Hybrid Propulsion for Regional Aircraft: a Comparative Analysis based on Energy Efficiency

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***Abstract*—This article assesses the potential benefits of transient energy storage for a hybrid regional aircraft. The mission profile of a reference aircraft is analyzed according to energetic intermittence and the results are compared to typical figures for cars, trains, and ships. Also, the opportunity of recovering energy in descent and during landing is studied. This article shows that energy saving potential brought by transient energy storage is much smaller than for ground-based transportation. In addition, energy recovering does not bring benefit on a hybrid aircraft in normal operation. Nevertheless, the best energy management strategies in descent are highlighted and the use of a hybrid propulsion system in this phase shows significant potential energy savings. Finally, the article addresses other strategies enabled by hybrid propulsion to improve the aircraft energy efficiency.**

Keywords—hybrid propulsion, gas turbine, energy storage, energy recovering, power management, distributed electric propulsion

I. Introduction

Propulsion system innovations have been a key driver of aeronautic evolution. The increase of propulsion performance and efficiency has enabled aircraft to travel at higher speeds over longer ranges while carrying larger payloads. Today the improvement of conventional engine technologies is reaching an asymptote, while future demands on the air transport systems still dictate that aircraft should be less polluting, less noisy and more fuel efficient. In this context, hybrid architectures offer the opportunity to transform in the long term the landscape of aircraft propulsion and furthermore enable new aircraft configurations.

In this article the term hybrid aircraft is used to define an aircraft that operates more than one type of energy source and/or power flow for propulsion means. Aircraft propulsion is indeed currently limited to kerosene and mechanical transmissions. Hybrid electric propulsion provides the opportunity to combine different energy sources or power flows by integrating new technology bricks. Those give additional degrees of freedom to improve overall aircraft performance, limit the use of non-renewable fossil resources and reduce the aircraft environmental footprint.

Today, hybrid technology has mainly been applied to ground-based transports, cars, buses and trains but also ships. However, the feasibility of hybrid architectures in the air industry has to be established and the improvement in aircraft performance has still to be demonstrated.

This paper aims to assess the potential benefits of transient energy storage for a hybrid regional aircraft. These opportunities are evaluated with respect to a reference conventional aircraft that was designed for the purpose of this study. At first order, results are independent of the hybrid propulsion architecture due to the methods used.

II. Reference Aircaft and Reference Engine

The reference aircraft is a conventional twin-turbo propeller designed with an in-house preliminary aircraft design tool assuming a 2035 technology level. The engine size and the reference area are constrained by the time to climb to 20,000 ft (17 min) and the approach speed (113 kt) requirements. Despite the range capability of 400 nm, the aircraft performance is evaluated on a 200 nm mission (Table I) as this aircraft is expected to operate most of its life on such range. The reference aircraft is fitted with two turbopropeller engines of 3500 thermal horsepower each. Fig. 1 provides the power profile of one engine along the 200 nm mission.

III. Transient Energy Storage

A. Energy Sharing

Generally, for hybrid architectures using energy storage devices, the main energy generator provides the average load of the mission while energy storage devices provide peak loads. This allows the main energy generator to be downsized and to be used at a better efficiency. In [1], the authors propose two criteria to assess the relevance of a propulsion system to be hybridized with energy storage devices: the potential for hybridization in power and the potential for hybridization in energy. For reasons linked to power density and rarefied air operation, the main energy generator of hybrid aircraft will

TABLE I. MISSION OVERVIEW

Phase	Time (min)	Distance (nm)	Fuel (kg)	% Block Fuel
Taxi out	3.0	0.0	9	2.0%
Take-off	1.3	0.0	21	4.8%
Climb	16.1	54.6	177	40.0%
Cruise	22.0	101.0	186	42.1%
Descent	9.9	44.4	32	7.2%
Approach & Landing	2.0	0.0	14	3.2%
Taxi in	1.0	0.0	3	0.7%
Total	55.3	200.0	442	100.0%

likely remain gas turbine. As the maximum available output power of a gas turbine evolves with speed and altitude, a new definition of the potential for hybridization in power is proposed hereafter. Also, the potential for hybridization in energy is slightly modified for a better characterization of the storage unit.

1) *Potential for Hybridization in Power PHP*

The potential for hybridization in power PHP defined by (1) expresses the potential reduction in size of the main source of power enabled by the use of an energy storage. This definition assumes that the state of energy of the storage unit at both start and end times of the mission are the same (i.e. the storage unit is recharged to its initial state). This energy management strategy is surely not best suited for aircraft mission profile but is convenient for the purpose of this mission profile comparison. Note that if the maximum available output power $P_{maxNRJgen}$ of the main source of power is independent of time–typically the case for ground-based application–(1) is strictly identical to the definition in [1].

$$PHP=1- \langle P_{mission}\rangle/\langle P_{maxNRJgen}\rangle \qquad (1)$$

Where <X> is the mean value of the function X(t) along the mission.

PHP=0 expresses a mission profile that is strictly unsuitable for the reduction of the main energy generator size through hybridization while PHP=1 expresses a mission profile that firmly supports it.

2) *Potential for Hybridization in Energy PHE*

The potential for hybridization in energy PHE defined by (4) is the ratio of the maximum power delivered or received by the storage unit to the useful energy E_u of the storage device during the mission. The useful energy can be determined according to (3) from the evolution of the energy $E_s(t)$ in the storage device given by (2). Thus, the PHE is homogenous to a frequency which relates to the inverse of a time constant τ_{sto} that characterizes the storage unit in terms of dynamic performance and can be placed in the Ragone chart accordingly. Based on its definition, it can be stated that the smaller the PHE, the more energy abundant the storage.

$$E_s(t)=\int_{t0}^{t} [P_{mission}(\tau)-(1-PHP)P_{maxNRJgen}(\tau)]d\tau \qquad (2)$$

$$E_u = max\ E_s(t)-min\ E_s(t) \quad t\in[t_0;t_f] \qquad (3)$$

$$PHE=max[P_{mission}(t)-(1-PHP)P_{maxNRJgen}(t)]/E_u \quad t\in[t_0;t_f] \qquad (4)$$

3) *Mission Profile Analysis and Comparison*

The two indicators are now used to characterize the power profile of the reference aircraft shown in the next figure.

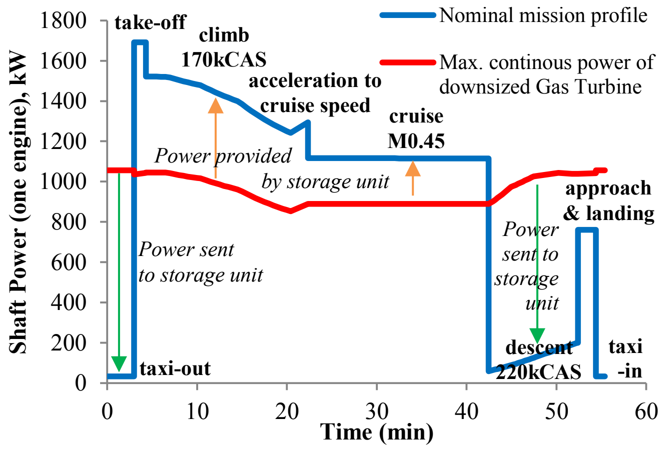

Fig. 1. Power profile of the reference aircraft

Same calculations are performed for typical mission profiles for cars, trains and ships (Table II). In the case of cars, calculations are based on Common Artemis Driving Cycles assuming a vehicle mass of 1400 kg, a reference area of 2.7 m² (frontal area), a drag coefficient of 0.25 and a 0.028 rolling friction coefficient. Results for trains are based on the study carried out in [2]. Note that local service refers here to the transportation of freight between two cities that are within 40 km from each other. Mission profiles for ships are taken from [3] and the power required is calculated assuming a proportional increase with the ship speed to the third power.

The PHPs of regional aircraft and container ship are very low compared to the other applications. This can be explained by the fact that their conventional propulsion systems operate at a relatively high level throughout the mission versus its maximum capability. Therefore the potential reduction in size of the main energy source is small. Obviously, the longer the cruise phase, the smaller the PHP. This emphasizes why a regional aircraft is chosen as a reference aircraft in the paper.

The time constant τ_{sto} of the regional aircraft falls into the battery category. However, the small PHE calculated for the regional aircraft expresses a huge capacity need that might be critical for this application.

TABLE II. MISSION PROFILE COMPARISON

	Car			Train [2]			Ship [3]		Aircraft
	Urban	Rural road	Motorway (150km/h)	Local service	Switching	Urban transportation	Container	Ro/Ro passenger ferry	Regional (200 nm)
PHP (%)	94	85	74	65	83	91	43	63	32
PHE (mHz)	66	30	12	3	29	20	n/a	n/a	0.22
τ_{sto}	15 s	34 s	1.4 min	5.8 min	35 s	50 s	n/a	n/a	77 min

B. Energy Recovering

While hybrid vehicles are now entering the market in increasing numbers, their interest is mainly limited to urban driving cycles characterized by its numerous stops and starts. Main savings come from the ability of the hybrid architecture to recover kinetic energy during deceleration. This section analyses potential energy savings of the reference aircraft through energy recovering at landing and during the descent phase.

1) Braking Energy

In order to stop at landing an aircraft dissipates its kinetic energy through several braking systems: disc brakes, airbrakes and thrust reversers. Calculating the maximum kinetic energy at landing of the reference aircraft using the maximum landing weight and the reference approach speed yields to 36 MJ or 0.19% of the total energy consumed during the nominal mission. Assuming a Fuel Lower Heating Value FLHV of 42.8MJ/kg and a gas turbine efficiency of 40%, 36MJ is the energy that can be obtained by burning 2 kg of fuel (to be compared with the total fuel burn of Table I). Also, as the landing phase lasts only few seconds, the energy recovering system should be able to withstand very high power flows leading to a heavy and complex device. Regarding the small portion of energy that can be recovered and the additional complexity brought by an energy recovering system, the potential benefit of braking energy recovering will not be investigated further.

2) Gravitational Potential Energy

With its cruise altitude of 20,000 ft the reference aircraft benefits from a 1183 MJ potential energy at the end of cruise (19,800 kg). That is, 6.3% of the energy consumed over the mission. Hybridization could enable aircraft to convert gravitational potential energy during descent through windmilling propellers, store it in electric batteries, and use it during a later phase. The following study addresses this point and tends to highlight the best energy management in descent.

Let D_{ac} be the drag force applied to the reference aircraft without its propeller blades, but including nacelles and spinners. In constant-speed cruise, the thrust generated by the propulsion system exactly compensates D_{ac}. For the purpose of this study, four different operating modes of the propellers in descent are defined:

- Folded: propeller blades are fully folded along or in the nacelles to reduce as far as possible the propeller drag in descent. The aircraft drag penalty associated to this propeller mode is assumed to be zero.
- Feathered: the propeller blades can rotate parallel to the airflow reducing the propeller drag in comparison with uncontrolled windmilling. Still, a feathered propeller generates drag that is taken into consideration by scaling the drag coefficient of [4] with respect to the propeller diameter and the number of blades. In this propeller mode, both propellers of the reference aircraft are assumed to be feathered, and a drag penalty of 60 drag counts in the aircraft reference area is imparted to D_{ac}.
- Transparency: the propeller is rotating but produces neither drag nor thrust. The small amount of power required to operate this mode is taken into consideration using the propeller efficiency map [5] and optimizing the propeller speed as a function of flight conditions to minimize the required amount of shaft power. No drag component is added to D_{ac}.
- Wind turbine: the aircraft recover some energy during the descent. The additional drag is defined proportionally to D_{ac} through the energy recovering coefficient *k*. The total aircraft drag is therefore "$(1+k)D_{ac}$". The shaft power extracted from the windmilling propellers is calculating using the actuator disk theory, hence neglecting friction losses and blade tip losses.

Fig. 2 illustrates the effect of the different propeller modes on the aircraft flight path. The distance covered in folded mode was chosen as the reference distance to destination from cruise altitude. Note that under the assumptions of this study, the transparency mode involves the same flight path as the folded mode. The feathered mode and the wind turbine propeller mode require a steeper descent slope due to the additional drag. As a consequence the distance covered in descent is less than the reference and the cruise flight must be extended to reach the destination. Note that the comparison between propeller operating modes is performed at iso-time-to-descent which explains why the descent speeds are different. Nevertheless, the cruise part is flown at the design speed.

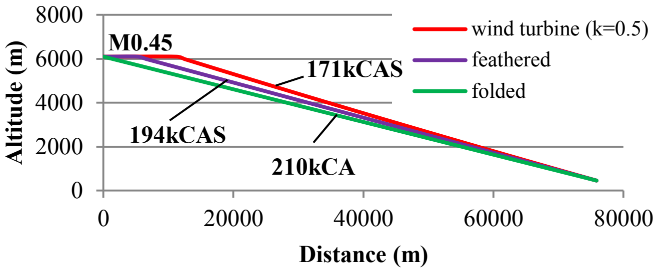

Fig. 2. Flight path comparison for 10 min descent time

This study aims to compare the onboard energy consumption of the aircraft in descent depending on the propeller operating mode and the descent time. In this analysis the following assumptions are considered:

- The aircraft weight is supposed to be constant and equal to 19,800 kg during the descent (Table I).
- Five different descent times are considered ranging from 16 min to 5 min.
- The distance covered in folded mode for the 16 min descent time is chosen as the reference range to destination as the descent speed for this case approaches the speed of best lift-to-drag ratio.

- Descent speeds are adjusted to match the required descent time while the cruise speed is fixed to Mach 0.45.
- For the wind turbine mode, coefficient k was varied from 0.1 to 3.0 with a 0.1 step for each descent time as far as the stall speed was not reached. In the results (Fig. 4-6) only the case providing the minimum overall energy consumption is depicted.
- The energy consumption of non-propulsive systems is taken into account throughout the range to be covered by assuming a constant power consumption P_{sys} of 140 kW.
- The propeller efficiency for the cruise segment is set to 90%.

To go even further, additional assumptions are made on the efficiency of the power generation system depending on the flight segment.

- If the additional cruise segment is performed with a gas turbine type system its efficiency is set to 40% which applies between the energy source and the propeller shaft but also between the energy source and the non-propulsive systems. For the descent segment, an efficiency of 10% is considered for this type of system to account for the low efficiency of gas turbines in idle [5].
- If an electrical power generation system is used in place of the thermal system for the additional cruise and/or the descent a 90% efficiency is considered.

The power flows and possible efficiency combinations are illustrated in Fig. 3. Results of this trade study are depicted on Fig. 4-6. The onboard energy consumption is represented as a function of gravitational potential energy between cruise altitude and 1500ft (i.e. 1093 MJ).

The energy management strategy of the reference aircraft can be analyzed through the 10 min descent and the transparency mode of Fig. 4. The propeller does not operate in a transparency mode in reality but the average thrust along the descent approaches zero. It can be shown that going to the feather mode would reduce the energy consumption by 20% for the same descent time. Of course this may entail a complex modification of the engine architecture as the mechanical off-takes have to be provided even if the propeller gearbox output shaft is stopped.

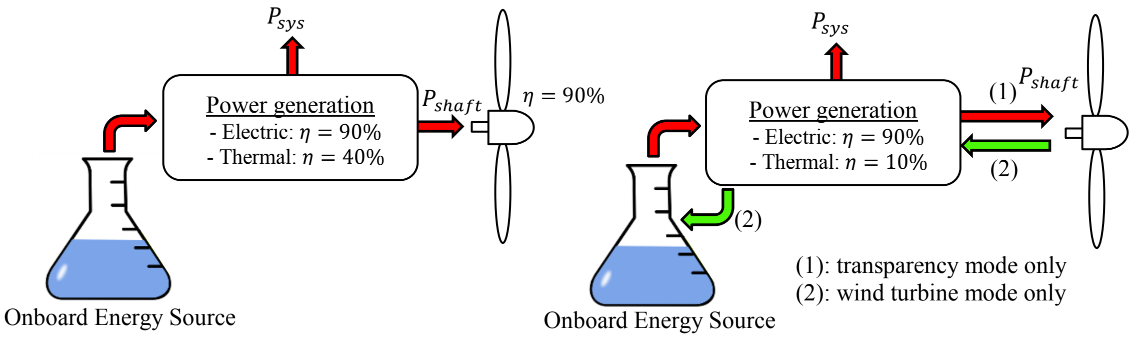

Fig. 3. Possible power flows for cruise segment (left) and descent (right)

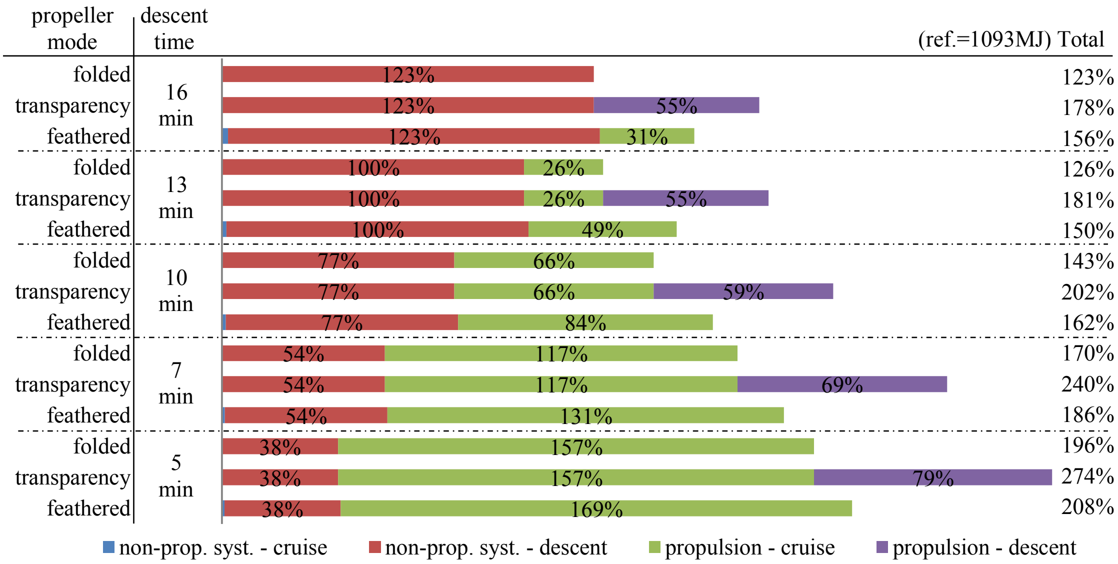

Fig. 4. Comparison of onboard energy consumption for full thermal power generation system – Cruise: Thermal/Descent: Thermal

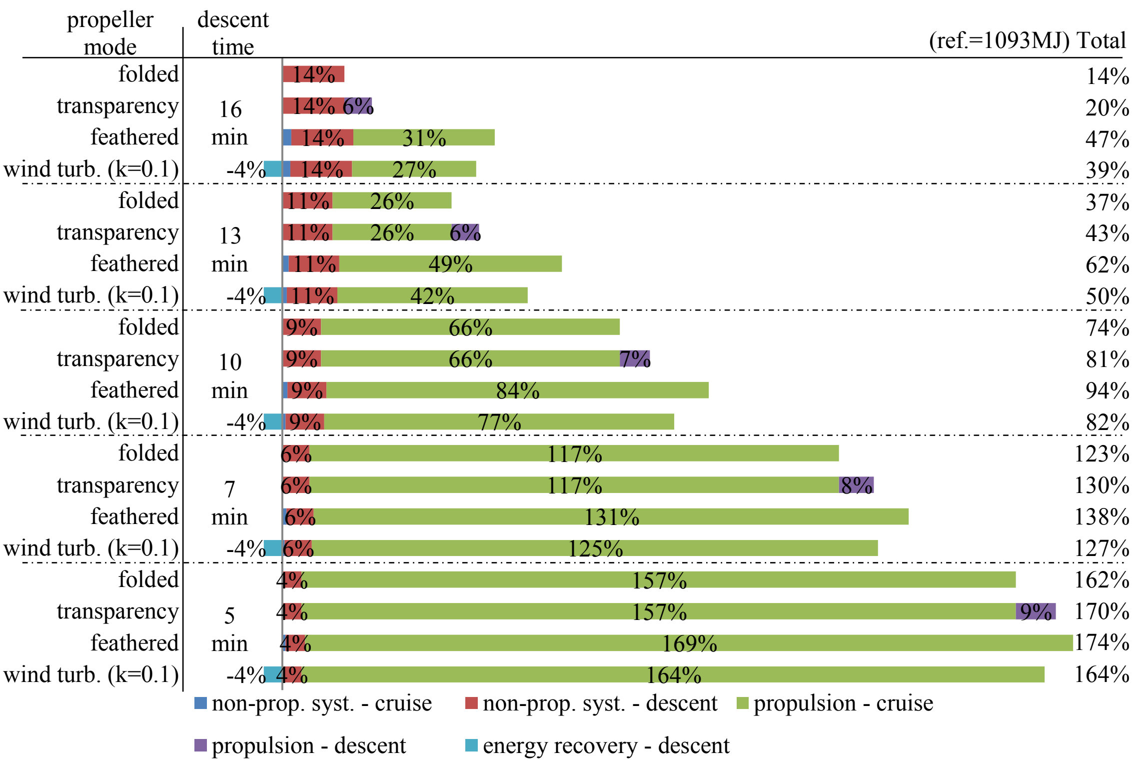

Fig. 5. Comparison of onboard energy consumption for hybrid power generation system – Cruise: Thermal/Descent: Electric

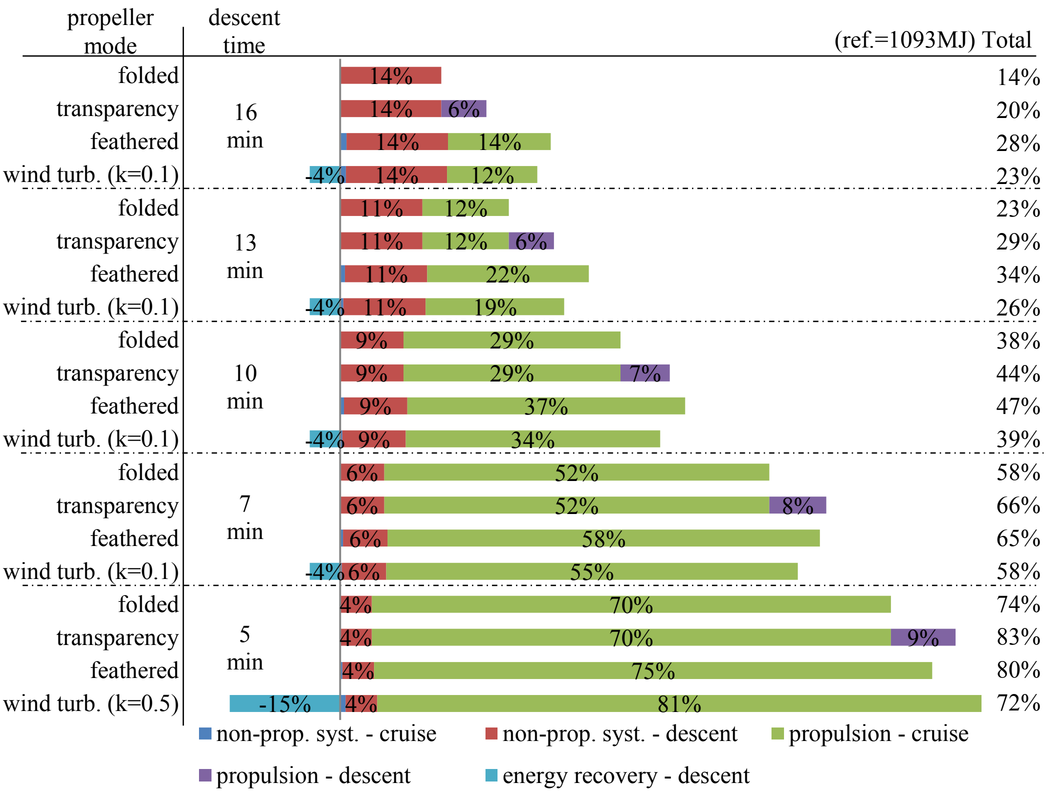

Fig. 6. Comparison of onboard energy consumption for full electrical generation system – Cruise: Electric/Descent: Electric

The hybrid power generation system (Fig. 5) brings significant reduction in overall energy consumption versus the full thermal system due to its high efficiency in descent. Contrary to the full thermal power generation it is better to perform the descent in transparency mode rather that in feather mode: the energy cost for keeping the propellers rotating is much less than the energy required to fly the additional cruise segment when feathered propellers are used. As energy recovering is now assumed possible with this system, it can be noted that the lowest overall energy consumption with the wind turbine mode is performed with a 4% recovery of the gravitational potential energy only. Still, the transparency and folded modes are always more energy efficient than the wind turbine mode for descent time longer than 10 minutes. Note that the descent time is generally constrained by cabin repressurization limits and will likely never be shorter than 7 minutes in normal operation.

For the full electrical power generation system, the overall energy consumption with the wind turbine mode is generally better than the transparency mode as the energy cost for additional cruise is much less than with the previous hybrid system. The recovered energy also participates in lowering this cost even further. Nonetheless, the most efficient case in transparency mode (16 min) to cover the reference distance is still better than the most efficient case in wind turbine mode (16 min also).

This analysis based on efficiency considerations shows that:

- If possible, propellers should be folded during the descent whatever the power generation system.
- The use of a hybrid power generation system could largely help reducing the energy consumption in descent (-60% for 10 min descent time versus full thermal power generation). With the high efficiency of such system in descent, the propeller should be operated in transparency mode rather than being feathered or being used as wind turbines for descent in normal operation.
- Finally, energy recovering through windmilling propellers is definitely not the most energy efficient way to use the gravitational potential energy of the aircraft if there is no constraint on the descent time: the aircraft should descend at the speed of best lift over drag with the propellers folded or operated in transparency mode.

These results are of course to be mitigated with possible weight penalties imparted by new power generation systems, in particular for the full electric system.

IV. Other Strategies

If transient energy storage and energy recovering are not promising concepts for a hybrid regional aircraft, other strategies could be implemented to take benefit from the hybrid architecture and to decrease the overall energy consumption.

A. *Power Management and Efficiency*

Reference [5] analyses the power chain efficiency of the reference aircraft along the nominal mission and points out potential energy savings related to the following technologies:

- Low propeller rpm in Taxi: the minimum propeller speed of the reference aircraft is limited by the minimum frequency required by non-propulsive systems and other hydraulic power generation equipment connected to the gearbox. Using hybrid-electric systems during taxi should enable to release this minimum speed constraint: the propeller efficiency could be increased by 49%.
- Secondary Energy source for Start and Stop: assuming that this start and stop function can be mature and reliable enough, including rapid re-activation of the gas turbine, the descent could be flown with the gas turbines off as already studied in this paper. In the same way, taxi phases could be performed on a full electric mode. The energy consumption in taxi could be decreased by 90%.
- Single Engine Aircraft: using one big gas turbine of twice the power of the reference engine would enable to save 10.5% on the prime mover efficiency at design point. However, having a single turbine in nominal operation requires a back-up system sized to cope with the failure of this turbine.
- Engine downsizing: as the reference engine is sized by the time-to-climb constraint, the cruise power is approximately 14% less than the design power at cruise level. Designing the engines for cruise power would result in a 0.5% penalty on the specific fuel consumption that will be imparted to the block fuel. Nonetheless, economic aspects have to be considered to come to a conclusion.

B. *Improved Aerodynamics*

Driving wheels, propellers or fans electrically instead of mechanically provides great flexibility as far as locating is concerned. Electrical power is thus a key enabler for distributed propulsion. Reference [5] also focuses on aerodynamic improvements for the reference aircraft enabled by new propeller or fan integrations and the associated concepts such as differential thrust, blown wing and boundary layer ingestion.

References

[1] C. Turpin, S. Astier, X. Roboam, B. Sareni and H. Piquet, Systemic Design Methodologies for Electrical Energy Systems: Analysis, Synthesis and Management, Chapter 6, John Wiley & Sons, 2012.

[2] C.R. Akli, X. Roboam, B. Sareni and A. Jeunesse, “Energy management and sizing of a hybrid locomotive,” 12th International Conference on Power Electronics and Applications (EPE'2007), Aalborg, 2007.

[3] J. Carlton, Marine propellers and propulsion, 2012.

[4] D.M. Black, R.W. Menthe and H.S. Wainauski, “Aerodynamic design and performance testing of an advanced 30° swept, eight bladed propeller at mach numbers from 0.2 to 0.85,” NASA CR3047, 1978.

[5] J. Thauvin et al., “Hybrid regional aircraft: a comparative review of new potentials enabled by electric power,” AIAA Propulsion and Energy Forum and Exposition, Salt Lake City, UT, July 2016, in press.