Hybrid Electric Propulsion Systems

Integrated performance analysis applied on short-range aircraft

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Hybrid Electric Propulsion Systems
Integrated performance analysis applied on short-range aircraft

by

A.W.X. Ang

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Supervisor NLR: Dipl.Ing. T. Kanakis
Thesis committee: Dr.ir. M. Voskuijl TU Delft
Dr.ir. A. Sahai TU Delft

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TU Delft
Delft University of Technology
During my study at the faculty of Aerospace engineering at the Delft University of Technology, I discovered my interest in the design of high-speed vehicles. I am grateful that I can finish my study in Flight Performance and Propulsion with an interesting topic: the Hybrid Electric Propulsion System (HEPS).

I would like to thank my supervisors, Arvind Rao and Toni Kanakis, for their great inspiration, insightful comments, and for giving me the opportunity to do my thesis at the NLR. Their feedback and time have been very valuable to me and I could not have obtained this result without them.

Special thanks goes to Wim Lammen, who has always helped me when I got stuck in my research, Oscar Kogenhop for his assistance in using GSP and Edward Rademakers for providing me with insights on the simulation of emissions. I also wish to thank Mark Voskuil and Abhishek Sahai for participating in the exam committee and taking the time to review and assess my work. My gratitude also goes to my fellow thesis interns at the NLR for the enjoyable time: Allard, Andy, Bas, Claudia, Emiel, Nabil and Sebastiaan.

I would also like to thank my parents for their relentless support. Without them, I would not have had the opportunity to reach this milestone. Lastly, I would like to thank Yapman for her encouragement and support, especially in the finishing stages of my research.

With the addition of a journal article to be submitted (Ang et al. 2016), I hope that this thesis work provides interesting insights in the power management of a HEPS, which may be further used in the development of this novel propulsion concept.

_A.W.X. Ang_
_Delft, August 2016_
The growing level of environmental implications of aviation and a significant increase in air traffic have been driving technological advancements in the aerospace industry. In the mean time, the rising developments in battery technology allowed the automotive industry to build hybrid and fully electric cars. However, the limited power-to-weight ratio of components up till now impede the development of fully electric commercial passenger aircrafts. In this regard, a Hybrid Electric Propulsion System (HEPS) is more viable.

With a HEPS, the aero-engine is combined with an electric system. This brings several technological challenges, such as the increased complexity in the performance and sizing methodology of the propulsion system and the necessary offset of the weight increment. Because of these issues, the different state of the art HEPS concepts largely depend on the development of new technologies, as well as maintaining efficient power management during the different phases of the flight envelope. The power management system adjusts the supplied power ratio between the energy sources during operation, as power can come from fuel and/or electrical energy.

The objective of this study is to analyse the power management of a HEPS, focusing on passenger transport aircraft. To examine the performance of a HEPS, an integrated aircraft-propulsion system simulation model is developed to determine the power requirements of a flight mission. In this model, a comparison is made between an Airbus A320 with and without a parallel HEPS. It is assumed that the aircraft is propelled fully electric during taxi and partially electric during take-off and climb. During the cruise phase, only the engine is used. In the descent phase, the battery is recharged to enable full electric propulsion during the taxi-in phase. The effects of different power management strategies are analysed by applying different take-off and climb power split combinations.

The application of the HEPS in the mid/long-term is heavily dependent on the technology maturity level of electric components. From a fuel burn perspective, the HEPS become viable for short-range flights (1000 km) when electric components have a specific energy of 600 Wh/kg and a specific power of 12500 W/kg, which is predicted to be feasible by the year 2030. However, increasing the flight range means that the additional weight of the electric system is carried over a longer distance, resulting in a higher fuel burn during cruise. This will mitigate the benefits of the HEPS. Thus, for the mid/long-term, the HEPS will only be beneficial for short-range flights when taking into account the predicted technology level of 2030.

The addition of an electric system has several advantages over conventional engines. Firstly, an increase in the power split can lead to greater fuel savings. As power is generated from two different energy sources, total energy consumption should be considered as well. This can be significantly higher due to the greater specific energy of fuel. Performed simulations have shown that with a climb power split of approximately 14%, most fuel is saved for the smallest incremental increase of total energy consumption. Secondly, it leads to higher overall efficiency as it allows the engine to be scaled down. This will shift the design point of the engine from the take-off phase towards the cruise phase. However, optimising both the power management strategy and the downscaling of the engine is limited by the allowed turbine inlet temperature.

An optimal power management strategy has been derived, using a take-off and climb power split of approximately 25% and 14% respectively, while scaling down the engine to 90%. This will reduce the fuel burn by 7.5% and total energy consumption by 2%. As a result, emissions will reduce as the utilisation of an electric system affects the way the engine operates. With the chosen HEPS and power management strategy, CO₂ and NOₓ emissions can be reduced by 7.5% and 3.7% respectively.
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<td><strong>VMO</strong></td>
<td>Maximum Operating Speed</td>
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</tbody>
</table>
Nowadays attention is paid to the air pollution caused by road transport, but the contribution of aircraft emissions on air pollution is raising concerns and the aviation industry is expanding. Air travel has tremendously increased and its unrestrained growth will double in the next twenty years [1, 2]. Figure 1.1b and 1.1a both show the forecasted rise in demand for air traffic. Figure 1.1a is a market forecast of Boeing’s fleet which will increase from 21,600 to 43,560. Figure 1.1b shows a market forecast of air traffic that increases annually with 4.6%. By 2034 air traffic is predicted to double.

![Figure 1.1: global market forecasts of aviation](image)

Unsustainable exploitation of non-renewable fossil resources not only leads to its depletion but with fossil fuels being the dominant source of energy, undesired changes in climate also becomes inevitable. Statistics provided by the European Commission [3] show that in 2012 only 9% of the EU’s mobility volume in passenger-kilometers was made by air transport. From the greenhouse gas (GHG) emissions produced by transport, only 12.8% comes from civil aviation. Air pollution caused by aircraft is however more significant as emissions are not only produced on ground, but also at higher altitudes. Due to the lower atmospheric pressure and "cleaner" air, a given volume of emissions can have a much greater impact [4].

Next to GHG, aircraft noise emissions can have a significant effect on the health. Chronic aircraft noise exposure on children impairs reading comprehension and long-term memory and may be associated with raised blood pressure. These noise emissions may also contribute to the effects of environmental noise on annoyance, sleep and cognitive performance in adults and children [5]. A rise in air traffic will therefore lead to an increase in the amount of complaints from residents, living close to airports.

The environmental impact of aircraft, exploitation of non-renewable fossil fuels and rising demand for air transport has necessitated both the European Commission[6] and National Aeronautics and Space Administration (NASA)[7] to set goals that offset the impact of growing air traffic. These goals are summarised in Appendix A.

Due to the advancement in battery technology, the automotive industry has been able to lower its environmental impact with hybrid and fully electric cars. In the aerospace industry, the concept of complete
electric propulsion will be introduced on small airplanes from 2017 [8]. However, the restricted power-to-weight ratio of electric components up till now holds back the development of fully electric commercial passenger aircraft, as high power requirements make it impossible to carry the electric system [9]. Therefore, the turbofan is still required to propel the aircraft. Combining the state of the art turbofan engine with an electric motor could be a potential solution to meet the requirements of future air travel. Such a propulsion system is called a Hybrid Electric Propulsion System (HEPS).

Different examples of HEPS applications have been developed [10–12]. They all show that the use of a HEPS have the potential to increase efficiency and reduce emissions and hence, are in line with the goals for future air traffic. However, the development of these concepts depends on whether new technologies are able to compensate the weight increase. Moreover, sizing becomes more complicated as propulsive power comes from two different types of energy sources. The determination of the ratio of power coming from both energy sources is called the power management. The power management is thus an important aspect in the sizing of HEPS. It determines the amount of electric or chemical energy to be carried during flight and the weight of power components. Hence, the feasibility of a HEPS and its potential to meet the requirements depends on the power management of the HEPS [13].

1.1. Research objective

The Netherlands Aerospace Centre (NLR) has done extensive research in new concepts for a sustainable future of aviation and has set up a study within the area of power management of the HEPS for future aircraft. Power management strategies on hybrid systems have been well established in the automotive industry, but are still to be explored to a further extent in the aerospace industry. The aim of this research is to provide insight in the power management of an aircraft HEPS. This leads to the following research objective:

The objective of this research project is to analyse the power management of a Hybrid Electric Propulsion System (HEPS) during flight of passenger transport aircraft.

To attain this objective, the following goals need to be achieved throughout the research project:

- Develop a simulation model to determine the power requirements of a predefined flight and validate this with open literature.
- Identify the performance parameters of a HEPS and investigate the effect of technology advancements on performance
- Define the HEPS architecture and power management strategy
- Analyse the effect of a power management strategy on the performance of the aircraft

This report starts with an orientation on the topic HEPS in Chapter 2. This Chapter describes the parameters that configure a HEPS, gives an overview on the state of the art technologies and concepts, and provides equations that are required for the analysis of propulsion system performance. Chapter 3 explains in detail the components of the propulsion system. Subsequently, Chapter 4 discusses the power management strategy considered in this research. This is followed by Chapter 5, which shows how the hybridisation of the propulsion system is simulated and validated. Results of the simulation are presented and discussed in Chapter 6. This report ends with the conclusions in Chapter 7. This Chapter also describes the contributions to the field of HEPS and provides some implications for further research.
Literature review of HEPS

Aviation has dramatically transformed society over the past 100 years. Fast and efficient transportation has essentially been "shrinking the planet" and changing the landscape in terms of financial and societal conditions. The growth of air traffic over the past 50 years has been spectacular, and will continue in the future. This anticipated growth carries along challenges and opportunities in various aspects of life, from economics to the environment. Research must meet these emerging challenges by producing concepts and breakthrough technological achievements in air transport. One of the concepts under investigation is the use of a HEPS.

This Chapter introduces the topic HEPS, based on literature research. Section 2.1 defines the definition of a HEPS and gives a detailed explanation of the different architectures of the HEPS. Subsequently, Section 2.2 describes how the performance of the HEPS can be determined. This is followed by Section 2.3, which shows how the power from both the electric and combustion system can be controlled.

2.1. Hybrid electric propulsion system architectures

A possible answer to meet with the environmental goals, mentioned in Appendix A, is to use electric energy to generate propulsive power. The improvements made in battery technology stimulated the automotive industry to develop hybrid and even fully electric cars. And although a fully electric aircraft would be the logical response from the aerospace industry, the still limited power-to-weight ratio of electric components means that a more feasible solution is to be sought [9]. One such solution is to combine the conventional combustion engine with an electric motor, also called a HEPS [13].

A HEPS has the potential to meet the goals of future air traffic as it utilises the benefits of an electric motor and compensates for the lack of total required power with the conventional engine. This allows the engine to be sized more specifically for one phase (e.g. cruise) of the mission. This means that less power is required from the combustion engine and therefore emissions can be reduced, while efficiency can be increased. A Hybrid Electric Propulsion System (HEPS) can be defined as a propulsion system that combines a combustion engine with an electrical power component to achieve a better overall performance than each subsystem would on its own [13, 14].

Over the years different concepts of HEPS have been developed and considered for the propulsion of aircraft that meet the requirements of future air traffic. These HEPS concepts can be categorised by the way in which the combustive and electric part are combined: series, parallel or a combination of both series and parallel [14]. A series configuration means that the power supplied to the fan is supplied by electric motors only, which in turn are driven by electric power produced by the turbo generators. In the parallel configuration power is supplied by both the electric motor, which is powered by a battery, and the combustion engine. Summarised, the architecture is defined by the way the power from the combustion engine and the electric power component come together to drive the propulsor. The point where the power from the subsystems are combined is also called the power node. This can also be seen in Figure...
2.1. The left side of the Figure illustrates that there are different ways to link the components of the HEPS. The configuration described in the middle represents a series architecture. As can be seen, the resulting power supplied to the propulsor only comes from the electric system. The configuration on the right points out the parallel architecture. As one can observe, the power comes from either the turbofan engine, the electric system or a combination of both.

The next Subsections will describe different HEPS architectures. Each Subsection contains an overview of the lay-out and ends with an example that shows how the architecture is applied in existing concepts and what its challenges are. Note that the Power Management And Distribution (PMAD) system controls both subsystems. This component determines the amount of power generated by both systems. Thereafter, Subsection 2.1.5 presents an overview of the advantages and disadvantages of the different HEPS architectures and concludes with the HEPS architecture that is going to be considered in the remainder of the research project.

2.1.1. Series Hybrid Electric Propulsion System
In a series HEPS the power node is electrical [14]. This means that the turbine engine is connected to a generator that converts the mechanical power output of the turbine engine into electrical power. This electric power is then supplied to an electric motor which is mechanically connected to a fan. Figure 2.2 shows a schematic of this architecture.

An advantage of the series HEPS is that the engine is mechanically decoupled from the fan [7]. As a result the engine can run at its peak efficiency, independent from the RPM of the fan. Moreover, the size of the combustion engine can be reduced when energy is being supplied from an electrical storage [17]. This also results in a high fuel efficiency due to a high effective engine RPM [11, 18]. Another advantage is that the series HEPS enables design freedom in the position of the engine and generator [18]. As mechanical
energy is converted into electrical energy the engine does not have to be positioned in line with the fan. The advantage of this is that the engine can be positioned such that it brings aerodynamic benefits, e.g. Boundary Layer Ingestion (BLI). Moreover, the fans can be positioned such that its noise will be shielded by for example the fuselage. A disadvantage however is that the use of an extra generator adds significant weight to the propulsion system [18]. Moreover, an extra conversion of energy leads to additional energy conversion losses [13, 19].

Turbo-electric propulsion system

The turbo-electric propulsion concept is an example of the series HEPS and is applied on NASA’s N3-X Hybrid Wing Body (HWB) aircraft concept, developed to meet with NASA’s N+3 goals described in Appendix A. The N3-X features two turbogenerators, one on each wingtip, that generate mechanical energy and convert this into electrical energy. This electrical energy is distributed by superconducting cables over a number of high-power electric motors that drive a continuous array of propelling fans, this is also known as Turbo-electric Distributed propulsion (TeDP). Figure 2.3 shows the TeDP on NASA’s N3-X HWB aircraft concept.

Figure 2.3: NASA N3-X HWB aircraft concept with TeDP [20]

Having the turbogenerators located at the wing tip allows the inlets to ingest free stream air, maximising the power of the turboshaft engine. Moreover, with thrust producing devices located on the wing tip an induced drag reduction of up to 40% can be achieved [20]. This is due to the fact that the strength of the wing tip vortex downstream of the wing is reduced by the higher velocity thrust stream. The nozzle of the turbogenerators are sized such that it produces enough thrust to compensate for the drag it generates. The turbogenerator’s primary function is to generate electricity. This means that most of the energy of the gas stream is extracted by the power turbine that is connected to the generator. This results in a low exhaust velocity and hence a low jet noise [21]. The propelling fans are positioned in a continuous fan nacelle across the rear fuselage to ingest the thick boundary-layer flow from the upper fuselage utilising the benefits of BLI [22]. The use of more fan modules increases the redundancy and thereby enables symmetric thrust in the event of a turbine engine or generator failure [11]. This also allows yaw control by asymmetric fan thrust.

If conventional technologies were to be utilised for the transfer of power, they would result in low efficiency factors, thereby leading to poor performance and hence higher fuel consumption than conventional systems [23]. This concept will become feasible when superconducting electrical machines, that are cryogenically cooled, can be implemented [24] and therefore heavily depends on further research and development of High Temperature Superconductors (HTS) and refrigeration technology.

E-Thrust

Another example that implements a series HEPS is the E-Thrust concept. This concept is applied on the eConcept developed by the Airbus Group and Rolls Royce, Figure 2.4. This concept has been developed to meet with the goals of Flightpath 2050 (Appendix A) and is comparable to the TeDP on NASA’s N3-X concept, but differs in the aircraft configuration on which it is applied and the use of an energy storage system. As can be seen on Figure 2.4 the E-Thrust features numerous electric fans arranged in clusters along the length of each wing. These electric fans are powered by a battery which in its turn is powered by one turbogenerator embedded in the fuselage.
2. Literature review of HEPS

Like the N3-X, a key enabling technology for the E-thrust is using superconductivity for the cables, generators and motors for the transfer of electrical power from the turbogenerator and energy storage to the fans. The E-thrust concept is also based on the assumption that the required level of energy density for the storage of energy can be achieved within the 25-year timeframe envisioned for the concept to mature. [12]

2.1.2. Parallel Hybrid Electric Propulsion System

In the parallel HEPS, the power node is mechanical [14], meaning that the electrical power component is used to convert electrical power into mechanical power. This mechanical power is added to the mechanical power provided by the turbine engine. Figure 2.5 shows a schematic of the parallel architecture.

The advantage of the parallel HEPS is that the electrical system and engine system operate independently. This allows temporary operation with either the engine or an electric motor. Having a parallel configuration also enables independent design of the power share between both subsystems. Moreover, the power provided by the electric motor with respect to the power provided by the engine can be adjusted during operation [13]. A disadvantage however is that since the engine is mechanically linked to the fan, it cannot operate at its optimal RPM during the complete flight envelope [25].
Subsonic Ultra Green Aircraft Research (SUGAR) Volt
The Subsonic Ultra Green Aircraft Research (SUGAR) Volt concept has been developed by a team led by Boeing Research & Technology to meet with the NASA N+3 goals. The SUGAR Volt implements a parallel HEPS on an aircraft with a large span and high-aspect-ratio wing. This increases the fuel efficiency as it increases the lift and decreases the drag. This would reduce take-off distance and generate less noise.
To enable operation on airport, part of the wings are hinged so that they can be folded [10]. Figure 2.6 shows the SUGAR Volt concept and gives a detailed view of the fan of the HEPS.

Figure 2.6: Boeing SUGAR Volt; reproduced from [10]

The SUGAR Volt has both a gas turbine and an electric motor attached to the Low Pressure (LP) spool. This allows the use of both jet fuel and battery power. The flexibility in the power extraction from the gas turbine or battery means that the electrical system does not have to supply all the power. This yields a reduced required motor size and power output from the battery. The percentage reduction in fuel will depend on the development of battery, electric motor and gas turbine technologies over the next three decades [19].

2.1.3. Series-parallel Hybrid Electric Propulsion System
In the series-parallel HEPS the architectures of the series and parallel HEPS are combined. The combustion engine, like in a series architecture, is connected to an electric generator that is linked to the electric motor that subsequently will drive the fan. The difference with the series architecture is that the combustion engine is also directly connected to the fan. Moreover, the electric motor is able to drive the fan independently as well. Figure 2.7 shows how this architecture can look like. As one can see, this architecture contains two power nodes.

The series-parallel architecture combines both advantages of the series and the parallel architecture [18]. The electric motor is driven from either the electrical storage or by the generator which receives its energy from the combustion engine. It can drive the fan on its own, but can also add power to the power from the combustion engine. The engine can run at its optimal RPM while it can also run independent from the electrical part.

A disadvantage however is that it is inherently heavier than the series and parallel architecture due to the extra mechanical coupling. Moreover, being able to run the engine either independent or through the generator requires an additional mechanical link [26]. Another disadvantage is that the increased freedom in energy transfer, results in an even more complicated control strategy for the propulsion system [25, 27].

2.1.4. Integrated Hybrid Electric Propulsion System
An innovative HEPS architecture is the integrated HEPS. In this configuration the electric motor, powered by a battery, powers the compressor instead of the turbine. The high pressure turbine is therefore redundant and can be removed from the architecture, see Figure 2.8. The remaining turbine drives the fan.
As this architecture allows the high pressure turbine to be removed weight can be reduced. Moreover, as the compressor is now decoupled from the turbine, the power turbine operates within unexpanded
2.1.5. Trade-off of HEPS architectures

A HEPS combine the advantage of electric components with the advantages of aircraft engines. Due to the high efficiency of electrical components [14], the overall efficiency of the HEPS increases. Moreover, due to the use of electric power, less power is to be generated by the engine resulting in a reduction of CO₂ and NOₓ emissions. Furthermore, noise reductions can be achieved as operating electric motors induce less noise and reduces the required power from the engine. Besides that, a reduced required power from the engine means that the engine can be sized more specifically for one phase of the mission or can be downsized [16]. The combination of a more optimally sized engine and reduced required combustion power leads to a reduced fuel consumption, which postpones the depletion of non-renewable fossil fuels.
The benefits of a HEPS therefore help in achieving the environmental goals stated in Appendix A, as follow:

- reduce CO\textsubscript{2} and NO\textsubscript{x}, due to power generated from electric energy
- reduce noise emissions, due to use of more efficient electric motor
- increase efficiency, due to implementation of high efficient electric system and more optimal sizing of engine
- reduced fuel consumption, due to optimally sized engine and electric power generation

As a HEPS contains an extra electric system and extra components (e.g. transmission lines, coupling components) the weight of the propulsion system increases [10, 24]. This also brings rise to sizing challenges. As the propulsion system now needs more space, conventional sizing methods needs to change. Moreover, the power management becomes more complicated as the power is now generated from two different energy types [27]. During the flight mission the amount of power to be generated from both energy types can vary. The disadvantages of a HEPS can be summarised as follow:

- increase weight
- increase complexity of sizing method
- increase complexity of power management

Table 2.1 presents a comparison between the different HEPS architectures. One can see that there is no clear winner. Ref. [13, 18, 19] compare the parallel architecture with the series architecture and choose for the parallel architecture over the series architecture. In contrast, Ref. [7, 11, 21, 23, 24] (see Subsection 2.1.1) investigate the series architecture, but apply this architecture in a distributed propulsion system which also changes the aircraft configuration. Ref. [18, 25, 27] agree that, although the series-parallel combines the advantages of the series and parallel architectures, the additional extra motor will make the configuration heavier and more complicated. Moreover, the series-parallel HEPS is not mentioned in the other literature that considers the series or parallel HEPS. Ref. [13, 16] explain the integrated HEPS, which is also developed and patented by its author [28]. The integrated HEPS does not utilise the benefit of the electric component optimal as the electric energy has to go through a longer load path [16].

In the series HEPS architecture the extra generator does not only add weight, but also induces an extra conversion of energy. This decreases the efficiency. To utilise the benefits of the series configuration, aircraft configuration needs to change drastically. Since the research project is focussed on the power management strategy, changing aircraft configuration is beyond the scope of this research. Therefore, focus is put on the parallel HEPS architecture for the remainder of the research project.

2.2. Metrics for performance & sizing of HEPS

Before evaluating the power management of a propulsion system, it is important to understand how the performance of a HEPS is determined. Aside from the technical challenges mentioned in Section 2.1, the increasing complexity of the propulsion system requires a new method for the sizing and performance assessment [13, 29]. This is done by applying the three fundamental principles for electrical flight [30], Subsection 2.2.1. Thereafter, the sizing of the electric system is explained based on the thrust requirement of the flight mission, Subsection 2.2.2.

2.2.1. Fundamental feasibility assessment

A HEPS can be assessed by applying the following three fundamental principles of electric flight [15, 31].

1. exergy concept
2. specific power and Ragone metrics
3. hybridisation degrees of freedom
### Table 2.1: advantages and disadvantages of different HEPS architectures

<table>
<thead>
<tr>
<th></th>
<th>Series HEPS</th>
<th>Parallel HEPS</th>
<th>Series-parallel HEPS</th>
<th>Integrated HEPS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>• Engine runs on optimal RPM during operation</td>
<td>• Independent operation between electrical and engine system</td>
<td>• Combines advantages of series and parallel architectures</td>
<td>• Removal of High Pressure Turbine (HPT) saves weight</td>
</tr>
<tr>
<td></td>
<td>• Higher effective Bypass Ratio (BPR) as size of engine can be decreased</td>
<td>• Independent design of power share between both subsystems</td>
<td></td>
<td>• Potential energy of expansion process is not used to drive compressor</td>
</tr>
<tr>
<td></td>
<td>• Design freedom in positioning of engine and fan</td>
<td>• Power share between electrical system and engine can be adjusted during operation</td>
<td></td>
<td>• Decoupling between turbine and compressor reduces internal component loss</td>
</tr>
<tr>
<td></td>
<td>• Power share between electrical system and engine can be adjusted during operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>• Extra generator adds weight</td>
<td>• Engine cannot run at optimal RPM throughout the complete flight mission</td>
<td>• Extra generator and mechanical link increases weight</td>
<td>• Inefficient utilisation of electric energy as the electric power goes through a longer load path</td>
</tr>
<tr>
<td></td>
<td>• Extra conversion decreases efficiency</td>
<td></td>
<td>• Even more complex control strategy</td>
<td></td>
</tr>
</tbody>
</table>

**Exergy concept**

A propulsion system can be evaluated by its performance. To maximise the performance, thermodynamic optimisation plays an important role [32]. In case of a HEPS, this means a thermodynamic optimisation of a propulsion system that combines two different types of energy. The performance of a propulsion system is affected by the amount of work the system can deliver. An effective method to evaluate this is the exergy analysis. Exergy is defined as the availability or available energy. The exergy represents the maximum useful work that could be obtained from the system at a given state in a specified environment. The maximum work output that could be obtained is when the system is in the dead state. A system is said to be in the dead state when it is in thermodynamic equilibrium with the environment it is in. In practice systems are rarely in the dead state. The evaluation of exergy alone is therefore not sufficient. The quantities reversible and irreversible work are related to the actual initial and final states of the system. The reversible work is the maximum amount of useful work that can be produced (or the minimum work that needs to be supplied) as a system undergoes a process between the specified initial and final states. Adversely irreversibility is the wasted work potential during a process. This is also called the unavailable energy which is the portion of energy that cannot be converted to work by even a reversible heat engine.[33] The advantage of an exergy analysis is that it takes into account the different energy sources
and thereby allows consistent exploration of the conversion processes, meaning that it can be used as a valuable tool to determine the work potential of different energy sources or systems [16, 33].

In the HEPS energy comes from two different sources. If fuel can be saved with the HEPS, the useful energy of fuel needs to be compensated by electric energy. Although the useful energy of batteries may be greater, the specific energy density of batteries is significantly lower. This affects the weight and thereby the required energy to propel the aircraft. The use of two different types of energy sources affects the performance of the aircraft. Moreover, when to use which type of energy can play an important role in the fuel burn and total energy consumption of an aircraft. The ratio of power supplied from both subsystems is called the power split $\Phi$ [34].

\[
\Phi = \frac{P_{\text{supp, ElecSyst}}}{P_{\text{tot}}} \tag{2.1}
\]

As the power split determines the ratio of power supplied, efficiency of the propulsion system will change. The efficiency of the electric system may be greater, but the amount of energy that can be subtracted from a given amount of fuel is greater than the energy from a defined battery size. A HEPS can be compared to another by its efficiency during flight. Conventional propulsion systems can be compared by their Thrust Specific Fuel Consumption (TSFC). For hybrid propulsion systems the Thrust Specific Power Consumption (TSPC) can be used, Equation 2.2. [16, 29, 34–36]

\[
T_{\text{SPC}} = \frac{P_{\text{supp}}}{F_N} = \frac{V}{\eta_{\text{ov}}} = \frac{V}{\eta_{\text{ec}} \cdot \eta_{\text{tr}} \cdot \eta_{\text{pr}}} \tag{2.2}
\]

Where $P_{\text{supp}}$ is the supplied power, $F_N$ is the net thrust, $V$ is the velocity of the aircraft and $\eta_{\text{ov}}$, $\eta_{\text{ec}}$, $\eta_{\text{tr}}$ and $\eta_{\text{pr}}$ represent the overall, energy conversion, transmission and propulsive efficiency respectively. This Equation can be rewritten into Equation 2.3, which calculates the efficiency by considering the power supplied from both energy sources.

\[
\eta_{\text{ov}} = \frac{P_{\text{req}}}{P_{\text{supp}}} = \frac{F_N \cdot V}{P_{\text{batt}} + P_{\text{fuel}}} = \frac{F_N \cdot V}{P_{\text{batt}} + \eta_{\text{fuel}} \cdot FHV} \tag{2.3}
\]

Specific power and Ragone metrics
The HEPS can be characterised and compared to a conventional propulsion system by using a Ragone diagram [15, 30, 31]. The Ragone diagram features the relative specific power and the relative specific exergy on the vertical axis and horizontal axis respectively. The relative specific power is calculated by dividing the power by the mass of the systems that provides the power. This metric is used to determine whether the power system provides sufficient power for flight. The relative specific exergy is calculated by dividing the exergy by the mass of the systems that provide the exergy and can be interpreted as a measure of endurance [30, 31].

Figure 2.9 shows an example of the Ragone Diagram. The diagram is divided into different regions. Propulsion systems in region A and B provide insufficient power for take-off. The propulsion systems in region C1, C2 and D do provide sufficient power for electric flying. The propulsion systems in C1 however cannot provide this power for period long enough to achieve a medium range flight mission.[31]

Hybridisation degrees of freedom
When considering a HEPS, it is important to determine how much of the required power is provided by which part of the HEPS [18]. This is done by the degree of hybridisation. The degree of hybridisation ($H_p$) is the ratio of electric power ($P_{\text{Elr}}$) to the total power ($P_{\text{tot}}$), Equation 2.4 [14, 34].

\[
H_p = \frac{P_{\text{Elr}}}{P_{\text{tot}}} \tag{2.4}
\]

However, the degree of hybridisation is limited [37] as it for example does not take into account the possibility of having an energy storage. Therefore, an energy based hybridisation parameter needs to be introduced [14] which is defined as the ratio of stored electric energy ($E_{\text{Elec}}$) to stored total energy ($E_{\text{tot}}$), Equation 2.5.
In Figure 2.10 each HEPS can be identified by a point. The origin, \((\hat{H}_E, \hat{H}_P)\) is \((0,0)\), represents the conventional propulsion system. The fully electric propulsion system is defined as \((\hat{H}_E, \hat{H}_P)\) is \((1,1)\). The power output and the total energy carried are both completely electric. The parameter \((\hat{H}_E, \hat{H}_P)\) is \((0,1)\) means that all power is provided electrical \((\hat{H}_P = 1)\) while the energy provided is not \((\hat{H}_E = 0)\). This refers to a (purely) series HEPS as there is no electric energy storage (Figure 2.10). The point \((\hat{H}_E, \hat{H}_P)\) is \((1,0)\) lies in the unfeasible region. This namely would mean that all energy carried is electric whereas the power would come from a conventional combustion engine. It does not make sense to carry more energy in electrical form than the system is able to extract and provide to the drive shaft with an electric motor.
2.2.2. Sizing of electric system
The sizing of the electric system is determined by the maximum shaft power \( P_{\text{MaxElecSys}} \) it should deliver and the duration of time it should supply the power. The power required by the electric system is dependent on the applied power management strategy, as it determines the amount of power that needs to be supplied by the electric system and the duration of electric power supply. The maximum shaft power of the electrical system is dependent on the maximum installed power of the electric motor (EM) \( P_{\text{MaxEM}} \) and the inverter \( P_{\text{MaxInv}} \), the efficiency of the electrical system \( \eta_{\text{ElecSys}} \) and the energy of the battery pack. Equation 2.6 shows that the mass of the electric components is dependent on the maximum power and the specific power. The specific power \( \bar{p} \) is dependent on the technology maturity level of electric components.

\[
m = \bar{p} \cdot P_{\text{Max}}
\]  
(2.6)

The power each component should deliver depends on the power split (Equation 2.1). The power split determines the required shaft power to be delivered by the electric system. The required power of the electric system, determines the power required by the electric motor and inverter; Equations 2.7 and 2.8.

\[
P_{\text{EM}} = \eta_{\text{ElecSys}} \cdot P_{\text{Elec}}
\]  
(2.7)

\[
P_{\text{inv}} = \eta_{\text{EM}} \cdot P_{\text{EM}}
\]  
(2.8)

Where the efficiency of the electric system \( \eta_{\text{ElecSys}} \) is computed by Equation 2.9.

\[
\eta_{\text{ElecSys}} = \eta_{\text{PMAD}} \cdot \eta_{\text{EM}}
\]  
(2.9)

The required inverter power comes from the battery. Equation 2.10 computes the required power from the battery.

\[
P_{\text{batt}} = \eta_{\text{inv}} \cdot P_{\text{inv}}
\]  
(2.10)

Although all electric components are sized on the maximum power they should deliver, the sizing of the battery is dominated by the energy it should contain. The energy required by the battery is dependent on the period of time the battery should supply a certain amount of power, Equation 2.11.

\[
E_{\text{batt}} = \int P_{\text{batt}}(t) \cdot dt
\]  
(2.11)

The mass of the battery is dependent on the specific energy and the energy required. The specific energy \( e \) is dependent on the technology development of electric components. Equation 2.12 computes the mass of the battery.

\[
m_{\text{batt}} = \int e_{\text{batt}} \cdot E_{\text{batt}}
\]  
(2.12)

2.3. Power management strategies
As a HEPS is operating during the flight mission, the power settings can be controlled in different ways. A HEPS cannot yield satisfactory performance without an efficient power management [25]. The power management therefore plays an important role in bringing out the benefits of a HEPS over its increasing weight and complexity. Power management has been extensively explored in the automotive industry. This however differs from the aeronautical industry as weight affects the performance of aircraft more than it does on the performance of land-based vehicles.[38]

Ref. [38] covers an extensive literature review on power management strategies of the HEPS. It extends on the methodology described in Section 2.2. This Reference lays down the groundwork to construct an integrated hybrid-electric modelling environment that can be used for the optimisation of power management. The author applies the methodology on a series HEPS architecture. In order to apply this methodology on a complementary case study, the research project will focus on a parallel HEPS architecture (see also 2.1.5).
The strategy must be designed such that all the individual components operate with each other to achieve the maximum efficiency [9]. Figure 2.11 displays a simplified diagram on how the PMAD module ensures the cooperation of different components within the HEPS. The PMAD controller determines the amount of fuel flow and electric power based on the thrust that is required. Consequently the HEPS generates thrust as fuel and electric power are added. This puts the aircraft in a different state. As a reaction the mission analysis module will send the PMAD module the required thrust based on the aircraft state.

Another loop that can be observed from Figure 2.11 is the information sent by the HEPS to the PMAD controller. As a reaction on the received information, the HEPS will not only produce thrust but will also send information back to the power management. The required fuel flow and electric power will namely change the battery state of charge and fuel level.

Figure 2.11: the role of the power management controller in HEPS, based on [29, 38, 39]

Figure 2.11 also shows the different control strategies that can be applied in a PMAD controller [40]:

- deterministic rule based
- fuzzy rule based
- instantaneous optimisation
- global optimisation

One can clearly see that these strategies can be divided into two groups: rule based and optimisation based control strategies. In a rule based strategy deterministic rules are designed based on heuristics, intuition, human expertise, and even mathematical models. The mission is usually unknown. In optimisation based control strategies the mission is predefined and the optimal variables are computed by minimisation of a cost function that represents the fuel consumption or emissions. The goal of this type of control strategy is to find a global optimum solution. [40]
The HEPS is a propulsion system that combines the power from the engine with the power from an electric system to propel the aircraft. As mentioned in Section 2.1 there are different configurations in which the electric system can be combined with the engine. The parallel HEPS architecture is chosen for the conventional aircraft configuration. First, Section 3.1, describes the engine and its emissions and explains how the size of the engine affects the parameters of the propulsion system. Thereafter, a description is provided of the electric system (Section 3.2). The Chapter then ends with description of how both subcomponents work together, Section 3.3.

3.1. Engine

The engine plays an important role in the performance of the aircraft. The design of the engine depends on the aircraft and its operating conditions. The engine is sized such that it is able to deliver the maximum required thrust, which is needed to lift the aircraft from ground to air. Hence, the design point of the engine is the take-off phase. Another aspect to consider is the environmental impact of the aircraft. The engine emits chemical substances called emissions, which pollute the environment. The emissions of the engine do not only depend on the fuel consumption, but also on the thrust setting of the engine.

3.1.1. Turbofan engine

Due to its high efficiency at transonic speeds, most modern commercial jet engines are turbofan engines. Figure 3.1 illustrates a cross-section of a twin-spool turbofan. In a twin-spool turbofan, the fan, Low Pressure Compressor (LPC) and Low Pressure Turbine (LPT) are connected to the LP spool (green). The LP spool mainly drives the bypass airflow. The High Pressure Compressor (HPC) and HPT are linked to each other by the High Pressure (HP) spool (purple). The components connected to the HP spool are also referred to as the core engine.

Figure 3.1: cross-section of a twin-spool turbofan
In a turbofan engine, part of the inlet air is compressed by a LPC or fan (green) and bypasses the core (purple) of the engine. Accelerating the large amount of air through the bypass yields a more efficient propulsion system. A high BPR increases the efficiency, but reduces the thrust it can deliver. A greater BPR also reduces thrust lapse rate. The thrust lapse rate is the variation of thrust with altitude, that the engine can produce. A lower thrust lapse rate, thus means that the design (take-off) and off-design (cruise) point are closer to each other. The efficiency of the engine increases the closer it operates at its design point. Hence, the design point is an important aspect of the engine. The efficiency of the engine can thus be increased by either moving the operating conditions to the design point or by designing the engine such that the design point is as close as possible to most operating conditions. The latter one can be achieved by scaling of the engine.

3.1.2. Engine scaling
The scaling of the engine affects the weight of the engine. Engine weights are reasonably well correlated to their take-off static thrust by Equation 3.1. [41]
Note that the static take-off thrust \( F_{NTO} \) in this equation needs to be in pound force. The outcome of this Equation is the mass of the engine (\( m_{\text{engine}} \)) in pounds.

\[
m_{\text{engine}} = 2.7 \cdot F_{NTO}^{0.75}
\]

Equation 3.2 represents the mass flow scaling parameter [42]. When scaling the engine, this parameter should remain constant. For example: scaling the inlet design mass flow rate \( \dot{m} \) with 80% means that the characteristic diameter \( D_I \) needs to scaled with the square root of 80%.

\[
\text{mass flow scaling parameter} = \frac{\dot{m} \cdot \sqrt{\theta}}{D_I \cdot \delta}
\]

Consequently, to maintain the same tip Mach number of the engine blades, the shaft speeds of the engine need to be scaled as well [43]. Equation 3.3 represents the shaft speed scaling parameter. Like, the mass flow rate scaling parameter, this parameter should remain constant as well when scaling the engine. As a result, a reduced characteristic diameter leads to a higher shaft speed. In case of the previous example this means that the shaft speed should increase with the inverse of the square root of 80%.

\[
\text{shaft speed scaling parameter} = \frac{D_I \cdot N}{\sqrt{\theta}}
\]

The \( \theta \) and \( \delta \) represent the temperature and pressure parameter respectively. Both parameters are computed using the reference values for pressure and temperature from the International Standard Atmosphere (ISA) standard sea level static conditions.

\[
\delta = \frac{P_{\text{tot}}}{P_{\text{tot,ref}}}
\]

\[
\theta = \frac{T_{\text{tot}}}{T_{\text{tot,ref}}}
\]

Scaling down the engine thus increases the shaft speeds of the engine and thereby the centrifugal forces on the disks. Equation 3.6 describes the relation between the shaft speed, centrifugal force, radius and mass of the disks. To ensure the disks do not fail under the increased load, mass of the disks should increase with the square of the increment in rotational speed \( \omega \) in rad/s.

\[
F_c = m_{\text{disk}} \cdot \omega^2 \cdot R
\]

Scaling of the engine is also limited by the turbine inlet temperature \( T_{i4} \). Thermal stresses occur at high temperature. At the turbine inlet this temperature is maximum. Although mass of the disks can increase with increasing shaft speed, there is a limit to the operating temperature of the disks.
3.1.3. Engine emissions

Table 3.1 gives an overview on the actual combustion products of the aero-engine. The International Civil Aviation Organisation (ICAO) has set emission standards for Carbon monoxide (CO), Unburned hydrocarbons (UHC), Nitrogen oxides (NO\textsubscript{x}) and soot [44]. The Emission Index (EI) is the ratio of the amount of a pollutant substance (i) in gram per kg of fuel consumed (Equation 3.7).

\[
EI_i = \frac{m_i}{m_{fuel}}
\]  

(3.7)

Table 3.1 also displays the EI of each pollutant produced by the engine. Carbon dioxide (CO\textsubscript{2}) and water (H\textsubscript{2}O) are products of complete combustion and are proportional to the fuel burned. Reduction of these pollutants thus requires a reduction of fuel consumption. CO, UHC and soot are products of incomplete combustion and hence are dependent on the thrust setting of the engine. NO\textsubscript{x} are by-products of complete combustion and, together with Sulfur oxides (SO\textsubscript{x}), products of fuel impurities. The production of CO and UHC increases with lower thrust settings, while the production of NO\textsubscript{x} and SO\textsubscript{x} increases with higher thrust settings. The SO\textsubscript{x} emissions are neglectable for kerosene type fuels used in aero-engines [45]. Figure 3.2 shows the engine dependent emissions.

![Figure 3.2: emissions characteristics of gas turbine engines][46]

CO, UHC, soot and NO\textsubscript{x} can thus be reduced by improved combustion techniques and can be reduced by changing how the engine performs, which is in this case the implementation of a HEPS. The emission of CO leads to the formation of ozone. UHC emissions leads to the formation of aromatic (benzene) and polycyclic hydrocarbons (PAH). Soot are carbon rich particles and combined with fog results in smog. Soot can also be specified by the Smoke Number (SN) [44]. The SN represents the “degree of darkening” of the exhaust and is related to the core exhaust flow of the engine [47]. The impact of NO\textsubscript{x} emissions can lead to acid rain and pose a risk on health to animal and plant life. In aircraft engines the largest part of emissions is NO\textsubscript{x}.

Table 3.1: typical kerosene emission levels [45]

<table>
<thead>
<tr>
<th>substance</th>
<th>EI in [g/kg] fuel</th>
<th>emission depends on</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2}</td>
<td>3150</td>
<td>fuel consumption</td>
</tr>
<tr>
<td>H\textsubscript{2}O</td>
<td>1250</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>0.4 - 65</td>
<td>thrust setting;</td>
</tr>
<tr>
<td>UHC</td>
<td>0.2 - 12</td>
<td>max production at idle</td>
</tr>
<tr>
<td>soot</td>
<td>± 0.015</td>
<td>thrust setting;</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>4 - 30</td>
<td>max production</td>
</tr>
<tr>
<td>SO\textsubscript{2}</td>
<td>0.02 - 6</td>
<td>at full thrust</td>
</tr>
</tbody>
</table>
3.2. Electric system

The main components, when considering a parallel architecture (see Figure 2.5), that affect the weight of the electric system are the battery, the inverter and the electric motor. The development in electric components technology can be expressed in terms of specific power or energy. The specific power represents the amount of power per weight a component can supply. The specific energy is the amount of energy per weight a battery can contain. The development and state of the art therefore need to be considered for the performance of a HEPS. Figure 3.3 displays the development of electric component technology as predicted by Rostek (2015) [48].

![Figure 3.3: performance targets on system component level; presented by Rostek (2015) [48]](image)

Next to the specific power and energy of electric components the efficiencies will have an effect on the weight as well as it determines the power or energy output. Table 3.2 shows the assumed efficiencies of the electrical components.

<table>
<thead>
<tr>
<th>component</th>
<th>efficiency in [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>battery</td>
<td>90.0 [16]</td>
</tr>
<tr>
<td>inverter(^1)</td>
<td>99.5 [49]</td>
</tr>
<tr>
<td>electric motor</td>
<td>93.0 [50]</td>
</tr>
</tbody>
</table>

3.2.1. Development in battery technology

The electric energy can be stored in batteries. The development in battery technology has led to hybrid and fully electric cars. In the aerospace industry, weight plays an important role in the performance of aircraft and thus battery specific energy is important. One of the most widely used technologies in advanced electrified vehicles is the Lithium-ion (Li-ion) battery. Although, development in Li-ion battery rapidly improves, the technology begins to approach the theoretical energy density limits of 200-250Wh/kg [51].

In order to attain higher specific energy levels, new technologies are currently under investigation. One promising technology is the Lithium-Sulfur (Li-S) battery. Theoretically, Li-S batteries can attain a specific energy of 2567Wh/kg [52, 53]. The theoretical specific energy is the energy obtained per unit mass of the active components of the anode and cathode of the battery and are determined based on the cell reactions. In practice however, the specific energy for Li-S battery is limited to 500-600Wh/kg [51, 52]. This is four times greater than the current specific energy of Li-ion batteries, although maturity is held back by limitations such as low cyclability, capacity fade and self-discharge [51, 52, 54].

Another potential technology to meet the specific energy target is the Lithium-air (Li-air) battery. With Li-air battery technology a theoretic specific energy of 11586Wh/kg can be obtained. However, as air

\(^1\) including cryocooler required for HTS technology
oxidises during discharge, the mass of the Li-air battery increases. This brings down the theoretic specific energy to 3505Wh/kg and 3582Wh/kg for the battery system with a non-aqueous and aqueous electrolyte respectively [53]. The Li-air battery is expected to achieve specific energy densities of 750-2000Wh/kg [15, 55].

3.2.2. Development in inverter technology
The inverter converts the Direct Current (DC) from the battery into Alternating Current (AC) for the electric motor. State of the art inverters are relatively efficient, light and well developed for ground applications. Conventional solid-state switching power converters may have an efficiency of 95%. This is not sufficient for the application in the propulsion of aircraft. Efficiency can be increased by using the power converters in parallel.[56] This however increases the weight of the electric system.

The sizing of the inverter is determined by the maximum power it should convert and supply. The specific power is therefore an important parameter. Currently inverters with a specific power of 8 kW/kg are available [49]. The specific power of inverters are predicted to increase to 20 kW/kg by the year 2030. For this forecast, it is assumed that cryocoolers ensure an efficiency of 99.5%. [57]

3.2.3. Development in electric motor technology
The electric motor supplies the electrical output power of the electric system to the engine. Table 3.3 provides a comparison between the Switched Reluctance (SR), AC, Surface mounted Permanent Magnet (SPM) and Interior Permanent Magnet (IPM) motors that are used for aircraft applications.

<table>
<thead>
<tr>
<th></th>
<th>SR motor</th>
<th>AC motor</th>
<th>SPM motor</th>
<th>IPM motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>usable in high temperature</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>high speed rotation</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>high environment resistance</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>size and weight</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>vibration and noise</td>
<td>0/-</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>efficiency</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>fixed output variation range</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>startup torque</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>torque density</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>system cost</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.3 shows that selecting the SR motor is most beneficial compared to the other electric motors when assuming all factors are of equal importance. The SR motor also offers the best specific power (5 kW/kg) levels within industrial motor category and has an efficiency of approximately 93%. [50] Siemens has also developed an electric motor (including inverter & gearbox) with a specific power of 5 kW/kg. Unfortunately this motor is only scalable up to 1 MW and therefore not sufficient to power commercial aircraft [58]. The use of cryocoolers could lead to a specific power of 20 kW/kg [15, 49] and increase the efficiency to 99%. However, the use of cryocoolers still needs further research [24].

3.3. Selected Hybrid Electric Propulsion System
The HEPS consists of an engine and an electric system. Section 2.1 has compared the different HEPS architectures. An unconventional aircraft configuration is required to fully exploit the benefits of the series architecture. Since the focus of this research is on the power management, the selected propulsion system is to be retrofitted on a conventional aircraft configuration. This allows a comparison with existing aircraft. Consequently, a parallel architecture is used for this research, see Figure 3.4. The Figure gives an overview of the efficiencies of the electric components and illustrates how the energy from the battery adds power

---

2 + = good
0 = Intermediate
- = poor
to the shaft of the fan. The electric motor is attached to the LP spool. The power split (Equation 2.1) is therefore defined as the supplied power of the electric motor to the shaft over the total shaft power of the LP spool. The power split determines which part of the required thrust needs to be delivered by the engine and which part needs to come from electric power from the electric system.

![Diagram of engine and electric system connection](image)

Figure 3.4: connection between the engine and the electric system
While flying, it is essential to determine when and to what extent the electric system assists the propulsion system. This is called the power management strategy. The sizing of the electric system is dependent on the power management strategy, because the latter determines the maximum amount of electric power and energy that is needed during flight. The additional weight of the electric system needs to be offset by its performance, which depends on the power management strategy. To analyse the effect of power management strategy from an overall mission perspective, a global optimisation strategy is applied. This means that the strategy considers the complete mission as it controls the power split and thus the flight mission is predefined.

The engine operates most efficiently during cruise. The efficiency during take-off and climb is rather low and therefore overall efficiency can be significantly increased by the use of the electric system. Due to low thrust requirements, the engine operates at part load during taxi yielding a lower overall efficiency. This overall efficiency increases when considering fully electric taxi phases. Moreover, the use of fully electric taxi phases, reduces noise and emissions at airports.

Figure 4.1 shows the power management strategy considered in this research. The power management strategy is segmented by the following flight phases:

1. taxi-out: fully electric
2. take-off: assistance of electric system can be controlled with the take-off power split
3. climb: assistance of electric system can be controlled with the climb power split
4. cruise: engine only
5. descent: engine recharges electric system
6. taxi-in: fully electric

The input variables for the power management strategy are the take-off and climb power splits. The power split during take-off lowers the maximum thrust required from the turbine engine, whereas the power split during climb increases the efficiency and thereby allows the propulsion system to save fuel. The take-off and climb power splits have an effect on the sizing of the electric system and thereby also the weight of the aircraft. Moreover, as less fuel is being burnt during taxi-out, take-off and climb, the weight of the aircraft during cruise is relatively larger. This allows the engine to operate closer towards it design point during cruise.
In this power management strategy the power split is a percentage of the average power per flight phase, and therefore the power supplied by the electric system is constant during each flight phase.
Simulation model

The hybridisation of the propulsion system has a non-linear relation with the performance of the propulsion system. Adding hybridisation would save fuel burn, but due to the additional weight of the electrical system more fuel is required during cruise to propel the heavier aircraft. Also, the power management strategy will affect how much weight is added due to the electrical system and how much additional fuel is required to fly the aircraft for the same mission. Therefore a simulation model is required. The simulation model is developed in the MATLAB® and Simulink® environment and contains a Gas turbine Simulation Program (GSP) Application Programming Interface (API)® for the simulation of the engine in GSP®.

This Chapter provides an overview of the used simulation model. The input for the simulation model is the reference aircraft, flight mission and power management strategy. The output of the simulation model is the performance of the propulsion system over the complete flight mission. The propulsion system consists of a reference engine and an electric system of which the sizing will change when hybridisation changes. As mentioned before, the power management strategy is important as it determines when and how much electric power will be added to the propulsion system during each phase. The simulation model can therefore be divided in five parts:

- reference aircraft (Section 5.1)
- flight mission analysis module (Section 5.2)
- engine model (Section 5.3)
- electric system model (Section 5.5)
- hybridisation propulsion system (Section 5.6)

The reference aircraft determines what is required from the propulsion system to fly a certain mission. Section 5.1 presents the variables of the aircraft required for the simulation model. In order to have the aircraft fly a certain mission, the reference engine needs to be known. This is followed by Section 5.2 which explains how the flight is simulated. Section 5.3 explains how the reference engine is modelled, using the program GSP®, and validated using data from the engine manufacturer and type date certificate sheet. As the flight mission, aircraft and engine are modelled, Section 5.4 validates the simulation model. Next, hybridisation of the propulsion system means that an electric system is added. Section 5.5 describes what components are considered for the electric system and how the components are sized accordingly. Finally, Section 5.6 explains how these parts are combined to simulate the effect of hybridisation.

5.1. Reference aircraft

Due to the availability of data, the Airbus A320 is chosen as reference aircraft for this research. As there are different variations of this aircraft, this Section specifies which data is used. Figure 5.1 presents the dimensions of the Airbus A320. It can be seen that the aircraft has two engines. Details regarding these engines are specified in Section 5.3.
The Airbus A320 is a single-aisle aircraft, designed for short- to medium-haul routes and its key data is as follow:

- number of passengers: 150 [65]
- max fuel capacity: 23825 kg (with density of 0.8 kg/L) [65, 66]
- Maximum Operating Mach (MMO): 0.82 [65]
- Maximum Operating Speed (VMO): 350 kt (180 m/s) [65]

Figure 5.2 shows the mass characteristics of the Airbus A320. The Maximum Zero-Fuel Mass (MZFM) is the mass of the aircraft without fuel. Together with the Maximum Take-off Mass (MTOM), this is an important parameter. For the investigation of the HEPS the aircraft mass may not exceed the MTOM. Furthermore, the aircraft still needs to be able to carry the same amount of payload.
5.2. Flight mission analysis module

This Section describes the flight mission used for this research project. First it defines what flight is being taken as reference in Subsection 5.2.1. Thereafter Subsection 5.2.2 describes how the simulation model simulates the flight. This Section ends with a validation of the simulation model, Subsection 5.4.1.

5.2.1. Reference flight

The effect of hybridisation from an overall mission perspective is greater for short range flight than for long range flight. The reason for this is that current engines are already efficient during cruise. The effect of the electric system therefore has more impact on the take-off and climb phases. The power management strategy (see Chapter 4) is to add hybridisation during the take-off and climb phase. Therefore the effect of a HEPS is better observed at shorter flight missions. Moreover, Figure 5.3 shows that most airports/landing fields are at a distance of 1000 km away from each other, meaning that most potential airport links are approximately 1000 km. In Europe, air traffic is mainly performed over short and medium distances. [67]

![Figure 5.3: distribution of the European airport pair distances](image)

Figure 5.3: distribution of the European airport pair distances [67]

Figure 5.4 displays the reference flight mission of approximately 1000 km. The flight mission consists of the taxi-out, take-off, climb, cruise, descent and taxi-in phase. The landing phase has not been considered, as the dynamics for landing are complex. Furthermore, the landing phase is only a short period when considering the complete flight mission.

![Figure 5.4: reference flight mission](image)

(a) altitude profile of reference flight mission
(b) velocity profile of reference flight mission

Figure 5.4: reference flight mission
5.2.2. Simulation model

The flight mission analysis module is based on the three-dimensional point-mass differential equations. These differential equations result in seven state variables:

- \( \gamma \); the flight path angle in [rad]
- \( V \); the velocity in [m/s]
- \( h \); the altitude in [m]
- \( \phi \); the bank angle in [rad]
- \( \psi \); the heading angle in [rad]
- \( x_{east} \); the aircraft in [m]
- \( x_{north} \) the aircraft in [m]

As fuel is being consumed, the mass of the aircraft changes during the flight mission. Equation 5.1 computes the change in aircraft mass \( \Delta m \).

\[
\Delta m = -\dot{m}_{\text{fuel}} \tag{5.1}
\]

Based on the state of the aircraft (Mach number \( M \), altitude \( h \) and the thrust required \( F_N \)), GSP® computes the fuel flow. The aircraft mass is used in the equations of motions of the aircraft (Equation 5.2 - 5.8):

\[
\dot{\gamma} = \frac{L + F_N \cdot \sin \alpha}{m \cdot V} \cdot \cos \phi - \frac{g}{V} \cdot \cos \gamma \tag{5.2}
\]

\[
\dot{V} = \frac{F_N \cdot \cos \alpha - D}{m} - g \cdot \cos \gamma \tag{5.3}
\]

\[
\dot{h} = V \cdot \sin \gamma \tag{5.4}
\]

\[
\dot{\phi} = p \tag{5.5}
\]

\[
\dot{\psi} = \frac{g \cdot \tan \phi}{V} \tag{5.6}
\]

\[
\dot{x}_{east} = V \cdot \cos \gamma \cos \psi - V_{wind} \cdot \cos X_{wind} \tag{5.7}
\]

\[
\dot{x}_{north} = V \cdot \cos \gamma \sin \psi - V_{wind} \cdot \sin X_{wind} \tag{5.8}
\]

By assuming that the angle of attack \( \alpha \) is relatively small, \( \cos \alpha = 1 \) and \( \sin \alpha \approx 0 \). As a result Equation 5.2 and 5.3 are simplified to Equation 5.9 and 5.10:

\[
\dot{\gamma} = \frac{L}{m \cdot V} \cdot \cos \phi - \frac{g}{V} \cdot \cos \gamma \tag{5.9}
\]

\[
\dot{V} = \frac{F_N - D}{m} - g \cdot \cos \gamma \tag{5.10}
\]

To simulate the performance of the aircraft over the flight mission, the aerodynamic lift and drag need to be taken into account. Equation 5.11 calculates the lift coefficient \( C_L \), required for the computation of lift \( L \) (Equation 5.12).

\[
C_L = C_{L0} + C_{La} \cdot \alpha \tag{5.11}
\]

\[
L = C_L \cdot q_{dyn} \cdot S \tag{5.12}
\]
5.3. Engine model

The drag coefficient is composed of four components: zero-lift drag $C_D^0$, induced drag, drag due to flap extension $C_{D_{flaps}}$, drag due to landing gear $C_{D_{gear}}$ and the Mach-drag rise component $C_{D_{mach}}$. Equation 5.13 computes the drag coefficient.

$$C_D = C_D^0 + k \cdot C_L^2 + \Delta C_{D_{flaps}} + \Delta C_{D_{gear}} + \Delta C_{D_{mach}}$$

Equation 5.14 computes the drag, which like the lift, is dependent on the dynamic pressure $q_{dyn}$ and wing area $S$.

$$D = C_D \cdot q_{dyn} \cdot S$$

Ref. [68, 69] describe the flight mission analysis module in more detail.

5.3.1. Reference engine

The performance of the HEPS is compared with the CFM LEAP-1A state of the art turbofan engine. This engine powers the state of the art Airbus A320. Figure 5.5 shows the cross-section of the CFM LEAP-1A turbofan engine.

The CFM LEAP-1A is a high BPR engine, which has been certified in 2015 [71] and entered into service in 2016 [72]. Enlisted are some important key data of the CFM LEAP-1A[70–72]:

- engine mass: 2990 kg
- take-off thrust: 143.05 kN
- maximum continuous thrust: 140.96 kN
- LP spool (N1 100%): 3856 RPM
- HP spool (N2 100%): 16645 RPM
- BPR: 11
- Overall Pressure Ratio (OPR): 40
- compressor stages (fan/booster/HPC): 1/3/10
- turbine stages (HP/LP): 2/7
- 50% margin on NOx emissions versus CAEP/6 standards
- 15% reduction in fuel consumption and CO2 emissions versus state of the art engines
5.3.2. GSP engine model

The performance of the CFM LEAP-1A can be modeled by GSP®. Figure 5.6 shows the turbofan model within the GSP® environment. Due to the limited availability of data, unknown properties have been modified iteratively such that the output matches the available data.

![Figure 5.6: CFM LEAP-1A GSP® model](image)

To model the CFM LEAP-1A within the GSP® environment the shaft speeds and BPR have been used as input. The design turbine inlet temperature $T_{T1}$ of the engine is assumed at 1950 K. The pressure ratios of the fan, booster and LPC are tweaked such that they approximate the specified OPR. The design mass flow rate has been modified till the output take-off thrust was achieved. To ensure that the model is correct, the ratio between the jet velocities is checked. The ratio of the jet velocities is optimal when it is 0.9 and can be approached by changing the outer fan pressure ratio [73].

To model the emissions of the engine, the ICAO Aircraft Engine Emissions Databank is used [74]. Since the data of the CFM LEAP-1A is not available, the data of the CFM 56 is used. With the specified emission reductions, the data of the CFM 56 engine can be changed and used for the emissions of the CFM LEAP-1A. Table 5.1 shows the data used as input for GSP®.

<table>
<thead>
<tr>
<th>mode</th>
<th>$m_{fuel}$</th>
<th>$T_{T1}$</th>
<th>$p_{T1}$</th>
<th>El UHC</th>
<th>El CO</th>
<th>El NOx</th>
<th>SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>take-off</td>
<td>1.20</td>
<td>938.99</td>
<td>42.83</td>
<td>0.03</td>
<td>0.26</td>
<td>15.11</td>
<td>11.4</td>
</tr>
<tr>
<td>climb out</td>
<td>0.79</td>
<td>848.15</td>
<td>31.82</td>
<td>0.02</td>
<td>0.14</td>
<td>11.29</td>
<td>9.5</td>
</tr>
<tr>
<td>approach</td>
<td>0.13</td>
<td>547.84</td>
<td>6.72</td>
<td>0.04</td>
<td>2.4</td>
<td>5.74</td>
<td>1.8</td>
</tr>
<tr>
<td>idle</td>
<td>0.04</td>
<td>420.33</td>
<td>2.89</td>
<td>1.31</td>
<td>24.98</td>
<td>2.75</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 5.1: Emission data from ICAO emissions data bank for GSP®
5.4. Model validation

Now that both aircraft and engine model are described, the simulation model can be validated. This Section presents the validation of the flight performance model of an Airbus A320 with an integrated CFM LEAP-1A engine model.

5.4.1. Flight performance model validation

To validate the simulation model, the output is compared to the output from PianoX®. PianoX® is a performance software that gives fuel consumption, environmental emissions, drag and performance characteristics at any range and payload combination of specified aircraft. It is an aircraft analysis tool commonly used by airframe and engine manufacturers. PianoX® is freeware, it limits the available aircrafts that can be used in the program unless the licensed software is being used. This research is not focused on attaining an accurate flight mission, but to analyse the effect of a HEPS on a reference flight. Therefore the comparison with the results from PianoX® is only carried out to see whether similar trends can be observed. For the validation of the flight mission analysis module, a 1000 km flight mission of an Airbus A320 is simulated and compared with PianoX®. Figure 5.8 compares the output of the aircraft performance model with the output of PianoX®. Note that the validation of the flight mission starts at 1500 ft, because the data from PianoX® starts at this height.

5.4.2. Engine model validation

GSP® can now be used to simulate the CFM LEAP-1A turbofan engine. To determine whether this model is correct, the output is compared with provided key data. Table 5.2 shows that, when comparing the output data computed by GSP® with the provided key data, the engine model can be used for the remainder of the research.

<table>
<thead>
<tr>
<th>parameter</th>
<th>GSP® output data</th>
<th>provided data</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1 (100%)</td>
<td>3856</td>
<td>3856 [71]</td>
</tr>
<tr>
<td>N2 (100%)</td>
<td>16645</td>
<td>16645[71]</td>
</tr>
<tr>
<td>Tt4</td>
<td>1950</td>
<td>1950</td>
</tr>
<tr>
<td>OPR</td>
<td>38.25</td>
<td>40 [70, 72]</td>
</tr>
<tr>
<td>take-off thrust</td>
<td>142.88</td>
<td>143.05 [71]</td>
</tr>
<tr>
<td>jet velocity ratio</td>
<td>0.73</td>
<td>0.9 [73]</td>
</tr>
</tbody>
</table>

Figure 6.23a compares the fuel burn dependent emissions simulated by the Aircraft performance model with PianoX®. Both simulations simulate the emissions of the Airbus A320, but since the CFM LEAP-1A engine is relatively new, the A320 in PianoX® is propelled by a CFM 56 engine. The difference in CO₂ emissions is 12.2%, which resembles the reduction promised by Ref. [72].

Figure 5.7: comparison of fuel burn dependent emissions between simulation model and PianoX®
Figure 5.8: comparison of simulation model with PianoX®
Figure 5.9 compares the engine dependent emissions. Figure 5.9a shows that the engine dependent emissions of the CFM LEAP-1A are significantly lower than the emissions of the CFM 56. More interestingly, the distribution of the emissions are different (Figure 5.9b). Although, the emissions are significantly reduced, the percentage of NOx emissions of the total engine dependent emissions are higher. This can be explained by the fact that the CFM LEAP-1A has a higher BPR than the CFM 56 engine and thus has a lower thrust lapse rate. The lower thrust lapse rate means that the engine operates closer at its design condition, as design and off-design conditions are closer to each other. Consequently, the engine operates at relatively higher thrust settings and this leads to relatively higher NOx emissions.

5.5. Electric system model

This Section describes how the electric system is implemented in the simulation model. As part of the work a study has been performed using the Simscape environment of Simulink® to model the electric system. Within the Simscape environment, physical systems can be modelled by making physical connections between available components. Figure 5.10 shows an example of the electric system modelled within the Simscape environment.

The electric system in Simscape includes an inverter. This component requires simulation time steps of $1 \times 10^{-6}$. Although this model is able to simulate the dynamics of the electric system, the overall simulation
time would increase significantly. For the power management analysis in the frame of this research, such detailed transient simulation is considered out of scope.

The model of the electric system has been implemented in the simulation model based on simplified Equations. Considering the architecture from Figure 3.4, the electric system is integrated into the simulation model by adding a negative power off-take into GSP®. This means that electric power is added to the LP spool.

5.6. Hybridisation propulsion system

This Section describes how the simulation model calculates the effect of hybridisation of a propulsion system, when considering the average power per flight phase and the power management strategy as described in Chapter 4. The calculation steps can be divided in four parts (Table 5.3). A similar methodology is presented by United Technology Research Center (UTRC) [75].

<table>
<thead>
<tr>
<th></th>
<th>power of electric system</th>
<th>additional mass of electric system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>•</td>
</tr>
<tr>
<td>4</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

Firstly, the reference flight mission is simulated. This step is needed to determine the shaft power of the LP spool during flight. In the second step, the shaft power is calculated when part of this shaft power is supplied from the electric system; applying the power split. The electric power of the electric system is added to the LP spool as a power off-take. In this step the mass of the electric system is not considered. The third step computes the mass of the electric system, sized to provide the electrical power as applied in step 2, and simulates the performance of the aircraft with the additional mass, but without the electrical power. This results in new LP spool shaft power values to be delivered. Lastly, the electric shaft power determined in the second step is added to the required shaft power computed by the third step. Note that the power split value initially entered at the second step will be slightly lower at the last step, because the required shaft power increases while the electric system still supplies the power-off take of the second step.

Figure 5.11 shows the simulation steps in a flow diagram. Note that in order to compute the mass of the electric system (step 3), the shaft power supplied from the electric system needs to be known. This makes the second step redundant, as its results are also computed within the third step. However, the mass of the electric system is also dependent on the technology maturity level. With the second step, the power off-take as result of different combinations of take-off and climb power split are calculated. These are independent of the technology maturity level. As a result, the output of step 2 can be used to compute the mass of the electric system when assuming different technology maturity levels (see Figure 3.3). This reduces simulation time significantly.
5.6. Hybridisation propulsion system

Figure 5.11: flow diagram of simulation model
Results & discussion

Using the simulation model, the effect of the HEPS can be analysed and discussed. The technology development of electric components (see Section 3.2) has an important influence on the weight of the HEPS and thus on the weight of the aircraft. The weight increment due to the addition of the electric system thus needs to be considered when analysing the potential fuel saving. An important aspect in the analysis on the effect of the HEPS is the power management strategy. Moreover, as stated in Section 2.1, the power delivered by the HEPS is being supplied from two different energy sources. Therefore the effect of the HEPS on total energy consumption needs to be examined as well instead of fuel consumption only. Another advantage of HEPS is the possibility to modify the engine such that it operates more efficiently during cruise. Due to the additional power of the electric system during take-off, the engine can be sized smaller. This will have an effect on the fuel and total energy consumption from an overall mission perspective.

This Chapter shows the analysis results obtained with the simulation model. First, Section 6.1 provides an analysis on the effect of the flight range on the fuel burn and total energy consumption. Thereafter, the effect of energy technology on the mass of the electric system is analysed, Section 6.2. Next Section 6.3 discusses the effect of hybridisation on fuel burn and total energy consumption during the reference flight mission. After defining the electric system, the engine is resized to analyse the additional benefit of the parallel HEPS, Section 6.4. To investigate to which extent the use of the HEPS meet the environmental goals (see Appendix A), Section 6.5 compares the performance of the HEPS to a conventional engine. This comparison includes the amount of fuel burn and total energy consumption that can be saved and the difference in emissions and costs.

6.1. Range sensitivity

With the power management considered, the electric system only assists the engine during the taxi, take-off and climb phases and hence not during the cruise, descent and landing phase. During these phases the additional weight of the electric system increases the fuel burn. Figure 6.1 shows the fuel burn for a flight mission of 1000 km, 2000 km and 3000 km next to each other. From an overall mission perspective, fuel will be saved using the HEPS for a flight mission of approximately 1000 km. As the range increases, the (unused) weight of the electric system is being carried for a longer distance and thus yields in an increased fuel flow for a longer time. As a result, the benefits of the HEPS are mitigated.
6.2. Effect of technology development on weight increase

As mentioned in Section 3.2, the specific energy and power of electric components are currently not sufficient to save on fuel burn. The increase in aircraft weight would be greater than the amount of fuel that can be saved. Figure 6.2 shows the mass of the electric system as function of the take-off and climb power split. The battery specific energy $e_{batt}$ is assumed to be 600 Wh/kg; the specific power of electric machines $\bar{p}_{etm}$ is assumed to be 12500 W/kg.

Figure 6.2 indicates that, although the power split during take-off increases the mass of the electric system, the mass of the electric system is more affected by the power split during climb. The mass of the battery depends on the duration of the power supply, whereas the mass of the electric motor and inverter are determined by the maximum supplied power. The mass of the electric motor and inverter can depend on the power split during the take-off or climb phase. The sizing of the battery is dominated by the climb phase, because the climb phase is significantly longer than the take-off phase and impacts the electric energy needed. The greater slope in Figure 6.2 in the direction of the climb power split means that the mass of the electric system is dominated by the specific energy of the battery.

Consequently, Figure 6.3 displays the effect of technology development within the industry of electric components on the mass of the electric system for a constant take-off power split. The line that represents the specific energy and power of 600 Wh/kg and 12500 W/kg respectively, is marked in the plane of the climb power split and electric system mass in Figure 6.2. Increasing the climb power split increases the mass of the electric system. The technology development show a significant effect on the change in electric system mass and therefore is of great importance for the feasibility of the HEPS.
6.3. Effect of hybridisation on fuel burn and total energy consumption

Figure 6.3 shows the effect of the climb power split on fuel burn. The relative fuel burn is the difference in fuel burn compared to the fuel burn of the Airbus A320 without HEPS. The hybridisation of the propulsion system only becomes interesting when the technology of electric systems permits a specific energy of 600 Wh/kg and a specific power of 12500 W/kg.

Figure 6.4 displays the effect of power management strategy on the fuel burn. The line of Figure 6.4 that represents the specific energy of 600 Wh/kg and specific power of 12500 W/kg, is marked at the edge of the surface at a take-off power split of 0%. From a fuel burn perspective, increasing the climb power split results in an increase in fuel saving and increasing the take-off power split reduces fuel saving. It should however be noticed that the hybridisation of the propulsion system is limited by the MTOM (see Figure 6.4). When considering a climb power split of 26.1% during climb, 9.3% of fuel can be saved. After this point, the MTOM is exceeded.
Since the energy in the HEPS comes from two different energy sources, the total energy consumption should be taken into account as well. As mentioned in Section 2.2, the useful energy from fuel is different than the useful energy from a battery. Figure 6.6 shows the effect of the climb power split on the total energy consumption. The total energy consumption is the sum of the energy supplied from both the battery as from fuel. The relative total energy consumption is the change in total energy consumption with respect to the total energy consumption of the Airbus A320 without HEPS. Although fuel burn can be reduced with HEPS (see Figure 6.4), the total energy consumption increases except for a power split during climb below 25%.

Figure 6.6: effect of technology development on total energy consumption

Figure 6.7 shows the total energy consumption for different power management strategies. The line of Figure 6.6 that represents the relative total energy consumption is marked at the edge of the surface at a take-off power split of 0%. It can be observed that when considering the total energy consumption, the use of the HEPS shows an almost opposite trend compared to the fuel burn (see Figure 6.4).


It can be concluded from Figure 6.5 and 6.7 that saving fuel yields an increase in energy. As fuel is being saved, the high specific power of fuel (43 MJ/kg ≈12 kWh/kg) needs to be compensated by the specific power of electric components. As the specific power of electric components is significantly lower than the specific power of fuel this results in more weight. And although the efficiency of the electric system is almost three times greater than the efficiency of the gas turbine, the specific power is about 20 times smaller when assuming that the technology in electric components have reached the technology maturity level as specified in Figure 3.3 by the year 2030+.

The objective of saving fuel thus contradicts the objective of saving energy. Figure 6.8 displays these objectives in a Pareto efficiency plot for the different technology targets. Each point represents a different power management strategy, which also affects the weight of the electric system.

With the current maturity level of electric technology, the HEPS do not show any benefit at all. Not only does the energy increase significantly, the lack of specific energy and power means that more additional weight is required than fuel can be saved, yielding an increase in fuel burn. Figure 6.9 shows what this trend looks like when the electric technology targets are extrapolated into the far future (2040 and 2050).

It can be seen that when the battery specific energy is 1500 Wh/kg and the specific power of electric machines is 38000 W/kg, both fuel as well as energy can be saved. The development of technology in electric components depicted in Figure 6.9, is merely an extrapolation of the electric technology predicted by Rostek [48]. The purpose of Figure 6.9 only shows what electric technology is required to actually
Results & discussion

Figure 6.9: Pareto efficiency of HEPS with future electric technology

To obtain an optimum when the objective is to save both fuel and energy. For the remainder of the results the electric technology target for the year 2030+ is being used. Figure 6.10 displays the Pareto efficiency with the points labeled with the corresponding power management strategy. However, this Pareto efficiency does not consider the possibilities of resizing the engine for cruise.

Figure 6.10: Pareto efficiency of HEPS with electric technology by 2030+

6.4. Effect of engine sizing on HEPS performance

As the electric system assists the engine during take-off, the engine does not have to deliver maximum thrust by itself. As a result, the engine can be sized in a better way for cruise yielding a higher efficiency during cruise and subsequently a better fuel and total energy consumption. The resizing of the engine is a non-linear problem (here performed 'manually') and therefore only one point is being considered for the
6.4. Effect of engine sizing on HEPS performance

The remainder of the analysis. When considering the trend of the fuel burn versus the total energy consumption, the point with a power split of 0.0% during take-off and a power split of 13.9% during climb indicates a minimum amount of total energy consumption increase for the greatest amount of fuel burn decrease. Because a greater take-off power split allows for a smaller engine, the points with greater take-off power split are considered as well.

A conventional engine is sized such that it is able to supply sufficient thrust during take-off. Increasing the size of the engine increases the thrust the engine can deliver. On the other hand a smaller engine increases the efficiency of the engine during cruise (see Section 3.1). In the power management strategy considered in this research project, the electric system assists the engine during take-off, allowing the engine to be smaller as the maximum power required from the gas turbine decreases. This allows the engine to be scaled down and thus will shift the design point of the engine from the take-off phase towards the cruise phase. Table 6.1 shows which power management strategies from Figure 6.10 are considered to investigate the potential benefits of engine sizing.

<table>
<thead>
<tr>
<th>Pareto point</th>
<th>$\Phi_{TO}$ in [%]</th>
<th>$\Phi_{climb}$ in [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>13.9</td>
</tr>
<tr>
<td>2</td>
<td>13.3</td>
<td>13.8</td>
</tr>
<tr>
<td>3</td>
<td>24.9</td>
<td>13.6</td>
</tr>
</tbody>
</table>

For the engine sizing it is important to ensure that the engine is able to deliver the required power during take-off. As the take-off power split increases, this would mean that the engine can be sized smaller and therefore more optimal for cruise. A smaller engine affects the weight of the aircraft. Figure 6.11 shows the weight of one engine (which is calculated using Equation 3.1) when scaling the design mass flow rate of the CFM LEAP-1A high BPR turbofan (see Subsection 3.1.2).

Figure 6.11: effect of engine design mass flow scaling on engine mass

Although the weight of the aircraft reduces with smaller engines, the additional mass of the electric system when increasing the take-off power split increases the weight of the aircraft (see Figure 6.2). This increase in weight of the electric system offsets the reduced engine weight. As a result, the thrust requirement changes. Figure 6.12 shows the effect of power management strategy on the thrust requirement during the flight mission next to the effect of a smaller engine on the thrust requirement.
While an increasing take-off power split increases the required thrust (due to the weight of the electrical system), a smaller engine compensates this increase (Figure 6.12). The use of the electric system yields in an increase in overall efficiency (Equation 2.3). Moreover, the efficiency increases with smaller engines as the engine operates more towards its design point. Figure 6.13 shows the effect of the power management strategy and engine size on the efficiency of the engine.

Figure 6.12: effect of power management strategy and engine size on thrust requirement

Figure 6.13: effect of power management strategy and engine size on efficiency

Figure 6.13 points out that a higher take-off power split and a smaller engine result in a greater efficiency. But, considering the shaft speeds of the engine, there is a limit to both the take-off power split and the minimal size of the engine. To ensure that the engine is able to deliver sufficient power, the fan shaft speed need to be considered. Figure 6.14 and 6.15 shows the shaft speeds of the engine for Pareto point 1, 2 and 3 (see Table 6.1) and different engine sizes.
Increasing the power split yields an increase in rotational speed of the LP spool, but as electric power is added the rotational speed of the HP spool reduces. The rotational speed of the LP spool increases as power is added to the spool. Moreover, the lower fuel burn means that more thrust is required from the bypass of the engine, yielding an increase in the speed of the LP spool. An engine with a downscaled mass flow means that the engine needs to work harder to deliver the same amount of power. As a result, both shafts need to rotate at higher speeds. During cruise both shaft speeds are higher due to the additional weight of the electric system. The increased thrust requirement to fly on the same flight mission as the reference means that the engine needs to work harder during cruise. This increases the fuel burn during cruise, but this increment can be offset by the fuel save during take-off and/or climb. Figure 6.16 depicts the effect of the take-off power split and engine size on the fuel burn.

Increasing the power split during take-off reduces the fuel burn during take-off, but as the weight of the electric system increases, this weight is to be carried during the rest of the mission and hence increases the fuel consumption. However, increasing the take-off power split enables the design point to shift towards the cruise phase. In the cruise phase less thrust is required than during take-off. This would mean that during cruise a smaller engine can suffice the cruise thrust requirement and thereby is more efficient as it is closer to its design load. Figure 6.17 shows how the points mentioned in Table 6.1 shift in Figure 6.10.

A smaller engine results in a better solution, but a smaller engine also increases the shaft speed. Figure 6.18 provides an overview of the shaft speeds at different take-off power splits. The shaft speeds are rather high and are greater than the shaft speed of the engine without assistance of the electric system. The shaft speed is usually limited due to the performance of the disks. Greater shaft speeds means that the centrifugal forces increase and the disks needs to be redesigned stronger. This increases the mass of the disks and consequently the engine will become heavier. Figure 6.19 shows how the weight reduction
Results & discussion

Figure 6.15: effect of power management strategy and engine size on HP shaft speed

Figure 6.16: effect of power management strategy and engine size on fuel burn

(mentioned in Figure 6.11) due to down scaling of the engine is affected by the increase in disk weight.
Moreover, the turbine inlet temperature $T_{t4}$ needs to be taken into account as well. Figure 6.20 shows the turbine inlet temperature of the CFM LEAP-1A engine. Assuming this turbine inlet temperature to be the limit for the turbines and including a safety margin of 1.2, shows that scaling an engine to 80%
is not feasible. Taking the turbine inlet temperature into account, it can be seen that the chosen power management strategy in Section 6.3 results in an increase in turbine inlet temperature. However, the power management strategy with a take-off power split of 24.9% and a climb power split of 13.6% with a downscaled engine of 90% can result in a more optimal and yet feasible configuration. This would lead to a fuel saving of 7.5% and a reduction in total energy consumption of 2.0%. This configuration and power management setting is chosen as the ‘optimised’ HEPS and will be further analysed in the following sections. Note that in this analysis, the aerodynamic effects of a smaller engine are not considered. A smaller engine would result in less drag and thus allows the aircraft to operate more efficiently.

![Effect of engine scaling on turbine inlet temperature](image)

Figure 6.20: effect of engine size and power management strategy on turbine inlet temperature

### 6.5. Performance of the optimised HEPS

Figure 6.21 compares the Airbus A320 with HEPS against the Airbus A320 without HEPS for the reference flight mission stated in Subsection 5.2.1. The HEPS consists of an engine scaled down to 90%. The electric system is sized such that it supplies sufficient energy and power for a full taxi-out phase, a take-off power split of 24.9% and a climb power split of 13.6% (see Section 6.4).
The HEPS configuration yields to a fuel burn of 2988 kg and a total energy consumption of 37.85 MWh for a 1000 km flight mission. Comparing this to the Airbus A320 without HEPS, this results in a fuel saving of 7.5% and a total energy consumption reduction of 2%. Subsequently CO$_2$ and H$_2$O emissions reduce proportionally (see Subsection 3.1.3) to the fuel saving with 7.5% (Figure 6.22).
Results & discussion

Engine dependent emissions of Airbus A320 vs. Airbus A320 with HEPS

(a) relative to Airbus A320 without HEPS

(b) absolute in kilograms

Figure 6.23: Effect of HEPS on engine dependent emissions

Emissions are 94.0% of the total amount of emissions. The amount of NO\textsubscript{x} emissions reduces with 3.7% when using the HEPS. Note that in absolute sense these differences are significantly smaller, compared to the fuel burn dependent emissions.
Conclusions & recommendations

This Chapter presents the conclusions drawn from this research and gives recommendations for future work. Section 7.1 contains the conclusions. Subsequently, Section 7.2 provide the recommendations for future work.

7.1. Conclusions

The vast growth in the global airline industry and the depletion of non-renewable fossil fuels are making technological advancements necessary in order to mitigate adverse environmental impacts from aviation. Extensive research has already been done in conceptual propulsion systems that enable the use of renewable energy sources. Yet, those energy sources can neither provide the required power nor yield enough power over a sufficient range. A HEPS combines the benefits of an electrical power source with the necessary support of a conventional combustion engine. However, the additional electric system will increase the weight of the aircraft and complexity of the power management.

The objective of this research is to analyse the power management of a HEPS during flight of passenger transport aircraft. This is done by retrofitting the Airbus A320 with HEPS. However, before a comparison can be made between the A320 with and without HEPS, the electric system should first be sized. This depends on the applied technology maturity level of electric components and the power management strategy. The power management strategy determines the amount of power and energy required for the complete mission and has a significant impact on the performance of propulsion system.

The simulation model consists of an aircraft performance model, which is combined with a detailed propulsion model. The power management strategy is implemented within the simulation model, which allows an integrated performance analysis of an Airbus A320 on a flight mission of 1000 km. To isolate the effect of the HEPS and the power management strategy, the parallel architecture was used in this analysis, rather than the series architecture. This is because the parallel architecture can be retrofitted on a conventional aircraft configuration, whereas to exploit the benefits of series architecture would require an unconventional aircraft configuration, which is beyond the scope of this study.

Increasing the range means that the additional weight of the electric system is carried over a longer distance, leading to a higher fuel burn during cruise. The implementation of the HEPS in the mid/long-term depends heavily on the technology maturity level of electric components. With the current technology maturity, the HEPS would only make the aircraft heavier without being able to save any fuel at all. Technology forecasts show that a battery specific energy of 600Wh/kg and a specific power of 12500W/kg for electric machines would be feasible by the year 2030. If technology can reach this target, the use of the HEPS can lead to fuel burn reduction. However, the battery specific energy is still lower than the fuel specific energy. With the predicted technology maturity level, the additional weight of the electric system will lead to higher total energy consumption, despite the fuel savings.
In the power management strategy of this research, the aircraft is propelled fully electric during the taxi-phases and electrically assisted during the take-off and climb phase. The mass of the battery, which is predominantly sized for the climb phase, accounts for most of the mass of the electric system. The mass of the electric motor and inverter is determined by the maximum power supply of the electric system. This depends on the power split during take-off and climb. The different combinations of take-off and climb power splits result in different power management strategies, which will affect the sizing of the electric system. Increasing the power split during climb leads to reduced fuel burn, but a higher total consumption of energy. With a climb power split of approximately 14%, a trade-off is reached between minimal total energy consumption and minimal fuel burn. Furthermore, for climb power splits greater than approximately 26%, the MTOM of the aircraft is exceeded.

As the HEPS increases the weight of the aircraft, so will the required thrust and subsequently the shaft speeds and the turbine inlet temperature of the engine. Therefore, it is important to take into account the performance characteristics of the engine. The centrifugal forces limit the shaft speeds that the disks can withstand. The take-off power split is disadvantageous from fuel and total energy consumption perspective, but does allow the design point of the engine to shift from the take-off phase towards the cruise phase by downscaling the engine. A smaller engine is lighter than a larger engine, but will have a higher shaft speed. This is because it needs to work harder to deliver the same amount of thrust as a larger engine. Thus, the disks need to be redesigned in order to be stronger and heavier. As a result, the weight reduction of the engine will be less than before. Moreover, the turbine inlet temperature increases. The shaft speeds and turbine inlet temperature limit the size of the engine. The power management strategy with a take-off and climb power split of 24.9% and 13.6% respectively, while scaling down the engine to 90% is the most optimal and still feasible solution. This will lead to a fuel saving of 7.5% and a total energy saving of 2%. This is not only due to the contribution of electric power but also because the additional weight of the electric system and smaller engine ensures the operating conditions are closer to the design point and thus increases the overall efficiency of the propulsion system.

The CO₂ emissions vary proportionally with the fuel savings and the use of the HEPS thus reduces the CO₂ emissions by 7.5%. The addition of an electric system affects how the engine operates and as a result the NOₓ emission reduces with 3.7%.

7.2. Recommendations for further work

The developed simulation can be used for the investigation of different power management strategies. In this research the parallel architecture has been analysed, but the simulation model can also be expanded such that it is able to simulate a series architecture. This would allow a trade-off between the series and parallel architecture from a performance point of view. For the simulation model the efficiencies of electric components are assumed to remain constant during the flight mission, whereas the temperature of the battery affects its efficiency. This could be analysed in future studies. Moreover, development in the efficiency of electric components have not been taken into account. The use of superconductors may yield in greater efficiencies. Including a motor map for the electric motor will allow a detailed analysis on the performance of the electric system. The power management strategy assumes a recharge of the battery during descent to enable a full electric taxi-in phase. This detailed analysis also allows a more accurate simulation for the recharge procedure of the batteries. The integrated performance analysis included the effect of additional mass, but did not consider the volumetric density of the electric components. The reduced fuel burn allows more space for the electric system, but whether this is sufficient and if it fits in with spatial constraints should be considered in future work. Further work may also focus on the effect of alternate fossil fuels, i.e. drop-in fuels with a blend of Jet A-1 and bio-SPK reduce fuel burn consumption and hence fuel burn dependent emissions. Also noise emissions will have to be taken into account in future work regarding emissions.


A.1. Environmental goals set by the European Commission

In Flightpath 2050: Europe’s Vision for Aviation [6], a report of the High Level Group on Aviation Research, the European Commission has set the following goals for aviation in 2050:

- 75% reduction in CO₂ emissions per passenger kilometre
- 90% reduction in NOₓ emissions
- 65% reduction in perceived noise emissions of flying aircraft
- emission free aircraft movements during taxiing

These reductions are relative to typical new aircraft in 2000.

A.2. Environmental goals set by NASA

NASA’s goals for future aviation can be divided into three generations of aircraft in the near, mid and far term (2015, 2025 and 2035) for which the technologies are to be available around 2015, 2020, 2025, respectively. Table A.1 gives an overview of these goals, also known as the N+1, N+2 and N+3 goals [7].

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<td>LTO NOₓ emissions (below CAEP 6)</td>
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<td>cruise NOₓ emissions (relative to 2005 best in class)</td>
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<td>aircraft fuel/energy consumption</td>
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<td>explicit metroplex concepts²</td>
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¹ enabling technologies should reach TRL 4-6 by 2015, 2020 and 2025 for N+1, N+2 and N+3 respectively
² concepts that enable optimal use of the airports (with shorter runways) within the metropolitan areas
B.1. Executive summary

Aviation has dramatically transformed society over the past 100 years. Fast and efficient transportation has essentially been "shrinking the planet" and changing the landscape in terms of financial and societal conditions. The growth of air traffic over the past 50 years has been remarkable, and will continue in the future. This anticipated growth carries along challenges and opportunities in various aspects of life, from economics to the environment. Research must meet these emerging challenges by producing concepts and breakthrough technological achievements in air transport. One of the concepts under investigation is the use of HEPS.

The objective of this business case is to investigate how HEPS can respond to the sustainability demands of aviation. In order to attain the objective, the aerospace manufacturing industry has been analysed.

The high barrier for technology to enter the industry, makes it hard for HEPS to be introduced on aircraft. However, the need for a solution that responds to a growing market and the buyer-supplier collaboration makes the introduction of HEPS attractive. Moreover, the goals set by the European commission and NASA regarding sustainability and environmental impacts pushes the industry to come up with new technology, which may lower the barrier to enter. HEPS proves to be even more advantageous, when considering the Emission Trading System (ETS). Currently, aviation has not succeed to meet the emissions allowances. This yields in emission penalties. Furthermore, as non-renewable fossil fuels are being exploited by the rapid growth of transport, the price of of fuel increases. HEPS enables the aviation sector to reduce fuel burn and thereby avoid emission penalties. With the technology maturity level of 2030, the HEPS is a feasible solution which can meet the demand of growing air traffic and environmental goals on the one hand, and still be economical viable on the other hand.

B.2. Introduction

The increase in air traffic has been strong and resilient and will double over the next twenty years [1, 2]. While this development has greatly boosted the global economy, accounting for approximately 3.4% of the world’s Gross Domestic Product (GDP), it also has severe adverse impacts on the environment (emissions, noise) [76]. This makes it necessary for the aerospace manufacturing industry to come up with new technologies to respond to climate change. Therefore, the future growth of the industry will be inherently linked to environmental sustainability.

The objective of this business case is to investigate how HEPS can respond to the sustainability demands of aviation. The competition within and the external macro-environment of the aerospace manufacturing industry have been analysed. Moreover technological trends have been reviewed to understand where HEPS can play a role in the future of the aerospace manufacturing industry.
The next section will give a general overview of the aerospace manufacturing industry; Section B.3. This is followed by Section B.4, which gives an external and internal analysis of the aerospace manufacturing industry, by looking at the developments made in the past and the trends that are currently occurring. Thereafter, Section B.5 describes the competitive advantage of HEPS. Section B.6 provides the conclusion of this report.

### B.3. Background

Aerospace manufacturing is a high technology industry. It is a highly concentrated market, as it is dominated by a few large firms that have contracts to produce aircraft with government and private businesses. The largest segment is the civil transport aircraft for transportation businesses, which are mainly airliners and cargo transportation firms. General aviation is another segment, which includes small two-seaters for leisure use and corporate jets for business use. Civil helicopters make up one of the smallest segments of civil aircraft.

Many smaller companies work primarily as subcontractors to the largest manufacturers to produce specific systems and parts for their aircraft. As the work of aircraft engine manufacturers is very specialised, those engines are usually manufactured by separate firms. However, they need to follow the designs and performance specifications of the aircraft manufacturers. Those manufacturers can also opt to use different engines from various firms on the same type of aircraft.

### B.4. Current industry analysis

The highly concentrated aerospace industry is, both geographically as well as the small number of large firms, primarily located in the US, Europe and Canada. However, with the current industry globalisation, aerospace manufacturing is beginning to expand to emergent markets such as China, Mexico and India. The US and Europe are responsible for approximately 89% of the global commercial aerospace industry production [77]. They contract to produce aircraft with government (mostly related to defence) and private businesses, usually airline and cargo transportation companies. The aircraft parts industry is driven by the demand for commercial, military and private aircraft. The profitability of individual companies depends on efficient operations and the ability to secure long-term contracts [78].

In addition, relatively stable growth in global GDP, lower crude oil and other commodity prices, and continued increases in passenger travel demand are contributing to expected growth in production rates for next-generation commercial aircraft. The commercial aerospace subsector is expected to continue its decade-long trend of above-average growth rates, driven by growth in passenger travel demand and an accelerated equipment replacement cycle. Strong yearly increases in global revenue passenger kilometers are leading to an unprecedented level of aircraft production rates, which in 2015 were about twice the level experienced 10 years ago.

Aircraft manufacturing can be broken down into a defence and a commercial segment. While military aviation is likely to see a decline in revenue due to cuts in military spending, commercial aircraft production is forecast to experience a boom. In light of continued passenger traffic growth, airlines are expected to add new models to their fleets. Boeing’s Dreamliner and Airbus Group’s A350 are predicted to become the most sought-after models in this sector.

### B.4.1. Technology and innovations

Figure B.1 shows the development of civil air transport performance over the years. Throughout the history of aerospace certain periods of performance improvements can be seen; S-curves. The first S-curve is mainly due to the First and Second World War where the demand of fighter aircraft was high and pushed the aerospace industry to develop rapidly. After the Second World War the technology used for fighter aircraft was used to develop aircraft to transport people; the commercial age. In this period many commercial airplanes were built with different properties like the amount of people to transport and its range. The third S-curve is called the age of sustainable growth where the society demands sustainable
products, pushing the aerospace industry to develop rapidly again. New aircraft configurations to increase performance are extensively investigated; e.g. the box wing jet, blended wing body and airplanes with active aeroelastic wings. Research is being done in alternative fuels which have a lower impact on the environment. Moreover, propulsion technologies will play an important role in the future of aviation [79].

![Figure B.1: the S-curves of civil aviation performance](image)

Figure B.1 also shows that the innovations in the aerospace industry are developing quite slowly. The implementation of a technology advancement can take about decades to be introduced. The main reason for this slow development in aerospace is due to the complexity of aerospace products, which requires a significant amount of research. Each part needs to be designed and manufactured precisely so that it can withstand various operating conditions. As a result, parts are tested at each stage of the production process.

The technological advancements in the aerospace industry are also partly dependent on innovations from other industries such as the metal industry, electronic industry and engine industry. Recent developments in battery technology have now allowed the automotive industry to build hybrid and fully electric cars. However, it will require a far longer time to fully implement this technology in the aerospace industry, as weight presents another challenge in the development of fully electric commercial aircrafts. In the general aviation sector, the first small fully electric aircraft is in production and will set its maiden flight in late 2017 [8].

Currently, extensive research is done in various potential solutions to make the air transport industry more sustainable (see Figure B.1). New aircraft configurations such as the HWB, boxed-wing and strut-braced wing are potential solutions that may improve performance of aircraft in terms of efficiency. The HWB, for example, improves the aerodynamic performance, leading to reduced fuel burn. Moreover, noise from the engine can be shielded by the body of the aircraft [21]. As these solutions mean that aircraft are changed drastically, flying characteristics of the aircraft will change and new technical challenges will occur. Therefore extensive research is required before it can be commercially certified.

Another substitute is the use of alternative fuels. Fuels under investigation are: biodiesel, ethanol, dimethyl ether (DME), hydrogen, syngas and Fisher Tropsch fuels such as gas to liquid (GTL) and coal to liquid (CTL),[79] Alternative fuels have higher energy density than current aviation fuel and have lower emissions. Moreover, costs of fuel are lower [81]. However, the greater volumetric energy density of alternative fuels requires new storage technology.

Inspired by the rise of hybrid and fully electric cars in the automotive industry, fully electric aircraft is considered as a technology for future aviation. However, as weight poses another restriction, fully electric aircraft are even ambitious in the long-term [9, 13].
**B.4.2. Internal competition analysis**

The competitive landscape of the aerospace manufacturing industry will be analysed using M.E. Porter’s five forces tool [82]. Figure B.2 gives an overview of the five forces model of the industry.

**Threat of new entrants**

The threat of new entrants in the aerospace manufacturing industry is low. This is due to its highly regulated nature and the high complexity of the industry’s technology [83]. There are a few big key players in the market, which makes it difficult to compete with their existing cost and differentiation strategies as a new entrant. Both Airbus and Boeing are dominating the aircraft manufacturing market [84].

Furthermore, the initiation of new technologies is time consuming, as it requires a significant amount of research to achieve technological advancements due to the high risks involved with great uncertainty. The learning curve goes with the amount of time the company has been in the industry, as testing and certification processes are very strict. The industry also requires professional trained and skilled staff. There are high capital requirements involved in order to obtain economies of scale. Typically, many parties are involved for funding, which means that exit barriers are high. For instance, firms may depend heavily on government subsidies. Though, this may be less relevant in the parts manufacturing subsector, as entry is less difficult based on the lower cost and quantity of machinery required.

**Power of suppliers**

Bargaining power of suppliers is medium low. As the aerospace industry works with many subcontractors in a concentrated market, the dominating firms have the negotiation power regarding price of supplies due to the economies of scales. Because nearly all of the purchases done are very expensive, the buyer’s decision is very much affected by the price. Furthermore, all the major suppliers need to compete with one another for market share.

However, suppliers with innovative key technology or rare resources and materials have higher bargaining power, particularly in a highly specific sector as the aerospace manufacturing industry. It is also of impor-
tance that developing new products is complex and requires in-depth knowledge from suppliers as well. Hence, the industry shows a trend towards inter-firm learning, where suppliers are more involved in the design and R&D processes, which makes it important for firms to have capable suppliers [85], shifting the bargaining power to suppliers.

Power of buyers
Bargaining power of buyers is medium high, as the aerospace manufacturing industry is dominated by only a few large players. Airline companies often force cutthroat competition between the aircraft manufacturers, Boeing and Airbus. Furthermore, as there are high economies of scale involved, most of the purchases are in bulk. However, suppliers require large capital investments by buyers, which often involve long-term contracts. This will lower the bargaining power of buyers due to higher switching costs [85].

Threat of substitute
Threat of substitute is medium high in the aerospace manufacturing industry at the part/component level. New materials and/or new technology can replace current materials and/or technology in airplanes and engines. As it is a high technology industry, part of the business requires adapting to newer and more advanced technologies. However, it takes a relatively long time to fully implement these changes. While buyer's propensity to substitute is high, the ease of substitution is low. Buyers are easily convinced if technology proves to reduce costs and increase revenue, but testing and certification are extensive and time consuming.

Rivalry among existing competitors
The intensity of rivalry among existing competitors is high. Aerospace manufacturers seek to win large orders to offset the high investment costs to develop new aircraft and engines. The competitors are similar to one other and have little differentiation in their product lines. This increases the intensity of the competition.

Conclusion of Porter's five forces
The five forces model analysis gives insight into the competition of the industry. The specific knowledge within the aerospace industry is highly advanced and complex, and therefore needs to be shared between the suppliers and the buyers. This creates a strong collaboration between supplier and buyer, which makes it easier to develop technologies.

The aerospace manufacturing industry is a research-based industry. Different potential concepts are extensively being investigated before a certain technology is introduced. It can take decades for a technology to be found on an aircraft. As a result, the barrier for technology to enter the industry is high. The threat of substitutes is low, due to the buyer-supplier collaboration. The attractiveness according to M.E. Porter's five forces can be concluded as medium. Due to the high entry barrier, it may prove hard to enter the industry. However, with a potential new technology and the right supplier-buyer collaboration new entrants can have an opportunity to impact the industry.

B.4.3. Macro-economic factors
The PEST analysis, introduced by F. Aguilar [86], is used to obtain a greater understanding of the external factors affecting the aerospace manufacturing industry.

Political
Unsustainable exploitation of non-renewable fossil resources not only leads to its depletion but, with fossil fuels being the dominant source of energy, undesired changes in climate also becomes inevitable. Statistics provided by the European Commission [3] show that in 2012 only 9% of the EU's mobility volume in passenger-kilometers was made by air transport. From the GHG emissions produced by transport, only 12.8% comes from civil aviation. Air pollution caused by aircraft is however more significant as emissions are not only produced on ground, but also at higher altitudes. Due to the lower atmospheric pressure and "cleaner" air, a given volume of emissions can have a much greater impact [4].

Next to GHG, aircraft noise emissions can have a significant effect on the health. Chronic aircraft noise exposure on children impairs reading comprehension and long-term memory and may be associated with
raised blood pressure. These noise emissions may also contribute to the effects of environmental noise on annoyance, sleep and cognitive performance in adults and children [5]. A rise in air traffic will therefore lead to an increase in the amount of complaints from residents, living close to airports.

The environmental impact of aircraft, exploitation of non-renewable fossil fuels and rising demand for air transport has necessitated both the European Commission and NASA to set goals that offsets the impact of growing air traffic. In Flightpath 2050: Europe’s Vision for Aviation [6], a report of the High Level Group on Aviation Research, the European Commission has set the following goals for aviation in 2050:

- 75% reduction in CO₂ emissions per passenger kilometre
- 90% reduction in NOₓ emissions
- 65% reduction in perceived noise emissions of flying aircraft
- emission free aircraft movements during taxiing

These reductions are relative to typical new aircraft in 2000. NASA’s goals for future aviation can be divided into three generations of aircraft in the near, mid and far term (2015, 2025 and 2035) for which the technologies are to be available around 2015, 2020, 2025, respectively. Table B.1 gives an overview of these goals, also known as the N+1, N+2 and N+3 goals [7].

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Economic

To urge the industry to fight global warming, the European Union has launched the Emission Trading System (ETS). The ETS has been developed such that CO₂ emissions are limited. It works on the ‘cap and trade’ principle. The cap limits the amount of greenhouse gas (GHG) emissions. The emissions allowances are provided to the companies regulated by the scheme. The companies are required to measure and report their carbon emissions and to hand in one allowance for each tonne they release. Exceeding the allowed emissions leads to a penalty which was €100 per tonne of CO₂ in 2013 [76]. This value rises annually with the annual rate of inflation in the Eurozone. To date, the aviation sector has exceeded the emissions cap [87]. The emissions allowances can be bought, sold, traded, or banked for use in future years. Thus, reduction of emissions gives investors certainty about the return on investment in emissions reductions. Moreover, due to the cap, emissions allowances remain valuable.

As fuel is a non-renewable fossil fuel, the growing air traffic accelerates its depletion. As fuel becomes more scarce, prices will increase. The fuel price fluctuates according to Figure B.3 [1]. The price of fuel in 2030 is predicted to be €0.81/l. This price will only increase, considering the trend and the availability of fuel.

1 enabling technologies should reach TRL 4-6 by 2015, 2020 and 2025 for N+1, N+2 and N+3 respectively
2 concepts that enable optimal use of the airports (with shorter runways) within the metropolitan areas
B.4. Current industry analysis

Social

The long-term market for passenger aircraft depends primarily on passenger demand for air travel, which is itself primarily driven by economic or GDP growth, fare levels and demographic growth. Air travel has tremendously increased and its un-restrained growth will double in the next twenty years [1, 2]. Figure B.4b and B.4a both show the forecasted rise in demand for air traffic. Figure 1.1a is a market forecast of Boeing’s fleet which will increase from 21,600 to 43,560. Figure 1.1b shows a market forecast of air traffic that increases annually with 4.6%. By 2034 air traffic will thus be doubled.

![Figure B.4: global market forecasts of aviation](image)

(a) global market forecast of airplane fleet by Boeing [2]  
(b) global market forecast of air traffic by Airbus [1]

Technological

To respond to the growing air traffic, solutions are sought in making the aircraft more efficient. Both Boeing and Airbus have introduced more composite aircraft. The use of composites reduces the weight and thereby saves fuel and subsequently lowers the environmental impact. The Boeing B787’s construction consists primarily of composite materials and Boeing is also incorporating more composite materials in its fleet [88]. Also Airbus is applying more and more composite into its fleet [89].

Another trend visible, is the use of higher bypass ratio engines [90]. These engines are more efficient and thereby reduce their fuel consumption [70]. Developments in the turbofan has increased the thrust-to-weight ratio and reduced the noise emissions.

Conclusion of PEST analysis

The PEST analysis gave insight in the external factors that have impact on the aerospace manufacturing industry. With the increasing demand of air traffic [1, 2], the environmental impact of aircraft becomes...
a primary concern. As a result, both the European Commission and the NASA has set goals for future aircrafts to reduce emissions\[6, 7\]. The depletion of fuel, does not only make it necessary to reduce fuel consumption in a growing industry, but also increases the costs of non-renewable fossil fuels. The introduction of more composite aircraft has reduced aircraft weight and thereby reduced the fuel consumption for flight. The technology advancements in aero-engines have reduced the environmental impact even more.

**B.5. Competitive advantage of HEPS**

Figure B.1 shows that the aerospace industry is currently in the age of sustainable growth. The depletion of non-renewable fossil fuels, the environmental goals set for future aviation and the ETS give opportunities for new technological advancements to be introduced within the industry.

Due to the advancement in battery technology, the automotive industry has been able to lower its environmental impact with hybrid and fully electric cars. In the aerospace industry, the concept of complete electric propulsion will be introduced on small airplanes from 2017\[8\]. However, the restricted power-to-weight ratio of electric components up till now holds back the development of fully electric commercial passenger aircraft, as high power requirements make it impossible to carry the electric system\[9\]. Therefore, the turbofan is still required to propel the aircraft. Combining the state of the art turbofan engine with an electric motor could be a potential solution to meet the requirements of future air travel. Such a propulsion system is called a HEPS.

The implementation of the HEPS in the mid/long-term depends heavily on the technology maturity level of electric components. Figure B.5 displays the development of electric component technology as predicted by Rostek (2015)\[48\]. With the current technology, the HEPS would only make the aircraft heavier without being able to save any fuel at all. With the predicted technology level of 2030, the parallel HEPS proves to be beneficial for a short-range flight of 1000 km. With the predicted technology maturity level, the additional weight of the electric system will lead to higher total energy consumption, despite the fuel savings. However, the HEPS allows the engine to become smaller, which ensures the engine operates closer towards its design point.

![Figure B.5: performance targets on system component level; presented by Rostek (2015) [48]](image)

Extensive research is still required to make the HEPS a feasible solution. However, as it can be retrofitted on existing aircraft, the process of introducing this novel technology on aircraft can be shortened. Moreover, as the electric technology maturity level increases HEPS will become more and more beneficial. This increases the value of the technology. Also, the reduction of emissions enables the aviation sector to emit less pollutants than allowed and thereby emission penalties can be avoided.
B.6. Conclusion

The aerospace manufacturing industry is a high technology industry, where profit is mainly made by the efficiency of operations and long-term contracts. Additionally, the industry is growing due to the increase of air traffic. This stimulates the global economy, but has adverse impacts on the environment. As a result, the aerospace industry requires new technologies that push the performance of civil air transport, while complying with new sustainability plans. Thus, the objective of this business case is to investigate how HEPS can respond to the sustainability demands of the changing aerospace manufacturing industry, providing implications for future prospects and technology trends of the industry.

Although, the aerospace manufacturing industry is at the forefront of technology, the industry is dictated by technology advancements that can take decades to be found on operating aircraft. As a result, the level of market entrants can be considered as low. The advanced technology in the industry requires specific knowledge. Due to its complexity, it is becoming increasingly important that information is shared between supplier and buyer. This will create a strong collaboration, which will further stimulate the development of new technology and consequently lowers the threat of substitutes. However, the introduction of novel concepts may still take decades, leading to high barriers to enter the industry. Nonetheless, with a potential new technology, collaboration can be sought with current market players. This will lower the barrier to enter the industry. The introduction of new technology will only be beneficial in the long-term.

As a result of the increasing demand of air transport and its environmental impact, the European Union and NASA has set environmental goals to reduce emissions. In order to reduce the fuel consumption and emissions, more composite aircraft are being introduced. Advancements in turbofans have increased the thrust-to-weight ratio and have led to reduced noise emissions. Still, the aviation industry exceeds the allowable emissions. The exploitation of fuel as an energy source leads to an increase in costs as its becomes more limited. Moreover, the European Union has set up the ETS to fight global warming. The ETS sets a limit on the emissions and thereby stimulates the industry to come up with new technologies to answer the rapidly growing air transport and reduce costs due to emissions penalties.

When looking at other high-technological industries, such as the automotive industry, we can see that it has been able to lower its environmental impact with the introduction of electric mobility. Nevertheless, due to the high power requirements of commercial passenger aircraft, a fully electric aircraft is not feasible yet. With the predicted technology maturity level of 2030, the combination of an electric system with the conventional aero-engine is a potential solution. The HEPS can reduce fuel consumption and emissions and hence is able to meet the environmental goals set by the European Union and NASA. Although this development may take decades, the increase in technology maturity level makes the HEPS more and more beneficial. This will even allow the aviation sector to avoid emission penalties and meet the emissions allowances.
Integrated performance analysis of a parallel hybrid electric propulsion system applied on short-range aircraft

Andy Ang¹, Toni Kanakis², Wim Lammen² and Arvind Gangoli Rao¹

Abstract
The huge growth in the global airline industry and the depletion of non-renewable fossil fuels are making technological advancements necessary in order to mitigate adverse environmental impacts from aviation. A Hybrid Electric Propulsion System (HEPS) combines the benefits of an electrical power source with the necessary support of a conventional combustion engine. However, the additional electric system will increase the weight of the aircraft and complexity of the power management. The objective of this research is to analyse the power management of a HEPS during flight of passenger transport aircraft. The developed simulation model consists of an aircraft performance model, which is combined with a propulsion model. The power management strategy is integrated within the simulation model, which allows a performance analysis of an Airbus A320 on a flight mission of 1000 km. With the proposed propulsion system and power management strategy, the HEPS is able to reduce fuel burn, total energy consumption and emissions.

Keywords
Hybrid Electric Propulsion System, power management strategy, performance sizing

Introduction
With the increasing demand of air traffic¹², the environmental impact of aircraft becomes a primary concern. As a result, both the European Commission and the NASA has set goals for future aircrafts to reduce emissions.³⁴

Due to the advancement in battery technology, the automotive industry has been able to lower its environmental impact with hybrid and fully electric cars. In the aerospace industry, the concept of complete electric propulsion will be introduced on small airplanes from 2017⁵. However, the restricted power-to-weight ratio of electric components holds back the development of fully electric commercial passenger aircraft, as high power requirements make it impossible to carry the electric system⁶. Therefore, the turbofan is still required to propel the aircraft. Combining the state of the art turbofan engine with an electric motor could be a potential solution to meet the requirements of future air travel. Such a propulsion system is called a Hybrid Electric Propulsion System (HEPS).

Different examples of HEPS applications have been developed⁷⁻⁹. They all show that the use of a HEPS have the potential to increase efficiency and reduce emissions and hence, are in line with the goals for future air traffic. However, the development of these concepts depends on whether new technologies are able to compensate the weight increase. Moreover, sizing becomes more complicated as propulsive power comes from two different types of energy sources. The determination of the ratio of power coming from both energy sources is called the power management. The power management is thus an important aspect in the sizing of HEPS. It determines the amount of electric or chemical energy to be carried during flight and the weight of power components. Hence, the feasibility of HEPS and its potential to meet the requirements depends on the power management of HEPS¹⁰.

Power management strategies on hybrid systems have been well established in the automotive industry, but are still to be explored to a further extent in the aerospace industry. The objective of this research project is to analyse the power management of Hybrid Electric Propulsion Systems (HEPS) during flight of passenger transport aircraft. To

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analyse the power management, power requirements are derived from a flight performance model of the Airbus A320, which is developed in the MATLAB\textsuperscript{©} \textsuperscript{11} and Simulink\textsuperscript{©} \textsuperscript{12} environment. To simulate the propulsion system, GSP\textsuperscript{®} \textsuperscript{13,14} is used and implemented in the simulation model by the GSP API\textsuperscript{©} \textsuperscript{15}. Finally, the HEPS and its power management strategy is integrated within the simulation.

**Hybrid electric propulsion system**

A HEPS has the potential to meet with the goals of future air traffic as it utilises the benefits of an electric motor and compensates for the lack of total required power with the conventional engine. This allows the engine to be sized more specifically for one phase (e.g. cruise) of the mission or allows the engine to be downsized. This means that less power is required from the combustion engine and therefore emissions can be reduced, while efficiency can be increased. A Hybrid Electric Propulsion System (HEPS) can be defined as a propulsion system that combines a combustion engine with an electrical power component to achieve a better overall performance than each subsystem would on its own\textsuperscript{10,16}. In this research, the electric motor is attached to the low pressure (LP) spool of the turbofan engine.

Over the years different concepts of the HEPS have been developed and considered for the propulsion of aircraft that meet the requirements of future air traffic. These HEPS concepts can be categorised by the way in which the combustive and electric part are combined: series, parallel or a combination of both series and parallel\textsuperscript{16}. A series configuration means that the power supplied to the fan is supplied by electric motors only, which in turn are driven by electric power produced by the turbo generators. In the parallel configuration power is supplied by both the electric motor, which is powered by a battery, and the combustion engine. Summarised, the architecture is defined by the way the power from the combustion engine and the electric power component come together to drive the propulsor. The point where the power from the subsystems are combined is also called the power node.

The series architecture has been investigated by various authors\textsuperscript{4,8,17–19}. They all analyse the series architecture as a distributed propulsion system on a hybrid wing body configuration. In the series configuration the extra generator does not only add weight, but also induces an extra conversion of energy. This decreases the efficiency. In order to utilise the benefits of the series configuration, aircraft configuration needs to change drastically. Since the focus is on the power management strategy, changing aircraft configuration is beyond the scope of this research. As a result the parallel HEPS is chosen.

**Parallel HEPS**

In the parallel HEPS the power node is mechanical\textsuperscript{16}, meaning that the electrical power component is used to convert electrical power into mechanical power. This mechanical power is added to the mechanical power provided by the turbine engine. Figure 1 shows a schematic of the parallel architecture.

![Figure 1. Lay-out of the parallel HEPS; based on \textsuperscript{10,20}](image)

The advantage of the parallel HEPS is that the electrical system and engine system operate independently. This allows temporary operation with either the engine or an electric motor. Having a parallel configuration also enables independent design of the power share between both subsystems. Moreover the power provided by the electric motor with respect to the power provided by the engine can be adjusted during operation\textsuperscript{10}. A disadvantage however is that since the engine is mechanically linked to the fan, it cannot operate at its optimal RPM during the complete flight envelope\textsuperscript{21}.

**Metrics for performance & sizing of HEPS**

In a HEPS energy comes from two different sources. If fuel can be saved with HEPS, the useful energy of fuel needs to be compensated by electric energy. Although the useful energy of batteries may be greater, the specific energy density of batteries is significantly lower. This affects the weight and thereby the required energy to propel the aircraft. The use of two different type of energy sources affects the performance of the aircraft. Moreover when to use which type of energy can play an important role in the fuel burn and total energy consumption of an aircraft. The ratio of power supplied from
both subsystems is called the power split $\Phi$ \textsuperscript{12}.

$$\Phi = \frac{P_{\text{supp,ElecSyst}}}{P_{\text{tot}}}$$ \textsuperscript{(1)}

As the power split determines the ratio of power supplied, efficiency of the propulsion system will change. The efficiency of the electric system may be greater, but the amount of energy that can be subtracted from a given amount of fuel is greater than the energy from a defined battery size. A HEPS can be compared with another by its efficiency during flight. Conventional propulsion systems can be compared by their TSFC. For hybrid propulsion systems the Thrust Specific Power Consumption TSPC can be used, Equation \textsuperscript{2} \textsuperscript{20,22–25}

$$\text{TSPC} = \frac{P_{\text{supp}}}{F_N} = \frac{V}{\eta_{\text{ov}}} = \frac{V}{\eta_{\text{ec}} \cdot \eta_{\text{tr}} \cdot \eta_{\text{pr}}}$$ \textsuperscript{(2)}

Where $P_{\text{supp}}$ is the supplied power, $F_N$ is the net thrust, $V$ is the velocity of the aircraft and $\eta_{\text{ov}}$, $\eta_{\text{ec}}$, $\eta_{\text{tr}}$ and $\eta_{\text{pr}}$ represent the overall, energy conversion, transmission and propulsive efficiency respectively. This Equation can be rewritten into Equation \textsuperscript{3}, which calculates the efficiency by considering the power supplied from both energy sources.

$$\eta_{\text{ov}} = \frac{P_{\text{req}}}{P_{\text{supp}}} = \frac{F_N \cdot V}{P_{\text{batt}} + P_{\text{fuel}}}$$ \textsuperscript{(3)}

Where $P_{\text{batt}}$ and $P_{\text{fuel}}$ are the power from the battery and fuel respectively. The power from fuel is dependent on the fuel flow $\dot{m}_{\text{fuel}}$ and fuel heating value $FHV$ (Equation \textsuperscript{4}).

$$P_{\text{fuel}} = \dot{m}_{\text{fuel}} \cdot FHV$$ \textsuperscript{(4)}

The main components that affect the weight of the electric system are the battery, the inverter and the electric motor. The development in electric components technology can be expressed in terms of specific power or energy. The specific power represents the amount of power per weight a component can supply. The specific energy is the amount of energy per weight a battery can contain. The development and state of the art therefore need to be considered for the performance of the HEPS. Figure \textsuperscript{2} displays the development of electric component technology as predicted by Rostek (2015) \textsuperscript{26}.

Next to the specific power and energy of electric components the efficiencies will have an effect on the weight as well as it determines the power or energy output. Table \textsuperscript{1} shows the assumed efficiencies of the electrical components.

![Figure 2. performance targets on system component level; presented by Rostek (2015)\textsuperscript{26}](image)

<table>
<thead>
<tr>
<th>component</th>
<th>efficiency in [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>battery</td>
<td>90.0\textsuperscript{20}</td>
</tr>
<tr>
<td>inverter\textsuperscript{*}</td>
<td>99.5\textsuperscript{27}</td>
</tr>
<tr>
<td>electric motor</td>
<td>93.0\textsuperscript{28}</td>
</tr>
</tbody>
</table>

\textsuperscript{*}including cryocooler required for HTS technology

**Power management strategy**

While flying, it is essential to determine when the electric system assists the propulsion system. This is called the power management strategy. The sizing of the electric system is dependent on the power management strategy, because it determines the maximum amount of electric power and energy to be carried. The additional weight of the electric system needs to be offset by its performance, which depends on the power management strategy. To analyse the effect of power management strategy from an overall mission perspective, a global optimisation strategy is applied. This means that the strategy considers the complete mission as it controls the power split and thus the flight mission is predefined.

The engine operates most efficient during cruise. The efficiency during take-off and climb is rather low and therefore overall efficiency can be significantly increased by the use of the electric system. Due to low thrust requirements, the engine operates at part load during taxi yielding a lower overall efficiency. This overall efficiency increases when considering fully electric taxi phases. Moreover, the use of fully electric taxi phases, reduces noise at airports.

Figure \textsuperscript{3} shows the power management strategy considered in this research. The power management strategy is segmented by the following flight phases:

1. taxi-out: fully electric
2. take-off: assistance of electric system can be controlled with the take-off power split
3. climb: assistance of electric system can be controlled with the climb power split
4. cruise: engine only
5. descent: engine recharges electric system
6. taxi-in: fully electric

In this power management strategy the power split is a percentage of the average power, and therefore the power supplied by the electric system is constant during each flight phase.

![Power management strategy during flight mission](image)

**Figure 3.** Power management strategy during flight mission

The input variables for the power management strategy are the take-off and climb power splits. The power split during take-off lowers the maximum thrust required from the turbine engine, whereas the power split during climb increases the efficiency and thereby allows the propulsion system to save fuel. The take-off and climb power splits have an effect on the sizing of the electric system and thereby also the weight of the aircraft. Moreover as less fuel is being burnt during taxi-out, take-off and climb, the weight of the aircraft during cruise is different. This allows the engine to operate closer towards its design point during cruise.

The assistance of the electric system during the take-off and climb phase allows the engine to be sized more optimally for cruise. This affects the weight and the performance of the engine. A smaller engine has a lower mass, but as shaft speed increase this reduction is mitigated. The mass of the engine is reasonably well correlated to the takeoff static thrust by Equation 5.\(^2^9\) Note that the static take-off thrust \(F_{N,TO}\) in this equation needs to be in pound force. The outcome of this Equation is the mass of the engine \(m_{\text{engine}}\) in pounds.

\[
m_{\text{engine}} = 2.7 \cdot F_{N,TO}^{0.75}\tag{5}
\]

Equation 6 represents the mass flow rate scaling parameter.\(^3^0\) When scaling the engine, this parameter should remain constant. For example: scaling the design mass flow rate \(\dot{m}\) with 80% means that the characteristic diameter \(DI\) needs to scaled with the square root of 80%.

\[
\text{mass flow scaling parameter} = \frac{\dot{m} \cdot \sqrt{\theta}}{DI^2 \cdot \delta}\tag{6}
\]

Consequently, to maintain the same tip Mach number of the engine blades, the shaft speeds of the engine need to be scaled as well\(^3^1\). Equation 7 represents the shaft speed scaling parameter. Like, the mass flow rate scaling parameter, this parameter should remain constant as well when scaling the engine. As a result, a reduced characteristic diameter leads to a higher shaft speed. In case of the previous example this means that the shaft speed should increase with the inverse of the square root of 80%.

\[
\text{shaft speed scaling parameter} = \frac{DI \cdot N}{\sqrt{\theta}}\tag{7}
\]

The \(\theta\) and \(\delta\) represent the pressure and temperature parameter respectively. Both parameters are computed using the reference values for pressure and temperature from the ISA standard sea level static conditions.

\[
\delta = \frac{p_{\text{tot}}}{p_{\text{tot,ref}}}\tag{8}
\]

\[
\theta = \frac{T_{\text{tot}}}{T_{\text{tot,ref}}}\tag{9}
\]

Scaling down the engine thus increases the shaft speeds of the engine and thereby the centrifugal forces \(F_c\) on the disks. Equation 10 describes the relation between the shaft speed, centrifugal force and mass of the disks. To ensure the disks do not fail under the increased load, mass of the disks should increase with the square of the increment in rotational speed \(\omega\).

\[
F_c = m \cdot \omega^2 \cdot R\tag{10}
\]

Scaling of the engine is also limited by the turbine inlet temperature \(T_{\text{t1}}\). Thermal stresses occur at high temperature. At the turbine inlet this temperature is maximum. Although mass of the disks can increase with increasing shaft speed, there is a limit to the operating temperature of the disks.

**Modeling of power management strategy**

To simulate the effect of power management strategy, a flight performance model of the Airbus A320 is used to determine the power requirements for a 1000 km flight. This simulation model has been developed in the MATLAB\(^1^1\) and Simulink\(^1^2\) environment. To simulate the performance of the propulsion system, the CFM LEAP-1A engine has been modelled in GSP\(^1^3;1^4\). The required power and state of the aircraft (altitude, Mach number) are inputs for the engine model. Furthermore to simulate the electric system, a negative power off-take is fed to the engine model. These inputs are provided from the flight performance model to the
engine model by the GSP API\textsuperscript{15}. The output of the engine model is the fuel flow, which affects the weight and thereby the required power of the aircraft. Figure 4 shows the engine model within the GSP\textsuperscript{©} environment. GSP\textsuperscript{©} is also able to output the emissions. These outputs are used to determine the effect of the HEPS and its power management strategy.

![Figure 4. CFM LEAP-1A GSP\textsuperscript{©} model](image)

The power management strategy determines the amount of electric energy to be carried and the amount of power to be supplied and is thus essential for the sizing of the electric system. This affects the initial weight of the aircraft and leads to different power requirements. To integrate the power management strategy and thereby the sizing of the electric system, several calculation steps are required (Table 2). A similar methodology is presented by the United Technology Research Center (UTRC)\textsuperscript{32}.

![Figure 5. flow diagram of simulation model](image)

### Table 2. computation steps of hybridisation

<table>
<thead>
<tr>
<th>power of electric system</th>
<th>additional mass of electric system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>⬤</td>
</tr>
<tr>
<td>2</td>
<td>⬤</td>
</tr>
<tr>
<td>3</td>
<td>⬤ ⬤</td>
</tr>
<tr>
<td>4</td>
<td>⬤ ⬤</td>
</tr>
</tbody>
</table>

Firstly, the reference flight mission is simulated. This step is needed to determine the shaft power of the LP spool during flight. In the second step, part of this shaft power is then supplied from the electric system; the power split. The third step computes the mass of the electric system and simulates the performance of the aircraft with the added mass. This results in new LP spool shaft power values. Lastly, the electric shaft power determined in the second step is added to the required shaft power computed by the third step. Note that the power split value initially entered at the second step will be slightly lower at the last step, because the required shaft power increases while the electric system still supplies the power-off take of the second step.

Figure 5 shows the simulation steps in a flow diagram. The second step can be omitted, but simulation time can be saved if the combinations of take-off and climb power split are simulated first. This would mean that the amount of power does not have to be computed again for the determination of electric system mass. Step three may be repeated to simulate the different technology targets (see Figure 2).

### Simulation results

The fuel burn and total energy consumption of the Airbus A320 for a 1000 km flight mission is 3231 kg and 38.62 MWh respectively. The electric system may reduce the fuel burn, but as fuel is not the only source of energy the total energy consumption needs to be considered. As fuel is being saved, the high specific power of fuel (43 MJ/kg \(\approx\) 12kWh/kg) needs to be compensated by the specific power of electric components. As the specific power of electric components is significantly lower than the specific power of fuel this results in more weight. And although the efficiency of the electric system is almost three times greater than the efficiency of extracting power from fuel, the specific power is about 20 times smaller when assuming that the technology in electric components have reached the technology maturity level as specified in Figure 2 by the year 2030+.

The objective of saving fuel thus contradicts the objective of saving energy. Figure 6 displays these objectives in a Pareto efficiency for the different technology targets. Each point represents a different power management strategy, which also affects the weight of the electric system.

With nowadays electric technology, the HEPS does not show any benefit at all. Not only does the energy increase significantly, but the lack of specific energy and power means that more additional weight is required than fuel can be saved, yielding an increase in fuel burn. With the technology maturity level of 2030, the use of a HEPS can save both fuel burn and total energy consumption. Figure 7 displays the Pareto efficiency for the year 2030 with three power management strategies labeled.
As the electric system assists the engine during take-off, the engine does not have to deliver maximum thrust by itself. As a result, the engine can be sized more optimal for cruise yielding a higher efficiency during cruise and subsequently a better fuel and total energy consumption. The resizing of the engine is a non-linear problem and therefore only one point needs to be considered for the remainder of the analysis. When considering the trend of the fuel burn versus the total energy consumption, the point with a power split of 0.0% during take-off and a power split of 13.9% during climb indicates a minimum amount of total energy consumption increase for the greatest amount of fuel burn decrease. Because a greater take-off power split allows for a smaller engine, the points with greater take-off power split are considered as well.

Moreover the Pareto efficiency (Figure 7) does not consider the performance characteristics of the engine; i.e. extreme high shaft speeds are possible, while in reality this may require the redesign of the disks. The shaft speed is usually limited due to the performance of the disks. Greater shaft speeds means that the centrifugal forces increase and the disks needs to be redesigned stronger. This increases the mass of the disks and consequently the engine will become heavier. Equation 5 and 10 are used to compute the mass of the engine. Figure 8 shows the mass of the engine as a function of the relative design mass flow, which is a percentage of the reference design mass flow.

Moreover the turbine inlet temperature $T_{t4}$ needs to be taken into account as well. Figure 9 shows the turbine inlet temperature of the CFM LEAP-1A engine. Assuming this turbine inlet temperature to be the limit for the turbines and including a safety margin of 1.2, shows that scaling an engine to 80% is not feasible.
saving. Figure 10 shows the fuel dependent emissions of the Airbus A320 with and without HEPS next to each other.

![FIGURE 10. effect of HEPS on fuel dependent emissions](image)

The electric system is attached to the LP spool of the turbofan engine and, as a consequence, affects the way the engine operates and correspondingly affects the emissions that depend on the thrust setting of the engine. Figure 11 depicts the effect of the HEPS on emissions that are dependent on the thrust setting of the engine. The HEPS emits 3.3% less engine dependent pollutants than the conventional turbofan engine. The largest part of emissions consists of NO\textsubscript{x}. For the turbofan engine the NO\textsubscript{x} emissions are 94.0% of the total amount of emissions. The amount of NO\textsubscript{x} emissions reduces with 3.7% when using the HEPS.

![FIGURE 11. effect of HEPS on engine dependent emissions](image)

**Conclusion**

The growing level of environmental implications of aviation and a significant increase in air traffic have been driving technological advancements in the aerospace industry. The rising developments in battery technology allowed the automotive industry to build hybrid and fully electric cars. However, the limited power-to-weight ratio components impede the development of fully electric aircrafts. In this regard, Hybrid Electric Propulsion Systems (HEPS) are more viable. A HEPS combines the benefits of an electrical power source with the necessary support of a conventional combustion engine. However, the additional electric system will increase the weight of the aircraft and complexity of the power management.

In this article, the power management strategy of a HEPS of an Airbus A320 has been analysed on a predefined flight of 1000 km. First, a flight performance simulation model has been used to determine the power requirements. This simulation model has been expanded with an engine model and integrated with a power management strategy.

The implementation of the HEPS in the mid/long-term depends heavily on the technology maturity level of electric components. With the current technology, the HEPS would only make the aircraft heavier without being able to save any fuel at all. With the predicted technology level of 2030, the parallel HEPS proves to be beneficial for a short-range flight of 1000 km. With the predicted technology maturity level, the additional weight of the electric system will lead to higher total energy consumption, despite the fuel savings.

In the power management strategy of this research, the aircraft is propelled fully electric during the taxi-phases and electrically assisted during the take-off and climb phase. With a climb power split of approximately 14%, the increase in total energy consumption is minimised, while fuel savings are maximised. The take-off power split is disadvantageous,
but does allow the design point of the engine to shift from the take-off phase towards the cruise phase by downscaling the engine. A smaller engine is lighter than a larger engine, but will have a higher shaft speed. Moreover, the turbine inlet temperature increases. The shaft speeds and turbine inlet temperature limit the size of the engine. The power management strategy with a take-off and climb power split of 24.9% and 13.6% respectively, while scaling down the engine to 90% is the most optimal and still feasible solution. This will lead to a fuel saving of 7.5% and a total energy saving of 2%. The CO2 emissions vary proportionally with the fuel savings and the use of the HEPS thus reduces the CO2 emissions by 7.5%. The addition of an electric system affects how the engine operates and as a result the NOx emission reduces with 3.7%.

The developed simulation can be used for the investigation of different power management strategies. In this research the parallel architecture has been analysed, but the simulation model can also be expanded such that it is able to simulate a series architecture. This allows a trade-off between the series and parallel architecture from a performance point of view. For the simulation model the efficiencies of electric components are assumed to remain constant during the flight mission, whereas the temperature of the battery affects its efficiency. Moreover, development in the efficiency of electric components have not been taken into account. The use of superconductors may yield in greater efficiencies. Including a motor map for the electric motor allows a detailed analysis on the performance of the electric system. The power management strategy assumes a recharge of the battery during descent to enable a full electric taxi-in phase. This detailed analysis also allows a more accurate simulation for the recharge procedure of the batteries. The integrated performance analysis included the effect of additional mass, but did not consider the volumetric density of the electric components. The reduced fuel burn allows more space for the electric system, but whether this is sufficient should be considered in future work. Further work may also focus on the effect of alternate fossil fuels, i.e. drop-in fuels with a blend of Jet A-1 and bio-SPK reduce fuel burn consumption and hence fuel burn dependent emissions. Also noise emissions will have to be taken into account in future work regarding emissions.

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