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NLR-TP-2019-358 | August 2019

Parallel hybrid electric propulsion architecture for single aisle aircraft - powertrain investigation

CUSTOMER: Netherlands Aerospace Centre

NLR – Netherlands Aerospace Centre

EXECUTIVE SUMMARY
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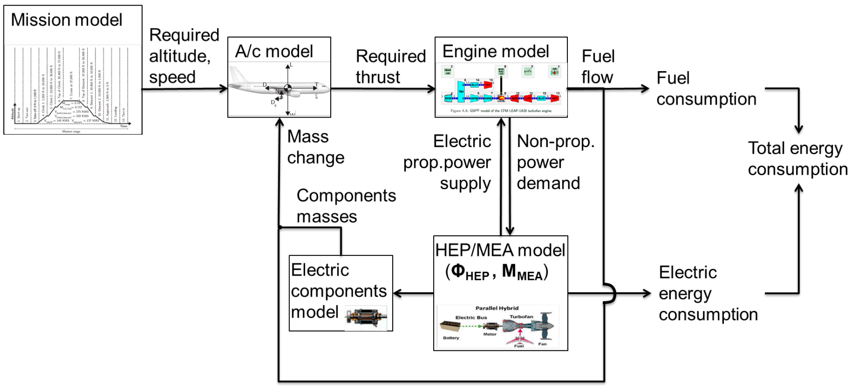

Problem area

Air travel has increased considerably over the past decades and it is expected to double in the next two decades. The combination of the rising demand for air transport and the need to decrease environmental impact of aircraft (exploitation of non-renewable fossil fuels, emission of greenhouse gasses and particles, and noise) put a strong challenge on the aircraft industry to come up with innovative technologies.

In the automotive industry hybrid and fully electric cars are rapidly developing in order to reduce environmental impact. In the aircraft industry, the fully electric propulsion has been introduced for light aircraft so far. The low power-to-weight and energy-to-weight ratios of electric components (in particular of batteries) hold back the development of fully electric commercial passenger aircraft. Nevertheless, Hybrid Electric Propulsion (HEP) systems may bring solutions, combining state of the art turbofan engines with innovative electric systems.

Another clear trend in aircraft design is the electrification of non-propulsive systems. More Electric Aircraft (MEA), like the Boeing 787, feature advanced electrically powered systems instead of conventional hydraulic and pneumatic counterparts.

There is a strong interest to analyze the fuel and energy saving potential of HEP – e.g. in combination with the MEA approach - for single aisle passenger aircraft.

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Description of work

This paper presents an aircraft level model study of the fuel- and energy-saving potential of parallel HEP in combination with MEA retro-fitted on an A320NEO aircraft. This study was performed in the context of the EU Clean Sky 2 project NOVAIR. The following main electric systems are considered: electric motors, batteries and power electronics for parallel HEP, electric components for replacement of the main hydraulic and pneumatic non-propulsive systems like the environmental control system (ECS), flight control system (FCS), ice protection system (IPS) and landing gear (LG) actuation. Besides these electric system models, also models of the aircraft, turbofan engine and flight mission are used to quantify the power and fuel needs and account for system mass changes involved with the electric components replacements. The results in terms of fuel- and energy consumption for the considered missions, as well as some transport energy metrics are reported.

Results and conclusions

A potential trip fuel reduction of about 14% is found for the HEP+90%TF+MEA-architecture with 2040-level of electric technologies. About half of this reduction comes from the HEP with downscaled engine (HEP+90%TF) and the other half from the introduction of the MEA systems. But it should be noted that this reduction is found in this study where only short mission range (800nm) is considered. Also for parallel HEP it is assumed that the electric motor, which is sized at about 4MW, can be installed on the fan shaft of CFM-LEAP and friction- or gear losses have been neglected.

Applicability

Besides the reference mission with a design range of 1500km, cruise speed of Mach 0.78 and design payload of 150pax, the parallel HEP technology can be applied to other missions. Indications are found that specific transport energy metrics can be further improved mainly by higher pax missions and also slightly by longer range missions.

GENERAL NOTE

This report is based on a presentation held at the EASN 2019 conference, Athens, Greece, 2 September 2019.

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Contents

Parallel hybrid electric propulsion architecture for single aisle aircraft - powertrain investigation

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Abstract. This paper presents an investigation of the fuel- and energy-saving potential through the introduction of several hybrid electric propulsion (HEP) and more electric aircraft (MEA) systems on single aisle aircraft. More specifically, for an A320NEO aircraft the following main electric systems are considered: electric motors, batteries and power electronics for parallel HEP, electric components for replacement of the main pneumatic and hydraulic non-propulsive systems like environmental control system and actuators, and electric power transport and supply. The power sizing of the electric components, as well as their mass effects on overall aircraft mission performance are evaluated by system modelling of the aircraft, turbofan and the considered electric components. It is found for the considered aircraft and missions that the fuel saving potential of parallel HEP systems alone is very limited or absent. Typically the combination of HEP and MEA technologies shows potential for improved energy efficiency due to synergies of the involved systems and their operation. System evaluations indicate potential, in comparison to the reference A320NEO aircraft, of approximately 14% reduction of trip fuel and 11% reduction of trip energy for short haul missions of about 800nm.

Keywords: HEP, MEA, A320NEO, GSP, mission evaluation

1 Introduction

In response to the ongoing strong growth in air traffic (e.g. [1]) and its impact on the natural environment, ambitious targets and roadmaps for future aviation have been defined (e.g. [2], [3]). One of the key components to achieve the necessary reduction of fossil fuel consumption and global air traffic emissions is the further advancement of airframe and propulsion innovations and the related technology developments. Hybrid electric propulsion (HEP) has been identified as one of the potential solution areas [4],[5]. HEP systems were first introduced on a large scale in the automotive sector and are now making their way to the aviation industry. These HEP systems attempt to reduce fuel consumption and emissions of traditional combustion engines through hybridisation via electrical energy sources. Another trend in the aviation industry is the electrification of aircraft subsystem architectures. Such so-called "more electric aircraft" (MEA), as for example the Airbus A350 or the Boeing 787, feature advanced electrically powered subsystems instead of the conventional hydraulic and pneumatic counterparts for non-propulsive on-board functions.

With the current state of technology, full electrification of propulsion for large civil aircraft and medium haul or long haul flight is not realistic. This is because such flights require very high levels of power and energy. With the current relatively low values of specific power and specific energy of state-of-the-art electrical systems, this would lead to very high mass of the electric propulsion and energy storage system. Therefore it is expected for the next decades that gas turbines will remain to play a crucial role in propulsion of large aircraft. But it is also expected that the combination of gas turbines with electric motors in HEP systems has potential to reduce fuel consumption and gas and noise emissions of large aircraft [5].

A variety of system architectures can be applied for aircraft HEP powertrains [6]. The feasibility of these HEP powertrains and their potential for improving the fuel- and energy efficiency of aircraft depends on the choice of HEP system architectures and power management strategy. This paper focuses on the power management and system sizing of a so-called parallel HEP architecture. This parallel architecture applies an electric propulsion powertrain in parallel to a conventional gas turbine powertrain that is typically installed as a turbofan engine. In such a parallel HEP architecture the electric powertrain supports the aircraft propulsion in flight phases where power demand is very high, typically the take off and climb phases. In addition, the electric systems in such HEP architecture can be combined well with more electric non-propulsive systems as found in MEA, yielding potential savings in overall fuel and energy consumption due to synergies in

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systems deployment. This paper presents an aircraft level model study of the fuel- and energy-saving potential of HEP in combination with MEA retro-fitted on an A320NEO aircraft. The following main electric systems are considered: electric motors, batteries and power electronics for parallel HEP, electric components for replacement of the main hydraulic and pneumatic non-propulsive systems like the environmental control system (ECS), flight control system (FCS), ice protection system (IPS) and landing gear (LG) actuation. Besides these electric system models, also models of the aircraft, turbofan engine and flight mission are used to quantify the power and fuel needs and account for system mass changes involved with the electric components replacements. The results in terms of fuel- and energy consumption for the considered missions, as well as some transport energy metrics are reported.

The investigations described in this paper have been performed as part of the NOVAIR project, which is carried out at Delft University of Technology (TU Delft) and the Royal Netherlands Aerospace Centre (NLR) as part of the EU Clean Sky 2 program for Large Passenger Aircraft (EU CS2 LPA) [7].

2 Modelling approach and implementation

2.1 HEP architecture

The investigations in this study focus on a parallel HEP architecture implemented as an electrically assisted turbofan powertrain. This powertrain is assumed as a traditional turbofan engine, with an electric motor that provides additional power to the Low Pressure Turbine (LPT) shaft (Fig. 1). The exact installation details of the electric motor on the LPT shaft are not considered in this study and it is assumed that the electric motor can provide a desired torque at a given LPT shaft-speed as dictated by the turbofan engine controller. Such a controller is typically the so-called FADEC (full authority digital engine control), which however also is not explicitly considered in detail in this study.

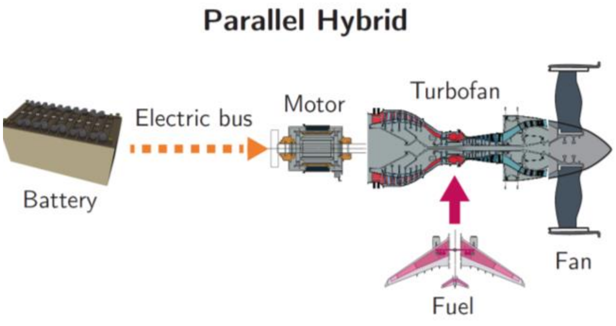

Fig. 1. Schematic of the parallel HEP architecture as considered in this study [6].

The sizing of the electric motor and the other electric components (batteries, etc) is based on the level of power (and energy) that shall be supplied to the fan shaft. This power level is expressed as an electrification ratio (φ_H) of the HEP system which is defined as the momentary electric power supply divided by the momentary total power. For simplification, the electrification ratio is assumed constant within one flight-phase. Suitable values for the electrification ratio have been determined in previous studies [8] from multiple sweeps of mission-evaluations aimed for minimal trip-fuel and –energy. The values 0.15 in take-off, 0.1 in climb and 0.0 in all other flight-phases are used in this study.

The implementation of the HEP architecture is achieved as an integrated system model in MATLAB [9]. It integrates the other component models that will be explained in the following sub-sections.

2.2 Engine model

The turbofan engine is modelled with NLR's Gas-Turbine Simulation Program (GSP) [10], which is based on thermodynamic modelling of mass- and energy-balances of the main engine components (compressors, combustor, turbines, fan etc.) (Fig. 2). The GSP model allows to simulate effects on fuel consumption of the common primary aircraft operational parameters like thrust, speed, altitude and payload. But also does it allow to simulate effects on fuel consumption of secondary parameters like bleed off-takes from the various compressor stages or mechanical shaft power off-takes from the LPT or High Pressure Turbine (HPT) shafts. Vice versa, the GSP model also allows to simulate the supply of mechanical power to the LPT or HPT shafts, and the effects of that on fuel flow in the engine. That is exactly what is of interest in parallel HEP system studies: the effects on the turbofan fuel flow of mechanic power supply through electric motor drives to the LPT or HPT shafts. Moreover, for MEA system studies there is typically an interest in the effects of bleed off-take variations on fuel flow. Also these effects can be simulated with the GSP model. The use of such a GSP engine model in HEP system studies is described in more detail in [11].

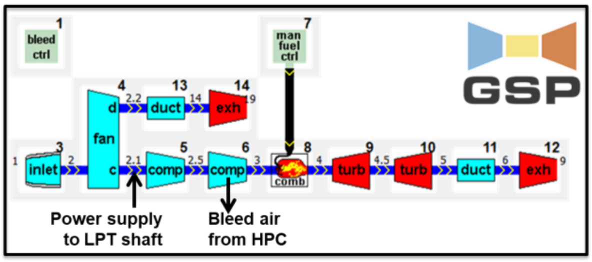

Fig. 2. Turbofan engine model as implemented in NLR's software tool GSP (Gas-Turbine Simulation Program) [10].

In the present study an engine model of the CFM-LEAP-1a26, which is one of the engine options on the

A320NEO aircraft, has been implemented in the GSP software. The main specifications of the CFM-LEAP engine as incorporated in the GSP model are given in table 1 below.

Table 1. Main specifications of the CFM-LEAP engine as incorporated in the GSP model. [12]

CFM-LEAP-1A property	Value
Engine mass (wet) [kg]	2990
Max. take-off thrust [kN]	120
Max. continuous thrust [kN]	119
Overall pressure ratio [-]	40
LP rotor speed (N1 100%) [RPM]	3856
HP rotor speed (N2 100%) [RPM]	16645
Number of compressor stages (fan/LPC/HPC)	1/3/10
Number of turbine stages (HPT/LPT)	2/7

A surrogate model was derived from the GSP model for integration with the system model in MATLAB. Details on the surrogate modelling process are given in [13].

2.3 HEP electric components models

The electric components in the HEP system that are considered in this study are the electric motors that drive the LPT shafts, power electronics (mainly inverters), electric power cables and batteries. The electric components are included as mass contributions in the overall system model. As such, the electric components are included as basic "black box" models, with electric power and/or energy demands as inputs, and predicted component mass as output (Fig. 3).

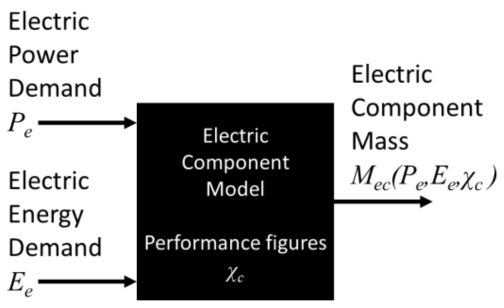

Fig. 3. The electric components are included as basic "black box" models.

For electric motors and power electronics the mass is determined from the required *maximum power level* of the electric system and from the specific power and the energetic efficiency of these components. For batteries the mass is determined from the required *maximum energy consumption* of the electric system and from the specific energy of the batteries. Of course, also the required *maximum power level* and the specific power of the batteries is important, but in this study the *maximum energy consumption* of the battery dominates the sizing process. Furthermore the battery energy efficiency and minimum state of charge (SoC) are taken into account in the sizing process. The batteries' energetic efficiency accounts for the recharge energy losses and therefore is only used for the total energy calculation, not for the battery mass calculation. Energetic efficiencies of electric power cables are also accounted for. The electric components models are described in more detail in [8].

There is a strong technology development ongoing in this field of electric components, mainly driven from other industrial sectors like automotive and consumer electronics. Because this development is expected to continue in the coming decades, short term and long term levels of technology development are considered here. These levels correspond to the year 2020 onwards (expressed here as 2020+) and the year 2040 onwards (expressed here as 2040+), respectively. For both levels, performance numbers in this study were derived by averaging results from publicly available feasibility studies, as given in table 2 below. It should be noted that the uncertainty of these numbers is high because of the large spread in the numbers obtained from literature.

Table 2. Main performance numbers of the electric components for the two technology levels (2020+ and 2040+) considered in this study.

Electric components performance	2020+	2040+
Batteries		
Efficiency [%]	92.5	95.0
Specific power [kW/kg]	3.0	6.0
Specific energy [kWh/kg]	0.5	1.0
Electric motor		
Efficiency [%]	95.0	98.0
Specific power [kW/kg]	7.5	15.0
Power electronics		
Efficiency [%]	95.0	98.0
Specific power [kW/kg]	7.5	15.0
Power cables		
Efficiency [%]	99.0	99.6

With these electric components performance numbers, the sizing of the components and their weight calculations can be done from the power and energy requirements that come from the aircraft level analysis. Of course, these component weights and sizes have effects on the aircraft level power and energy evaluations and therefore shall be determined in an iterative system level design process. This process is explained in [13].

2.4 Aircraft model

For the prediction of the aircraft thrust requirement during the mission a basic aerodynamic "point mass" model is used in this study (Fig. 4). Only forward flight and flight path angle is included in the present study's flight mission; turns and manoeuvres and roll and yaw rotations are not considered.

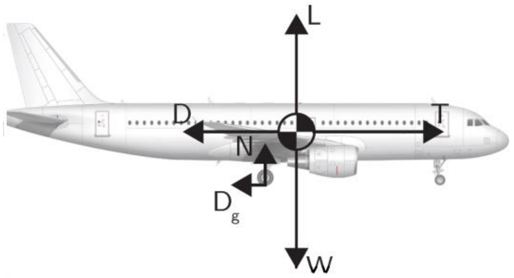

Fig. 4. Illustration of the basic aerodynamic "point mass" model that is used for prediction of the aircraft thrust requirement during the mission.

The main characteristics like the various mass components (airframe, engines, electric components, fuel, payload) and the aircraft lift and drag coefficients are included in this model. Because the HEP system investigations are focussed on certain flight phases, the aircraft model is intended to be representative for these flight phases, including taxi-out, taxi-in, take-off, climb and descent/landing. To account for this, also the dependency of the aerodynamic coefficients on flap and gear settings and Mach number and the ground rolling friction are incorporated, as well as the actual time-dependent fuel mass. Hence the aircraft model also allows for simplified calculation of the required thrust during taxi, take-off, descent and landing. This model is described in more detail in [13].

The implementation of this aircraft model has been achieved in MATLAB. The main model parameters used for the A320NEO aircraft (A320-251N, [14],[15]) that is considered in this study are given in the table below (table 3).

Table 3. The main specifications for the A320NEO aircraft.

A320NEO property	Value
Max. take-off mass [t]	73.5
Operating Empty mass [t]	45.7
Max. landing mass [t]	66.3
Wing area [m^2]	122.0
Wing span [m]	34.1

2.5 Mission model

The mission model produces all the relevant flight path variables (distance, altitude, speed, flight path angle, flap and landing gear settings) as a continuous function of time. As inputs, these variables shall be prescribed at the start and end of each of the considered flight-phases expressed as function of distance. Linear interpolation between start and end of each flight-phases is used for each of the prescribed variables. Flight time for each flight-phase is calculated from the distance travelled at the interpolated speed.

Table 4. Inputs for the relevant flight path variables that are used in the mission model, values derived from (Airbus, 2002). Flight phase indicators: (0): start of mission; (1): end of taxi out; (2) end of take-off; (3) end of climb; (4) end of cruise; (5) end of descend; (6) end of taxi in.

Flight-phase id	(0)	(1)	(2)	(3)	(4)	(5)	(6)
Distance [km]	0	4.5	18	289	1308	1514	1534
Altitude [m]	0	0	457	11277	11277	457	0
Calibrated air speed [m/s]	0	15	129	130	130	129	15
flight path angle [deg]	0	0	5	1	0	-3	0
flap settings [deg]	0	42	0	0	0	35	0
landing gear settings [-]	1	1	0	0	0	1	1
electrification ratio [-]	0	0	0.15	0.1	0	0	0

For the considered mission the resulting relevant flight path variables as function of time are given in the figure below (Fig. 5).

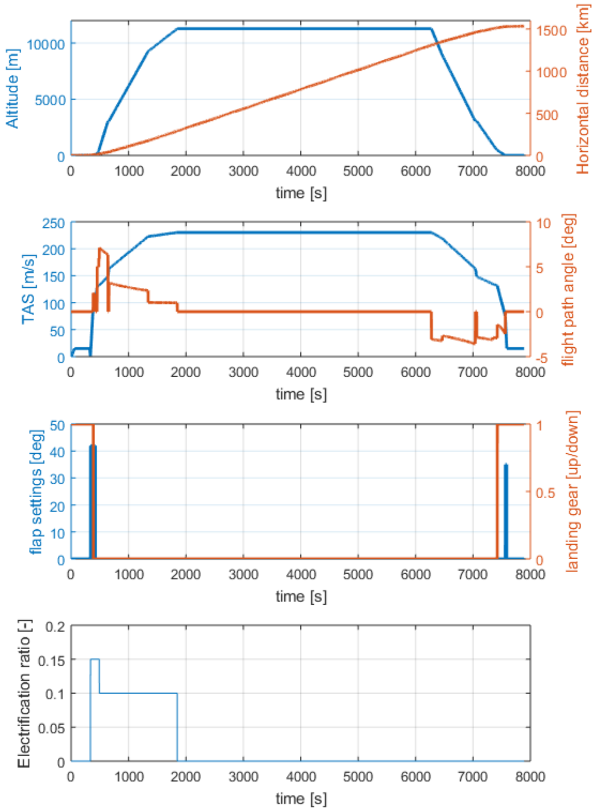

Fig. 5. The resulting relevant flight path variables (distance, altitude, air speed, flight path angle, flap settings, landing gear settings, electrification ratio) as function of time for the considered mission.

2.6 System model

All the models described in the previous sub-sections are integrated in an aircraft level system model. This system model is implemented in MATLAB and is used in the aircraft level design process for the iterative evaluation of power and energy consumption during the considered mission. A schematic representation of this iterative evaluation process with the system model is given in (Fig. 6) below.

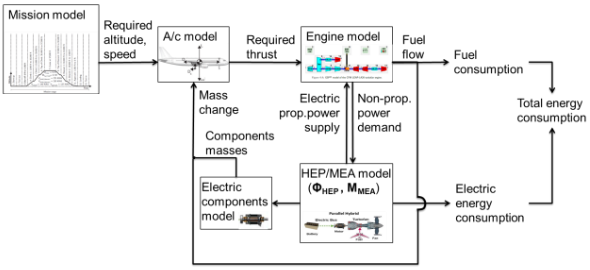

Fig. 6. Schematic of the iterative system level design process with the system model for the aircraft level power and energy evaluation.

The system model has been validated in a previous study [8] for an A320 aircraft and a 1000 km mission with 17t payload. The results for this mission were compared with Piano-X [16] and showed good correspondence, as illustrated below (Fig. 7) for the fuel flow prediction.

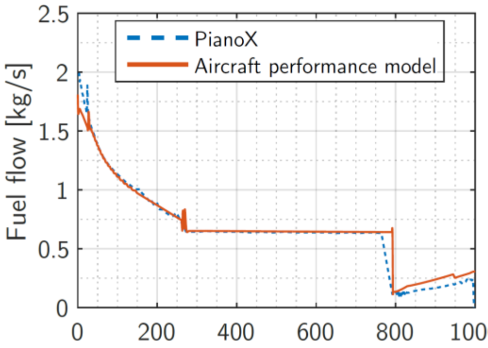

Fig. 7. Illustration of the fuel flow prediction validation of the aircraft performance model with Piano-X [8].

In the present study, the mission evaluation is first performed for the reference aircraft, i.e. the A320NEO with the LEAP-1A engine without any HEP or MEA systems. Then subsequently the various components of the HEP and MEA systems are included in the system model and the corresponding power demands and systems sizing are accounted for. First the evaluations will be done using the performance numbers of the electric components for the 2020+ technology level and subsequently for the 2040+ technology level. This procedure will be briefly explained in the following section, along with the presentation of the results.

3 RESULTS

For the HEP and MEA system sizing we consider as mission requirements, among others, a short mission range of 1500km (800nm), cruise speed of Mach 0.78, and a payload of 150pax (i.e. 14.3t). Furthermore a fixed fuel mass of 1.8t is used, which is assumed as the total of alternate, contingency and reserve fuel masses (estimated from [17]). Also the system sizing respects the main aircraft level specifications of the A320NEO like MTOW.

3.1 Reference aircraft

In the reference aircraft mission evaluation the fuel consumption is calculated with the system model presented in the previous section. This mission evaluation includes representative settings for bleed air off-takes and mechanical shaft-offtakes from the engines. The reference aircraft model is based on the A320NEO and does not comprise any of the HEP or MEA components.

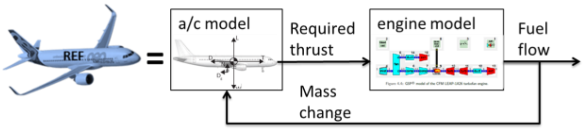

Fig. 8. Illustration of the reference aircraft model as considered in this section, shown in the colouring scheme used in this section (i.e. blue for reference aircraft).

The bleed air mass flow fractions and LPT shaft power off-takes in all flight phases that are used are given in the table 5. The flight phase numbers correspond to the numbers used in table 4.

Table 5. The bleed air mass flow fractions and LPT shaft power off-takes, per engine, in all flight phases. [18]

Flight-phase id	(0)	(1)	(2)	(3)	(4)	(5)	(6)
bleed air mass flow [%]	0	0.1	0.03	0.05	0.06	0.1	0.04
LPT-offtake [kW]	0	35	37	42	40	35	35

From the reference aircraft mission evaluation it is found that the trip fuel consumption for this mission is about 5.5t. This results in a take-off mass for the reference aircraft of 67t. Because 73.5t is used as the maximum take-off weight (MTOW) of the A320-NEO [12], this leaves an approximate 'mass budget' of about 6.5t that can be spent on HEP and MEA system components.

3.2 HEP

First we consider the sizing of only the HEP system for the parallel hybrid architecture as explained above (sec. 2.1). The main change in comparison to the reference aircraft is the installation of an electric motor on the fan shaft of the turbofan, batteries for the electric energy supply of electric motor and the necessary wiring and power electronics. The turbofan engine is not changed. Effectively in the system model these changes are included as additional system masses from all the electric equipment and as mechanical power supply (from the electric motor) to the fan shaft of the engine model. The sizing of the electric components is based on the level of power that shall be supplied to the fan shaft, which depends on the total propulsive power demand and the electrification ratio of the HEP (φ_H) (see table 4). The sizing of the electric equipment for the considered mission and for the 2020+ technology level yields a total mass increase of about 5906kg, resulting in higher lift-, drag- and required thrust forces. Integration of the fuel flow over the whole mission, as calculated with the engine model, leads to an overall change in trip fuel of about +2% (126kg) and trip energy of about +5%, in comparison with the reference aircraft. (see fig. 7).

3.3 HEP + 90%TF

The electric components of the HEP system introduce additional mass, which obviously leads to increased fuel consumption (+2%). But the HEP also provides additional power to the fan shaft, which allows to reduce the maximum power capacity of the turbofan (TF) core. Therefore we also include the downscaling of the TF in the engine model, here approximated as a reduction of engine core diameter with corresponding mass reduction and other dependent engine parameters like mass flow and shaft speed as explained in [8]. In this way the GSP engine model is extended and allows to predict the main effects in engine mass and fuel flow for downscaled engine size. With the 15% power supply from the HEP system in take-off condition it was estimated that 15% downscaling of the TF engine would be allowable. However it turned out from the mission evaluations with the extended GSP engine model that in this case more than 10% downscaling (i.e. below 90% of the reference core diameter) yields in-allowable exhaust gas temperatures at the HPT first stage. Therefore we limit the TF engine downscaling to 90%, expressed here as 90%TF. This results in, among others, an engine mass reduction of about 400kg (total for two engines) and slightly improved cruise SFC (SFC decreases with 3%: from 17.7 g/kN/s to 17.1 g/kN/s).). This yields an overall change in trip fuel of about -5% (273 kg) and trip energy of about -5% (-3MWh), in comparison with the HEP-only aircraft.

3.4 HEP + 90%TF + MEA

To better exploit the electric systems of the HEP architecture and to optimize synergies in systems deployment, we also include more electric non-propulsive systems. In such a MEA system architecture, all pneumatic and hydraulic components in the non-propulsive systems, like ECS, ice protection, landing gear, flight controls, are replaced by electric systems. This was investigated in some detail for single aisle aircraft in [19], and the main changes in system masses are given in table 6 below.

Table 6. Mass changes for converting from conventional to electrical subsystem architecture [19].

MEA system	Mass change [kg]
Actuation of FCS and LG	-455
LG brakes and steering	-99
IPS	+34
ECS	+80
Other (removal of hydraulic and pneumatic systems)	-540
Total	**-980**

The non-propulsive power demands for the MEA architecture during the mission are assumed to be constant per flight phase, as listed in Table 7.

Table 7. Total non-propulsive electric power demands for the MEA architecture during the mission [19], [18].

Flight-phase id	(0)	(1)	(2)	(3)	(4)	(5)	(6)
MEA power demand [kW]	0	258	256	352	354	286	204

For this configuration, the sizing of the electric equipment yields a total mass increase of about 359 kg (1339 kg increase due to additional battery mass minus 980 kg saving due to application of the MEA systems architecture).). Integration over the whole mission of the fuel flow leads to an overall change in trip fuel of about -7% (~380kg) and trip energy of about -7%, in comparison with the HEP+90%TF aircraft.

To clarify which mission and which aircraft architecture are considered in this section, we present the colouring scheme shown in Fig. 9 below.

Fig. 9. Illustration of the reference mission (left picture, illustrating a generic mission altitude profile) and each of the aircraft architectures as considered in this section, shown in the colouring scheme for the reference aircraft (blue) and HEP architectures (i.e. red, green, purple for the various HEP architectures) for the 2020+ scenario.

An overview of the main results from the mission evaluations for each of the HEP architectures is given in Figs. 9-10 below.

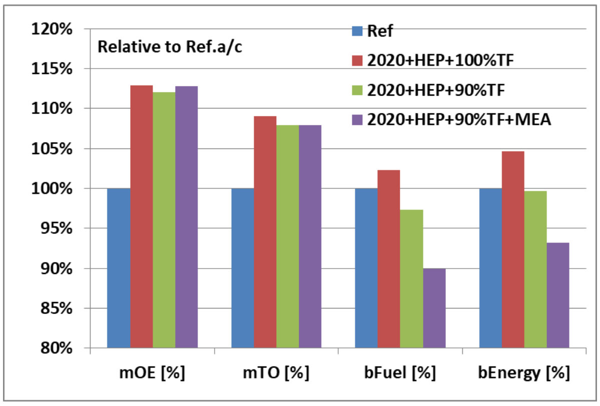

Fig. 10. Main masses (operative empty mass (mOE) and take-off mass (mTO)) and performance results (trip fuel mass (bFuel) and trip energy (bEnergy)) of the analysed HEP architectures according to the 2020+ scenario. All results are given as relative change in percent compared to the values that were found for the reference aircraft, and shown in the colouring scheme for the HEP architectures.

3.5 2040+ technology level

To take the technology development of the electric components into account, the mission evaluations for each of the HEP+MEA configurations are also performed for the 2040+ technology level. The performance numbers of the electric components given in table 2 for 2040+ are now used for the sizing of the components and their weight calculations in these mission evaluations, with all other settings unchanged. An overview of the main results is given in the Figs. 11-12 below.

Fig. 11. Illustration of the reference mission (left) and each of the aircraft architectures with 2040+ technologies as considered in this section, shown in the colouring scheme for the aircraft propulsion architectures.

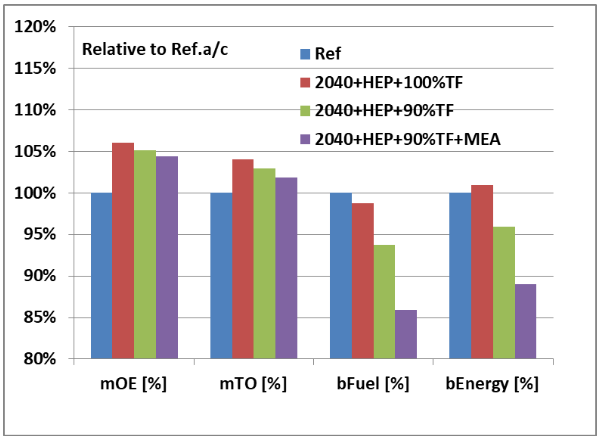

Fig. 12. Main masses of the analysed HEP architectures according to the 2040+ scenario. All results are given as relative change in percent compared to the values that are found for the reference aircraft, and shown in the colouring scheme for the HEP architectures.

3.6 Mission range, cruise speed and payload

The mission evaluations so far were only performed for the design range of 1500km, cruise speed of Mach 0.78 and design payload of 150pax. To investigate the effects of range, speed and payload variations on the potential reduction of trip fuel and –energy, we evaluate the mission of the 2020+ scenario for each of these variations. Therefore, variations of ±150km in range, ±0.04M in cruise speed, and ±15pax in payload are considered.

From the evaluations in the previous sections 3.1 to 3.4 it was found that for the 2020+ scenario the HEP+90%TF+MEA-architecture showed the best potential for reduction of trip fuel and –energy. Therefore the mission variations are evaluated only for this aircraft architecture. The main results of the evaluations for this architecture in the 2020+ scenario for each of these mission variations are given in the graph below (Figs. 13-14). The results from these variations are compared to the results for the reference mission with the same HEP+90%TF+MEA-architecture. To make extra clear that in this section only *one HEP architecture* and *several different missions* are considered, this is expresses in fig. 13 in the corresponding colour coding (i.e. purple for the HEP+90%TF+MEA-architecture).

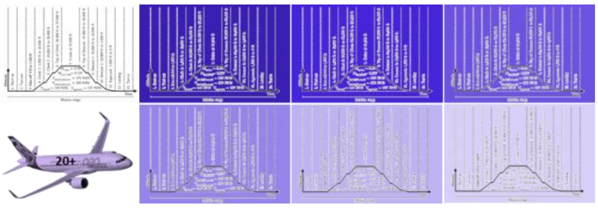

Fig. 13. Illustration of the reference mission and the 2020+HEP+90%TF+MEA aircraft architecture (on the left), and each of the 6 mission variations (on the right) as considered in this section, shown in the colouring scheme for the HEP architectures.

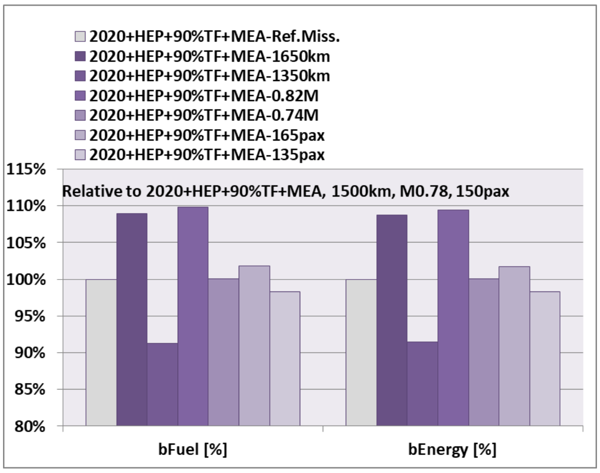

Fig. 14. Trip fuel mass and trip energy results of the mission variations for the HEP+90%TF+MEA-architecture according to the 2020+ scenario. All results are given in percent relative to the values that are found for the same architecture in the reference mission (1500km, M0.78, 150pax).

In a closer look at the results, we find that the variations in *range* and *pax* yield consistent sensitivities, i.e. similar gradients for increase and decrease of the independent variable, see the table 8 below. However, the variations in *speed* yield very different sensitivities for increase and decrease of the independent variable. This implies that flying at cruise Mach higher than 0.78 would increase trip fuel and -energy, but lower than 0.78 would also increase slightly the trip fuel and –energy. So Mach 0.78 seems to be an optimum speed for this aircraft architecture.

Table 8. Sensitivities of trip fuel and -energy to the variations of range, speed and pax for the HEP+90%TF+MEA-architecture.

Variable: *Range*	Δfuel/Δrange [kg/10km]	Δenergy/Δrange [MWh/10km]
range 1650km	29.36	0.356
range 1350km	28.65	0.347

Variable: *Speed*	Δfuel/Δspeed [kg/0.01mach]	Δenergy/Δspeed [MWh/0.01mach]
speed M0.82	12.04	0.144
speed M0.74	-0.066	-0.00127

Variable: *Pax*	Δfuel/Δpax [kg/pax]	Δenergy/Δpax [MWh/pax]
165pax	5.866	0.0717
135pax	5.608	0.0686

3.7 Transport energy metrics

The analyses so far have focussed on the trip fuel and –energy consumption for the considered missions. That is adequate for comparison of the various HEP architectures. But for a wider assessment of the fuel- and energy-efficiency of these architectures (e.g. taking into account mission variables such as range, speed and payload) also some other energy metrics can be considered, for example as addressed in [20].

For sensible quantification of the effects of the mission variations we can calculate the *energy-efficiency* metrics that are used in transport analysis, which express the distance that can be travelled per amount of energy [21]. However, the more commonly used metric in transport is the *energy-consumption* metric, which expresses the inverse, i.e. the amount of energy needed to move a certain payload over a certain distance. This can also be considered as a *specific-transport-energy* (STE) metric, that would be typically expressed as unit of energy per unit of mass per unit of distance (in SI: J/kg/m). Because in this study we only look at passenger transport aircraft we will express this metric in the unit that is more commonly used in air transport studies: kg_fuel/pax/100km, where kg_fuel represents 1kg of Jet-A1 kerosene with a specific energy of 43MJ/kg, pax represents 1 standard passenger with a mass of 95kg and 100km represents 100.000m of travelled distance. It should be noted that for the HEP mission evaluations, where besides the energy from fuel burn also the energy from electric discharge of batteries (or from other electric energy storage systems) is consumed, both the direct fuel burn and the total amount of energy can be expressed in kg_fuel. As such, three variants of this metric should be distinguished: the *specific-transport-energy-fuel-only* (STEF), the *specific-transport-energy-battery-only* (STEB) and the *specific-transport-energy-total* (STET). For easier comparison with other (hybrid-) electric transport studies, the second (STEB) may also be expressed in kWh/pax/100km. The results for the STEF, STEB and STET metrics for the mission variations are given in Fig. 15 below.

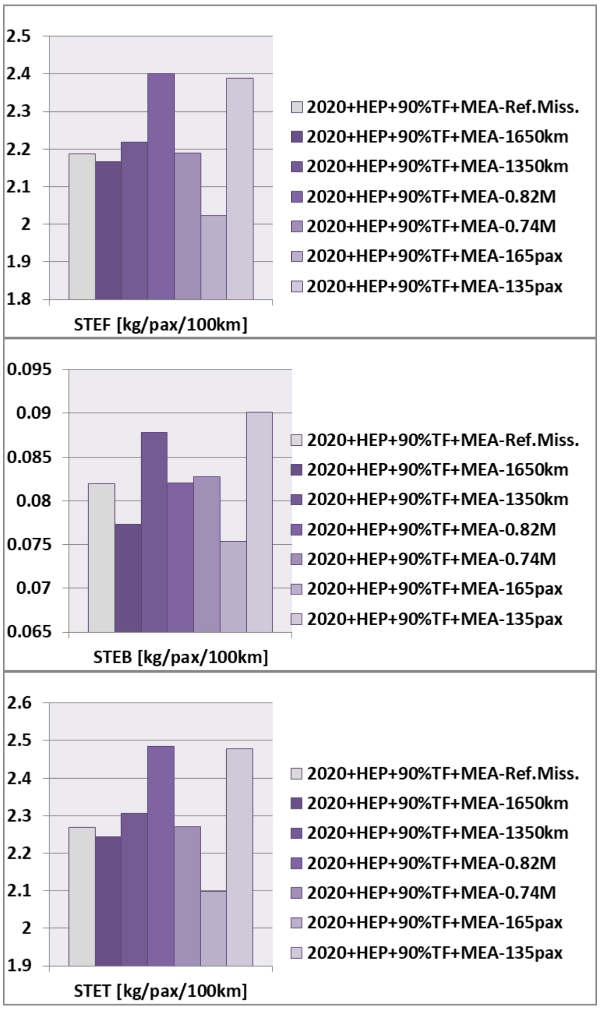

Fig. 15. STEF, STEB and STET results of the mission variations for the HEP+90%TF+MEA-architecture according to the 2020+ scenario. All results are given in the units indicated.

Clearly, the best (lowest) STEF, STEB and STET values are found for the 165pax mission. The worst STEF and STET values are found for the Mach 0.82 mission, which indicates the energetic disadvantage of high speed transport. Quite poor (high) values for STEF, STEB and STET are also found for the 135pax missions. These results underline that maximizing payload is quite important for transport energy efficiency.

In the mission variation studies we include the variation of cruise speed. Because drag force is an important factor for air transport energy-consumption and because drag force is proportional to the square of air speed and because it increases even more with high Mach numbers, a variation in cruise speed will lead to a change of the *transport-specific-energy* metric. As such, the *transport-specific-energy* metric does account for the *energetic effects* of changing the speed of travel. But it does not account for the *trip-time effects* of changing the speed of travel. Motivation for taking the trip-time into account is that a reduced trip-time that results from increased cruise speed yields a benefit to the passenger, which should also be incorporated in the metric. Therefore, to take this trip-time effect for variation of speed into account, we introduce an additional metric that will be used to evaluate our results: the *specific-transport-energy-speed-corrected* (STES). Just like STE, this metric also can be considered for fuel-only consumption (STESF), only battery energy consumption (STESB) or total energy consumption (STEST). We will limit this paper to only STEST, because the total energy consumption is most relevant for the considered HEP architecture. The STEST metric may be expressed with the units used so far in MWh/pax/100km/(100km/hr), but interpretation of results would be cumbersome. Therefore we choose the energy based representation and simplify the unit to SI: [J/kg/m/(m/s)], which further simplifies to [1/s].

The results for the STEST metric are given in Fig. 16 below.

Fig. 16. STEST results of the mission variations for the HEP+90%TF+MEA-architecture according to the 2020+ scenario. All results are given in the units indicated.

In comparison with the STET values (given in Fig. 15) the benefit of the increased cruise speed for the STEST values (Fig. 16) can be clearly observed. The energetic in-efficiency of the high speed missions (as found with the STET metric) is much compensated with the benefit of the shorter mission duration. The vice versa result is found for the low speed mission. (The STET value is close to the STET value of the reference mission, but the STEST value is higher than the STEST of the reference mission)

We can also compare the results of the STET and STEST metrics for our HEP aircraft configuration for the reference mission (2.3 kg/pax/100km and 0.054 1/s, resp.) with typical values for other transport modes, where we made assumptions for the passenger occupation and average trip speed for these transport modes [21] as indicated in the table 9 below. It should be noted though that estimated average passenger occupation of cars and trains is much lower than 100% [21].

Table 9. STET and STEST metrics for HEP aircraft configuration for the reference mission compared with typical values for other transport modes.

Transport Mode	Avg. trip pax /max pax [-]	Avg. trip speed [m/s]	STET [kg/pax/100km]	STEST [1/s]
Bicycle	1/1	4.2	0.26	0.280
Toyota Prius high occupation	4/5	27.8	0.84	0.135
Train ICE-3 (Cologne-Berlin 475km/4.3h)	441/ 441	30.8	0.88	0.130
HEP+90%TF+ MEA-Ref.mission	150/ 150	190.1	2.28	0.054
Train Fuxing (Beijing-Shanghai 1302km/4.3h)	1193/ 1193	81.1	0.32	0.018

For the STET metric we find unbeatable performance of bicycle transport, but range and speed are very low resulting in a poor STEST value. Automotive transport with high pax occupation has much higher range and speed and thus a better STEST value. With its much higher speed, HEP aircraft has a better STEST value than medium range train transport. But long range train transport with full pax occupation beats all in STEST value and has a STET value competitive to bicycle transport.

4 Conclusions

An aircraft level model study has been executed of the fuel- and energy-saving potential of HEP in combination with MEA retro-fitted on an A320NEO aircraft. System models of the aircraft, turbofan engine, the more electric components and the flight mission are used to quantify the power and fuel needs and account for system mass changes involved with the electric components replacements. The results in terms of fuel- and energy consumption for the considered missions, as well as some transport energy metrics are reported.

The aim with the considered parallel HEP architecture is to electrically support the turbofan engine in the flight phases where thrust demand is high and efficiency is low, thus allowing for down-scaled, smaller, lighter and more efficient turbofan engine core. In combination with MEA the potential efficiency can be further improved.

A potential trip fuel reduction of about 14% is found for the HEP+90%TF+MEA-architecture with 2040-level of electric technologies. About half of this reduction comes from the HEP with downscaled engine (HEP+90%TF) and the other half from the introduction of the MEA systems. But it should be noted that this reduction is found in this study where only short mission range (800nm) is considered. Also for parallel HEP it is assumed that the electric motor, which is sized at about 4MW, can be installed on the fan shaft of CFM-LEAP and friction- or gear losses have been neglected.

From the mission variations it was found that the specific transport energy metrics can be further improved mainly by higher pax missions and also slightly by longer range missions.

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