

Elements of Cycle Design for Parallel Hybrid Mixed Flow Turbofans: Select Trade-Offs in Performance and Energy Efficiency

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Abstract

In the last decade, parallel and serial hybrid combining gas turbine propulsion with electric power systems have been investigated. For the commercial aviation sector, they provide fuel burn and emission reduction potential and have been explored to some extent. Depending on the chosen concept of operation, propulsion cycle, and reference basis, minimal to mild double digit fuel consumption reductions are anticipated. A key challenge remains the low specific energy of current battery technology, leading to a high penalty on electrical energy use. High-speed civil propulsion has gained interest in recent years due to advances in material capabilities and technology enhancements, especially for what concerns aircraft and sonic boom noise reductions. As a result, there is now a renewed and stronger focus on developing supersonic transport aircraft that are environmentally sustainable, technologically feasible, and economically competitive with the existing civil subsonic aviation market sector. The propulsion system for supersonic civil aircraft must satisfy more stringent requirements and more limiting constraints compared to a subsonic application, due to the more severe operating conditions. In this context, the publicly available literature is more oriented towards aircraft rather than propulsion system design. For high-speed propulsion and supersonic transport, and the corresponding mixed-flow turbofan cycles, very limited research propulsion system-centred is available, both for the conventional design and for hybrid electric integration. For these cycles, both emission reductions, noise requirement compliance, and performance improvement potential are of substantial interest, thus widening the metrics of interest. In this work, a hybrid mixed-flow turbofan configuration is investigated and modelled, and cycle design trade-offs are identified and selected. A non-hybridised baseline configuration targeting low bypass ratios based on performance data obtained from the open literature is considered for comparison. A multipoint synthesis scheme for the gas turbine is combined with a hybrid concept of operations through physics-based cycle modelling and previously published polytropic efficiency corrections. Trade studies are conducted introducing hybrid configuration, analysis on key performance and fuel consumption metrics are presented and recommendations on hybrid potential exploitation are provided.

Keywords: Supersonic Civil Transport, Mixed Flow Turbofan, Multi Point Synthesis Scheme, Parallel Hybrid Configuration, Shafts Hybridization

Abbreviations

AR Area Ratio.

BPR Bypass Ratio.

BTR Begin of Transonic Acceleration.

EIS Entry Into Service.

ETR End of Transonic Acceleration.

FPR Fan Pressure Ratio.

HPC High Pressure Compressor.

HPS High Pressure Shaft.

HPT High Pressure Turbine.

JPL Jet Propulsion Library.

LPS Low Pressure Shaft.

LPT *Low Pressure Turbine.*
LTO *Landing and Take-Off.*
MFTF *Mixed Flow Turbofan.*
MPR *Mixer Pressure Ratio.*
MPS *Multi Point Synthesis.*
MTO *Maximum Take Off.*
NGV *Nozzle Guide Vane.*
OPR *Overall Pressure Ratio.*
PR *Pressure Ratio.*
SFC *Specific Fuel Consumption.*
SFN *Specific Thrust.*
SMCR *Supersonic Mid Cruise.*
SST *Supersonic Transport.*
STOC *Supersonic Top of Climb.*
SV *Synthesis Variable.*
TBU *Uniform Blade Metal Temperature.*
TV *Target Variable.*

1 Introduction

Despite the Concorde's retirement from service in 2003 — driven by technological, environmental, and economic factors — interest in *Supersonic Transport* (SST) persists [1]. Over recent decades, numerous projects and industry collaborations have addressed both longstanding and emerging SST challenges. In [2], the aim is to develop a multidisciplinary framework deepening the understanding for the emissions, *Landing and Take-Off* (LTO), and global environmental impact of supersonic aircraft, strengthening the perspective on required regulations for a novel civil supersonic transport market. Similarly, in [3] the intention has been to pave the way for a sustainable supersonic transport sector, focusing on the environmental impact of the potential high speed propulsion market, investigating different aircraft configurations, propulsion system technologies, and alternative fuels. NASA launched several activities around the supersonic propulsion framework, leading the Supersonic Cruise Research [4] as well as the N+ [5], and the more recent Quiet Supersonic Technology QueSST [6], aimed at designing, building and flying NASA's X-59 supersonic aircraft demonstrator, in order to collect data from public responses, informing regulation and certification processes.

A propulsion system capable of reaching supersonic regimes must endure harsher operating conditions and sustain high fuel efficiency — particularly during supersonic cruise — while complying with low-altitude noise limits and mitigating sonic booms to remain technically and economically viable [7].

Current efforts are therefore mainly concentrated on the environmental impact of the potential supersonic civil aviation sector, and most of the publicly available SST studies focus on environmental constraints, either related to noise during LTO cycles or to pollutant emission evaluations: in [8] the authors carried out a preliminary design of a Mach 1.6 supersonic business jet, considering an initial trade off between efficiency, size and noise during LTO, and through preliminary emissions and noise assessment, confirmed the possibility to achieve satisfactorily current regulations and limitations; similarly, in [9] a design space exploration is performed to

evaluate the effect of additional variabilities (the nozzle throat area in this case) on engine design, focusing again on LTO, and showcasing the interactions between the different requirements at different flight conditions. Different take-off procedures can be considered to evaluate the noise and emission performances during low altitude flight regimes, as investigated in [10], for a supersonic power plant derived from a subsonic turbofan engine maintaining the same core spool. Here noise and emission prediction results are compared with the current available regulations. In [11] and [12] preliminary cycle design investigations are conducted, and the chosen design has been coupled with pollutant emission models, compared with currently available emission estimation methods, and with current limitations.

As anticipated, most of the studies are focused more on the effect of specific flight conditions, especially related to low altitude and LTO operations, and a comprehensive performance assessment of the propulsion system behaviour in other critical condition (i.e. Supersonic Cruise) is not presented.

In subsonic aviation, parallel hybrid-electric configurations have demonstrated *Specific Fuel Consumption* (SFC) benefits without undue complexity [13].

Due to the rising interest in electrified and hybrid propulsion systems, and thanks to the reductions that can be achieved in terms of fuel burned [14], different studies have been carried out for different configurations, mainly related to subsonic applications [15], [16], [17].

This study investigates cycle-design trade-offs for a two-spool *Mixed Flow Turbofan* (MFTF) in a SST application. We compare a baseline configuration to a parallel hybrid-electric architecture, evaluating hybridization potential and system synergies. A *Multi Point Synthesis* (MPS) is employed to identify the engine configuration best able to satisfy the stringent performance requirements of supersonic flight.

The purpose is to highlight the capabilities of the employed methodologies for the specific supersonic application, in order of being able to identify and select engine design trade-off, while adhering to requirements and/or constraints in specific flight conditions.

2 Methodology

In this work, parametric studies are performed to identify possible cycle design trade-offs for a conventional MFTF configuration. Starting from currently available technology levels, the baseline conventional configuration is firstly defined by assuming a future *Entry Into Service* (EIS) year.

The expected improvements linked to the future EIS concerns mainly technological constraints in terms of maximum allowed temperatures, and turbomachinery component efficiencies. The analysis is carried out using a MPS matching scheme approach considering critical corner points in the flight envelope.

Once a suitable baseline configuration is defined, a hybrid-electric configuration is investigated. The effect of the hybridization on the engine design is evaluated and cycle design trade-offs considerations are discussed. The engine schematic considered is presented in Figure 1.

This section is intended to provide additional details on the

simulation platform, the methodology employed, the engine model features, and the description of the case study considered in this work.

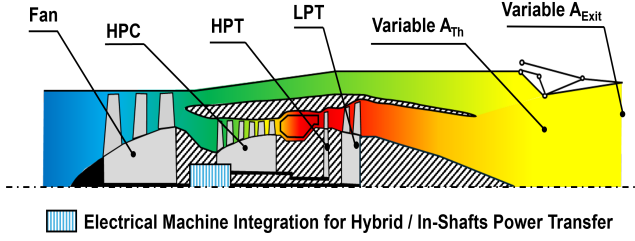


Figure 1: Conventional Hybrid-Electric MFTF Engine Architecture

2.1 Propulsion System Simulation Environment

The gas turbine engine model has been developed in Modelon in-house simulation platform, Modelon Impact. Modelon Impact is a Modelica based simulation tool. It supports system level modelling, simulation, optimisation, and provides a wide range of customizable model libraries. Thanks to the object-oriented and a-causal nature, the resulting equations are processed and symbolically simplified as much as possible, it does not require clear distinction between input and output, and the models developed can be defined through layered and reusable structures [18].

The *Jet Propulsion Library* (JPL) has been deployed in the development of the propulsion system model [19]. It includes a fully rigorous approach for the computations of thermodynamic properties ensuring accurate predictions [20], physics-based component models for aviation and aerospace applications, and custom functions created for the on- and off-design analysis of aero engines, as well as capabilities for the generation of MPS matching schemes.

2.2 Engine Design Process

The methodology employed in the engine design process follows a recent approach based on MPS matching schemes, which gained increasing interest in recent years [17, 21–23]. Traditional aero engine design methods are distinguished by an iterative nature, where the design problem is initially carried out by selecting a specific flight condition in the operating envelope for dimensional sizing. Then the performance evaluation in other key off design conditions is conducted through matching procedures. The design point provides the scaling factors for the turbo machinery characteristic maps and the flow path dimensions, in terms of intake, mixer and nozzle throat areas [24]. Following this approach, the design process might result in an engine configuration that does not satisfy the performance requirements in other key operating conditions, forcing a sequential update of the on-design condition. The introduction of MPS matching schemes allows to consider various key corner points of the flight envelope during the design phase, while concurrently defining a reference condition. Following the terminology proposed in [25] and then later further discussed in [26] and [27], the variables of in-

terest are defined either as synthesis or target. A *Synthesis Variable* (SV) is a user defined independent variable, being iterated in the synthesis matching scheme by setting residual closure equations on the corresponding *Target Variable* (TV), representing instead the actual performance target or technological constraints to be considered in the overall design process. Figure 2 provides a flowchart example of the methodology employed.

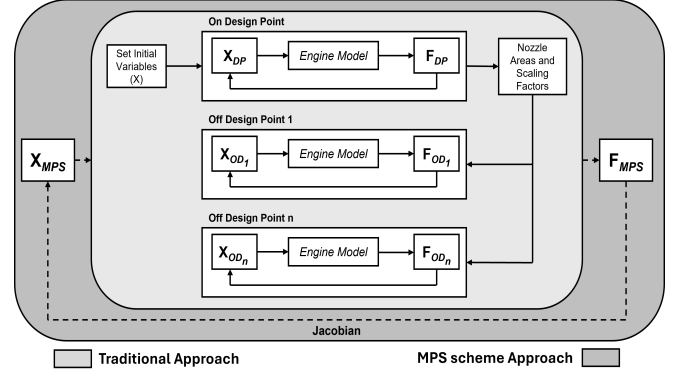


Figure 2: Traditional and MPS scheme Engine Design Approaches

2.3 Engine Model

The engine model considered and developed in Modelon Impact is depicted in Figure 4. It consists of a MFTF architecture, with the Fan component connected to the *Low Pressure Turbine* (LPT) through a low-pressure shaft, and with the *High Pressure Compressor* (HPC) powered by the *High Pressure Turbine* (HPT), connected via the high-pressure shaft.

2.3.1 Intake and Installed Performances

An estimation of the engine installed performance is also included [28], through an intake model based on the PIPSI methodology [29, 30]. The inlet is typically designed for the condition that requires the engine maximum captured air flow. When the engine operates in off-design conditions, the excess flow is either bypassed or spilled from the frontal area, and it contributes significantly as an additional drag component. Due to the high flight velocities reached in supersonic regimes, and due to the detrimental effect of the ram drag on engine net thrust, having an indication of the actual installed performances is crucial for realistic expectations of the propulsion system behaviour.

2.3.2 Fan

The fan compressor is modelled as a split component to account for bypass and core side characteristics, as highlighted in Figure 4 by the red-dashed box. The methodology proposed in [31] is implemented to account for the correct distribution of the mass flow while passing through the fan stages. The flow streamlines bend when being processed in the component, depending on the position of the splitter at the fan out-

let, different amounts of mass flow are actually compressed by either the bypass or core characteristic, and then are mixed back in their respective ducts, as depicted in Figure 3. The different bypass and core fan characteristics are represented in practice by the different assumptions made on *Fan Pressure Ratio* (FPR)s and polytropic efficiencies, to account for how differently the flow gets compressed along the blade span [32, 33].

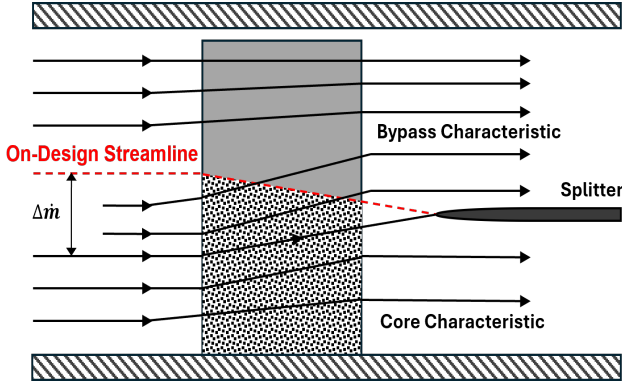


Figure 3: Visual representation of the Fan Bending Streamlines approach

2.3.3 Turbine Cooling

The HPT and LPT are equipped with row-by-row dedicated bleeds, for *Nozzle Guide Vane* (NGV) and rotor blade cooling. The cooling model employed is the one proposed in [34] and extensively compared with other publicly available methods in [35]. Due to the nature of the study and to the assumptions done from the thermodynamic point of view, the cooling model considered represents a valuable choice for the current analysis.

A relevant difference must be accounted for when defining the maximum allowed temperatures and therefore the cooling requirements for a SST application: differently from a subsonic engine, the highest temperatures achieved internally are not at take off or during initial climb segments, but rather during

supersonic conditions, due to the ram compression. The time-dependent effects on engine health and safe operation are here predominant, and the cooling fractions are therefore defined at supersonic cruise condition, by targeting a maximum allowed *Uniform Blade Metal Temperature* (TBU).

2.3.4 Variable Geometry Nozzle

A fully variable convergent-divergent nozzle is included in the engine model. Despite the absence of a reheat system that would require a variable nozzle throat area, the extremely different operating conditions of SST propulsion systems imply the need for this additional variability. The throat area can be modulated either to respect noise regulations for take off and landing, and low altitude flight regimes [8, 9, 12, 36] or as a control variable to maintain sufficient margin from the surge line in the fan characteristic map, avoiding disruptive operation.

Differently from most of the studies that include a variable geometry convergent-divergent nozzle, the nozzle exit area is not obtained from an ideal isentropic expansion towards ambient pressure, but it accounts for the limitations imposed by the nozzle hardware geometry, in terms of maximum achievable *Area Ratio* (AR) and the maximum allowed petal angle. The empirical correlation proposed in [37] based on test measurements, is employed for the definition of the static pressure at the nozzle exit area.

2.3.5 Hybrid-Electric Integration

The hybridization potential is considered in this study as an additional operational variable, either as extracted or injected power. Generally, power augmentation is referred as power included or removed from the engine shafts, in addition to the one used to operate the engine's air compression system [38]. Additionally, a different concept of shafts hybridization considering intra-shaft-power-transfer is investigated. This solution of transferring power from one shaft to the other, loading or unloading in this way either the HPT or the LPT, can act as a control strategy potentially substituting variable geometries in the hot section of the engine. This since variabilities introduced with variable NGVs in the turbine component require

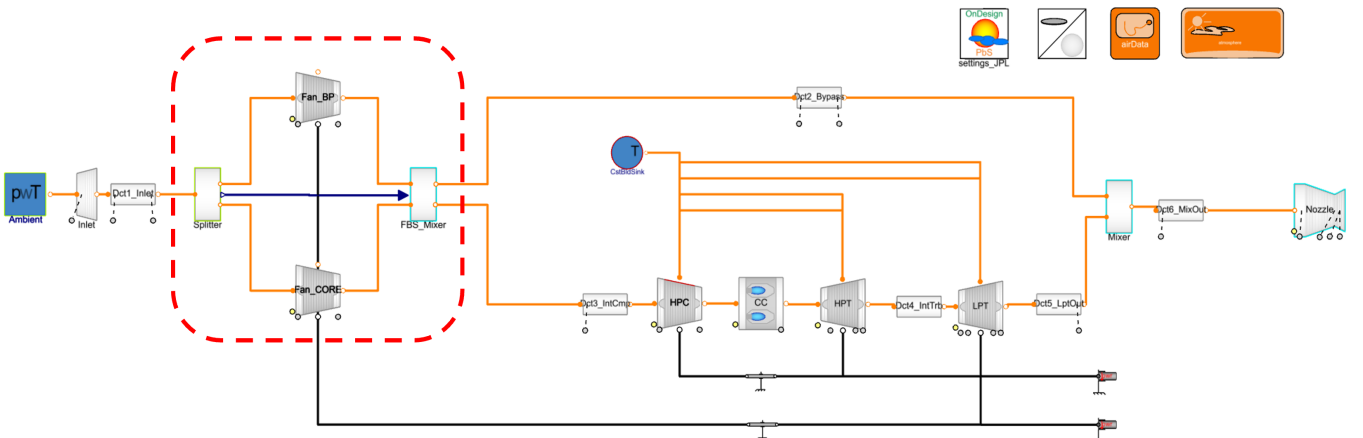


Figure 4: Modelon Impact View of the Engine Model

adjustable structures that must withstand high temperatures in the dedicated section, complicating therefore the mechanism integration [39].

Since this work is focused on engine performance, the detailed design of the electrical power system is not included. The interested reader is referred to [17] for such considerations.

2.4 Case Study Description

The case study considered in this work refers to an engine design for a Mach 1.6 - 10 passenger supersonic business jet, designed for a flight route of 4000 nm [40]. The operating conditions considered and included in the MPS matching scheme, namely *Supersonic Top of Climb* (STOC) (considered in this study as reference condition), *Supersonic Mid Cruise* (SMCR), *Maximum Take Off* (MTO), *Begin of Transonic Acceleration* (BTR), and *End of Transonic Acceleration* (ETR), are reported in Table 1.

Table 1: Engine Performance Requirements from [9]

Operating Point	Altitude [m]	Flight Mach [-]	Thrust Req. [kN]
STOC (Ref.)	14800	1.6	25.8
SMCR	16300	1.6	18.2
MTO	0	0.3	67.9
BTR	10000	0.95	27.6
ETR	10000	1.3	38.3

The engine technology levels for a 2020 EIS year are based on public domain [9], [11], and [41]. The assumptions for future improvements, related to EIS2040, are reported in Table 2 and 3.

Table 2: Polytropic efficiencies η_{pol} @ STOC

Component	EIS2020	EIS2040	Unit
<i>Fan Bypass</i>	<i>Ref.</i>	+1%	<i>Abs. Δ</i>
<i>Fan Core</i>	<i>Ref.</i>	+1%	<i>Abs. Δ</i>
<i>HPC</i>	<i>Ref.</i>	+0.5%	<i>Abs. Δ</i>
<i>HPT</i>	<i>Ref.</i>	+0.5%	<i>Abs. Δ</i>
<i>LPT</i>	<i>Ref.</i>	+0.5%	<i>Abs. Δ</i>

A constant ratio of the core and bypass FPR is assumed, because for low *Bypass Ratio* (BPR) configurations this would result in a fan blade design with constant span-wise work distribution [42].

Table 3: Compressor Pressure Ratio (PR)s @ STOC

Parameter	Value	Unit
FPR_{BP}	$f(SFN)$	[-]
FPR_{Core}	$FPR_{BP} \times 0.8875$	[-]
HPC_{PR}	$f(OPR)$	[-]

Table 4 reports the technological constraints assumed for the EIS years considered. As mentioned in section 2.3.3, different assumptions on the maximum accepted temperature levels must be accounted for when considering different operating conditions. In supersonic flight regimes, the maximum cycle temperatures must be selected allowing a continuous and safe operation.

Table 4: Engine Limiters

Parameter	EIS2020	EIS2040	Unit
$HPT\ TBU_{max}$	<i>Ref.</i>	+60	<i>Abs. Δ [K]</i>
$LPT\ TBU_{max}$	<i>Ref.</i>	+60	<i>Abs. Δ [K]</i>
T_{03max}	<i>Ref.</i>	+100	<i>Abs. Δ [K]</i>
T_{04max}	<i>Ref.</i>	+100	<i>Abs. Δ [K]</i>
$Fan \ \& \ HPC\ N/N_{Ref}$	1.03	1.03	[-]
$Fan \ \& \ HPC\ N_c/N_{cRef}$	1	1	[-]
$Nozzle\ AR_{max}$	1.6	1.6	[-]

The MPS matching scheme considered is included in Figure 5. In the matching scheme presented the operating condition considered as reference for the actual sizing of the engine (in terms of inlet mass flow) is STOC, while the SMCR flight condition is being used as flight condition for the definition of the compressors pressure ratios; MTO, BTR, and ETR are considered as check of the required performances, while adhering to engine aerothermodynamic constraints.

3 Results and Discussions

In this section, the main outcomes of the performed studies are presented. Sections 3.1, 3.2 and 3.3 detail the results of the parametric studies *Overall Pressure Ratio* (OPR), *Mixer Pressure Ratio* (MPR), and *Specific Thrust* (SFN), respectively.

Once identified the cycle design trade-offs for the conventional architecture, the cycle design parameters chosen are applied to retrieve an optimal configuration, serving as baseline for hybridization potential investigations, presented and discussed in Section 3.4.

Before proceeding to the parametric study sections, a comparative analysis between different EIS conventional MFTF configurations (2020 to 2040) is presented, highlighting main cycle performance metrics and engine efficiencies.

Both configurations are set to achieve the same MPR and SFN levels during the SMCR flight condition. However, for the EIS2040 technology levels, an increase in OPR at supersonic cruise is assumed, enabled by the increased temperatures that can be achieved at the HPC outlet. Additionally, higher level of combustor outlet temperature is assumed, accounting for a 5 K/year increase.

Detailed improvements in component efficiencies and maximum allowed temperatures are discussed in Section 2.4, and a summary of the performance parameters considered for the comparison is provided in Table 5.

	Variables	STOC	SMCR	MTO	BTR	ETR
Target	OPR		TV1			
	Specific Thrust		TV2			
	Mixer PR		TV3			
	HPT TBU NGV	$\leq TBU_{max}$	TV4	$\leq TBU_{max}$	$\leq TBU_{max}$	$\leq TBU_{max}$
	HPT TBU Rotor	$\leq TBU_{max}$	TV5	$\leq TBU_{max}$	$\leq TBU_{max}$	$\leq TBU_{max}$
	LPT TBU NGV	$\leq TBU_{max}$	TV6	$\leq TBU_{max}$	$\leq TBU_{max}$	$\leq TBU_{max}$
	LPT TBU Rotor	$\leq TBU_{max}$	TV7	$\leq TBU_{max}$	$\leq TBU_{max}$	$\leq TBU_{max}$
	HPC Outlet Temperature	$\leq T3_{max}$	$\leq T3_{max}$	$\leq T3_{max}$	$\leq T3_{max}$	$\leq T3_{max}$
	HPT Inlet Temperature	DP T1	$\leq T4_{max}$	$\leq T4_{max}$	$\leq T4_{max}$	$\leq T4_{max}$
	Net Thrust	DP T2	OD Target	OD Target	OD Target	OD Target
	Power Augmentation HPS/LPS			Fixed		
	Power Transfer			Fixed		
Synthesis	HPC PR	SV1				
	Fan Bypass PR	SV2				
	BPR	SV3				
	HPT NGV cooling flow fraction	SV4				
	HPT Rotor cooling flow fraction	SV5				
	LPT NGV cooling flow fraction	SV6				
	LPT Rotor cooling flow fraction	SV7				
	Fuel Mass Flow	DP V1	OD Variable	OD Variable	OD Variable	OD Variable
	Engine Inlet Mass Flow	DP V2				
	Bypass to Core Fan PR ratio	Fixed				

Figure 5: MPS matching scheme considered for the conventional and parallel hybrid EIS2040 MFTF

Table 5: Performance parameters relative change due to EIS assumptions for STOC and SMCR at constant uninstalled net thrust

Parameter	Relative ΔEIS @STOC	Relative ΔEIS @SMCR
OPR	+27.83 %	+25.00 %
T_{04}	+5.71 %	+6.56 %
SFN	-3.48 %	+0.00 %
MPR	-0.10 %	+0.00 %
$\eta_{overall}$	+4.63 %	+1.31 %
η_{prop}	+1.22 %	+0.00 %
$\eta_{thermal}$	+3.21 %	+1.40 %
SFC	-3.80 %	-1.31 %
Inst. Thrust	-0.50 %	-4.23 %
Inst. SFC	-3.31 %	+3.04 %

The improvements in cycle efficiencies are primarily due to increased pressure levels within the engine core. A higher OPR and enhanced component efficiencies directly boost engine thermal efficiency. The reduced SFN levels reached at STOC due to increased fan maximum diameter lead to increased propulsive efficiency, contributing slightly to the improvements in engine overall efficiency. Nonetheless, engine overall efficiency improvements are largely dominated by the increased core pressure levels, resulting in lower specific fuel consumption.

The reduction in installed thrust and the resulting rise in installation losses are to be attributed to the increase in fan max-

imum diameter (+1.75%), which affects considerably engine performances in high speed flight regimes.

The main cycle design parameters obtained through the MPS matching scheme outlined above serve as the starting point for subsequent parametric studies. Each analysis maintains constant HPT and LPT TBUs, as well as HPT inlet temperature in design condition. Only one target variable at the time is varied while keeping the others at the assumed EIS levels. The investigated range for each parameter considered in the following sections is included in Figure 5. The goal of these studies is to gain insights and identify an optimal configuration, serving as baseline for the hybrid integration analysis.

3.1 Overall Pressure Ratio

The increase in OPR at SMCR results in improved cycle efficiencies, thereby leading to reduced fuel consumption, as illustrated in Figure 6. Compared to the reference value, the increased pressure levels within the engine core contribute to a reduction of installed and uninstalled SFC at supersonic cruise condition, respectively of almost 3% and 6%.

At STOC, the SFC remains almost constant up until around an OPR = 31, where an inverting trend is noted. This slight rise is due to the activation of the engine limiter on the HPC outlet temperature, which limits the overall pressure ratio that can be achieved.

Direct consequence of the engine limiter activation is the increase of engine size, in terms of inlet mass flow or equivalently fan diameter, to achieve the design thrust requirement.

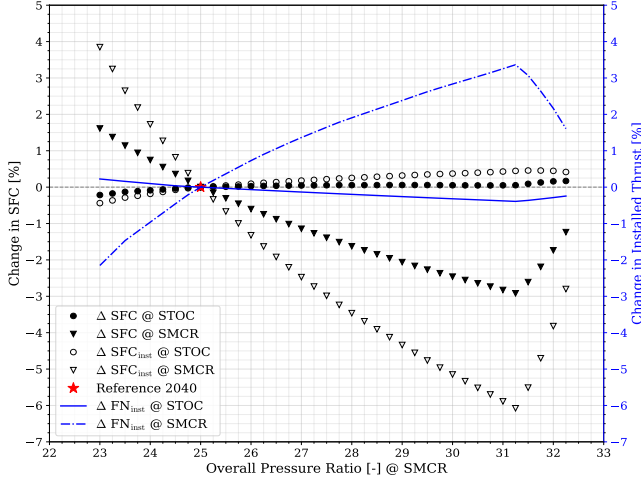


Figure 6: Effect of OPR variation on engine SFCs and installed thrust

The considerations discussed above are further supported by Figure 7. The fan diameter decreases until the maximum allowable temperature at the HPC outlet is reached. Once this limiting condition is met, the engine size increases again in order to achieve the uninstalled thrust requirement at STOC condition. As the engine approaches the minimum achievable diameter, propulsive efficiency reduces due to the higher SFN, at the same operating condition (STOC). However, this reduction is balanced by the thermal performance improvements, resulting in a slight increase of engine overall efficiency.

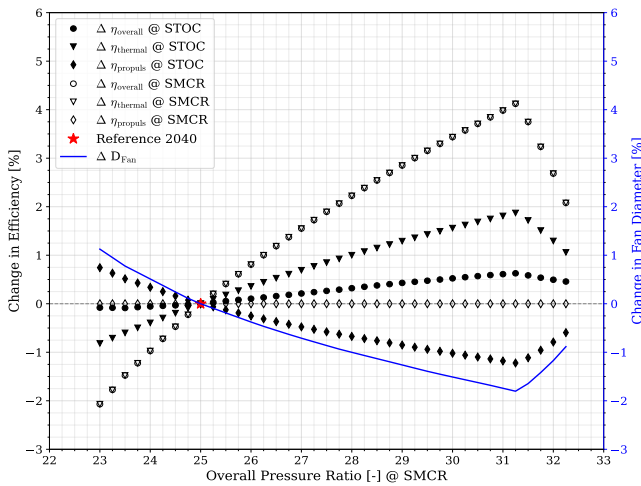


Figure 7: Effect of OPR variation on main cycle efficiencies

Further efficiency gains can be achieved at the SMCR flight condition. In this case, propulsive efficiency remains unaffected by the OPR increase, as both SFN and uninstalled thrust are held constant, and the improvement in engine overall efficiency can be directly attributed to the higher pressure levels within the engine core. Increasing the OPR enables enhancements in overall engine efficiency up to 4%.

Additional thoughts on engine limitations and constraints related to a possible increase in OPR would be directed to the definition of minimum allowed core size in terms of minimum HPC last stage blade height, as highlighted in [37] and more recently in [21]. These considerations require additional assumptions on the conceptual and mechanical design of the component, and they are not accounted for in this study.

3.2 Mixer Pressure Ratio

The range of MPR variation is constrained by the Mach numbers in the bypass duct. Although the engine configuration considered here does not include a reheat system - which would have otherwise narrowed down the mixer's operating range - the optimal MPR must be chosen carefully, due to the direct effect on the incoming flow conditions, and on the related losses.

As shown in Figure 8, the higher the chosen MPR is - defined as total-to-total pressure ratio between bypass and core mixer inlet conditions - at supersonic cruise, the higher the difference in flow velocities at the mixing section becomes.

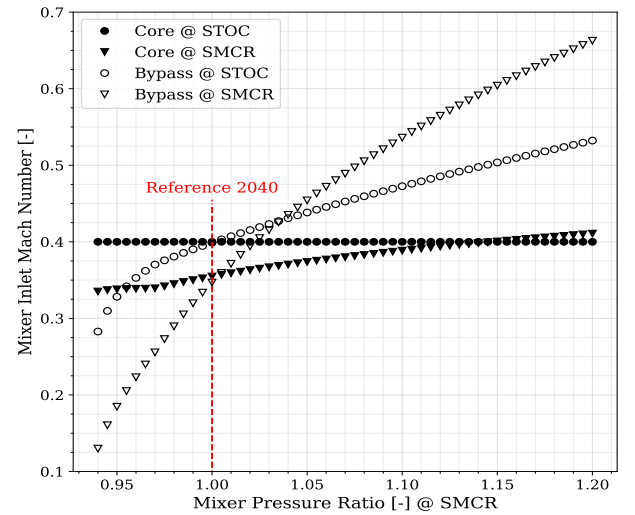


Figure 8: Effect of MPR variation on mixer inlet Mach numbers

When looking at the range of applicability for the MPR variation and choice, additional constraints must be considered, as reported in Figure 9.

The MPR is limited on the lower bound by the performance requirements at SMCR. Reducing the MPR below approximately 0.97, would lead to a reduction in uninstalled engine thrust, as well as to a dramatic increase in SFC.

Interestingly enough, by raising bypass and core total pressure ratio above unity in the proposed range, an increase of installed net thrust at SMCR condition is achieved, reducing in that way the installation losses. The main explanation is related to the potential reduction that can be obtained in terms of maximum fan diameter, up until approximately 4%, as reported in Figure 10.

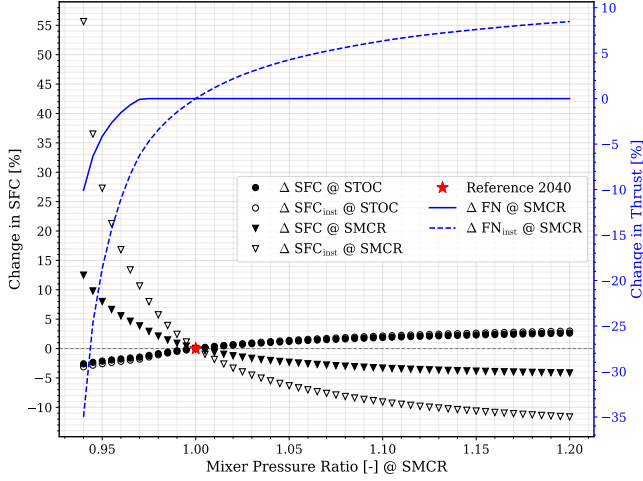


Figure 9: Effect of MPR variation on performance parameters

This behaviour can also be explained by the combined influence of overall pressure ratio, bypass ratio, mixer pressure ratio and specific thrust at SMCR. As the MPR increases during supersonic cruise, the bypass ratio at design condition decreases.

Given that OPR and SFN are kept constant throughout the parametric study, the HPC and Fan PRs exhibit opposite trends: the core side processes an increased mass flow, resulting in a reduced pressure ratio across the HPC. Conversely, the bypass side of the fan must counterbalance the effect occurring on the core, by increasing pressure in the outer duct due to the reduced bypass mass flow. Consequently, this leads to a higher bypass FPR at design condition, thereby increasing the available specific thrust at STOC condition.

The higher SFN levels at design condition lead to a reduction in propulsive efficiency, as illustrated in Figure 10.

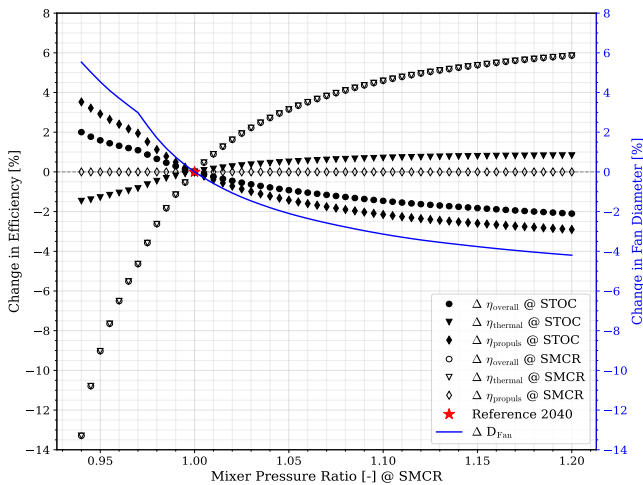


Figure 10: Effect of MPR variation on cycle efficiencies and engine size

In this case, the overall efficiency trend is mainly driven by

the propulsive contribution, leading to a reduction relative to the reference point.

Conversely, at the SMCR flight condition, improvements in overall cycle efficiency are observed, approximately up to 6%, and consistent with the previously discussed trends in specific fuel consumption.

3.3 Specific Thrust

Specific thrust represents a significant indicator for SST applications, since it is strictly correlated to the overall size of the propulsion system - which can be considered as the primary source of losses due to installation effect - and to the actual performances of the engine, in terms of achieving supersonic cruise capability while maintaining at the same time an almost subsonic-comparable specific fuel consumption.

Low BPR engines provide high specific thrust, at the cost of a lower propulsive efficiency, and therefore higher fuel consumption. The advantage here lies, for the same net thrust levels, into a smaller size, which is crucial for high speed propulsion applications.

In any case increasing SFN at supersonic cruise condition will have an effect on performance requirements at other off-design conditions, limiting the range. The steep reduction in installed thrust at MTO operating condition is referred to an engine limiter activation, namely the Fan corrected speed ratio. As shown in Figure 11, the increase in SMCR SFN leads to a reduction in installation losses, due to engine size shrink at fixed thrust levels.

It should be noted that the main reductions in installation effects that can be achieved are strictly related to the operating condition in the supersonic regime.

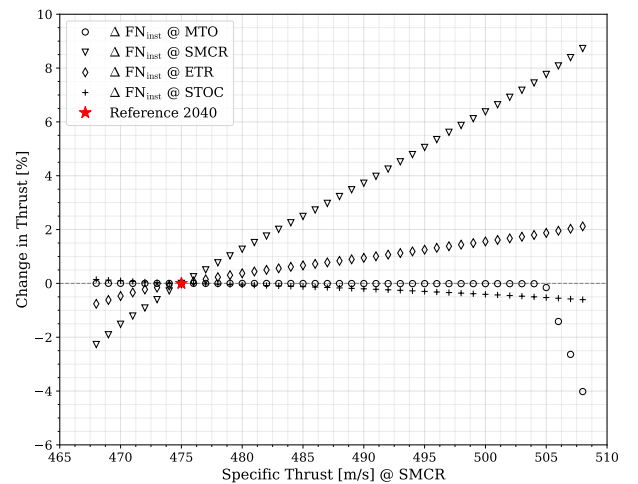


Figure 11: Effect of SFN variation on engine installed thrust

This results also in a installed specific fuel consumption reduction, at the same operating condition.

On the other hand the SFN rise leads also to an increased SFC at STOC condition. The explanation can be found in Figure 12 and 13, which present the effect of the SFN variation on main engine performance parameters, as installed and unin-

stalled SFC and cycle efficiencies, for the design and supersonic cruise conditions. As expected the increase in specific thrust results into a propulsive efficiency reduction, which dominates the trend on the overall efficiency at design condition. In this case the increase in thermal efficiency is mildly notable, differently from what can be observed on propulsive efficiency.

Nevertheless, the propulsive efficiency reduction at supersonic cruise is compensated by the moderate rise in thermal efficiency, resulting in a slightly more efficient configuration. The increase is in any case limited and below 3%.

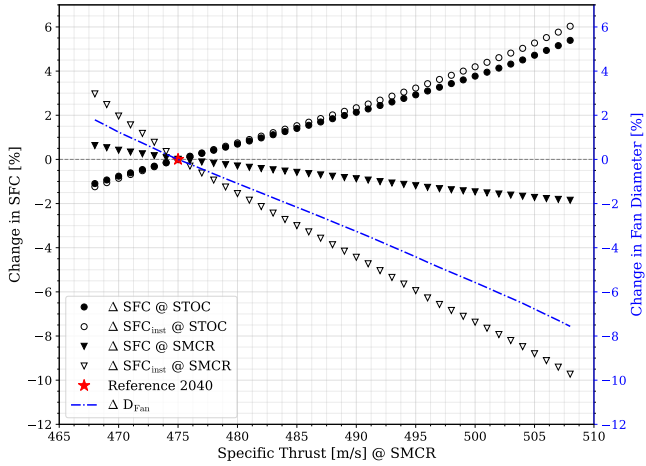


Figure 12: Effect of SFN variation on engine specific fuel consumption and size

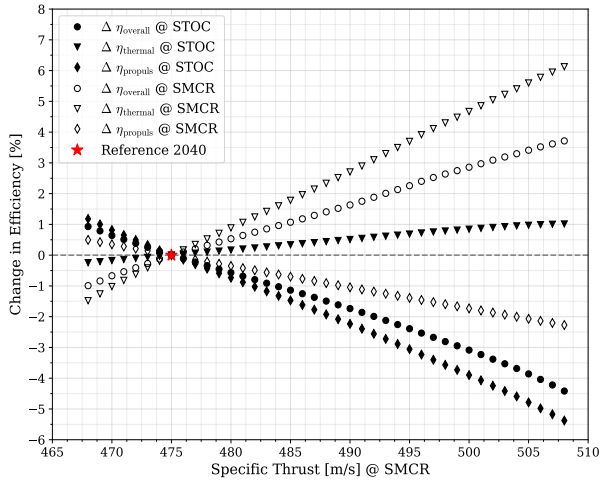


Figure 13: Effect of SFN variation on engine main cycle efficiencies

3.4 Hybridization Potential

The parametric studies conducted and presented in the previous sections served as exploratory analyses aimed at identifying and selecting a possible and suitable combination of main cycle design parameters. The baseline configuration, defined by the chosen target variables from the preceding analysis, is now further investigated by independently evaluating differ-

ent power hybridization settings on both *High Pressure Shaft* (HPS) and *Low Pressure Shaft* (LPS), as presented in Figure 5.

Fan and HPC PRs are now maintained constant at STOC condition, and in the studies presented below OPR and SFN at supersonic cruise are not considered anymore as MPS target variables.

Power augmentation is considered - in terms of both power extraction and injection - in each operating condition considered in the MPS matching scheme, with exception of the design STOC condition. Similarly, intra-shaft power transfer capability are investigated following the same approach. The hybridization effect is therefore investigated in the proposed studies as an additional off design variable.

3.4.1 High-Pressure Shaft Power Extraction/Insertion

The impact of HPS power extraction and insertion on the reported performance parameters is illustrated in Figure 14. Under SMCR condition, power extraction is constrained by mission performance requirements. Specifically, extraction beyond 400 kW prevents the engine from delivering the required thrust, as it triggers the combustor outlet temperature limit. Furthermore, extracting power from the high pressure shaft results in an increased SFC, which rises sharply once the maximum temperature limit is reached.

In contrast, power insertion under supersonic cruise conditions provides performance benefits. Assisting the engine in this manner yields reductions of installed and uninstalled SFC, by up to 10% and 5%, respectively.

It is important to highlight that the present study addresses electrical machine integration primarily from a cycle performance perspective. A comprehensive assessment will require additional analyses accounting for system mass, volume, and integration constraints.

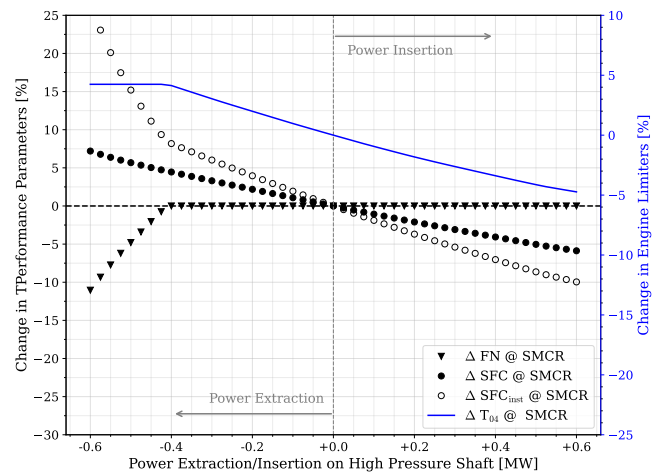


Figure 14: Effect of HPS power augmentation on cycle performance parameters

3.4.2 Low-Pressure Shaft Power Extraction/Insertion

Unlike the previously examined case, power extraction and insertion on the LPS are not constricted by mission perform-

ance requirements.

The engine is capable of meeting the thrust demand across all operating conditions without activating any of the defined engine limiters. The resulting trends are broadly consistent with those observed for high pressure shaft power augmentation, as shown in Figure 15.

In this configuration, power insertion on the low-pressure shaft produces only a marginal impact on engine dimensions, yielding a modest reduction in installation losses, limited to less than 2%.

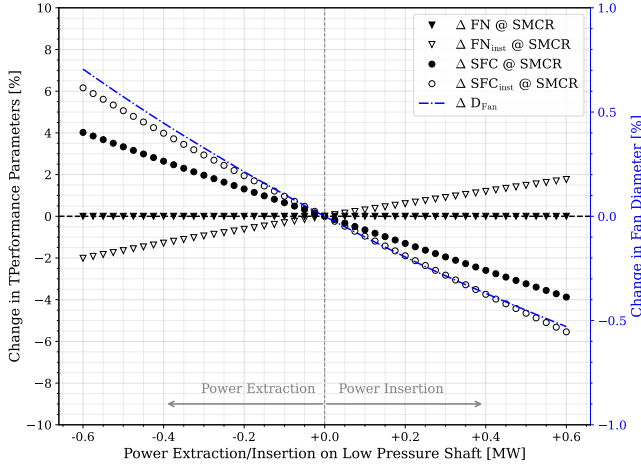


Figure 15: Effect of LPS power augmentation on cycle performance parameters

3.4.3 Power Transfer

Power transfer in between shafts also imposes constraints on supersonic cruise performance, as it is illustrated in Figure 16. When transferring power from the LPS to the HPS, the combustor outlet temperature limit is reached, restricting additional transfer as it would compromise the thrust required for sustained supersonic cruise.

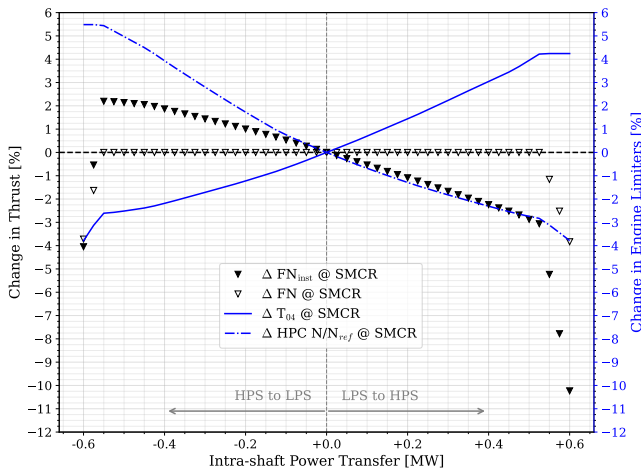


Figure 16: Effect of intra-shaft power transfer and range of possible applicability

Conversely, when transferring power from the HPS to the LPS, the limiting factor is the maximum allowable rotational speed of the HPC, which prevents further transfer beyond this threshold. Within the investigated range of intra-shaft power transfer, no other performance parameters exhibited significant variations, and these are therefore not reported.

The effects of this hybridization strategy are illustrated in Figure 17.

The central row of the operating maps corresponds to the neutral case, in which no power is being exchanged between the shafts. The top row depicts power transfer from HPS to LPS, while the bottom row the opposite condition (low pressure shaft to high pressure shaft). It should be noted that at the power transfer level reported in both top and bottom row, the thrust requirement at SMCR condition is not met.

The high pressure compressor is only mildly influenced by the power transfer. In this case, operating points shift along the same characteristic line, resulting in minor variations in component efficiency when power is drawn from the low pressure shaft (bottom row).

In contrast, the impact on the fan characteristic maps is more pronounced. When unloading the HPS and transferring power to the LPS, the operating line in the core map shifts towards the choke region, leading to a consistent increase in surge margin. On the bypass side, moves towards the stall region, but remains below the design-point operating line.

The inverse behavior is observed when transferring power from the LPS to the HPS: in this case, the core-side operating line shifts towards the surge limit, while on the bypass side it approaches the choke region.

Depending on the operating condition - particularly at part load - transferring power from the low to the high pressure shaft provides an additional degree of control over the fan surge margin. This margin can be modulated according to the level of power transfer, with associated performance benefits linked to the increased core temperature. The performance benefits are translated into SFC reduction at SMCR, as shown previously in Figure 16. While only the SMCR is reported here, comparable trends were observed across the other operating points examined.

4 Conclusions

The study examined conventional and parallel hybrid-electric MFTF configurations.

A trade-off analysis was conducted to evaluate cycle design options for each configuration and identify potential synergies within the coupled systems.

An MPS matching scheme approach was used to assess how different choices and assumptions regarding key cycle-design parameters affect the overall engine design, while simultaneously satisfying performance requirements and adhering to technological limitations and constraints.

Parametric studies of OPR, MPR, and SFN were performed to determine an optimal engine configuration, which then served as the baseline for the parallel hybrid-electric integration assessment.

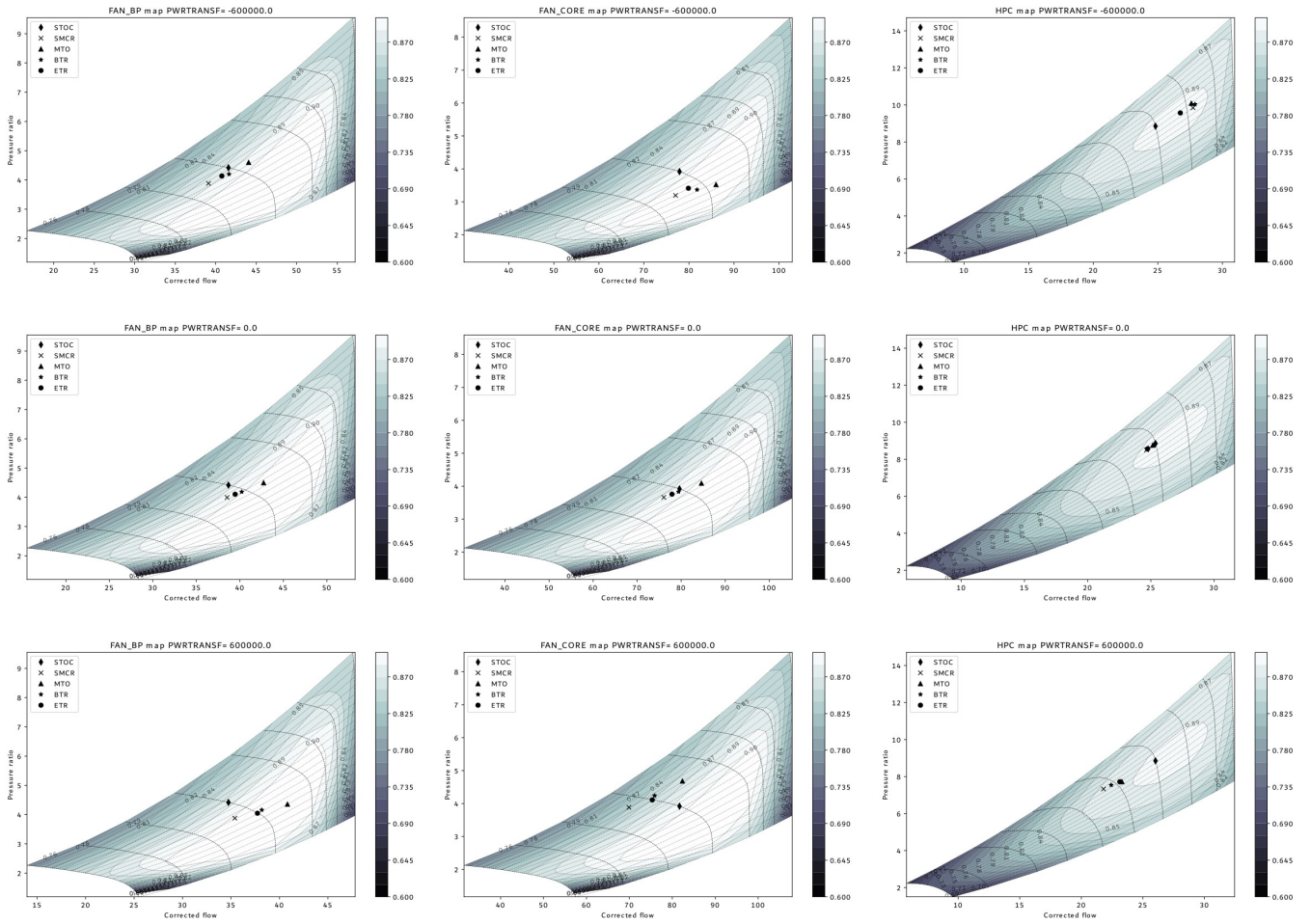


Figure 17: Effect of power transfer setting on Fan Bypass side (Left), Fan Core side (Middle), High Pressure Compressor (Right), characteristic maps

The analysis of power extraction and insertion revealed that HPS augmentation is constrained by combustor outlet temperature limits at SMCR, with excessive extraction preventing the engine from achieving the required thrust and driving up SFC. Conversely, power insertion on the HPS demonstrated measurable performance benefits, reducing both installed and uninstalled SFC.

LPS hybridization exhibited fewer operational restrictions, as the engine was able to meet thrust requirements across all investigated conditions without triggering limiters. Here, power insertion produced only marginal effects on engine size and installation losses, while following trends similar to those observed for the HPS, but with lower magnitude.

Intra-shaft power transfer was also investigated. Power transfer from the LPS to the HPS was limited by thermal constraints, while transferring power in the opposite direction was limited by the maximum rotational speed of the (HPC). Beyond these constraints, the main impact was seen in component operating maps: fan surge margin can be influenced depending on the operating condition, especially at part-load, opening possibilities for additional control and localized performance improvements.

In summary, the study showed that hybrid-electric concepts can deliver meaningful reductions in fuel consumption at supersonic cruise conditions, but the benefits depend strongly on how and where power is exchanged within the engine. While the present work focused on cycle performances, a complete overview of the hybrid architecture will also require system-level studies that account for the mass, volume, and integration of the electrical machines.

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Nomenclature

Designation	Denotation	Unit
D_{Fan}	Fan Diameter	m
FN	Net Thrust	kN
T_{03}	HPC Outlet temperature	K
T_{04}	HPT Inlet Temperature	K
SFN	Specific Thrust	m/s
SFC	Specific Fuel Consumption	g/kN*s

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