33RD CONGRESS
OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
STOCKHOLM, SWEDEN, 4-9 SEPTEMBER, 2022

More Electric Airplane: case study Stockholm – Copenhagen

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Abstract

As the global population and economy grow, the amount of people traveling around the world also increases. This creates a need for the aerospace industry to develop more energy efficient vehicles. The concept of electrification of vehicles has been adopted by the aviation industry in order to reduce environmental impacts and lower operating costs. Although much research has been done on various more electric aircraft technologies, almost all of them are conducted only for one subsystem, lacking the aim of optimizing the total energy outtake from the engines by all subsystems. This paper aims to fill this gap by applying optimization techniques to decide systematically when novel technologies are worthwhile, in terms of energy efficiency. Hence, the goal of this paper is to develop a methodology for evaluating when different MEA technologies are beneficial to implement in future airplanes. In this proposed approach, a Matlab model has been developed which takes publicly available non-propulsive power demands and efficiencies of various subsystems into account, integrates those with real flight data from a case study, and as a result gives the user a comparison of non-propulsive fuel burn. The result is a fuel burn of 1088.5 kg for conventional, 756.5 kg for more-electric, and 351.5 kg for all-electric architectures, depending on the level of electrification. The difference in total fuel burn between the conventional and all electric cases, including fuel consumption for propulsion, represents a reduction of total fuel burn on the order of 10 percent. Since as many electrical loads as possible are integrated into the proposed approach, this model can also be used for generator sizing as discussed in the results section of the case study.

Keywords: Fuel economy, electrification of airplanes, modelling of aircraft power systems

1. Introduction

The More Electric Aircraft (MEA) concept aims to replace conventionally hydraulic, mechanical and pneumatic systems with electrical counterparts. Power used by these systems is called non-propulsive or secondary power. Typically, in commercial airplanes, hydraulic systems are used for flight control actuation, pneumatic systems are used for environmental control and anti-icing, mechanical systems are used for fuel and oil pumping, and electrical systems are used to power avionics, in-flight entertainment and lighting. The Boeing 787 already adopted an electrified environmental control system and wing anti-icing, allowing them minimize the need for bleed air taken out from engines.[1] The Airbus A380, on the other hand, uses an electrified actuation system, allowing it to replace one of the three conventionally hydraulic channels with two electric channels instead.[2]

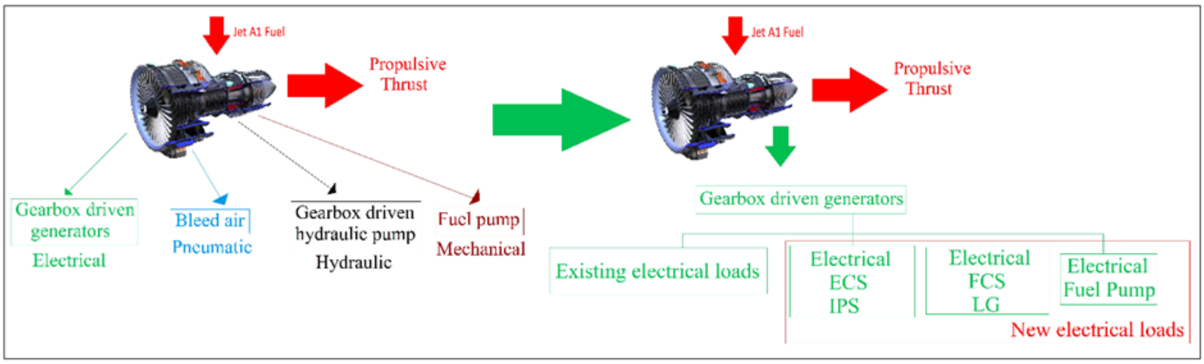

Figure 1 - The difference between a conventional and an all-electric architecture.

The structure of this paper will be as follows: firstly, the technical system descriptions will be presented, discussing the working principles of conventional subsystems, and suggesting electrical solutions for the given subsystems, i.e. environmental control system, ice protection system, flight control actuation, fuel pump, landing gears and taxi. Secondly, the proposed approach in this paper will be discussed, presenting system parameters, flight profile decision data, load analysis inputs & outputs, and presentation of results, to give the reader an idea about how the proposed approach is built. Following, a case study, investigating the fuel consumption of an airplane similar to Airbus A320, during a round trip between Copenhagen and Stockholm will be described. Electrical loads and real flight data used in the case study will be presented; results as fuel consumption comparisons of conventional, more-electric and all-electric architectures, as well as peak generator loads will be discussed. This chapter will end with a sensitivity analysis to indicate how sensitive the system is and how it is affected by introduced efficiency changes. Lastly, an overall discussion of the paper and suggestions for future work will be presented.

2. Technical System Description

2.1 Environmental Control System

The Environmental Control System (ECS) is responsible for pressurization, air ventilation and thermal regulation of an airplane cabin, plus cooling of avionics and other equipment that generates heat. Thermal regulation is done by estimating the thermal load between the cabin and the external environment first, followed by computing the required air mass flow. A similar approach is also valid for cabin pressurization, first estimating the pressure difference between the cabin and the external environment, then adjusting the cabin conditions as desired.[3] In a conventional airplane, ECS is pneumatically powered, which means that these functions are carried out by using bleed air extracted from the engine, and it is considered to demand the highest secondary power. Bleed air is either low or high-pressure air extracted from the compressor stage of jet engines. Low-pressure air is used during flight phases that require high power demands, while high-pressure air is used for low power operations. Starting with Boeing 787, which is the first commercial airplane using a no-bleed engine architecture, environmental control systems shifted from being pneumatically powered to using electrical power instead. With the removal of the pneumatic Boeing claims to have a fuel consumption improvement of 1-2 percent at cruise conditions.[4] Given the number of planes travelling every day, this improvement in fuel consumption will make a great impact both economically and also environmentally. Considering the high secondary power demand and the fuel consumption improvements by changing engine architecture, this research investigates the outcomes of electrifying ECS.

2.2 Ice Protection System

Ice Protection System (IPS) provides ice and rain protection for airplanes by extracting bleed air from the engines, thus it is also pneumatically powered in a conventional airplane. Especially during the climb and descent phases of flights, water on the leading edges of the wings and around engine nacelles might form ice, which can pose a threat for the flight safety by changing the airflow over the wing and tail causing reduced lift that might lead to loss of control. In order to overcome this threat, some of the hot bleed air extracted from the engine is directed to the wings to prevent water from forming ice. The same approach is also commonly used for engine nacelles to stop chunks of ice going into the engines. Depending on the proposed protection system, varying architectures for anti-icing or de-icing, namely bleed air, pneumatic boots, cyclic, parting strips, electromechanical expulsion, pulse electro-thermal de-icing etc.,[5][6][7][8] can be used to ensure ice protection. In any case, power demand of hot bleed air extraction is considerable, thus replacing the pneumatic IPS with electrical counterpart is also of interest when the electrification is investigated. However, in this paper IPS is neglected, since it would add more complexity to the model.

2.3 Flight Control System

The flight control actuation in conventional commercial airplanes is done by using hydraulic actuators powered by hydraulic pumps, which are driven by the engines with the help of a gearbox; hence the system is considered to be hydraulically powered. By using electrical actuators that are connected to the generators with a gearbox, the flight control actuation might also be electrified. In case of linear hydraulic actuators, the relation between force and velocity is used to determine optimal sizing of actuators, whereas for hydraulic rotating and electric rotary actuators, the relation between torque and angular speed can be used for achieving optimal sizing.[3] Comparing hydraulic and electrical actuators, while hydraulic systems require pressurization as long as the system is running, electrical actuators can be powered only when they are in use, thus the electrical actuators yield a higher power efficiency.[9] In case the actuation system is powered electrically, either electromechanical (EMA) or electrohydraulic (EHA) actuators can be used. Both EMAs and EHAs replace the conventional hydraulic tubes with electrical wires, which may result in lower operating costs with the help of improved controllability, accuracy, reliability and efficiency, as well as lower maintenance costs and weight savings. However, the failure modes of each electric actuator should be considered during the preliminary design phase. While EHAs take advantage of replacing the rather large, heavy and centralized conventional hydraulic system with distributed tiny local hydraulic parts, they tend to fail while floating free. On the other hand, EMAs get rid of the hydraulic fluid totally and use electric motors instead, yet they tend to fail at minimum or maximum extension.[10] Regarding these failure modes, EHAs are preferred in today’s airplanes because they are more mature and they can still be used in case of a failure, due to their tendency to fail while floating free.

2.4 Fuel Pump

Fuel pumps and fuel systems are used to feed the engines of airplanes with jet fuel. When the whole fuel system of an airplane is considered, it does not only include fuel tanks, but also fuel feed, pressure refueling pipes and the fuel booster pumps, which are usually electrically driven and used to increase the fuel flow from the airplane fuel system to the engine.[3] In case of an emergency such as engine fire, fuel pumps allow the crew to stop fuel reaching the engine. Another function of fuel pumps is to let the pilot to choose which fuel tanks feed the engines, an option that helps to balance fuel load of the airplane. In principle, fuel pumps operate based on pressure caused by fuel flow, taking engine interface pressure and pressure loses along fuel pipes into account, they adjust fuel flow into airplane engine.[3] In conventional airplanes, it is common that fuel pumps are operated either mechanically, electrically or by using fuel as the working fluid. In the model discussed in this paper, it is assumed that fuel pumps are directly driven by the engines with the connection of a gearbox for the conventional airplane case. For the electrified airplanes, it is assumed that fuel pumps are connected to the generators with a gearbox, which might provide an advantage in terms of controllability. As it will be presented later in Results of the Case Study section, the electrification of the fuel pumps in this model does not provide an advantage in terms of reducing the fuel consumption. However, it might be possible to reduce overall fuel consumption by turning off the pumps during cruise, only running them intermittently, or only using some of them to move fuel between different tanks during cruise. Nevertheless, it should be noted that electric fuel pumps are also typically used on commercial airplanes. The electrification of the pumps in this model does not focus on reducing the fuel consumption, and they are assumed to be always running, thus the controllability aspect is not explicitly examined in this paper.

2.5 Landing Gear

The main purpose of landing gears is to protect the vehicle from ground impact while it is not in the air, as well as allowing the airplane to move and brake on ground.[3] They are used during taxiing, take off and landing phases of a flight, and for the rest of the time they are retracted in order to reduce drag/air resistance. In conventional airplane, the extension/retraction movement of landing gears takes place by using gearbox driven hydraulic pumps attached to the engines, hence the system is conventionally hydraulically powered. The biggest advantage obtained from the electrification of the landing gear, at the expense of possible additional weight and complexity, is avoiding the loss of hydraulic fluid, which is the most common cause of hydraulic gear system failure. Additionally, the total removal of hydraulic fluid would yield lower maintenance needs and costs.

2.6 Taxi

Taxiing describes an airplane moving on ground from gate to runway before take off, or from the end of runway to gate after landing. Conventional airplanes are either tugged from gate to runway by ground vehicles, or they use their jet engines to move the vehicle to the desired location on ground. However, jet engines operate rather inefficiently at low thrust,[11] thus the use of auxiliary power unit (APU) for electric taxiing can improve reducing the fuel consumption by using smaller electrical motors which operate more efficiently at lower torques. As it is indicated, a short or medium range airplane spends 10 to 30 percent of its total journey time on taxiways, which results in burning up to 10 percent of their fuel on ground.[12] On the other hand, it should be noted that the use of electric taxiing with today's technology might require adding extra weight onto the vehicle due to newly added electric motors, power electronics, gearboxes and cabling.[13] Thus, it can be said that currently electric taxiing is more beneficial for short flights since this system is essentially considered deadweight off ground.

The potential benefits of electric taxiing include reduction in ground gas emissions by the use of APU, improved safety and health benefits for ground staff by avoiding the need of working around large jet engines and cost savings for airline companies by wheel brake wear reduction and flight time savings with no tugging needed.[12]

Table 1 indicates varying architectural solutions for conventional and electric taxiing. Jet engines are slow to accelerate and not optimized for improving fuel consumption efficiency for taxiing on ground. On the other hand, APUs are smaller engines with better efficiencies respectively, hence they tend to consume less fuel. As can be seen in Table 1, "2 engines taxi" solution consumes the most fuel, while "Single engine taxi + APU" is more efficient in terms of fuel consumption[18]. Moving onto the electric taxi case, "ground idle" is the lowest sustainable speed setting on a running engine. The lower the idling speed, the lower the wear and tear on the brakes while taxiing. By running one of the engines at "ground idle" in combination with APU, the fuel consumption can be reduced even more. However, it can be observed that the most efficient taxiing solution would be using only the APU.

Table 1 – Taxiing fuel consumption input for this approach, Airbus A320 estimated fuel consumptions and corresponding power demands during taxi

	Conventional Taxi		**E-Taxi**	
Architecture	2 engine taxi	Single engine taxi + APU	Hybrid E-Taxi (one engine at idle + APU)	Full E-Taxi (APU only)
Fuel*	12.5 kg/min	9.5 kg/min	7 kg/min	2 kg/min
Power	539.3 MJ/min	409.9 MJ/min	302 MJ/min	86.3 MJ/min

* The fuel consumption values are obtained from [12] as kg/min. These values are converted into corresponding power values by using the specific energy of Jet A1 kerosene.

3. Proposed Approach

In this part of the paper, the proposed approach will be discussed in detail. The model developed in this approach is implemented in Matlab and includes four files for the execution, namely:

1. System Parameters
2. Flight Profile Decision
3. Load Analysis
4. Presentation of Results

In the following subsections, parameters of the model, their roles, i.e. whether they are inputs, outputs or calculated intermediate values, will be presented with tables and figures, as well as providing the mathematical equations used to calculate the above mentioned intermediate values.

Table 2 – System parameters for the proposed approach

Name	**Input Intermediate Output**	**Description**
Scale	Input	Airplane scaling, depends on pax number or airplane size
A. System Architecture under research		
Electric ECS	Input	ECS electrified, true or false
Electric Actuation	Input	Actuation electrified, true or false
Electric Fuel Pump	Input	Fuel pump electrified, true or false
Electric Landing Gear	Input	L. Gear electrified, true or false
Electric Taxi	Input	Taxi electrified, true or false
B. Technical Specifications of Electrifiable Components		
Efficiency Gearbox	Input	Transmission efficiency
Efficiency Compressor	Input	Air cycle compressor efficiency
Efficiency Generator	Input	Generator efficiency
Efficiency Bleed	Input	Efficiency of bleed air system
Efficiency Hydraulic Pump	Input	Efficiency of hydraulic pump
Efficiency ECS	Input	ECS efficiency
Efficiency Electrical Actuator	Input	Electric actuator efficiency
Efficiency Conventional Actuator	Input	Hydraulic actuator efficiency
Efficiency Fuel Pump	Input	Fuel pump efficiency
Efficiency Landing Gear	Input	Landing gear actuation efficiency
Efficiency IPS	Input	Ice protection systeme efficiency
C. Technical Specifications of Always Electric Components		
Efficiency In-Flight Entertainment	Input	In-Flight Entertainment efficiency
Efficiency Passenger Cabin Light	Input	Cabin lighting (LED) efficiency
Efficiency Flight Compartment Lighting	Input	Flight compartment lighting (LED) efficency
Efficiency Exterior Lighting	Input	Exterior lighting (LED) efficiency
Efficiency Navigation	Input	Navigation system efficiency
Efficiency Communication	Input	Comms system efficiency
Efficiency Autopilot	Input	Autopilot system efficiency
Efficiency Indication and Recording	Input	Indication and recording efficiency
Efficiency Flight Control System	Input	Flight control system efficiency
Efficiency On Board Computers	Input	Onboard computers efficiency
Efficiency Toilet	Input	Toilet efficiency
Efficiency Galley	Input	Galley efficiency
Efficiency Water and Waste	Input	Water and waste efficiency

3.1 System Parameters

Table 2 indicates system parameters defined by the user. The model requires this stage to define the desired level of electrification. In other words, the subsystems which are under research for electrification are selected by the user at this stage. Six input values, (Scale, Electric ECS, Electric Actuation, Electric Fuel Pump, Electric Landing Gear, Electric Taxi) are required by the model at the start of its execution. If less than six inputs are given into the model, a warning message will be displayed saying 'Not enough inputs for electrification; (1,1,1,1,1,1) default values are assumed.'. This means the model will assume all subsystems will be electrified for a base scale airplane, in this case, a 180 passenger, twin engine, turbofan short haul airplane similar to Airbus A320.

In addition to the above-mentioned electrification inputs, this file also contains efficiency values of different components and subsystems, such as generator, bleed, landing gear, exterior lighting etc. efficiencies. These values are also inputs to the model, and lets the user compare different technical solutions by simply introducing an efficiency value into the system, which then can be used to analyze the fuel consumption for a given subsystem. Figure 3 indicates the flow of the proposed approach.

Note how Scale and System Architecture Parameters interact with different sections of the approach. In addition, input and process names presented in Figure 3 can be found in Tables (2)-(4), as well as in tables in Results of the Case Study section.

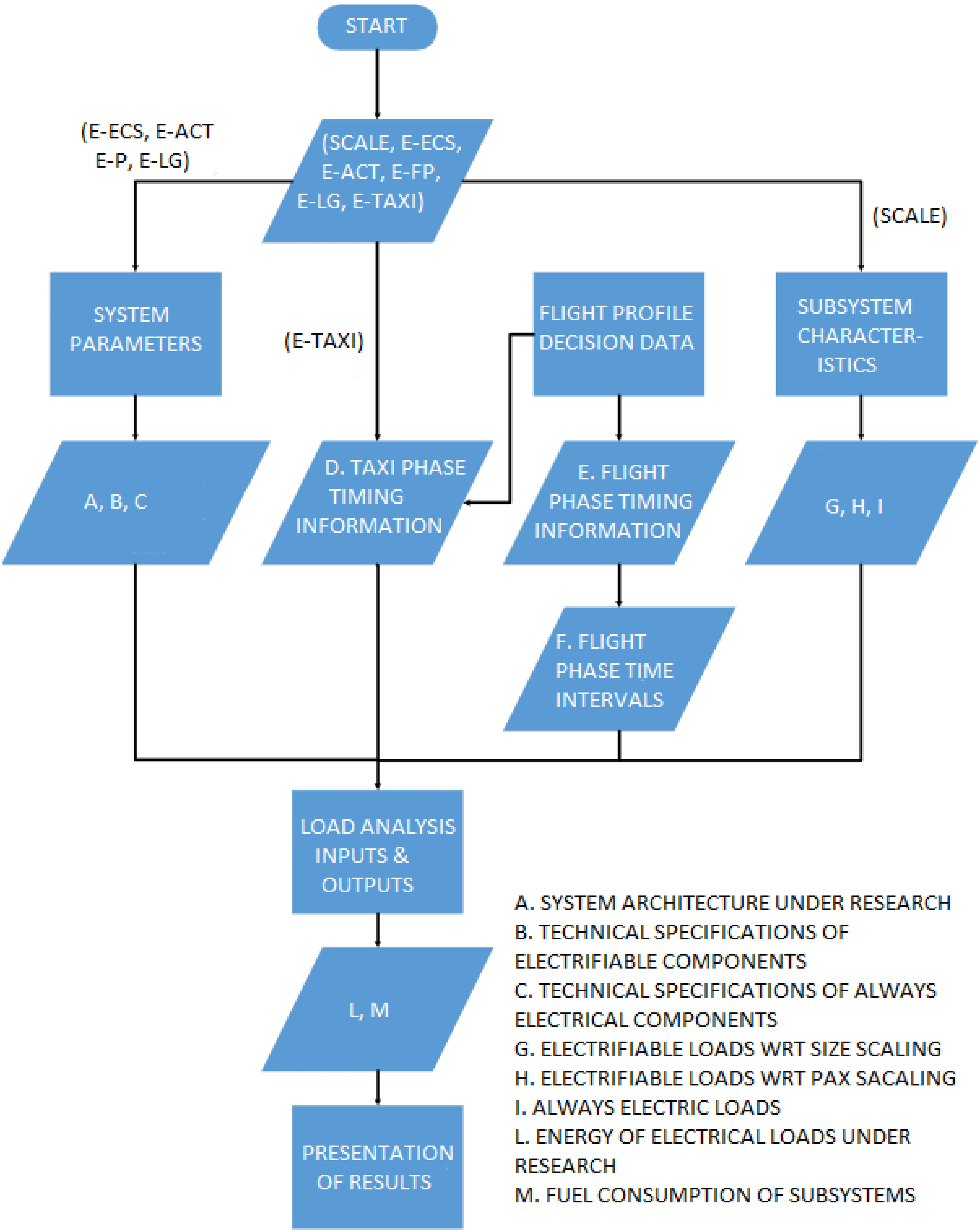

Figure 3 – Flowchart of the proposed approach

Table 3 – Flight profile decision data

Name	**Input** **Intermediate** **Output**	**Unit**	**Description**
D. Taxi Phase Timing Information			
duration on ground APU running	Input	[s]	E-taxi, from gate to runway

duration landed APU running	input	[s]	E-taxi, from runway to gate
duration on ground runway engines	input	[s]	Engines running, from runway to take-off
duration landed runway engines	Input	[s]	Engines running, from touchdown to runway
E. Flight Phase Timing Information			
duration take-off	Input	[s]	Take-off duration, before climb phase
duration climb	Input	[s]	Climb duration (until cruise altitude reached)
duration cruise	Input	[s]	Cruise duration
duration landing	Input	[s]	Landing duration, before touchdown
duration loiter	Input	[s]	Circling between cruise and descent
duration descending	Input	[s]	Descent, between loiter and landing
duration stationary ground support	Input	[s]	Time spent at airport between flights
F. Flight Phase Time Intervals			
on ground taxi	Intermediate	[s]	From gate to beginning of take-off
take off	Intermediate	[s]	From taxi to end of take-off
duration landed taxi	Intermediate	[s]	Taxiing duration after landing
landed taxi	Intermediate	[s]	Flight length after taxiing completed
climb	Intermediate	[s]	Climb phase interval
cruise	Intermediate	[s]	Cruise phase interval
descending	Intermediate	[s]	Descent phase interval
loiter	Intermediate	[s]	Loiter phase interval
landing	Intermediate	[s]	Landing phase interval

3.2 Flight Profile Decision Inputs and Outputs

Table 3 shows both the flight profile inputs defined by the user for different flight phase durations, and also intermediate phase intervals which are calculated for plotting purposes.

This stage provides the desired flight profile information as an input into the model. After receiving the relevant electrification and efficiency inputs in the first stage, System Parameters, the execution of the model continues with defining the flight profile to investigate the time spent for each flight phase. The flight phases this approach considers can be seen in Equation (1).

Total flight time:

$$T_{Total} = \sum_{n=1}^{2} (T_{n,taxi} + T_{n,take\,off} + T_{n,climb} + T_{n,cruise} + T_{n,descent} + T_{n,loiter} + T_{n,landing} + T_{n,taxi}) + T_{stationary} \quad (1)$$

The user will specify the time allocated for each phase, including taxiing durations for tugging or e-taxiing, and the engines running on the runway. Based on the time inputs provided by the user, the flight profile for an operational cycle (round trip) will be created and this timing information along with electrification and efficiency values will be passed on to the next stage of the model.

3.3 Load Analysis Inputs and Outputs

Table 4 shows load analysis inputs, outputs and intermediate values.

Table 4 – Load analysis inputs and outputs

Name	**Input Intermediate Output**	**Unit**	**Description**
Scale factor pax	Input	N/A	Scaling of power requirements per passenger
Scale factor size	Input	N/A	Scaling of power requirements wrt airplane size
G. Electrifiable loads wrt size scaling			
Actuator Power AC	Input	[kW]	Power requirement of actuators

Fuel Pump AC	Input	[kW]	Power requirement of fuel pumps
Landing Gears AC	Input	[kW]	Power requirement of landing gears
H. Electrifiable loads wrt pax scaling			
ECS Hot Day Power AC	Input	[kW]	Power requirement of ECS
In Flight Entertainment DC	Input	[kW]	Power requirement of IFE
Toilet AC	Input	[kW]	Power requirement of toilets
Galley AC	Input	[kW]	Power requirement of galley
Passenger Cabin Lighting DC	Input	[kW]	Power requirement of cabin lighting
Water and Waste AC	Input	[kW]	Power requirement of water and waste
I. Always Electric Loads			
Flight compartment lighting DC	Input	[kW]	Power requirement of flight comp. lighting
Exterior Lighting DC	Input	[kW]	Power requirement of exterior lighting
Navigation DC	Input	[kW]	Power requirement of navigation system
Communication DC	Input	[kW]	Power requirement of comms system
Autopilot DC	Input	[kW]	Power requirement of autopilot
Indication and Recording DC	Input	[kW]	Power requirement of I&R system
Flight Control system DC	Input	[kW]	Power requirement of flight control system
On Board computers DC	Input	[kW]	Power requirement of onboard computers
J. Time Intervals for Intermittent Loads			
FCS Test1	Input	[s]	Time intervals for actuation tests on ground
FCS Test2	Input	[s]	Time intervals for actuation tests on ground
Landing Gear1	Input	[s]	Time intervals for landing gear extension
Landing Gear2	Input	[s]	Time intervals for landing gear retraction
K. Taxi on Engines & on APU Time Intervals			
Tugging APU 1	Intermediate	[s]	e-taxi, gate to runway, 1st flight
Tugging APU 2	Intermediate	[s]	e-taxi, between runway and gate, 1st flight
Tugging APU 3	Intermediate	[s]	e-taxi, gate to runway, 2nd flight
Tugging APU 4	Intermediate	[s]	e-taxi, between runway and gate, 2nd flight
Conv Taxi 1	Intermediate	[s]	Conventional taxi, runway to TO, 1st flight
Conv Taxi 2	Intermediate	[s]	Conv. Taxi, touchdown to end of runway, 1st
Conv Taxi 3	Intermediate	[s]	Conv. Taxi, runway to take-off, 2nd flight
Conv Taxi 4	Intermediate	[s]	Conv. Taxi, touchdown to end of runway, 2nd
L. Energy of Electrical Loads under Research			
Partial Sum ECS Hot Day Power	Intermediate	[kJ]	Array storing ECS power data during flight
Partial Sum Actuator Power	Intermediate	[kJ]	Array storing actuator power data
Partial Sum Landing Gears	Intermediate	[kJ]	Array storing landing gears power data
Partial Sum Fuel Pump	Intermediate	[kJ]	Array storing fuel pump power data
Partial Sum In Flight Entertainment	Intermediate	[kJ]	Array storing IFE power data
Partial Sum Toilet	Intermediate	[kJ]	Array storing toilet power data
Partial Sum Galley	Intermediate	[kJ]	Array storing galley power data
Partial Sum Passenger Cabin Lighting	Intermediate	[kJ]	Array storing cabin lighting power data
Partial Sum Flight Compartment Lighting	Intermediate	[kJ]	Array storing flight comp. power data
Partial Sum Exterior Lighting	Intermediate	[kJ]	Array storing exterior lighting power data
Partial Sum Navigation	Intermediate	[kJ]	Array storing navigation power data
Partial Sum Communication	Intermediate	[kJ]	Arraying storing comms system power data
Partial Sum Autopilot	Intermediate	[kJ]	Array storing autopilot power data
Partial Sum Indication and Recording	Intermediate	[kJ]	Array storing I&R system power data
Partial Sum Water and Waste	Intermediate	[kJ]	Array storing W&W system power data
Partial Sum Flight Control System	Intermediate	[kJ]	Array storing FCS power data

Partial Sum On Bard Computers	Intermediate	[kJ]	Array storing onboard computers power data
M. Fuel Consumption of Subsystems			
Fuel ECS	Output	[kg]	Fuel consumption due to ECS power needs
Fuel Actuation	Output	[kg]	Fuel consumption due to actuators
Fuel Fuel Pump	Output	[kg]	Fuel consumption due to fuel pumps
Fuel Landing Gear	Output	[kg]	Fuel consumption due to gear actuation
Fuel Taxi	Output	[kg]	Fuel consumption due to taxiing
Fuel In Flight Entertainment	Output	[kg]	Fuel consumption due to IFE
Fuel Passenger Cabin Lighting	Output	[kg]	Fuel consumption due to cabin lighting
Fuel Flight Compartment Lighting	Output	[kg]	Fuel consumption due to flight comp. light
Fuel Exterior Lighting	Output	[kg]	Fuel consumption due to exterior lighting
Fuel Navigation	Output	[kg]	Fuel consumption due to navigation system
Fuel Communication	Output	[kg]	Fuel consumption due to comms system
Fuel Autopilot	Output	[kg]	Fuel consumption due to autopilot
Fuel Indication and Recording	Output	[kg]	Fuel consumption due to I&R
Fuel Flight Control System	Output	[kg]	Fuel consumption due to FCS
Fuel On Board Computers	Output	[kg]	Fuel consumption due to onboard computers
Fuel Toilet	Output	[kg]	Fuel consumption due to toilet
Fuel Galley	Output	[kg]	Fuel consumption due to galley
Fuel Water and Waste	Output	[kg]	Fuel consumption due to W&W

The intermediate values in Part K. represent the time intervals derived from the taxi durations introduced into the model. The intermediate values in Part L. represent the array storing the cumulative energy need of each subsystem, while values in Part M. represent the array storing the cumulative fuel consumption of each subsystem.

This stage of the model receives the electrification inputs, efficiency values of each subsystem or component, and flight phase duration information from the above-mentioned stages. On top of those values, the power load demands of each subsystem for varying flight phases are provided at this stage by the user. As can be seen in Table 4, flight control actuation, fuel pump and landing gear power scale with respect to the airplane size, while environmental control system, galleys etc. scale with respect to passenger amount. As discussed in [14], the secondary power demands of varying airplanes are published for certain flight phases. Based on the secondary power demands that were published and available during the development of this method, load analysis of each subsystem for each flight phase is conducted. By using the technical inputs, i.e. the level of electrification and subsystem efficiencies, and the flight profile information, the model calculates the total momentary secondary power, the energy consumed during an operational cycle and fuel consumptions for each subsystems under investigation. These values are based on the mathematical equations shown in Equations (2), (3) and (4).

Energy:

$$E_{Subsystem} = \int_0^{T_{Total}} P_{Subsystem} dt \quad (2)$$

Fuel consumption of each subsystem:

$$M_{Fuel,Subsystem} = E_{Subsystem} \cdot \Pi_i \eta_i \cdot \rho \quad (3)$$

Total fuel consumption:

$$M_{Fuel,Total} = \sum_{Subsystem} M_{Fuel,Subsystem} \quad (4)$$

Momentary fuel consumption:

$$M_{Fuel,Mom} = M_{Fuel,Total(n)} - M_{Fuel,Total(n-1)} \quad (5)$$

Momentary pneumatic fuel consumption:

$$M_{Fuel,Pneu} = (1 - Electric\ ECS) \cdot (M_{Fuel,ECS(n)} - M_{Fuel,ECS(n-1)}) \quad (6)$$

Momentary mechanical fuel consumption:

$$M_{Fuel,Mech} = (1 - Electric\ Fuel\ Pump) \cdot (M_{Fuel,FP(n)} - M_{Fuel,FP(n-1)}) \quad (7)$$

Momentary hydraulic fuel consumption:

$$M_{Fuel,Hydr} = (1 - Electric\ Actuation) \cdot \left(M_{Fuel,Act(n)} - M_{Fuel,Act(n-1)}\right) + (1 - Electric\ Landing\ Gear) \cdot (M_{Fuel,LG(n)} - M_{Fuel,LG(n-1)}) \quad (8)$$

Momentary electrical fuel consumption:

$$M_{Fuel,Elec} = M_{Fuel,Mom} - (M_{Fuel,Pneu} + M_{Fuel,Mech} + M_{Fuel,Hydr}) \quad (9)$$

Generator load

$$P_{Gen\ load} = P_{ECS} \cdot (Electric\ ECS) + P_{Act} \cdot (Electric\ Act) + P_{FP} \cdot (Electric\ Fuel\ Pump) + P_{LG} \cdot (Electric\ LG) + P_{Always\ Electric\ Loads} \quad (10)$$

In equation (2), $P_{Subsystem}$ represents the momentary power demand of each subsystem, hence $E_{Subsystem}$ can be obtained by integrating the power values over a time. In equation (3), $E_{Subsystem}$ is multiplied by η_i values, the factors in the product of efficiencies in the chain from engine to the useful work done in the subsystem, and ρ, the specific energy value of jet A1 kerosene multiplied by 3600 for hour to second conversion, to get $M_{Fuel,Subsystem}$, fuel consumption of each subsystem. In equation (4), the fuel consumptions of subsystems under investigation are integrated to calculate $M_{Fuel,Total}$, the total fuel consumption. Once $M_{Fuel,Total}$ is calculated, the change in total fuel consumption every second can be calculated as shown in equation (5). For equations (5)-(8), (n) represents time is equal to *n* in seconds, while (*n*-1) represents time is equal to *n*-1 in seconds; hence these equations indicate the difference between fuel burnt up to second *n* and *n*-1 . With equations (6)-(8), the momentary fuel consumptions depending on varying power sources are calculated, which in return give momentary electrical fuel consumption as shown in equation (9). Finally, fuel consumption graphs of each power source will be created, which can be seen in Results of the Case Study section. These graphs show the shift in fuel consumption from varying power sources to electrical fuel consumption, depending on the level of electrification.

FCS Test and *Landing Gear* are input parameters which define the hydraulic actuation tests on groundand the extension/retraction of landing gears, respectively.

The power requirements of different subsystems are defined as user inputs and separated based on their scaling factors and conventional power sources, as it can be observed in Table 4. Intermediate parameters with *Partial Sum* prefixes stores the sum of different subsystems' power requirements during the total flight duration. These integrated values are then used to calculate the corresponding fuel consumption of each subsystem.

Tugging APU represents either the time electric taxiing is used between gate and runway when electric taxiing is selected; or it might also represent the time tugging of the airplane if conventional taxiing is selected. *Conv Taxi* represents either the duration engines were used on the runway until take off, or the engines running after touchdown.

At this point, it should be noted that the model does not take the masses of the changing parts into account. Replacing the hydraulic, pneumatic and mechanical systems with electrical counterparts will most likely change the overall weight of the airplane. Every change in weight will have great impact, affecting aerodynamics, center of mass and so on. Although this part can be implemented as a future work and it is crucial to make this model more comprehensive, it should be underlined that estimating the weights for the future extension to the work is going to be challenging.

3.4 Presentation of Results

After completing the load analysis and the related calculations, the model moves on to this stage, which takes in every user defined input and intermediate values calculated on those inputs.

By using the results obtained from the previous stages of the model, plots can be created to observe the "Momentary Power Consumption of Subsystems", "Energy Consumption of Subsystems, and "Fuel Consumption of Subsystems". These results and plots together will help the user to make better preliminary decisions regarding generator sizing and the level of electrification, respectively.

4. Case Study

In this section, the case study will be discussed in detail. First of all, the airplane that is taken as a reference, as well as the reasons for choosing that airplane will be discussed. Following, the flight profile will be presented, and since real flight data is used for creating the flight profile, the grounds for selecting these specific flights will be discussed. Lastly, the results obtained by using the proposed approach will be presented with graphs and tables.

4.1 Description of the Case

For this case study, a 180 passenger, twin engine, turbofan short haul aircraft similar to the Airbus A320 is examined. There are couple of reasons why this aircraft is chosen for this case study. First of all, airline companies avoid to disclose confidential information due to both economical and safety reasons. Hence, the case study is created considering the availability of publicly published data. Secondly, the Airbus A320 is a commonly used aircraft travelling over medium range distances, such as between Copenhagen and Stockholm. Since this research is conducted in Stockholm, it is assumed that choosing the Copenhagen-Stockholm route will be relevant for this case study. Lastly, Airbus A320 already went through some levels of electrification, thus it seemed as a suitable option to consider.

The operational cycle can be divided into:

1) Turnaround event at CPH
2) Take-off from CPH
3) Flight to ARN
4) Landing at ARN
5) Turnaround event at ARN
6) Take-off from ARN
7) Flight to CPH
8) Landing at CPH

In addition to deciding on an airplane for this case study, modeling a real flight seemed to be a crucial part for this research. Since this paper discusses the outcomes of electrifying varying subsystems of an aircraft, cooling of the electrified equipment was an important part that needs to be considered.

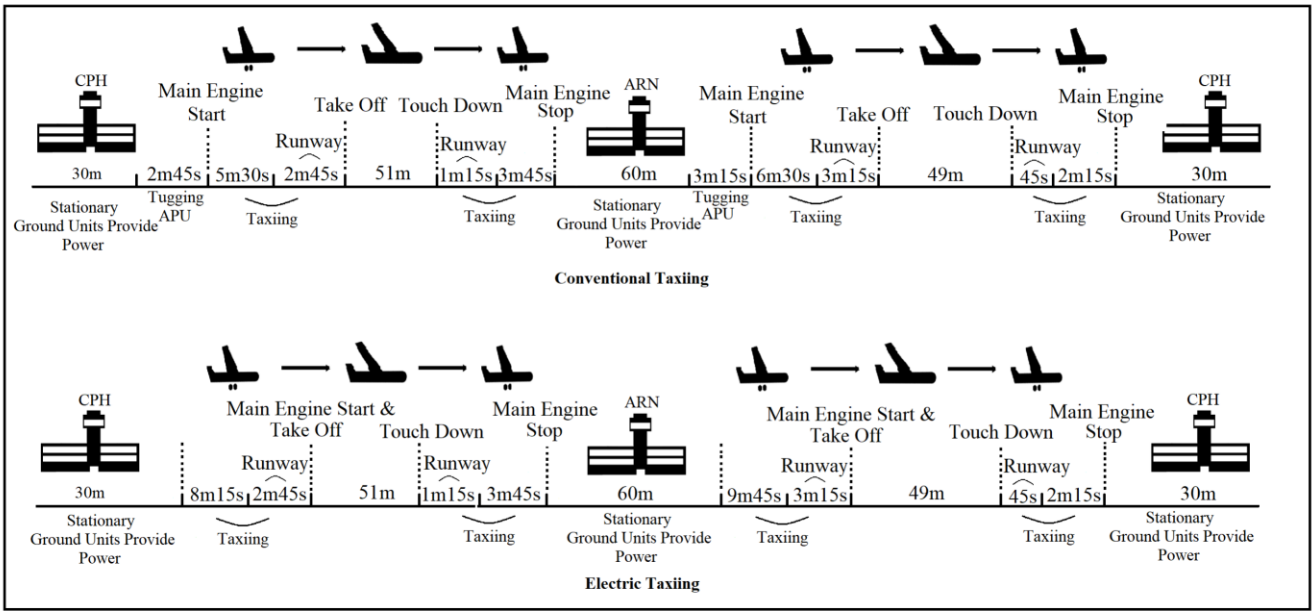

Figure 4 – Conventional v. electric taxiing, case study Copenhagen-Stockholm

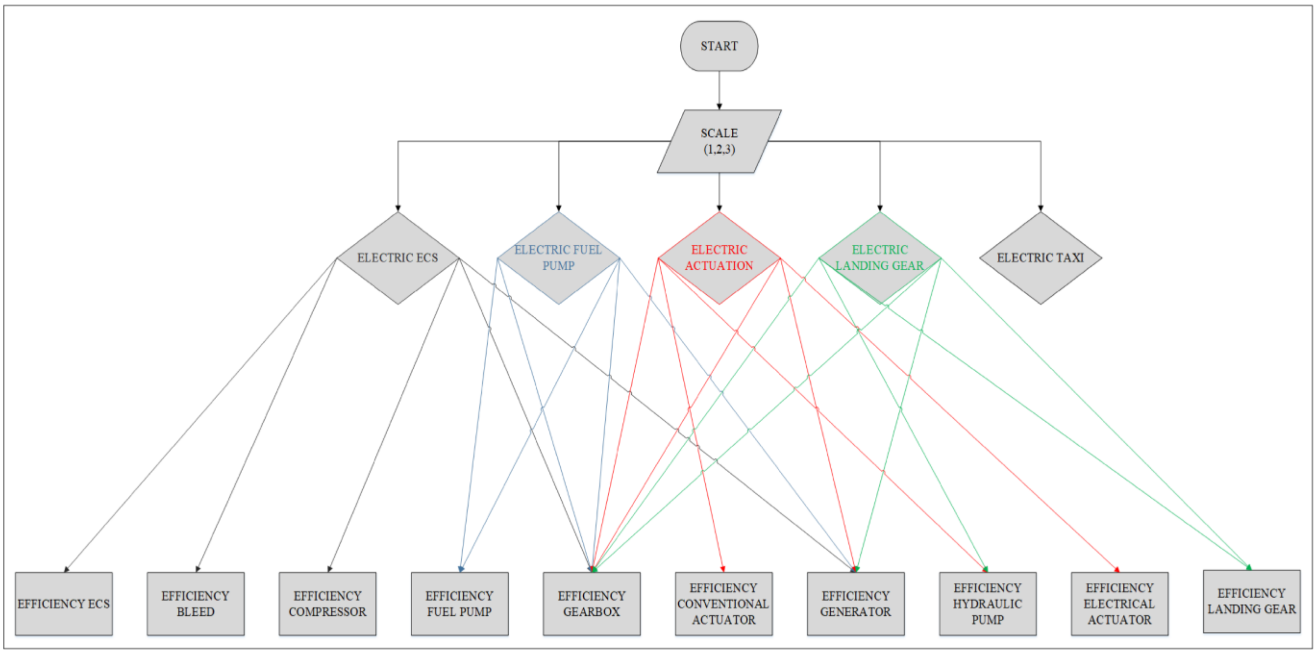

Figure 5 – Flowchart of subsystem components in the proposed approach

A hot day scenario is modelled in order to observe a maximal power demand from the ECS to be able to cool the equipment and cabin. Thus, as can be seen in Table 6, real flight data from July 24th and July 26th of 2018 were obtained from FlightAware. These dates were selected because around that time the temperatures were extremely high in Stockholm, being one of the hottest weeks in almost 300 years; and Airbus A320 flights were available on those dates.

Table 5 – Case study system parameters for the proposed approach

Name	**Input Intermediate Output**	**Value**	**Unit**	**Description**	**Ref.**
Scale	Input	[1,2,3]	N/A	Airplane scaling, depends on passenger number or airplane size	N/A
Kerosene energy density	Input	43.15	MJ/kg	Jet A1 type kerosene energy density	*
A. System Architecture under Research					
Electric ECS	Input	[0,1]	N/A	Decides if electric ECS is used	N/A
Electric Actuation	Input	[0,1]	N/A	Decides if electric actuation is used	N/A
Electric Fuel Pump	Input	[0,1]	N/A	Decides if electric fuel pump is used	N/A
Electric Landing Gear	Input	[0,1]	N/A	Decides if electric landing gear actuation is used	N/A
Electric Taxi	Input	[0,1]	N/A	Decides if electric taxi is used	N/A
B. Technical Specifications of Electrifiable Components					
Efficiency Gearbox	Input	0.95	N/A	Transmission efficiency	[15]
Efficiency Compressor	Input	0.75	N/A	Air cycle machine efficiency	[16]
Efficiency Generator	Input	0.65	N/A	Generator efficiency	[17]
Efficiency Bleed	Input	0.2	N/A	Bleed air system efficiency	[18]
Efficiency Hydraulic Pump	Input	0.2	N/A	Efficiency of pumps for hydraulic actuation	[17]
Efficiency ECS	Input	0.4	N/A	Efficiency of ECS	[19]
Efficiency Electric Actuator	Input	0.75	N/A	Electric actuator efficiency	[20]
Efficiency conventional actuator	Input	0.4	N/A	Hydraulic actuator efficiency	[9]
Efficiency Fuel Pump	Input	0.2	N/A	Fuel pump efficiency	**
Efficiency Landing Gear	Input	0.4	N/A	Landing gear actuation efficiency	**
Efficiency IPS	Input	0.4	N/A	Ice protection system efficiency	[8]

C. Technical Specifications of Always Electric Components					
Efficiency In Flight Entertainment	Input	1	N/A	IFE efficiency	***
Efficiency Passenger Cabin Lighting	Input	0.6	N/A	Passenger cabin lighting efficiency (LED)	***
Efficiency Flight Compartment Lighting	Input	0.6	N/A	Flight compartment lighting efficiency (LED)	***
Efficiency Exterior Lighting	Input	0.6	N/A	Exterior lighting efficiency (LED)	***
Efficiency Navigation	Input	1	N/A	Navigation system efficiency	***
Efficiency Communication	Input	1	N/A	Comms system efficiency	***
Efficiency Autopilot	Input	1	N/A	Autopilot efficiency	***
Efficiency Indication and Recording	Input	1	N/A	I&R system efficiency	***
Efficiency Flight Control System	Input	0.8	N/A	FCS efficiency	***
Efficiency On Board Computers	Input	1	N/A	Onboard computers efficiency	***
Efficiency Toilet	Input	1	N/A	Toilet efficiency	***
Efficiency Galley	Input	1	N/A	Galley efficiency	***
Efficiency Water and Waste	Input	1	N/A	W&W efficiency	***

* Specific energy of Jet A1 kerosene is assumed to be 43.15 MJ/kg.

** No references could be found for these efficiency values in Part B. However, considering the components involved, it is safe to assume that the efficiency of a fuel pump is similar to that of a hydraulic pump, and that of landing gear actuators to that of control surface actuators.

*** No references could be found for these efficiency values in Part C. However, these equipments are widely used in industry and they tend to work quite efficiently. Additionally, these equipments have a rather small impact on the load analysis, due to their relatively small power demands. Further, being always electric loads, they affect only the relative and not the absolute fuel savings.

Note that in Figure 4, the length of the flight is the same, as well as the total taxiing durations, independent of whether electric or conventional taxi is used. Figure 4 indicates whether tugging vehicles and main engines, or only the APU of the airplane is used to move it from gate to runway.

Table 5 presents the input values available for *Scale* and *System Architecture Parameters*, as well as for other Specifications. Figure 5 shows how *Scale*, *System Architecture Parameters* and *Technical Specifications of Electrifiable Components* interact with each other.

Note that in Figure 5 the arrows coming from the left hand side of the *Electric Subsystems* represent the conventional approach, while the arrows coming from the right hand side represent the electrified solution.

Electric Taxi is not connected to any efficiency value, since the approach calculates the taxi fuel consumption directly by using the values obtained from [12], and presented in Table 1 in Taxi subsection of Technical System Description.

Table 6 – Case study flight profile decision data

Name	**Input Intermediate Output**	**Value**	**Unit**	**Description**	**Ref.**
D. Taxi Phase Timing Information					
duration on ground APU running 1	Input	495	[s]	E-taxi, gate to runway, CPH	*
duration landed APU running 1	Input	225	[s]	E-taxi, runway to gate, ARN	*
duration on ground runway engines 1	Input	165	[s]	Runway to take-off, CPH	*
duration landed runway engines 1	Input	86	[s]	Touchdown to runway end, ARN	*
duration on ground APU running 2	Input	585	[s]	E-taxi, gate to runway, ARN	*
duration landed APU running 2	Input	135	[s]	E-taxi, runway to gate, CPH	*
duration on ground runway engines 2	Input	195	[s]	Runway to take-off, ARN	*
duration landed runway engines 2	Input	45	[s]	Touchdown to runway end, CPH	*

duration on ground APU running 3	Input	165	[s]	Conv taxi, gate to runway, CPH	*
duration landed APU running 3	Input	0	[s]	Conv taxi, runway to gate, ARN	*
duration on ground runway engines 3	Input	495	[s]	Runway to take-off, CPH	*
duration landed runway engines 3	Input	300	[s]	Touchdown to runway end, ARN	*
duration on ground APU running 4	Input	195	[s]	Conv taxi, gate to runway, ARN	*
duration landed APU running 4	Input	0	[s]	Conv taxi, runway to gate, CPH	*
duration on ground runway engines 4	Input	585	[s]	Runway to take-off, ARN	*
duration landed runway engines 4	Input	180	[s]	Touchdown to runway end, CPH	*
E. Flight Phase Timing Information					
duration take off 1	Input	30	[s]	Take-off duration	[21]
duration climb 1	Input	930	[s]	Climb duration	[21]
duration cruise 1	Input	759	[s]	Cruise duration	[21]
duration landing 1	Input	77	[s]	Landing duration	[21]
duration loiter 1	Input	120	[s]	Time circling before descent	[21]
duration descending 1	Input	845	[s]	Descent duration	[21]
duration take off 2	Input	64	[s]	Take-off duration	[22]
duration climb 2	Input	1003	[s]	Climb duration	[22]
duration cruise 2	Input	360	[s]	Cruise duration	[22]
duration landing 2	Input	18	[s]	Landing duration	[22]
duration loiter 2	Input	120	[s]	Time circling before descent	[22]
duration descending 2	Input	1288	[s]	Descent duration	[22]
duration stationary ground support	Input	3600	[s]	Time between flights	**
F. Flight Phase Time Intervals					
on ground taxi 1	Interm.	1-660	[s]	Gate to beginning of take-off, 1st	[21]
on ground taxi 2	Interm.	7322-8101	[s]	Gate to beginning of take-off, 2nd	[22]
take off 1	Interm.	661-690	[s]	Taxi to end of take-off, 1st	[21]
take off 2	Interm.	8102-8165	[s]	Taxi to end of take-off, 2nd	[22]
landed taxi 1	Interm.	3422-3721	[s]	1st flight length after taxi	[21]
landed taxi 2	Interm.	10955-11134	[s]	2nd flight length after taxi	[22]
climb 1	Interm.	691-1620	[s]	Climb interval for 1st flight	[21]
climb 2	Interm.	9169-9528	[s]	Climb interval for 2nd flight	[22]
cruise 1	Interm.	1621-2379	[s]	Cruise interval for 1st flight	[21]
cruise 2	Interm.	9169-10816	[s]	Cruise interval for 2nd flight	[22]
descending 1	Interm.	2380-3224	[s]	Descent interval for 1st flight	[21]
descending 2	Interm.	10817-10936	[s]	Descent interval for 2nd flight	[22]
loiter 1	Interm.	3225-3344	[s]	Loiter interval for 1st flight	[21]
loiter 2	Interm.	10817-10936	[s]	Loiter interval for 2nd flight	[22]
landing 1	Interm.	3345-3421	[s]	Landing interval for 1st flight	[21]
landing 2	Interm.	10937-10954	[s]	Landing interval for 2nd flight	[22]

duration landed taxi 1	Interm.	300	[s]	Taxiing after 1st flight	[21]
duration landed taxi 2	Interm.	180	[s]	Taxiing after 2nd flight	[22]

* Assumptions made on these taxi values are based on the real flight data faken from Flight Aware, as seen in [21][22], yet no exact taxi duration data could be found.

** This value is an assumption which represents the time the aircraft spends at the airport between two consecutive flights.

Table 7 shows the input values used in the case study for the proposed approach. The load values presented in Part G., Part H. and Part L. are cruise power demands of varying subsystems.

As can be seen in Part K., taxi stages can vary depending on whether electric taxi is available or not. Part L. shows energy demands of subsystems under research for the total flight duration.

Table 7 – Case Study load analysis inputs and outputs

Name	**Input Intermediate Output**	**Value**		**Unit**	**Ref.**
Scale factor pax	Input	1		N/A	N/A
Scale factor size	Input	1		N/A	N/A
G. Electrifiable loads wrt size scaling					
Actuator Power AC	Input	62.5		[kW]	[14]
Fuel Pump AC	Input	32		[kW]	[14]
Landing Gears AC	Input	0		[kW]	[14]
H. Electrifiable loads wrt pax scaling					
ECS Hot Day Power AC	Input	217		[kW]	[14][23]
In Flight Entertainment DC	Input	9		[kW]	[13][24]
Toilet AC	Input	5		[kW]	[14]
Galley AC	Input	78		[kW]	[13][24]
Passenger Cabin Lighting DC	Input	10		[kW]	[24]
Water and Waste AC	Input	48		[kW]	[14]
I. Always Electric Loads					
Flight compartment lighting DC	Input	0.8		[kW]	[14]
Exterior Lighting DC	Input	0.1		[kW]	[14]
Navigation DC	Input	8		[kW]	[14]
Communication DC	Input	4		[kW]	[14]
Autopilot DC	Input	4		[kW]	[14]
Indication and Recording DC	Input	4		[kW]	[14]
Flight Control system DC	Input	4		[kW]	[14]
On Board computers DC	Input	4		[kW]	[14]
J. Time Intervals for Intermittent Loads					
FCS Test1	Input	5		[s]	*
FCS Test2	Input	5		[s]	*
Landing Gear1	Input	15		[s]	[25]
Landing Gear2	Input	15		[s]	[25]
K. Taxi on Engines & on APU Time Intervals		**E-Taxi**	**Conv. Taxi**		
Tugging APU 1	Intermediate	1-165	1-495	[s]	**
Tugging APU 2	Intermediate	3721-3721	3496-3721	[s]	**
Tugging APU 3	Intermediate	7321-7516	7321-7906	[s]	**
Tugging APU 4	Intermediate	11134-11134	10999-11134	[s]	**
Conv Taxi 1	Intermediate	165-660	495-660	[s]	**
Conv Taxi 2	Intermediate	3421-3721	3421-3496	[s]	**
Conv Taxi 3	Intermediate	7515-8101	7906-8101	[s]	**
Conv Taxi 4	Intermediate	10954-11134	10954-10999	[s]	**

L. Energy of Electrical Loads under Research						
Partial Sum ECS Hot Day Power	Intermediate	144498			[kJ]	***
Partial Sum Actuator Power	Intermediate	836290			[kJ]	***
Partial Sum Landing Gears	Intermediate	1740			[kJ]	***
Partial Sum Fuel Pump	Intermediate	241088			[kJ]	***
Partial Sum In Flight Entertainment	Intermediate	67806			[kJ]	***
Partial Sum Toilet	Intermediate	37670			[kJ]	***
Partial Sum Galley	Intermediate	336660			[kJ]	***
Partial Sum Passenger Cabin Lighting	Intermediate	75340			[kJ]	***
Partial Sum Flight Compartment Lighting	Intermediate	6027			[kJ]	***
Partial Sum Exterior Lighting	Intermediate	16517			[kJ]	***
Partial Sum Navigation	Intermediate	60272			[kJ]	***
Partial Sum Communication	Intermediate	30136			[kJ]	***
Partial Sum Autopilot	Intermediate	4476			[kJ]	***
Partial Sum Indication and Recording	Intermediate	30136			[kJ]	***
Partial Sum Water and Waste	Intermediate	361632			[kJ]	***
Partial Sum Flight Control System	Intermediate	30136			[kJ]	***
Partial Sum On Bard Computers	Intermediate	30136			[kJ]	***
M. Fuel Consumption of Subsystems		**Conv.**	**MEA**	**AEA**		
Fuel ECS	Output	421.4	72.8	72.8	[kg]	***
Fuel Actuation	Output	256.8	256.8	42.1	[kg]	***
Fuel Fuel Pump	Output	0.53	0.53	0.11	[kg]	***
Fuel Landing Gear	Output	29.6	45.5	45.5	[kg]	***
Fuel Taxi	Output	336.3	336.3	147.3	[kg]	***
Fuel In Flight Entertainment	Output	2.56			[kg]	***
Fuel Passenger Cabin Lighting	Output	4.74			[kg]	***
Fuel Flight Compartment Lighting	Output	0.37			[kg]	***
Fuel Exterior Lighting	Output	1.04			[kg]	***
Fuel Navigation	Output	2.27			[kg]	***
Fuel Communication	Output	1.13			[kg]	***
Fuel Autopilot	Output	0.16			[kg]	***
Fuel Indication and Recording	Output	1.13			[kg]	***
Fuel Flight Control System	Output	1.42			[kg]	***
Fuel On Board Computers	Output	1.13			[kg]	***
Fuel Toilet	Output	1.42			[kg]	***
Fuel Galley	Output	12.72			[kg]	***
Fuel Water and Waste	Output	13.67			[kg]	***

Load values given in Parts G., H., and I. of the table represent cruise power demands of the various subsystems.

* Exact durations for flight control tests could not be found, these numbers are reasonable assumptions.

** These values come from real data taken from FlightAware, but no exact data are available.

*** These values are the results from the equations discussed in §3.2, hence no references are applicable.

Fuel consumptions of the systems under research are calculated according to the equations provided in Load Analysis Inputs & Outputs section, and are presented in Part M. depending on the level of electrification, while the rest of the column indicates fuel consumptions of the remaining loads.

4.2 Results of the Case Study

Table 8 presents fuel consumptions of subsystems under research for varying electrification degrees, as well as total fuel consumptions including the remaining systems. *Others* represents total fuel consumptions of systems such as the galley, autopilot, navigation and so on.

Table 8 - Fuel Consumption of varying subsystems

Subsystem	Case		
	Conventional	**MEA**	**AEA**
ECS	421.4 kg	72.8 kg	72.8 kg
Actuator	256.8 kg	256.8 kg	42.1 kg
Fuel Pump	29.6 kg	45.5 kg	45.5 kg
Landing Gears	0.53	05.3 kg	0.11 kg
Taxi	336.3 kg	336.3 kg	147.3 kg
Others	43.5 kg	44.5 kg	43.65 kg
Sum	**1088.5 kg**	**756.5 kg**	**351.5 kg**

Table 9 indicates varying electrical power demands of systems, depending on the level of electrification. These values are calculated as provided in Load Analysis Inputs & Outputs section. Note that, by replacing the conventional subsystems with electric counterparts, the electrical power demands rise. Both real and apparent powers are presented in this table, where a typical power factor of 0.85 is assumed for obtaining apparent powers. These results can be used to assist in generator sizing.

Table 9 – Peak generator loads

	Case		
	Conventional	**MEA**	**AEA**
Peak Real Load	178.9 kW	427.9 kW	627.8 kW
Actuator	210.4 kVA	503.4 kVA	738.5 kVA

5. Sensitivity Analysis

Sensitivity analysis results can be observed in Tables 10-12. These results indicate how sensitive the system is and how it is affected by changes. Note that BE stands for bleed efficiency, while GE stands for generator efficiency. For bleed system, an efficiency of 0.3 is investigated to observe the difference it would make if the efficiency is improved. On the other hand, for generators, efficiency values of 0.8 and 0.95 are investigated.

Table 10 - Fuel consumption (kg) with bleed efficiency 0.2 and generator efficiency 0.65

Subsystem	Conventional	More Electric	All Electric
ECS	421.4	72.8	72.8
Actuator	256.5	256.8	42.1
Fuel Pump	29.6	45.5	45.5
Landing Gear	2.1	2.1	0.65
Taxi	336.3	336.3	174.3
Others	43.5	44.5	46.65
Sum	**1090**	**758**	**352**

Table 11 - Fuel consumption (kg) with bleed efficiency 0.3 and generator efficiency 0.8

Subsystem	Conventional	More Electric	All Electric
ECS	280.9	59.1	59.1
Actuator	256.8	256.8	34.2
Fuel Pump	29.6	37.0	37.0
Landing Gear	2.1	2.1	0.50
Taxi	336.3	336.3	147.3
Others	35.9	35.85	35.7
Sum	**941.6**	**727.1**	**313.9**

Table 12 - Fuel consumption (kg) with bleed efficiency 0.3 and generator efficiency 0.95

Subsystem	Conventional	More Electric	All Electric
ECS	280.9	49.8	49.8
Actuator	256.8	256.8	28.8

Fuel Pump	29.6	31.1	31.1
Landing Gear	2.1	2.1	0.40
Taxi	336.3	336.3	147.3
Others	30.2	30.2	30.2
Sum	**935.9**	**706.3**	**287.6**

As may be seen, even a 50% increase in the assumed bleed efficiency does not change the results very much.

6. Discussions and Future Work

The proposed approach discussed in this paper has been developed to create an approach for evaluating when different MEA technologies are beneficial to implement in future airplanes. The approach focuses on the electrification of several subsystems, and analyzes the resulting secondary power demand; which distinguishes this research from many other, focusing on only one specific subsystem. Publicly available electrical load equivalents of varying subsystems using different power sources are integrated into the proposed approach, as well as real flight data for a round trip between Copenhagen and Stockholm. The results indicate the diminishing secondary power demands, when moved from conventional architectures to more-electric and all-electric alternatives. It should be pointed out that, the model calculates the peak real load and suggests the equivalent apparent generator loads for a power factor of 0.85 which can be used for generator sizing. It is shown that the proposed approach lets the user to choose the degree of electrification for varying subsystems on an airplane. By being able to introduce different efficiency values for subsystems, and to combine varying levels of electrification, the proposed approach will let the user to analyze fuel consumptions of subsystems under investigation for conventional, more-electric and all-electric airplane cases.

If the limitations of the proposed approach should be pointed out, the availability of the publicly available data should be addressed. For this reason, the validation of available electrical load equivalents of varying subsystems using different power sources could not be done. If more public data related to the electrical power demands of different subsystems was available, both the electrical loads used in this paper and the resulting fuel consumptions could have been compared. Another limitation of the proposed approach can be the absence of weight calculations regarding the newly introduced electrical power system. By replacing the hydraulic, pneumatic and mechanical systems with electrical counterparts, the overall weight of the airplane will most probably change, due to the addition and removal of generators, inverters and other power electronics units. Since airplanes are complex systems, every change in weight should be considered with respect to aerodynamics, center of mass and so on.

As a future work, a detailed weight calculation algorithm can be integrated into the proposed approach, which will allow the user to validate the results. Additionally, although ECS loads and bleed air efficiency are already included in the proposed approach, IPS loads are not, hence adding IPS loads can be one of the steps towards making the approach more comprehensive. Another future work can be integrating scaling with respect to airplane size into the approach. That feature is not included in this research, since it would add more complexity into the model, and weight changes would affect that, as well. Finally, calculation of carbon dioxide and other emissions can be integrated into the approach, to allow the user compare the emission rates with varying levels of electrification.

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8. Copyright Statement

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