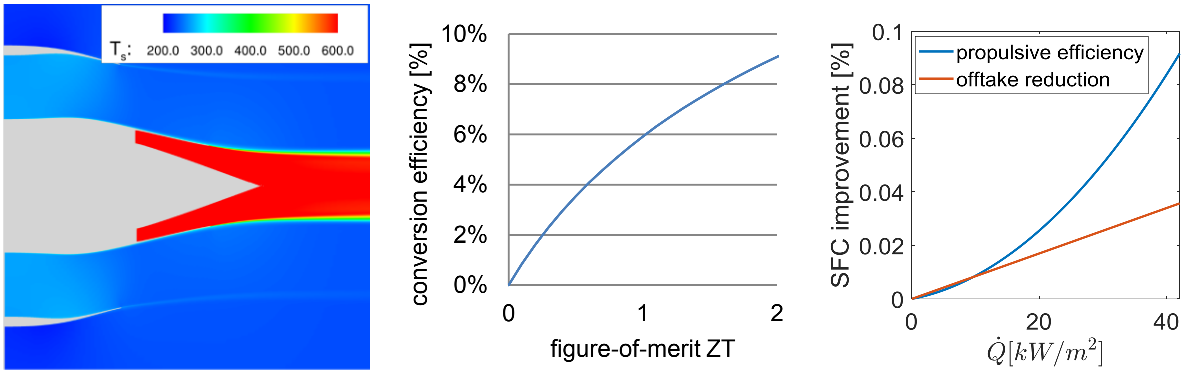

Figure 1: (Left) engine profile with temperature distribution (center) thermoelectric generation efficiency as function of figure of merit, *ZT* (right) engine improvement (exemplary) by heat flow and offtake reduction, assuming 1-m² nozzle area.

In state-of-the-art thermoelectric materials, ZT is near unity, with conversion efficiencies (thermal-electrical) around 6% at the respective temperature levels. Different material-systems are available for different temperature ranges, and higher valued ZT of up to 3.5 have been reported in nano-structured materials. Values of up to around 1.5 are available in certain bulk material systems [5], so the mid-term perspective concerning efficiency can be assumed to be around 8% for this application case. Maximum output power is

$$P_{\mathrm{TEG}} = \eta_{\mathrm{TEG}}\dot{Q}_{\mathrm{h}} \,. \tag{3}$$

Output power is limited by Carnot efficiency η_{carnot} and effective temperature difference according to eq. (2), and by the hot-side heat flux $\dot{Q}_{\mathrm{h}}$. Maximum power is achieved at the electrically load-matched condition $R_{\mathrm{L}}/R_{\mathrm{TEG}} = \sqrt{1+\mathrm{ZT}}$, and with a temperature drop across the TEG which is approximately half the temperature difference between source and sink. In the design of TEG for specific applications, overall efficiency, but also gravimetric power density and area-specific power density need to be considered, with operational temperature range and material properties in mind. These figures depend strongly on application-specific design optimization. Commercial TE-modules[2] may reach power densities of $500\,\mathrm{W/kg}$ at an area-specific density of about $2\,\mathrm{g/cm^2}$, or $20\,\mathrm{kg/m^2}$. This corresponds to an output power of about $10\,\mathrm{kW/m^2}$, under laboratory conditions. In the aircraft engine, a design (for TOC and Cruise conditions) heat flux (hot side) of approximately $\dot{Q}_{\mathrm{H}} = 21\,\mathrm{kW/m^2}$ was determined as a baseline from design-engine modeling based on computations of a thermal network with adiabatic RANS solution as input [7]. Therefore, with 8% TEG efficiency with regard to the input heat flux, a TEG output power of approximately $P_{\mathrm{TEG}} = 1.68\,\mathrm{kW/m^2}$ may be

[1] Courtesy of Fabian Ahrendts, TU Braunschweig
[2] http://www.komatsu.com/CompanyInfo/press/2009012714011528411.html

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expected, which is below the figure of the mentioned commercial module. At this power level, SFC is improved by approximately 0.02% in the model (cf. section 3.1).
In addition to the offtake reduction potential, the engine efficiency may also be improved by the re-energized bypass boundary layer due to an increase of temperature and inner energy, followed by a decrease of density. The accelerated bypass flow leads to an increased net thrust and propulsive efficiency due to a decreased momentum loss thickness. For design conditions an increase of approximately 0.05% propulsive efficiency with regard to adiabatic RANS computations can be achieved. This beneficial side effect leads to a synergetic behavior between the waste heat harvesting and engine performance. As a detrimental effect, the reduction of propulsive efficiency coming from the core flow has to be mentioned. Due to the cooling of the core flow the opposite trend compared to the bypass flow is observed. The boundary layer will be decelerated due to the cooling which finally leads to an increasing momentum loss thickness. However, this is overcompensated by the beneficial effects at the bypass flow.

2 METHODS

2.1 Breguet-based Evaluation

The Breguet range-equation can be used to perform a first estimation of the fuel savings potential of TEG. The Breguet-equation in the form [8]

$$s_0 = \frac{v}{\mathrm{SFC}_0}\frac{L/D}{g}\log\left(\frac{\mathrm{TOW}}{\mathrm{ZFW+RF}}\right) = \eta_{\mathrm{overall},0}\frac{\mathrm{FHV}\;L/D}{g}\log\left(\frac{\mathrm{TOW}}{\mathrm{ZFW+RF}}\right) \tag{4}$$

is used, with range s_0 of the design aircraft. Here, v is airspeed, SFC specific fuel consumption, TOW is the take-off weight, ZFW zero-fuel weight, RF reserve fuel, FHV fuel heating value, and $\mathrm{L/D}$ lift-to-drag ratio. In this model, L/D is assumed constant, neglecting the dependency on weight and airspeed. Overall efficiency of the engine, based on considerations of power, is defined as

$$\eta_{\mathrm{overall},0} = \frac{P_{\mathrm{p}}}{\frac{P_{\mathrm{p}}}{\eta_{\mathrm{core}}\,\eta_{\mathrm{tr}}\,\eta_{\mathrm{p}}}+\frac{P_{\mathrm{gen}}}{\eta_{\mathrm{tr}}^{\mathrm{gen}}\,\eta_{\mathrm{gen}}}}, \tag{5}$$

considering the required power P_{p} for propulsion with regard to the mechanical shaft power required for both propulsion ("core" and propulsive "p" efficiencies considered) and mechanical generator offtake ("GEN"), also considering mechanical transmission losses ("tr"). Both efficiency and system mass change when TEGs are introduced. The efficiency is modified as follows:

$$\eta_{\mathrm{overall,TEG}} = \frac{P_{\mathrm{p}}}{\frac{P_{\mathrm{p}}}{\eta_{\mathrm{th}}\,\eta_{\mathrm{p}}}+\frac{P_{\mathrm{gen}}-P_{\mathrm{TEG}}}{\eta_{\mathrm{gen}}^{\mathrm{tr}}\,\eta_{\mathrm{gen}}}}, \tag{6}$$

where core and transmission efficiencies $\eta_{\mathrm{core}}\,\eta_{\mathrm{tr}}$ have been substituted by thermal efficiency η_{th}. Considering the additional, averaged TEG power relieving the generator, this can be rearranged to

$$\frac{\eta_{\mathrm{overall,TEG}}}{\eta_{\mathrm{overall},0}} = \frac{P_{\mathrm{TEG}}}{\frac{\eta_{\mathrm{gen}}^{\mathrm{tr}}\,\eta_{\mathrm{gen}}}{\eta_{\mathrm{th}}\,\eta_{\mathrm{p}}}P_{\mathrm{p}}+P_{\mathrm{gen}}-P_{\mathrm{TEG}}}+1. \tag{7}$$

Assuming $\left(P_{\mathrm{gen}}-P_{\mathrm{TEG}}\right) \ll P_{\mathrm{p}}$ finally results in a relative efficiency improvement

$$\Delta\eta_{\mathrm{overall}} = \eta_{\mathrm{overall,TEG}}-\eta_{\mathrm{overall},0} = \frac{P_{\mathrm{TEG}}}{\frac{\eta_{\mathrm{gen}}^{\mathrm{tr}}\,\eta_{\mathrm{gen}}}{\eta_{\mathrm{th}}\,\eta_{\mathrm{p}}}P_{\mathrm{p}}+P_{\mathrm{gen}}-P_{\mathrm{TEG}}}\eta_{\mathrm{overall},0} \cong \frac{\eta_{\mathrm{th}}\,\eta_{\mathrm{p}}}{\eta_{\mathrm{tr}}^{\mathrm{gen}}\,\eta_{\mathrm{gen}}}\frac{P_{\mathrm{TEG}}}{P_{\mathrm{p}}}\eta_{\mathrm{overall},0}. \tag{8}$$

The efficiency improvement in eq. (8) is evaluated on aircraft level using eq. (4), considering a mass penalty from the required TEG components and a potential mass reduction of the conventional generator system.

This approach may produce different results, depending on the assumed boundary conditions. When maximum take-off weight (MTOW) is assumed at design range, TEG mass can only be traded with fuel mass. Adding TEG may improve fuel efficiency due to the SFC-improvement, compromising maximum range due to TEG weight impact, however. Therefore, at design range, the model produces a higher requirement on the specific power density compared to a shorter range, off-design mission. In the Breguet-based evaluation, we base the results on the "off-design" case, with subsequent discussion.

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2.2 Mission-based Evaluation

In addition to the Breguet-based analysis described above, which is restricted to the cruise-phase, a more elaborated and mission-based evaluation was implemented in Pacelab APD. In this case, engine sizing is also considered and the airframe is dimensioned accordingly. The mission-based analysis considers a design mission profile according to specification, and two off-design mission profiles for performance evaluation at 500 and $1000\,\mathrm{NM}$ mission length, respectively. The modeled mission profile, including diversion, is shown in Figure 2.

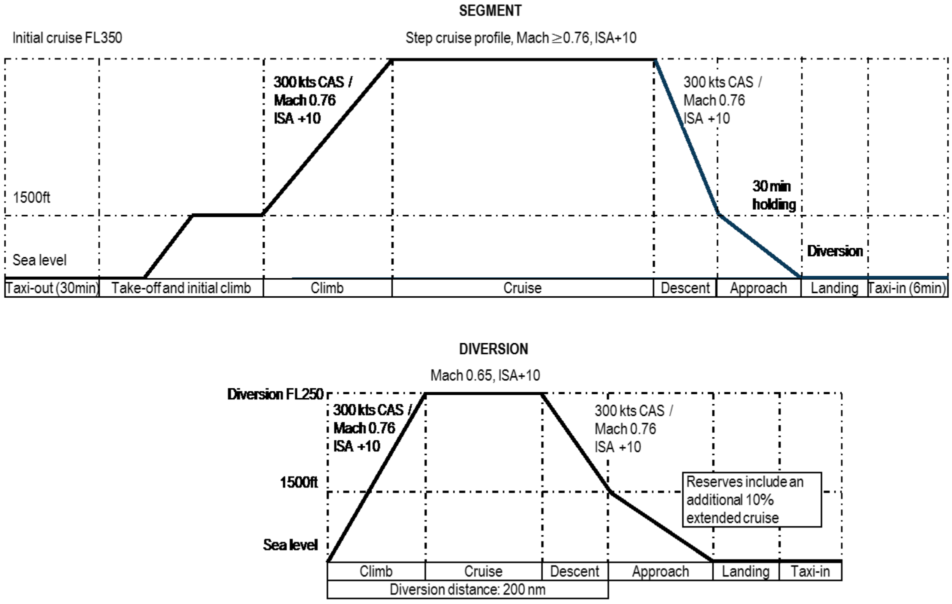

Figure 2: Design aircraft mission profile including diversion.

Work-flow is visualized in Figure 3. Engine performance tables, including off-design performance tables, are input as well as mission requirements and subsystem masses. For the evaluation of TEG, the subsystem masses and generator off-take power are varied to give a sensitivity study with regard to TEG design and performance. The aircraft is iteratively sized, considering low-speed and high-speed aerodynamics, design mission profile and engine tables to determine the optimum aircraft for each design point in the study.

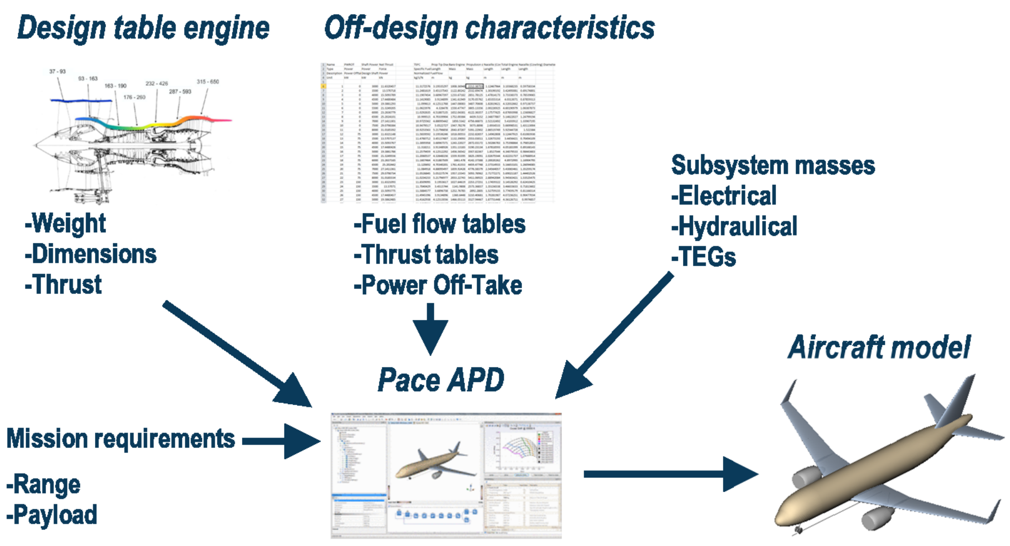

Figure 3: Pacelab APD workflow.

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3 RESULTS

3.1 Breguet-based Evaluation

The relative improvement in propulsive efficiency depends approximately on the ratio of TEG output power to that required for propulsion. The net propulsive power during the cruise phase is given by

$$P_{\text{cruise}} = \frac{m\,g\,v_{\text{cruise}}}{L/D}\,. \tag{9}$$

At a mean aircraft weight with payload and half-full fuel tanks m and $\frac{L}{D} = 17$, P_{cruise} is about $8.8\ \text{MW}$. Assuming $\eta_{\text{p}} = 80\%$ and $\eta_{\text{gen}} = 90\%$, according to eq. (8), engine overall efficiency improves by 0.01% per kilowatt of TEG power. In a conventional 180 seat aircraft with less than $100\ \text{kW}$ electrical offtake, the maximum savings potential based on SFC is thus below 1%. In the considered future aircraft, electrical power demand may be as high as $200\ \text{kW}$ per engine, assuming an electrical environmental control system (ECS) [9]. Therefore, the theoretical potential of compensating generator offtake power may approach 4% in this case, notwithstanding the achievable TEG output.
Break-even on aircraft level is reached if the efficiency improvement counteracts the weight impact. The weight of the conventional generator may be included in the weight estimation, using a linear scaling model coupling generator power to its weight [10].
The assessment of eq. (4) is conducted considering TEG weight and (mean) specific power density, which gives (mean) total output power and thus SFC improvement according to eq. (7). The weight impact considers the TEG system, as well as the reduction in generator weight. The result is depicted in Figure 4, were the relative impact of the system on mission fuel (in %) is shown.

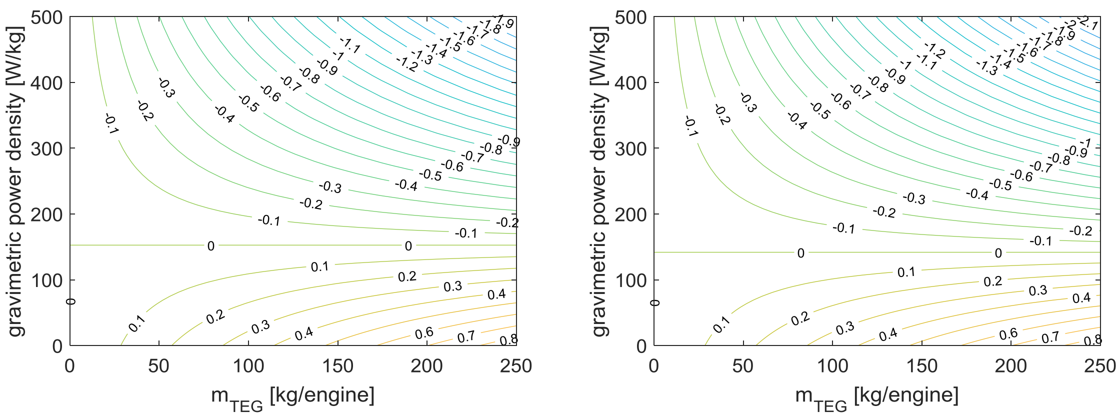

Figure 4: Mission fuel change (in percent) according to Breguet-model (only cruise flight considered). (Left) generator weight left unchanged, sized for 200-kW power per engine (right) generator weight adjusted to TEG output power.

Scaling of the conventional generator is considered in Figure 4, right, and is shown to have a small impact only. It is evident that there is a minimum requirement on the gravimetric power density of the TEG system of approximately $142\ \text{W/kg}$ and $153\ \text{W/kg}$, with and without generator weight savings, respectively. These values are approximately independent on TEG weight, or overall output power. Also, in order to achieve a savings potential approaching 1%, a heavy TEG ($> 100\ \text{kg}$ per engine) with an ambitious specific power density ($> 300\ \text{W/kg}$) would be required.
In the case when TEG weight can only be traded with fuel mass due to MTOW-limitation, the requirement on gravimetric power density increases to aprioximately $500\ \text{W/kg}$ in the Breguet-model, in order to reach design range, which does not preclude a better *specific* air range with TEG.

3.2 Mission-based Evaluation

Next, the results from the APD modeling environment are presented. In this case, the mission trajectory is considered including take-off, climb, and descent phases, and block fuel is calculated.

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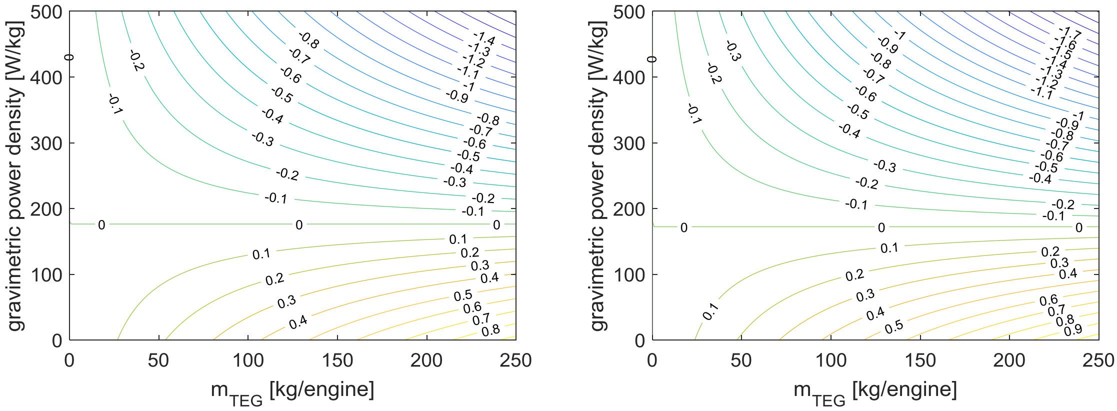

Figure 5: Block fuel change (in percent) according to APD-model (flight phases considered). (Left) generator weight left unchanged, sized for 200 kW power per engine (right) generator weight adjusted to TEG output power.

The resulting curves in Figure 5 are quite similar to the previous result, albeit with slightly reduced fuel-savings potential. One reason is the impact of take-off and descent flight phases, with different propulsive power requirements compared to cruise. The gravimetric power density requirement increases to $177\,\mathrm{W/kg}$, or $173\,\mathrm{W/kg}$ when a generator weight reduction is considered. The APD-based result, which considers an optimally sized aircraft for each combination of TEG weight and power, is much closer to the Breguet-result in "off-design" with the lower requirement on TEG specific power density, than the "design" result with MTOW limitation ($> 500\,\mathrm{W/kg}$).
In addition to the design mission, two off-design missions were evaluated in the APD modeling environment. In off-design, especially the ascent-phase has a considerable impact on propulsive power demand, with a reduced effect of TEG on mission fuel.

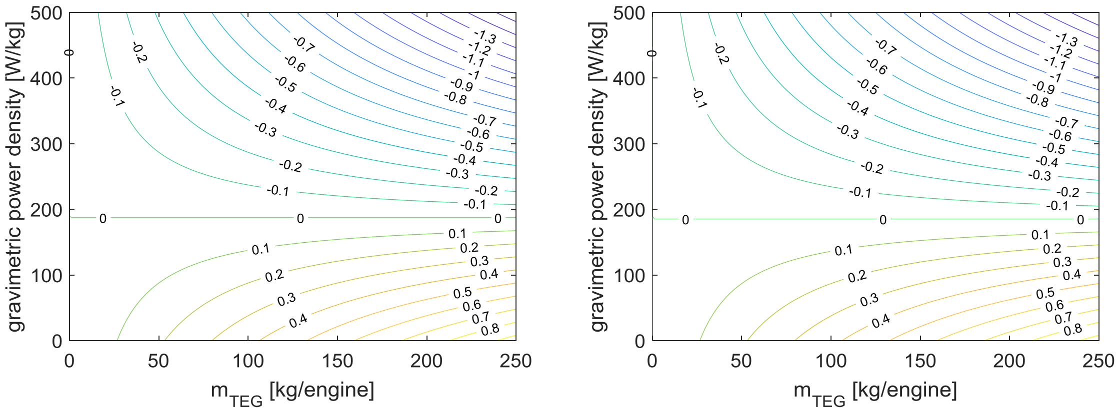

Figure 6: Block fuel change (in percent) according to APD-model. (Left) 500-NM mission (right) 1000-NM mission.

For the shorter missions (Figure 6), the specific power density requirement for TEG is increased, to $187\,\mathrm{W/kg}$ and $185\,\mathrm{W/kg}$, respectively (reduction of generator weight was not considered here).

3.3 Discussion of results

Above, the potential fuel savings employing TEGs within aero-engines was assessed and their specific characteristics were deduced on a general basis. In the following discussion, the area available for waste heat harvesting is limited to the nozzle. According to the geometry of the designed reference engine, depicted in Figure 1 (left), it is approximately one square meter. Moreover, a reference heat flow of $\dot{Q}_{\mathrm{H}} = 21\,\mathrm{kW/m^2}$ and, correspondingly, $P_{\mathrm{TEG}} = 1.68\,\mathrm{kW/m^2}$ (8% efficiency) are assumed. The TEG mass is an unknown parameter which is coupled to the gravimetric power density. As the gravimetric power density depends on TEG design, in particular on the fill factor [11], it is coupled to TEG system weight, and corresponding curves are plotted into the APD-based, reference-mission result from above (Figure 7).

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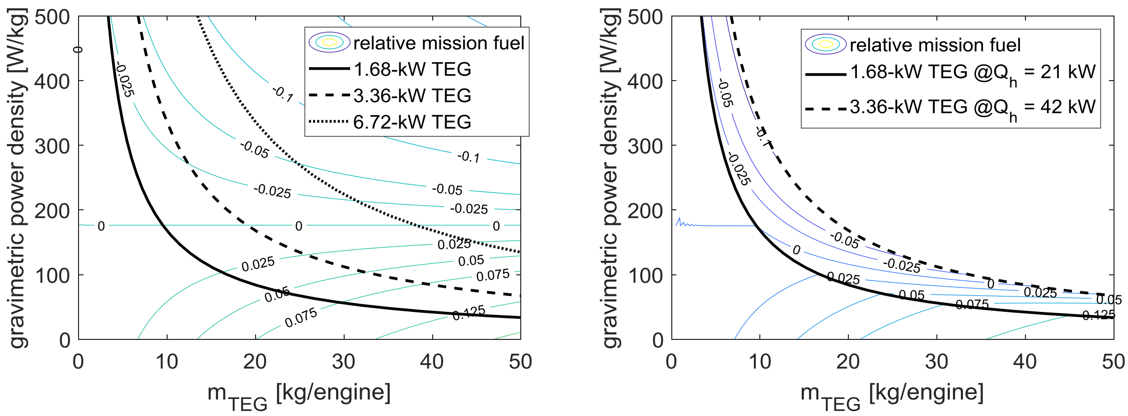

Figure 7: (Left) Block fuel change (in percent) according to APD-model; TEG assuming 1, 2 and 4 m² nozzle area (solid/dashed/dotted lines, respectively). (Right) potential with additional propulsive efficiency improvement, calculated with 1 m² area.

From Figure 7, left, the practical limitations, stemming chiefly from achievable heat throughput, become obvious. The three lines correspond to hypothetical TEGs using 1, 2 and $4\,\mathrm{m}^2$ available nozzle area. With an ambitious but plausible gravimetric power density of $270\,\mathrm{W/kg}$, an improvement of 0.05% in block fuel may be expected from a $25\,\mathrm{kg}$ TEG per engine. Given the heat flux limitation from the reference engine, the TEG area would, however, need to be increased to $4\,\mathrm{m}^2$ per engine in order to reach the corresponding output power.
In Figure 7, right, the improvement in propulsive efficiency is considered additionally, as discussed in the section on TEG integration, and the requirement on gravimetric power density drops. Here, a $21\,\mathrm{kW}$ offset was subtracted from the heat flux, to account for heat flow from core to bypass in an engine nozzle *without* TEG. Therefore, below the solid line, no positive effect is seen. Heat flux is increased up to twice the value of the reference engine, assuming that heat transfer coefficients at the engine walls may be improved, e.g. by vortex inducing elements on the surface [12]. Due to the coupling of heat flux to output power via efficiency (fixed to 8%), the effect is constant along the isolines of output power. A combined 0.05%-improvement in mission fuel could then be achieved with a $132\,\mathrm{W/m}^2$ TEG of $25\,\mathrm{kg}$ mass per engine, while a $270\,\mathrm{W/m}^2$ TEG of 13 kg could achieve a 0.1% block fuel reduction. In this case, the investigation is restricted to a discrete area of $1\,\mathrm{m}^2$, according to the available data on engine improvement potential due to increased heat flux.

4 CONCLUSION

In this contribution, the effect of integration of thermoelectric generators into the engine nozzle of a 180 PAX, entry-into-service 2035 airliner was discussed. Fuel savings potentials were evaluated based on a rudimentary Breguet range-equation based model, considering an "off-design" mission, and compared with a mission-based model considering aircraft sizing according to mission requirements and reference engine data tables.
Although an "off-design" mission is considered in the simpler model, results are comparable. A requirement on the specific power density of the thermoelectric system in order to reach break-even fuel efficiency of about $180\,\mathrm{W/kg}$ is derived, independent on overall output power. The integration of a thermoelectric generator in the engine nozzle is discussed with regard to space and heat flux limitations. It is shown that the fuel savings potential is in the 0.05%-range, with an "ambitious" TEG (gravimetric power density of $270\,\mathrm{W/kg}$ and assuming that $4\,\mathrm{m}^2$ area is available for integration).
An improvement in propulsive efficiency due to the heat transfer to the bypass can be considered. Due to the limited data on this effect, only the case of a $1\,\mathrm{m}^2$ nozzle / TEG is considered (corresponding to the design engine). In this case, the requirement on specific power density is reduced to around $100\,\mathrm{W/kg}$ – the result depends however on the actual engine geometry and sizing. Overall, 0.1% block fuel improvement may be achieved with a light-weight TEG. It must be noted here that, although thermoelectric materials typically exhibit low thermal conductivity, heat flux is limited by the heat transfer coefficient of the thermal boundary layer. Therefore, improvement of the heat transfer coefficient is a crucial factor in improving electrical output of the TEG, as well as

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potentially improving propulsive efficiency. Additional potentials may arise, on the one hand, by considering larger engine nozzles with additional space for TEG. Moreover, considering integration of TEG into the hotter areas of the engine may also increase TEG efficiency and specific power density, due to higher temperature gradients and heat flux potentials. Finally, specific benefits may be found by adding a DC-voltage source to the aircraft engine.

5 ACKNOWLEDGMENT

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