ELectric Innovative Commuter Aircraft

D3.1 Hybrid-electric Propulsion Architecture Report

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1 Executive Summary

In this report, some basic parallel and serial hybrid-electric propulsion systems are evolved from a conventional propulsion system and their operating properties are assessed and compared. The serial hybrid systems can be classified in two main types:

- the electric shaft topology, where the power is transformed by electric machines without the use of power electronics
- the DC link topology, where the mechanical power is transformed by electric machines and power electronics

The electric shaft topology has lower losses than the DC link topology and a lower system complexity as no control input is required. The DC link topology enables independent control of multiple propulsors without the use of variable pitch mechanisms.

The impact of the most relevant vehicle operational requirements on the hybrid-electric propulsion system design are elaborated. Aspects like the mission power profile, the mission altitude profile, the share of non-propulsive loads and the ability to recuperate the kinetic energy are covered and the possible benefit for ships, trains, cars and aircraft explained. Finally, the main benefits and drivers of hybrid-electric propulsion systems are explained for ships, trains and cars. With this knowledge, possible benefits for aircraft are derived and explained.

2 References

Definitions and Abbreviations

2.1.1 Terms & Definitions

Term	Definition
Sea Level Static	Operating point at sea level (0m) and zero velocity

Table 1: Terms & Definitions

2.1.2 Abbreviations & Symbols

Abbreviations	Description
SLS	Sea level static
ICE	Internal combustion engine
GEN	Generator
MOT	Motor
AC	Alternating current
DC	Direct current

Table 2: Abbreviations

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3 Hybrid propulsion systems synthesis

In this chapter, multiple hybrid propulsion systems are evolved from a conventional propulsion system and their benefits over the conventional system are discussed in a qualitative way. The systems are focused on aircraft application, which means that the system drives propellers and no wheels. However, the systems could also be used to drive cars or trains.

The assessment starts with a conventional propulsion system. In the following sections the system is extended step by step with electric components until the most complex hybrid system is presented in the end. Figure 1 shows the setup of a conventional propulsion system.

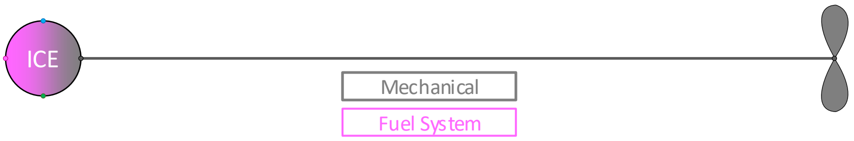


Figure 1: Conventional propulsion system

The system consists of an internal combustion engine (ICE), which transforms fuel to mechanical power. This may be a piston or a gas turbine engine. The right side shows a propulsor, which consumes the mechanical power to propel the vehicle. The entire propulsion system may contain multiple of these subsystems, however only one unit is considered to limit the number of propulsion systems to a meaningful number. There may also be gears and multiple shafts involved in the mechanical transmission, however this is not of interest for this high-level assessment.

Basic synthesis of hybrid-electric propulsion systems

In this chapter, multiple hybrid-electric propulsion systems are evolved from the conventional system setup by considering functional aspects only. This means that only different subsystem and component types and their impact on the hybrid system are considered. The number and the size of individual subsystems or components are not considered as this would lead to a large amount of systems, which cannot be compared in a meaningful manner in this report.

Hybrid propulsion systems can be split in two categories: serial hybrid and parallel hybrid systems. In serial hybrid systems, the entire propulsive power is transformed from one form to another. In parallel hybrid systems, only a share of the total propulsive power is transformed to a second energy form. The easiest way to extend the conventional propulsion system from Figure 1 to a parallel hybrid system is to add an electric energy storage, which can supply power to the propulsor shaft. The setup of this parallel system is shown in Figure 2.

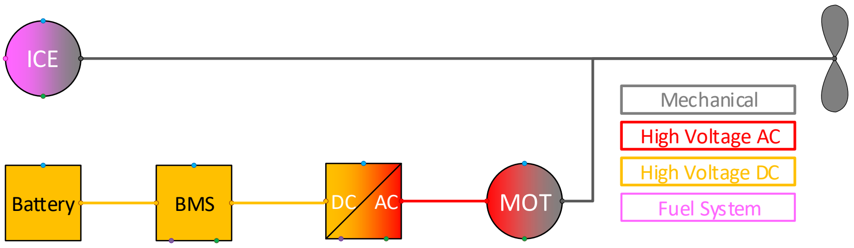


Figure 2: Parallel hybrid propulsion system

The idea of adding an electric energy storage is its buffering capability. The storage can supply additional power during short time mission segments. Hence, the ICE can be downscaled to an average continuous load and the peak loads are covered by the additional power from the electric energy storage. The higher load of a downscaled ICE is beneficial for its efficiency but disadvantageous for the lifetime of temperature limited parts such as turbines. When the ICE is operated at higher relative load, the cycle temperatures and pressures are higher, which results in lower turbine lifetime and shorter maintenance intervals. No studies have been found in literature, which stated to which extend and under which circumstances the net balance of those two effects is positive or not.

In this case, the electric energy storage is implemented as a battery, but it could be any electric energy storage or a fuel cell. The battery power is supplied to an inverter, which drives an electric motor. The mechanical power of the motor is supplied to the propulsor shaft. When the power electronics are designed accordingly, the energy flow can be bidirectional. Hence, the battery can be charged when the system is operative by absorbing mechanical power from the ICE. This is done during mission segments, where the propulsor does not require much power.

The second group of hybrid propulsion systems are serial hybrid systems. In these systems, the entire propulsive power is transformed to a second power form. To transform the conventional propulsion system shown in Figure 1 to a serial hybrid system, two electric machines are added. The system setup is shown in Figure 3.

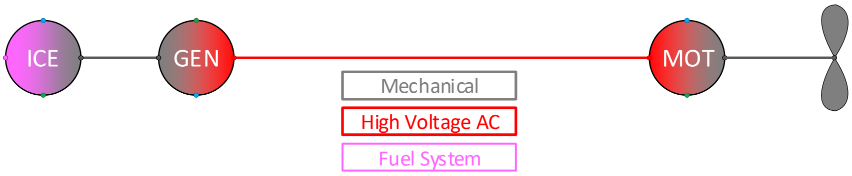


Figure 3: Electric shaft system

The generator (GEN) transforms the mechanical power of the ICE to electrical power. The motor (MOT) on the right transforms the electric power back to mechanical power which is then supplied to the propulsor. This system is called “electric shaft”, as there is no control input to manipulate the power transmission. The generator design, the rotational speed and the power of the ICE determine the voltage, current and the frequency in the AC transmission system. The motor configuration determines the rotational speed and the mechanic power of the propulsor. As the design of the electric machines is not considered to be modifiable during operation, the combination of the two electric machines has a constant transmission function like a mechanical gear stage. To adjust the load share between multiple propulsors, a variable pitch mechanism is required. Commercial propeller aircraft which cruise at Mach numbers around 0.5 already have a variable pitch propeller to achieve good low speed performance and maximum efficiency during cruise. With such a mechanism, the torque and power demand of each propulsor can be adjusted. This works for ship and aircraft propellers. For trains and cars, this mechanism is not possible. Moreover, this system requires a particular start-up sequence with very low load to enable the spool up the propulsors together with the engines and the generators. This requirement reduces the application to hybrid-electric aircraft with variable pitch propulsors as they can apply the wheel brakes and start to rotate the propulsor shafts. Trains and cars would start to move during the start-up and the higher share of viscous propeller losses (compared to the aircraft) results in high loads even with “feathered” propellers.

The advantages, which are introduced with the two electric machines are the simplicity of connecting multiple propulsors and generators to the AC transmission system as well as the simplicity of routing cables through the vehicle instead of rigid shafts. The drawback of this system is the cogging torque limit of the electric machines in such a setup. When the transmitted torque exceeds the cogging torque of synchronous machines, the machine gets desynchronised, which leads to the loss of power transmission and excessive mechanical forces.

The electric shaft system can also be extended with an electric energy storage, to provide additional power during short mission segments. An example system setup with a battery energy storage is shown in Figure 4.

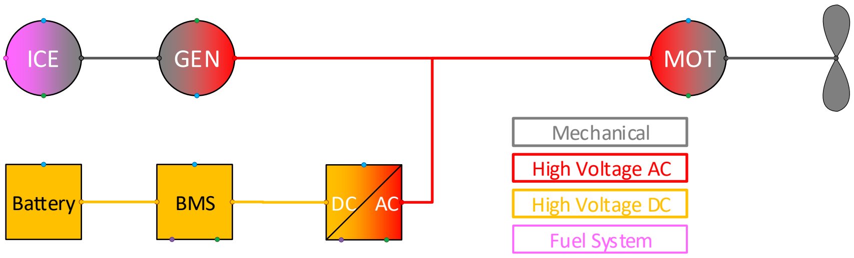


Figure 4: Electric shaft with electric energy storage

With an electric energy storage the ICE can be downscaled to increase its efficiency and to reduce its weight. When an energy storage is utilised that can operate at high frequency cycles, it can be used to compensate the reactive power in the AC transmission system. Moreover, the power electronics of the energy storage would allow to remove the cogging torque of the electric machines. This allows to reduce the size of both, electric machines and the cables. However, in this case all electric components are a single point of failure as the system would not be able to operate at rated power without the reactive power compensation.

To further extend the electric shaft system, a set of power electronic devices can be added to the AC transmission. The rectifier transforms the AC power from the generator to DC power. The DC power is transmitted to the propulsors, where an inverter transforms the power back to AC power. In the aerospace industry this system (without an energy storage) is called the turbo-electric propulsion system. The system is shown in Figure 5.

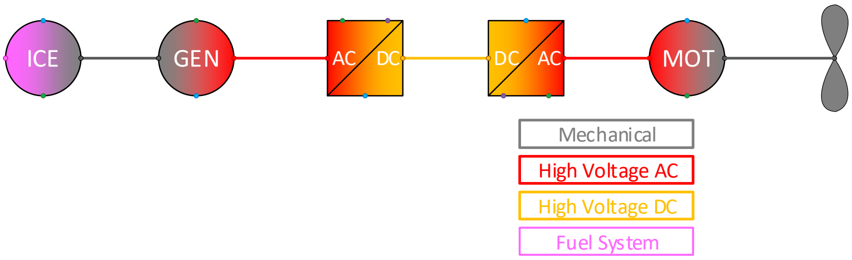


Figure 5: Turboelectric propulsion system

The introduction of the power electronic devices allows to operate the ICE and the propulsor at almost independent rotational speeds. Hence, the system could be compared to a mechanical gear stage with a variable transmission ratio. This allows to control multiple propulsors independently from each other, without the use of variable pitch mechanisms at the propulsors. Like this, multiple fixed pitch rotors could be controlled independently from each other. Of course, this system can also be extended with an electric energy storage, which supplies the DC link. A possible system setup is shown in Figure 6 below.

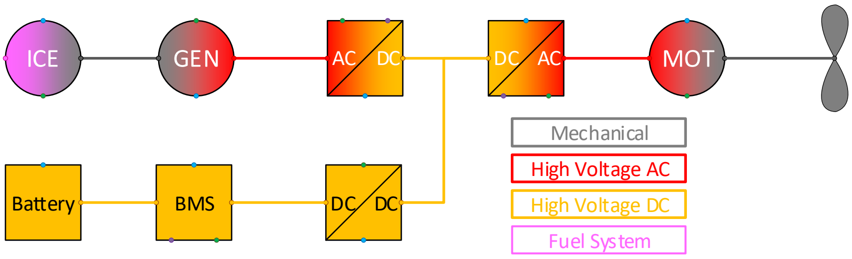


Figure 6: Serial hybrid propulsion system

This serial hybrid propulsion system with a DC link and an electric energy storage concludes the series of hybrid-electric propulsion systems from the functional point of view.
Three main hybrid topologies have been presented so far: the parallel hybrid system, the electric shaft topology and the DC link topology. In the last step, the electric shaft and the DC link topology are qualitatively compared with each other. Table 3 summarizes the comparison of the two topologies with respect to operational aspects, system level aspects and component level aspects.

	electric shaft	**DC link**
Operational aspects		
Electric machine rotational speeds are decoupled	No	Yes
Power split between multiple propulsor motors is variable without variable pitch mechanism	No	Yes
Peak torque capability	Low	High
System level aspects		
Battery integration possible	Yes	Yes
Non-propulsive power offtake possible	Yes	Yes
System complexity (number of components, control complexity)	Low	High
Component aspects		
Losses in electric machines	Low	High
Losses in power electronics	None	High
Mass of electric machines	High	Low
Mass of power electronics	None	High
Mass of cables	High	Low

Table 3: Comparison of the electric shaft and the DC link topology

In contrast to the electric shaft, the DC link topology allows to decouple the rotational speeds of the electric machines in the propulsion system. Hence, fixed pitch rotors can only be operated independently in a DC link topology. The electric shaft topology has a torque limit, which must not be exceeded during operation to ensure synchronization of all electric machines.

Both topologies can be extended with electric energy storage subsystems to benefit from buffering capability. The supply of electric non-propulsive loads is feasible in both topologies. The system complexity is significantly different. The electric shaft topology involves a lower number of components and it also involves only passive components. The electric machines do not require control, no communication (except for health monitoring and safety) and, hence, no complex hardware, which is a significant benefit over the DC link topology.

The electric shaft benefits from lower losses in the electric machines, as the iron losses from the high frequency switching signals of the power electronics do not occur. Only iron losses from the low frequency machine currents occur in the motor. As there are no power electronic devices, the losses in the electric shaft topology are lower than in a DC link topology. However, the masses of the electric machines and the cables will be higher as the machines must be designed for the maximum peak torque to avoid desynchronization and the cables must be sized for the reactive power in the system. For long distances between the electric machines, the electric shaft topology has the disadvantage that the power factor decreases with higher cable lengths.

Hybrid system synthesis with multiple components

In the previous chapter, the operational aspects of basic propulsion systems have been assessed. In this chapter, two additional system-level aspects are presented, which involve multiple ICEs and non-propulsive loads.

Figure 7 shows a basic hybrid-electric propulsion system which could be used to propel ships. Of course, the architecture for real ship applications would much more complicated as thrusters, batteries, etc are neglected here. But this architecture is sufficiently detailed to demonstrate the two major system level aspects.

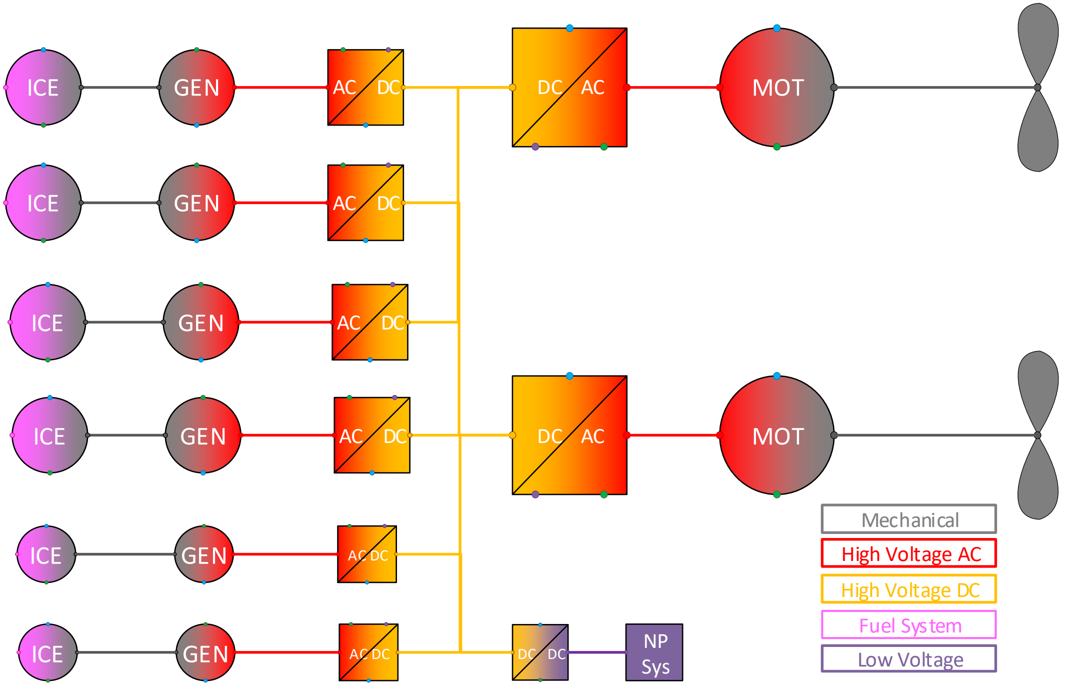


Figure 7: Propulsion system with multiple power sources and non-propulsive loads

The system supplies two large propellers to propel the ship, which are shown on the right. The propellers are driven by electric motors, which draw power from a high voltage DC link bus. This DC bus is supplied by four large engines with generators and rectifiers, which are shown on the upper left side. The system also contains two small engines with generators and rectifiers to supply the ship electric non-propulsive loads, which are connected via a DC/DC converter to the high voltage DC link bus.

The size of the symbols represents the installed component power. So, one large engine is not powerful enough to supply one propeller. Two engines are required to supply one propeller during full load. When the ship cruises at full power, the four large engines operate also at full power to supply the two propellers. When the ship does not cruise at full power, the engines go into part load operation, which considerably affects engine efficiency. Hence, for part load operation, individual engines are shut down to keep the load and the efficiency of the remaining engines high. Hence, for part load operations below 75% of power, one engine could be shut down, etc. The benefit of this setup is the fuel saving due to a higher engine efficiency and the reduced maintenance effort, as maintenance is required after a certain operating time. When some engines can be switched off, the maintenance interval can be increased.

The architecture shows four equally sized engines to drive the two propellers. Of course, the architecture could include multiple engines of different size. This would allow better adjustment of the power level of the remaining engines. On the other hand, using engines with the same power level has a communality bonus (eventually across the entire fleet), when multiple ships can use the same type of engine. Using multiple engines of the same type minimizes the maintenance effort and allows to reduce the development and production cost.

The second system level aspect is the supply of non-propulsive loads. For ships, these loads can have a share of more than 30% of the total installed power. By supplying non-propulsive loads which such a high share of the total installed power, the generators for the non-propulsive loads could also be used for propulsion and vice versa. This allows to better adjust the engine load and to maximise system efficiency.

4 Vehicle operational aspects

One main driver for the design of hybrid-electric propulsion system architectures are the vehicle operation requirements. These include power and altitude profiles for typical missions, the power profile of non-propulsive loads and the coupling of the vehicle kinetic energy to the propulsion system. These points are addressed in the following chapters.

Power profile for typical missions

The power profile during a typical mission has a large impact on the design of the hybrid propulsion system. Vehicles, which require a high-power throughput during short time intervals and a moderate power throughput during most of the mission will favour propulsion systems with a powerful energy storage that can supply the peak power during the short mission segments. The energy storage is recharged during the moderate power operation of the vehicle. Such systems are applied for example in Formula 1 cars, which have an electric energy storage to boost the propulsive power on straight track segments.

Vehicles with long missions and very low part power operation intervals will favour hybrid systems with two differently sized engines to maximize the system efficiency. A small engine covers the low power segments and a large engine (or both) covers the high-power segments. The total engine power may also be split to multiple engines, when the mission has certain part load segments for longer periods of time. In this case, engines are shut down during part power operation to keep the remaining engines at a high load and efficiency level. Such systems are applied on hybrid ships which are operated a lot in part power operation. Figure 8 shows the typical mission profile of a military destroyer vessel. Observations show that the typical ship spends more than 90% of its life below 60% load. [1]

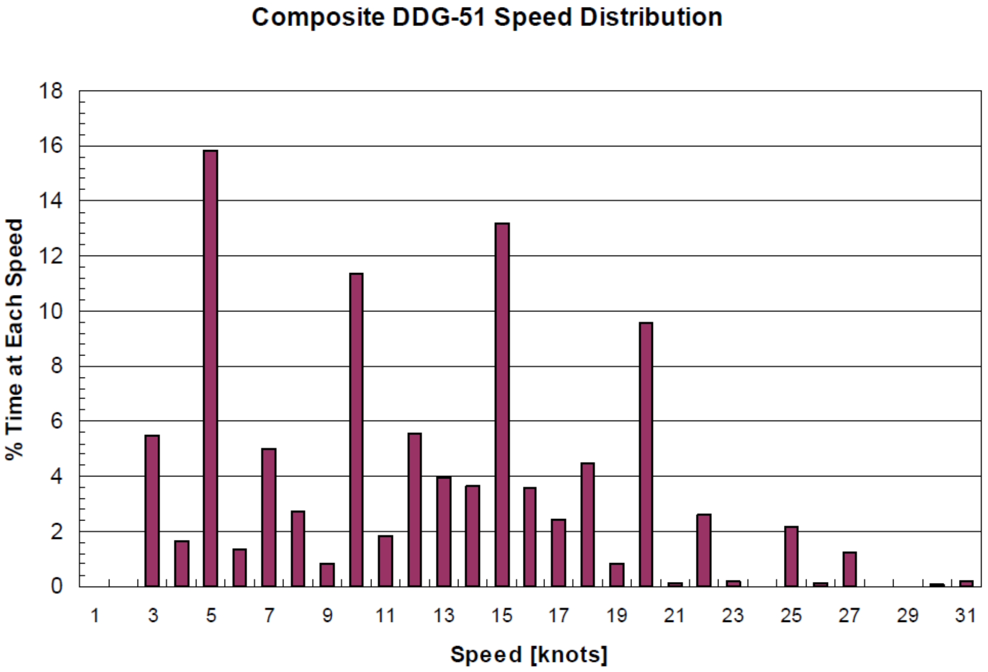


Figure 8: Typical mission profile of military vessel [2]

There may be requirements to be able to operate without local emissions for a given time. A ship could be designed to leave the harbour without local CO2, NOx or noise emissions. By reaching a certain distance from the shore the ship is allowed to start its engines. In this case, an electric energy storage or a fuel cell must be implemented to cover this mission segment and to supply all non-propulsive loads during this time.

Ferries and other civil ships, which have a long high-power operation during cruise have two modes of operating the hybrid-electric propulsion system. When manoeuvring in harbours and rivers, the ship uses multiple propellers and thrusters, which are supplied via a DC link bus. When the vessel starts the cruise segment, the motors of the main propellers and the engine generators are synchronised, and the power electronics are disconnected. In this case, a DC link topology implemented in such a way that it can be operated as an electric shaft topology. This reduces system losses and, hence, the operating cost.

Altitude lapse ratios

Besides the power profile, the altitude profile has a considerable impact on the architecture design, as it determines the available power of air breathing internal combustion engines and fuel cells. When the vehicle is operated in high altitudes, the available power of the engines and fuel cells decrease with the reducing air density. This may be compensated by higher compression ratios, but this is considered feasible for combustion engines and pressurized fuel cells only. For turbomachines the pressure ratio cannot be changed with altitude.

Figure 9 shows the power lapse ratio of a turboshaft engine with constant thermodynamic cycle parameters. The overall pressure ratio, the compressor and turbine isentropic efficiency and the burner exit temperature were kept constant and it was assumed that the engine can fully recover the dynamic pressure. The x-axis shows the flight Mach number and the y-axis shows the flight altitude in meters. The contour lines show the available engine power relative to sea level static (SLS) conditions.

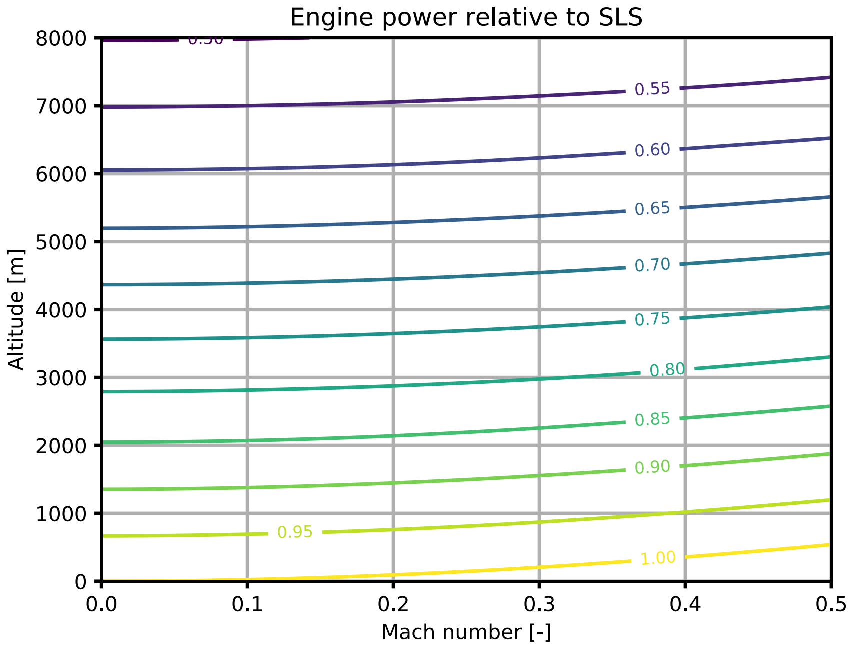


Figure 9: Power lapse ratio of a turboshaft engine

The plot shows that the available mechanical power of the engine decreases significantly with altitude as the air density decreases. The increase of the available power with higher flight velocities reflects the increase of the dynamic pressure. Although the absolute mechanical power decreases during an aircraft mission, the engine still operates at a high thermodynamic load and does not operate in deep part power operation. The engine efficiency is not noticeably affected, as the burner exit temperature and the turbomachine efficiencies are still high. This must be considered in the design of hybrid-electric propulsion systems for aircraft. This effect also applies for cars and trains in mountain areas. However, this is not the driving effect for hybrid-electric propulsion systems.

In contrast to air breathing engines, the power of electric components is not directly affected by altitude. There are effects on the cooling system and the environmental conditions require careful design of the insulation system, but the available power of electric components does not decrease with altitude. Hence, the mix of air breathing engines and electric components is particularly complex for aircraft applications.

Vehicle kinetic energy recuperation

Another reason to design a hybrid-electric propulsion system is the bidirectional power flow in electric components. Internal combustion engines can only convert a fuel flow to mechanical power. It is not possible to reverse this. If designed accordingly, electric components can reverse the power flow. This is very interesting for applications where the vehicle kinetic energy is linked to the propulsion system. In this case, the electric drive train can convert the vehicle kinetic energy back to electric energy and store it in a battery or a capacitor. This is very interesting for applications where the kinetic energy of the vehicle changes very often. This is the case for all vehicles that mostly operate in cities, such as buses, taxis, trams and local trains.

When slip is neglected, cars and trains can benefit from this function as their kinetic energy is directly linked to the wheels. The kinetic energy of ships and aircraft is not linked to the propulsor shaft. There is a certain slip between the surrounding fluid and the propeller, which prevents to recuperate the kinetic energy of ships and aircraft with a meaningful efficiency. Hence, this aspect of hybrid-electric propulsion systems is reserved to trains and cars.

The share of non-propulsive loads

The amount of electric power which is consumed by non-propulsive loads is another important design factor for hybrid-electric propulsion systems. The so-called secondary systems are all systems that do not contribute to the propulsion function. These are systems like entertainment, air conditioning, restaurant equipment, communication, lights, etc. The share of non-propulsive loads relative to the propulsive power varies considerably among ships, trains, cars and aircraft and a certain variation within each category is noticeable, too.

The aircraft industry is moving towards all-electric aircraft, where all non-propulsive systems are supplied by electric power taken from generators in the engines. Today’s aircraft have hydraulic systems to actuate the landing gear, the flaps and the control surfaces. Pneumatic systems are used for anti-ice, cabin environmental control and engine start-up. All these non-propulsive loads represent less than one percent of the installed propulsive power. Hence, the loads are supplied by power offtakes from the main engine and not via a dedicated engine like on ships. The auxiliary power unit can supply all non-propulsive subsystems in the aircraft, however it is implemented to operate during ground operation and emergency situations only.

The vast increase of electric components in cars has led to an increase of electric power demand for non-propulsive purposes. Small modern cars use alternators with roughly 1kW to supply all secondary systems and to charge the battery. Even with a small engine of 35kW, the share is still below 3%. Moreover, this refers to the size of the alternator compared to the engine power. The main power of the alternator is used to charge the battery, which is required to start the engine. Additionally, the installed power does not reflect the actual share of non-propulsive loads.

The share of non-propulsive loads of trains varies considerably. A freight train clearly has less non-propulsive loads than a passenger train with electric air conditioning and heating, an onboard restaurant and cabin lights. Although the Inter City Express 3 is not a hybrid train, it is chosen to estimate the share of non-propulsive loads of passenger trains. The ICE3 train has two 250kVA converters to supply non-propulsive loads from the main power line. Its total installed drive train power is 8000kW. Hence, the share of the secondary systems is in the order of 6% of the installed propulsion power. The actual consumed power share will be less, of course.

The share of non-propulsive subsystem power to the propulsive power is the highest for passenger ships. They have a much higher power share of non-propulsive loads than aircraft, cars or trains. This results from two factors: as the journey by ship takes much more time than the trips people do by car, by train or by aircraft, there is more space required for the passenger cabin, storage rooms and rooms for free time activities. All this space needs to be air conditioned and heated. The second factor is the very low power-to-weight ratio of ships compared to aircraft, cars and trains. Hence, large cruise ships can have a power share of non-propulsive loads of 30% and more. This enables synergetic effects of combining the primary propulsion system with the non-propulsive load power system.

Table 4 shows a comparison of the power-to-weight ratio of propeller aircraft, cars, trains and cruise ships. Assuming a certain power required per vehicle mass (for air conditioning, heating, lights, etc) then the power-to-weight ratio is a good indicator for the share of the non-propulsive loads in a vehicle. High power-to-weight ratios result in a low share of non-propulsive loads and vice versa.

	maximum mass	**installed power**	**power-to-weight ratio**
	[t]	[kW]	[W/kg]
Aircraft			
ATR 72-212A Basic	22,2 [9]	2 x 2051 [10]	185
Dornier 228-212	6,4 [8]	1880 [7]	294
Cars			
VW up! 1.0 take up!	1,3 [13]	44 [13]	34
VW Touran II 2.0 TDI	2,2 [11]	110 [11]	50
VW Scirocco III 2.0 TSI	1,8 [12]	125 [12]	69
Trains			
Siemens Velaro D	544 [14]	8000 [14]	15
Ships			
Titanic	53150	37510	0,7
Freedom of the seas	71000	42000	0,6
Voyager of the seas	64400	42000	0,7

Table 4: Power-to-weight ratio of passenger transport vehicles

5 Application and summary

In the previous chapters, multiple hybrid electric propulsion systems have been evolved from a conventional propulsion system and the possible benefits of hybridization have been presented. The goal of this chapter is to look at existing fields of hybrid-electric propulsion systems in ships, trains and cars to understand the benefits of hybrid-electric propulsion for these vehicles and to derive what the benefits for hybrid-electric aircraft could be.

For large passenger ships, hybrid-electric propulsion has become the standard choice. These ships have large engines to generate the high share of non-propulsive power. The combination of the propulsive power and non-propulsive power system allows to run a certain number of engines under high load and to switch some engines off. The different size of the engines and the "high" number of engines enables a good adjustment to the power demand of the ship. This maximized the engine efficiency and extends the maintenance intervals, which are determined from engine operating time. Routing cables through the ship chassis is much easier than having directly driven propellers with long shafts, which block a lot of space. Hence, hybrid systems allow to exploit more space in the hull for payload. The electric power transmission also enables the use of rotatable thrusters with fixed pitch propellers. This significantly increases the maneuverability and the ship is no longer dependent on tugboat services in harbors, which saves money. For long range cruise operating, hybrid-electric ships can switch to the electric shaft mode to maximize the system efficiency and to minimize fuel burn [1],[2].

Most passenger trains have electric propulsion systems as the tracks they operate on are mainly electrified. The electric power is delivered by the catenary and the kinetic energy of the train can be recuperated and fed back to the grid. The most important benefit of hybrid propulsion systems for train is the ability to operate on electrified and non-electrified tracks without changing the locomotive. Those hybrid systems may be a combination of the electric drive train and a diesel engine which supplies the power on non-electrified tracks. This solution is more affordable than the electrification of regional rail lines. Recently trains with a large battery are available that can drive a certain distance with the battery only. The second goal of hybrid propulsion systems is to reduce the fuel burn of diesel locomotives, which operate mainly on non-electrified tracks. Furthermore, serial hybrid-electric propulsion systems are used for the power transmission from the diesel engine to the locomotive wheels. As the locomotive must allow a certain flexibility of the undercarriages to achieve certain curve radii. Achieving this flexibility in a mechanic power transmission is difficult. Hence, the mechanical power of the diesel engine is electrified and supplied by electric motors on the axles [3],[4].

Hybrid-electric cars use batteries as an electric energy storage to recuperate the kinetic energy during braking and to be able to drive short distances in purely electric mode. The main target of hybrid-electric cars is to have the combination of local emission free driving in cities, where use of combustion engines will be more and more prohibited, and the long-range capability. As soon as the battery energy density reaches values that allow long ranges, hybrid-electric propulsion systems will be obsolete for cars [5],[6].

Many aspects of hybrid-electric propulsion which are beneficial for ships and cars are not necessarily beneficial for aircraft. Distributing the power generation over multiple engines like on ships is not meaningful, as the air density lapse reduces the available engine power as well as the aircraft power demand. During cruise, the engines do not operate in inefficient part load like on ships. Additionally, the share of non-propulsive loads is very small compared to ships. The engines also do not block any space in the aircraft fuselage as they are mounted on the wing or on the fuselage.

Hybrid-electric propulsion systems do offer some possible benefits for aircraft:

- On very short-range applications, a battery may enable fuel burn savings by switching off the engines during low part power operations such as descend, approach and ground operations.

- On long range missions, hybrid-electric propulsion systems may enable fuel-burn reduction if an aircraft configuration with multiple distributed propulsors leads to a drag reduction compared to a conventionally driven aircraft.
- The simplicity of distributing electric power along the chassis to multiple propulsors enables multi rotor vehicles with simple fixed-pitch rotors. In this way mechanical complexity is transferred to control complexity, which may result in a cost reduction for the operator.
- The aircraft can operate in purely electric mode on ground which reduces local emissions at the airport. When the according fees increase in the future, a hybrid-electric propulsion system may reduce operating cost for the airline.

6 The way towards a near zero CO_2 emission commuter aircraft

The preceding chapters have shown the synthesis of all kind of possible hybrid-electric propulsion system architectures and their characteristics. Chapter 5 presents a rough overview of the application of hybrid-electric propulsion systems in other transport sectors and it gives possible solutions for different aircraft applications. In this chapter, the landscape of hybrid-electric propulsion systems is narrowed down to show a possible way towards a near zero CO_2 emission aircraft.

The easiest solution to realise a propulsion system with absolutely no CO_2 emissions is a battery-electric propulsion system, in which batteries are the only energy storages and no fuel is burnt in combustion engines. Battery-electric propulsion systems are in use for certain aircraft applications, which do not require high range or endurance capability such as electric trainer aircraft [16] or sail plane towing [17]. However, the low energy density of batteries does not allow aircraft design with high range.

Without going in too much detail on the aircraft design, the limit of battery-electric propulsion systems is shortly calculated. Battery-electric propulsion systems are composed of multiple components, which contribute to the system mass and performance. Information on both aspects is required to assess the aircraft flight performance. The following assumptions are made for the components:

Component	(constant) Efficiency	Power-to-weight ratio
Propeller	90%	n.a.
Electric motor	95%	10 kW/kg
Power electronics	98%	30 kW/kg
Battery	95%	n.a.
Power distribution	100%	30 kW/kg
Cooling system	100%	2 kg/kW

Table 5: Component weight and performance assumptions

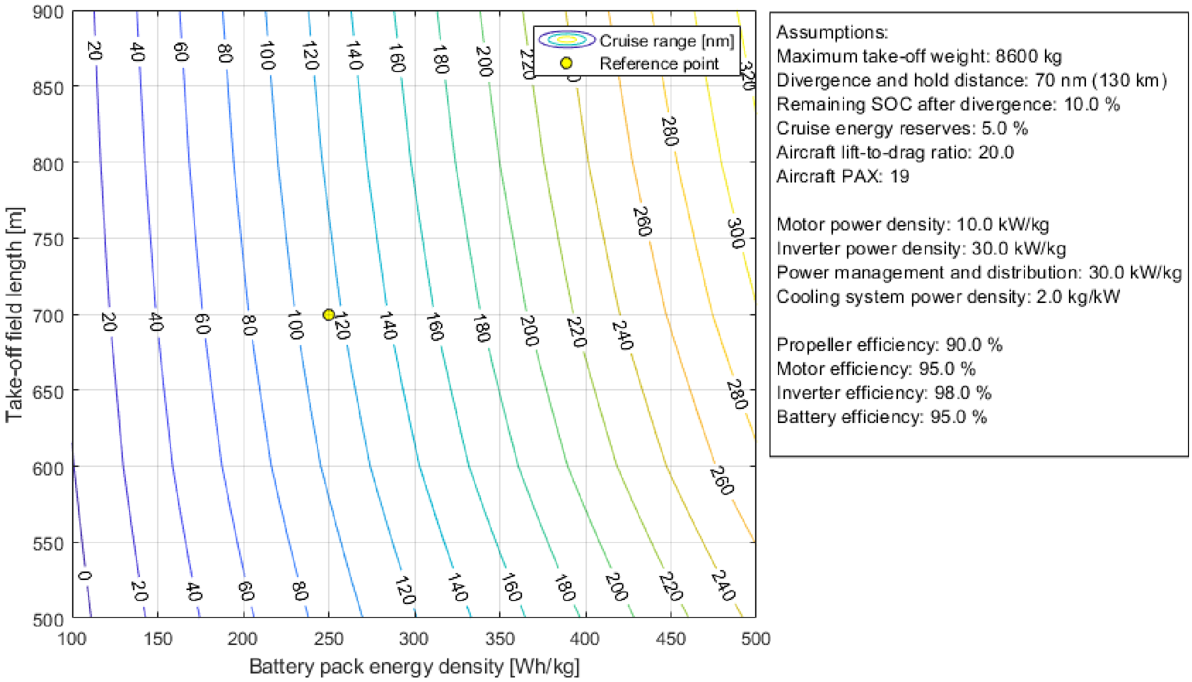
The efficiencies and the power-to-weight ratios represent advanced assumptions, which have not been demonstrated in the commuter aircraft power class so far.

The aircraft performance is calculated for a simple mission, which is sufficiently detailed to determine the required mission energy and the required take-off power for a given field length. The mission consists of a take-off point followed by a cruise segment from the origin to the destination airfield without climb and descend. It is assumed that the additional climb energy is harvested back during descend.

The structure mass is subtracted from the MTOW to obtain the remaining mass for the payload, pilots and the propulsion system. The aircraft is designed for 19 PAX and 2 pilots, which are assumed to have a mass of 95kg each. This results in a remaining mass 2978kg for the propulsion and the cooling system. The electric components and the cooling system are sized with the power-to-weight ratios and the installed power of the aircraft (the efficiency chain is considered). The mass of the battery is calculated from the total required energy and a specific energy density, which serves as an input parameter for this study.

With the lift-to-drag ratio, the drag force can be calculated from the aircraft weight and the product from drag force and the distance gives the required propulsive energy. In a first step, this is done for the diversion flight. To obtain the battery energy, the efficiency chain of the propeller and the electric components is considered. With this, the required battery mass for the diversion flight is calculated and subtracted from the remaining mass. What is left is the available battery mass for the cruise flight, which allows to calculate the achievable cruise distance.

The result of this study is shown in the figure below. The x-axis and y-axis show the two input parameters for the study, which are the specific energy density and the take-off field length respectively. The contours show the achievable cruise distance. The reference point is chosen to calculate the sensitivity of the cruise range on all input parameters.



Assumptions:
Maximum take-off weight: 8600 kg
Divergence and hold distance: 70 nm (130 km)
Remaining SOC after divergence: 10.0 %
Cruise energy reserves: 5.0 %
Aircraft lift-to-drag ratio: 20.0
Aircraft PAX: 19

Motor power density: 10.0 kW/kg
Inverter power density: 30.0 kW/kg
Power management and distribution: 30.0 kW/kg
Cooling system power density: 2.0 kg/kW

Propeller efficiency: 90.0 %
Motor efficiency: 95.0 %
Inverter efficiency: 98.0 %
Battery efficiency: 95.0 %

Figure 10: Integrated mission performance of battery electric commuter aircraft

How to read the Figure: with a battery energy density of 200Wh/kg and a TOFL of 700m, a commuter aircraft can be designed that carries 19 PAX over 80nm (plus 70nm diversion).

The figure shows that the battery energy density is the driving factor for the achievable cruise distance and that the impact of the TOFL is minor for low battery energy densities. The impact of the TOFL gets stronger as the battery energy density increases. The contour plot shows that the achievable cruise range decreases with smaller TOFLs. This is a result of the increasing installed system power and resulting the higher component masses. To achieve reasonable cruise distances of 200nm and more, batteries with an energy density of 400Wh/kg at pack level are required.

As batteries with this energy density **and** the required power density are not yet available in large scale quantities, commuter aircraft with low CO_2 emission rely on hybrid propulsion systems or hydrogen driven PEM fuel cells. The low efficiency in combination with the low operating temperature, require a significant cooling effort, which represent a huge challenge to integrate the fuel cells as the primary propulsion power supplier on aircraft. Hence, hybrid-electric propulsion systems with turbomachine engines remain the only solution for short term solutions.

Atanasov et al. presented an electric commuter concept, with a parallel hybrid propulsion system, which is able to cover short range missions with the battery energy only. The aircraft also carries fuel and turbines, which are used as a range extender for longer missions and for reserves in case of diversion. However, the aircraft is able to cover around 88% of its mission on battery energy only, which significantly reduces CO_2 emissions and does not restrict the aircraft usability for the operator [18].

The course of this project will show which aircraft and propulsion system configurations will prove as the most beneficial to fulfil to the goal of designing a near zero CO_2 emission commuter aircraft.

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