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Aircraft electrical system for carbon free flight – Technology review

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Abstract

The aviation industry sustains jobs, trade and tourism. The COVID-19 pandemic has been a systemic shock that has not only halted air travel worldwide, but has made people reevaluate priorities, namely, our own health and safety and that of our families, friends, and loved ones. Aviation plays a key role in this response. During the pandemic, we counted on aviation for delivering vital air cargo services to boost global supply chains, evacuating stranded passengers, and enabling time-critical life-saving emergency and humanitarian response missions. About 12 million passengers were carried on every single day in 2018 [1]. Despite big external shocks it has experienced continuous growth [2]. However, two major events in the last two years have significantly influenced this trend, Fridays for future and the Corona pandemic [3], [4]. These events have the potential to influence future aircraft (system) design. Game changer solutions to enable carbon free flight, quick re-configuration and rate adaptation are required. Based on seven dimensions, the effect on the aircraft electrical system due to the need for game-changer solutions will be evaluated. The results indicate that the effort in research can be reduced in some dimensions while it is recommended to be increased in others.

1 Introduction

The aviation industry develops and sustains jobs and trade. It is vital lifelines to connect remote communities and serves in rapid disaster response [1]. About 12 million passengers (pax) and \$18.8 billion worth of goods were carried on every single day in 2018 [1]. In that year, about 65.5 million jobs were directly or remotely connected to air transport [1]. These figures reflect a history of continuous growth of the aviation market. On the long run, it even had been resilient to big external shocks e.g. 9/11 and the financial crisis in 2008 [2]. This continuous growth had been fostered by a few key developments, e.g. dropping average price of air travel [1], evolution of the aviation industry into new markets, evolving technologies and changing political and legal systems. This has triggered a significant increase of both passenger and air freight transport. From 1993 to 2015, the European aviation market has developed from 360 to 918 million passengers [5]. Aircraft (A/C) and production system design have been guided by a dominant set of value drivers. Besides safety, this set of drivers has included fuel and cost efficiency, passenger comfort, revenue increase, manufacturability at rate and sustainability. Two major events in recent years have significantly influenced their weighting; Fridays for Future and the Corona pandemic.

Since 2019, the Friday for Future initiative has strongly affected the awareness of wide masses of human kind to act for a reduction of manmade carbon emissions. In the last 800000 years, the carbon (CO_2) average concentration in the earth's atmosphere has oscillated between 170 and 300 parts per million (ppm) reached about 350000 years ago [6]. In 1910, the value 300 ppm was reached again. Since then, this value has steadily risen to ~410 ppm in 2019. Hence, it is imperative that industries significantly reduce their carbon emissions to limit temperature rise and to meet the Paris agreement [7].

In 2020, the COVID-19 pandemic spread all over the world. Lockdowns in many countries made air traffic drop. Data for the Eurocontrol network showed that the quantity of flights per day dropped from about 24000 down to about 4000 flights per day within the second half of March 2020 [4]. For about three months this low level was kept. After a slight increase over summer 2020, new lockdowns cut the number of flights again with a similar course at global level. This scenario has had a big impact on the objectives of the aviation industry. Furthermore, the pandemic enforced the need for flexible means of re-configuration of in-service A/C to enable re-sales in the aftersales market demand on top of the existing demand for flexible re-configuration [8, 9]. Altogether, this shows the urgent need for "game changers" in A/C (system) development, in particular to enable carbon free flight. Aircraft elements that have the potential to become game changers require a courageous leap from re-use to step-change development.

2 The aircraft electrical system

To describe the effect of the adapted importance of value drivers on the A/C electrical system, its realisation on the A350 will be introduced first. It is one of the most modern electrical systems in service. Its architecture is shown in **Figure 1**, see also [10]. During normal flight operations four 230 VAC Variable Frequency Generators (VFG), will supply the electrical network. In parking position, the A/C is either powered by the Ground Power Units (GPU), rated 115 VAC, or by the Auxiliary Power Unit (APU), operated at 230 VAC (400 Hz). In an unlikely emergency event, the 230 VAC Ram Air Turbine (RAT) generator will feed flight relevant loads [10]. Busbars are voltage-rated according to the power source to which they are connected. Transformer Rectifier (TR) and Auto Transformer Units

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(ATU) interconnect the different voltage levels. Electrical loads can be found on all voltage levels. With the introduction of the voltage level 230 VAC for high power electrical consumers, the A/C has significantly decreased weight. Furthermore, with the carbon fibre fuselage, the return current network and fast fuse protective functions (e.g. arc fault detection) were introduced [10]. On either AC voltage level, Load/Power Management Functions (PM) were implemented to either protect the generators from damages or to govern the load on the respective wiring.

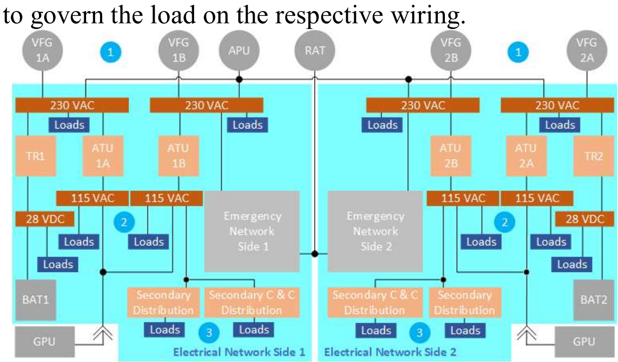

Figure 1: The architecture of the Airbus A350 electrical system (with Power Management levels 1, 2 and 3)

In **Figure 1** the generator level is marked with a 1, the main distribution feeder level with 2. The "last-meter" distribution to the loads is marked with 3. Two new PM functions were introduced on the A350 to achieve additional weight reduction, see Chapter 3. Hence, the A350 electrical system has evolved in many aspects compared to previous programs. In order to transition from evolutionary to revolutionary development, seven dimensions, depicted in Figure 2, shall be described, which characterize an A/C electrical system. Chapter 3 will address their role in future A/C configurations.

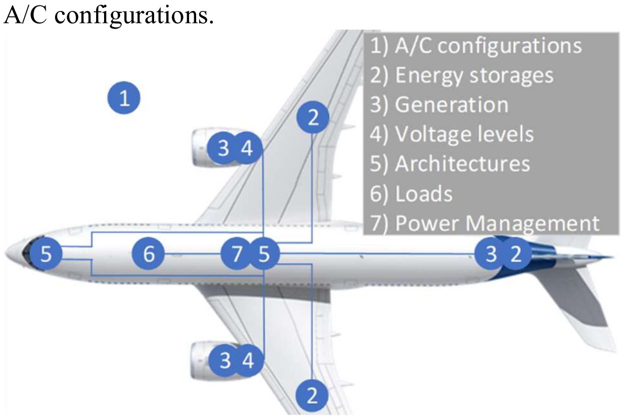

Figure 2: The 7 dimensions of an A/C electrical system

3 The seven dimensions

As described before, besides safety, a set of value drivers has dominated the decision making process in A/C (system) design. Recently, high rate manufacturability became more important. The Airbus announcement of the ZEROe initiative re-enforced the ambition of sustainability and emission free flight [11]. With three potential A/C configurations, addressing a mission envelop from less than 100 up to 200 pax and ranges from 1000 to 2000 nm, a wide scope of analyses will be performed. The effect of the shift of the value driver weighting, in particular for carbon free flight, on the design of the electrical system shall be considered along seven dimensions; A/C configuration, energy storages, electrical power generation, voltage levels, distribution architectures, electrical loads, PM, see **Figure** ***2***. The evaluation shall help review, for which components a continuous evolution is sufficient, and for which ones a game changing step is needed.

3.1 Aircraft configuration

The term "A/C configuration" shall refer to the A/C program, which directly implies characteristics such as system development epoch, architectures, geometry, structure materials and mission. **Figure 3** shows some A/C configurations with the specifics of the A/C electrical system. They show that further development has been dominated by continuous evolution. In this paper the A220 will not be referred to.

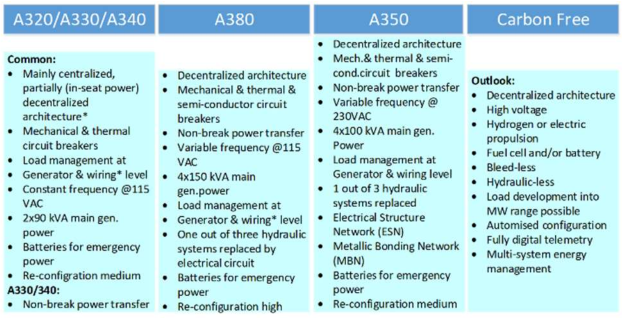

Figure 3: Aircraft configurations & electrical system

The objectives of emission free flight can impact the propulsion system, energy sources and storages. In this context, the "thrust demand" has to be addressed. **Figure 4** shows the approximate absolute and relative (per pax) engine power for a couple of civil A/C of different size (by quantity of pax) for turbofan and turboprop A/C.

[E1] $P = F_{\mathrm{N}} \cdot v = \dot{m}_{\mathrm{e}} v_{\mathrm{e}} - \dot{m}_{\mathrm{f}} v_{\mathrm{f}}$

According to E1, the net engine power P has been derived from the estimated engine net thrust force F_{N} (at 80 % of full thrust) and typical cruise speed v per A/C, created through the difference of products of mass flows times velocity at the exit e of the engine and free stream f, assuming that the nozzle of jet engine is designed to equalize pressure difference [12, 13].

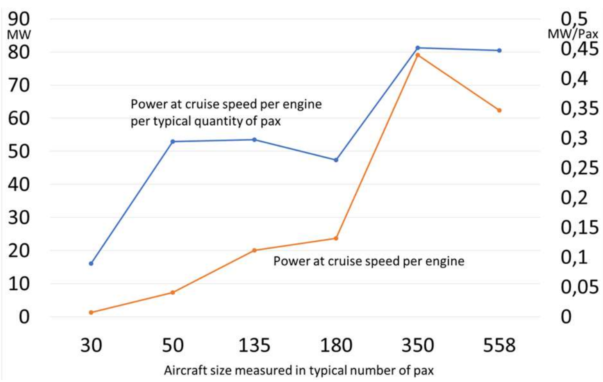

Figure 4: Absolute and relative engine power vs. typical A/C size (typical quantity per pax) - based on civil A/C developed between 1980s and today)

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3.2 Energy storage

Currently considered future energy storage systems for aeroplanes are centred on jet fuel (or synthetic ‘e-fuel’), hydrogen and batteries. Jet fuel is considered the baseline for comparison. Carbon free options are (liquid) hydrogen and batteries. While less polluting than jet fuel, both have considerable disadvantages in terms of weight and/or volume when compared with jet fuel.

Table 1 provides ‘fuel’ mass and volume for a given reference amount of energy[1] to be stored in an A/C system by comparing jet fuel, hydrogen and battery options. The increased efficiency of an electrical propulsion system[2] can compensate for the actual amount of stored energy needed for the reference mission [15].

	Jet Fuel	Liquid Hydrogen	Li-Ion Battery
Specific energy in kWh/kg	12	39	0.5
Energy density in kWh/l	10	2.7	1
Energy required for reference mission	30 MWh	30 MWh	30 MWh
Efficiency to thrust²	40%	60%	80%
Required storage size due to inefficiency	75.0	50.0	37.5
Required fuel mass in tons	6.3	1.3	75.0
Required fuel volume in cubic meters	7.5	18.5	37.5

Table 1: Weight and volume comparison

While jet fuel only requires about six tons and seven cubic meters, liquid hydrogen would require nearly three times the storage volume (18 m³) to contain just over one ton of fuel. The storage tank for liquid hydrogen requires thermal insulation in order to keep the content in its liquid phase. For batteries, even when assuming cells with 500 Wh/kg and 1000 Wh/l (not yet available), the mass and volume to store tens of MWh of energy is much larger.

When considering refuelling, liquid hydrogen can be pumped, potentially achieving similar speeds as refuelling with jet fuel. Batteries need to be swapped or recharged, with either a significant cost and maintenance factor in case of swapping or a significant effect on time and temperature management as well as ground infrastructure in case of (fast) charging (but a benefit of lower operating cost).

This simplified comparison shows the sensitivity of weight and volume for the alternatively available ‘fuel’ choices. The A/C electrical system on its own is unable to compensate for the negative effects in weight. However, depending on the modularity of the electrical system it might be able to contribute to the additional space for larger tanks.

[1] For simplification reasons, 10MW for 3 hours, equaling 30MWh, is selected for this reference mission energy amount

3.3 Electrical power generation

Electrical power generation has seen evolutionary improvements over the last century of commercial aviation. Airbus entered the market in the 1970s with the A300, when the dominant electrical generator technology was the Integrated Drive Generator (IDG). The IDG includes a mechanical gearbox to run the electrical machine at constant rpm to create a constant alternating current frequency of 400 Hz. With the VFG, first introduced on the Airbus A380, the gearbox is eliminated and the electrical machine runs at variable speed and produces variable frequency AC (360 Hz – 800 Hz) according to jet engine speed.

Research brought forward many different types of electrical machines. Most IDGs and VFGs are three-stage synchronous machines. Lockheed-Martin has for example studied ‘switched reluctance machines’ for its 270 VDC electrical system [16]. **Figure 5** charts the installed electrical generation capacity (and the main voltage level) for many well-known military and civilian aircraft programs.

For a carbon free aeroplane the three following electrical generation options are considered: a) Hydrogen burning turbine engine with shaft driven electrical generator (‘H_2 burn’), b) Hydrogen to Fuel Cells as electrical generators and c) Batteries as electrical power source

A comparison of the potential electrical generation system for these three options is provided in **Table 2**. Only the ‘H_2 burn’ variant requires rotating electrical machines for power generation, which could be integrated in the same manner as before into the engine nacelle. It also does not require propulsive electrical energy thereby eliminating the need for multi megawatt class electrical systems. Only about 5 % of overall energy needs to be converted for non-propulsive needs [17] and the electrical system footprint can be kept relatively small. Depending on some other system choices such as bleed-air extraction or hydraulic power generation (i.e. ‘More Electric A/C’), this configuration most closely resembles current aeroplanes and is the smallest carbon free electrical generation system.

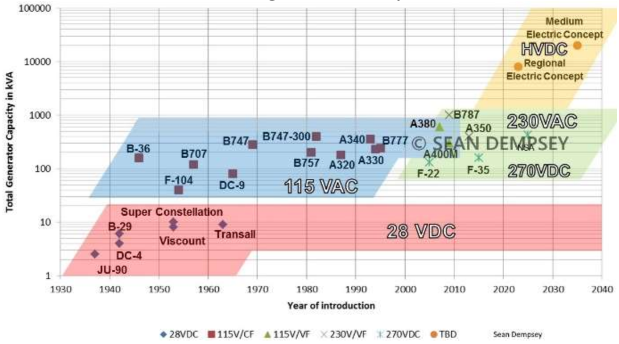

Figure 5: Generator Capacity & voltage level over time

Option b) is a very large fuel cell system covering the entire need for propulsive and non-propulsive electrical power

[2] Electric powertrains are more efficient than combustion based versions. Batteries are more efficient than fuel cells. [14] The efficiency to thrust figures in this table are simplified assumptions to illustrate the difference in energy storage size.

and is therefore in the multi megawatt range. Bleed air extraction and engine driven hydraulic pumps are not directly possible, therefore all energy needs must be satisfied with electricity from the fuel cell system.

Option c) is also a fully electric aeroplane. The clear distinction is the different energy source in batteries making the system potentially reversible. However, both a) and b) consume fuel during the mission making the aeroplane lighter, whereas c) does not consume fuel, only ‘charge’.

	H_2 burn	**Fuel Cell**	**Battery**
Propulsion	Turbofan	fully electric	fully electric
Energy Storage	H_2 in tank	H_2 in tank	Batteries
External component	O_2 from outside	O_2 from outside	n/a
Electrical Generation	rotating machine	electrochemical	electrochemical
Electrical System footprint	mostly unchanged	very large	extremely large
Nominal Voltage	design choice	less than 1V per fuel cell	Li-Ion ~4V per cell
System Voltage	design choice	serial circuit of cells	serial circuit of cells
Power	design choice	gas flow + parallel circuit of stacks	parallel circuit of cells/modules
Waveform	AC	DC	DC

Table 2: Carbon free electrical generation options

3.4 Voltage levels

Earliest A/C electrical systems relied on wind driven alternators, as did the automobile sector (6 V or 12 V with power ratings of up to 1000 W). However, increasing power needs coupled with the requirement for low weight led to the selection of 28 V as prevalent aviation standard [16].

With the introduction of jet engines, A/C became larger and faster and required more electrical power. Crossing the ~10 kW threshold led to the introduction of alternating current (AC) generation in A/C to avoid large wire diameters. 28 VDC systems were retained for low power consumers, converter-powered from the higher voltage AC system. In the 1940s, the US Army Air Corps selected what would later become an international standard (MIL-STD-704): 115/200 VAC three phase systems at 400 Hz constant frequency with an increase of factor two to three in power density of the generator system [16].

As the power demand kept growing, the next new voltage level deployed in civilian A/C was 230 VAC at variable frequency on the Airbus A350 and +/-270 VDC introduced with the ‘More-Electric’ Boeing 787 (up to 1 MW power demand). On the military side, the F-22 introduced a 270 VDC system in the early 2000s.

Future systems for electric propulsion with power demands in the ~10 MW area, consider voltages in the low kilovolt range. There are however some physical issues associated with high voltages that only come into effect in the aerospace sector. The environmental conditions of high altitudes with low ambient pressure can severely reduce the maximum voltage that can be used safely (see Paschen law). For internal compartments, there are failure modes that can include sudden loss of pressurization. This has a significant effect on the required insulation of any high voltage A/C electrical system.

In summary, the selection of a distribution system nominal voltage for an A/C network largely depends on the required power level. With a large range, from several hundred kilowatts to tens of megawatts considering the more electric vs. the fully electric options, it is highly unlikely that a single nominal voltage can be selected to cover all needs. It is more likely that, in case of a fully electric propulsion system, the nominal voltage level will be in the kilovolt range (e.g. 10 kV) and a non-propulsive electrical system will continue to utilize the hundred volt range (e.g. 115 VAC). Game changing technologies such as active cooling or superconductivity possibly in combination with a liquid hydrogen storage system could enable electrical distribution at lower voltages and higher currents than is likely to be feasible today. The choice of voltage level has the potential to be at least a differentiator to limit weight increase in alternative energy source scenarios.

3.5 Distribution architectures

This chapter will differentiate between the distribution architectures of “common”, “more-electric” and “fully-electric” aircraft. Most large commercial aircraft flying today are built on common architecture rules, e.g. Airbus A320 to A380. Today, only a few more-electric large commercial aircraft are flying and fully-electric large commercial aircraft are not existing.

On A320/A330/A340 the electrical power distribution is designed from engine-hosted generators to a centralized primary/secondary/emergency power centre under the flight deck, then distributed for the cabin into two secondary distribution locations in the (front and aft) door areas. From these distribution points all loads are connected as a star. This leads to long supply wires and, for low voltage supply lines, often to very thick wires to limit voltage drop. On A350/A380 the secondary power distribution was decentralized and distributed throughout the Aircraft in up to 14 locations. This brings benefit for the length of last meter connections of the loads and for wiring diameter [18].

It could be expected that in the future, more levels of distribution could be introduced, e.g. a tertiary or quaternary level below the secondary power distribution from which aircraft manufacturers expect benefits in the area of device design and configuration flexibility.

In case of an emergency, the distribution system of all current Airbus aircraft models will be reconfigured and the APU or the RAT will supply all flight-relevant. For new Airbus A/C models the emergency reconfiguration could be achieved in a different manner, depending on the selected electrical power source types (H_2, fuel cell, battery) and dependent on the inclusion of an electric propulsion system (fully electric architecture), the second independent electrical power source could cancel the need of the RAT.

For "More-Electric A/C architecture" the development of electrical replacements for hydraulic and pneumatic assisted equipment is foreseen, e.g. wing anti-ice, environmental control system, flight controls. It is expected, that future architectures require previously separated systems to be more tightly integrated on a common platform, e.g. the emergency lighting system, which is today independently battery operated.

3.6 Electrical loads

The A/C equipment evolved mainly with the introduction of new A/C models and state-of-the-art technologies. So, even future A/C trends will bring new requirements and new challenges to adapt to, as well.

The development of new technology which was already adapted for A/C use due to higher efficiency are e.g. Light Emitting Devices (for cabin lighting with 90 % power consumption savings vs. incandescent lamp), flat screen (for in-flight entertainment) and microwave ovens with reduced space demand in the galleys despite faster heating of meals. Additionally, the electronic designs of aircraft equipment evolve to higher electrical power input stage efficiency. The designs change from transformer-coupled to switch-mode, which leads to a different load behaviour at varied supply voltage levels. Most of this equipment behave now as constant power devices. The equipment weight and volume is reduced, accordingly.

The next equipment evolution steps could be necessary, e.g. due to supply voltage changes which come along with more efficient electrical distribution systems as well as new energy generation and propulsion systems. In general, all aircraft equipment can be classified into 3 distinct groups: resistive load, motor load, electronic load. Each group can be adapted to a new arising voltage level and/or voltage form, accordingly in different manner and the effect on weight and volume depend on the consumed electrical power. In addition, the Airbus more electric aircraft projects will cover the evolution of non-cabin systems like ECS, brakes, flight controls, engine start, landing gear, doors, anti-ice, as the energy source will be switched from pneumatic/hydraulic to electric [18].

3.7 Power management

Power Management (PM) functions have become an integral part of the A/C electrical system, driven by a continuous increase of electrical consumers. Their purpose is to protect the respective managed level in the electrical system and to allow weight-optimization [19-22]. The following PM functions have been implemented on the A/C listed in Table 3. The Generator Control Unit (GCU) is present on all A/C listed [17, 10, 23, 24]. The GCU together with the Overvoltage Protection Unit (OPU) is effective at level 1 (**Figure 1**) in the electrical system. It manages the regulation, performs overcurrent protection and ensures power demand limitation. In case of an overload, the generator will be disconnected from its circuit. An electrical network management function (ENMF), on A330/A340 the Electrical Contactor Management Unit (ECMU), manages the (dis-)connection of the power sources from the main busbar depending on their availability [10, 25, 26]. Furthermore, on level 1 to avoid overload on generators and permanent disconnection, the Electrical Load Management Function (ELMF) exists on the A340/A380/A350 [18, 10, 26]. ELMF is able to shed non-flight relevant loads (e.g. galleys or other cabin loads) if the load exceeds a threshold. Other than the GCU, ELMF can reconnect loads during flight.

Managed Level in according to Figure 1	A320	A330	A340	A380	A350
1	GCU	GCU	GCU	GCU	GCU
	-	ECMU	ECMU	ENMF	ENMF
	-	-	ELMF	ELMF	ELMF
2	-	-	-	-	LPMF
	PED-PM*	PED-PM*	PED-PM*	PED-PM	PED-PM
	-	-	-	-	Galley-PM
3	PED-PM*	PED-PM*	PED-PM*	PED-PM	PED-PM
*(MCU) if In-Seat IFE/Power is installed					

Table 3: PM functions on aircraft

To avoid increase of wiring weight proportional to the growth of non-flight relevant consumers, another three PM functions were introduced. They allow the over-installation of electrical loads on parts of electrical wiring at level 2 and 3 in **Figure 1**.

The Portable Electronic Devices PM (PED-PM) was initially introduced on the Airbus A320/A330 programs. It was re-developed for the A380/A350 programs [10, 21, 26]. The newest PM functions are the Local Power Management Function (LPMF) and the Galley-PM[3] [10, 21]. It allows over-installation of the wiring between the main power centre and the Secondary Power Distribution Boxes. This function will do so by monitoring the actual current on a feeder and shedding non-flight relevant loads, if the current on the feeder exceeds the feeder maximum. Furthermore, it has a provision to control smart loads.

Electrical PM functions will remain a crucial part of future aircraft electrical system generations. However, they might not be more than a supportive element. The higher mass and volume introduced e.g. by battery driven flight cannot be overcompensated by the weight reduction given by a PM only. Neither has it been shown to have the potential to strongly adapt the electrical system towards different form factors to free up space. A potential exception might be the battery PM itself to enable modular and distributed battery configurations.

[3] Non-ATA 24 function, not described in this paper

3.8 Role of dimensions in brief

Based on the above descriptions, Table 4 summarizes the role of the seven dimensions. It shows that e.g. a function like a PM function will yet be needed but might not have the potential to enable game changing solutions. However, the dimension "energy storage" will certainly be a game changer. Others such as e.g. "voltage level" can be the tipping point (differentiator) to feasibility in some scenarios. Game changers and differentiator technologies do require a continued focus of innovation projects around the A/C electrical system.

4 Summary & conclusion

A/C electrical systems have grown continuously with the demand placed upon them, in power, voltage, size, complexity, reliability. With the looming shift to carbon free energy transportation, the A/C electrical system is facing new challenges. The review described in this paper has cut the A/C electrical system into seven dimensions and investigated the potential of each dimension to foster the step-change to carbon free flight. It turned out that the energy storage will make a big difference (game changer), while the voltage level and the architectures can make a difference (to compensate for increased weight impact or volume demand) when energy storages (including tank for liquid hydrogen scenario) have reached the borderline to feasibility (e.g. sufficient energy density of batteries beyond 500 to 1000 Wh/kg). Research for the A/C electrical system should enforce its focus on the game changing and differentiator dimensions of the A/C electrical system. Furthermore, some other technology developments that are not discussed here might also contribute to the future aircraft electrical system design, e.g. the use of 3D printing parts with combined mechanical and electrical properties.

ATA 24 Dimension	Legacy aircraft	Next generation (e.g. eFuel)	Carbon free flight	
			H2 burn	Electric (BAT&FC)
A/C configuration	Defines the boundary conditions to solutions.			
Energy storages	S	S	GC	GC
Generator	D	S	S	N/A
Voltage level	D	D	D	D
Architecture	D	S	D	D
Loads	S	S	D	D
Power Management	S	S	S	S
Legend: Game Changer (GC), Technical Differentiator (D), Required Support (S)				

Table 4: Role of the dimensions

5 Literature

[1] Air Transport Action Group (ATAG): Aviation Beyond Borders Report 2018. https://aviationbenefits.org/media/166711/abbb18_full-report_web.pdf. October 10th, 2020

[2] Airbus SAS: Global Market Forecast - Cities, Airports and Aircraft 2019-2038, Blagnac Cedex, France, 2019, ISBN 978-2-9554-382-4-6

[3] Airbus SAS: Decarbonisation. https://www.airbus.com/company/sustainability/environment/decarbonisation.html, October 12th, 2020

[4] Eurocontrol - Aviation Intelligence: Daily Traffic Variations. https://www.eurocontrol.int/Economics/DailyTrafficVariation-States.html, August 30th, 2020

[5] European Commission: Mobility and Transport. https://ec.europa.eu/transport/modes/air/25years-eu-aviation_en, Brussels August 30th, 2020

[6] Climate.gov: Climate Change: Atmospheric Carbon Dioxide. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide. August 14th, 2020.

[7] Masson-Delmotte, V., P. Zhai, H.-O. Pörtner et al: IPCC, 2018 Summary for policy makers. In: Global Warming of 1.5°C, World Meteorological Organization, Geneva, Switzerland, October 6th, 2018 (also https://www.ipcc.ch/sr15/)

[8] A. Shamshed, N. Hampson et al: Aviation Finance – Fasten your seatbelts, PriceWaterHouseCoopers LLP, https://www.yumpu.com/en/document/read/50364077/pwc-aviation-finance-fastern-your-seat-belts-pdf, page 30, January, 2013

[9] G. Weissel, J. Luedeke: Best practices guide Cabin interior retrofits and entry into service program, IATA, page 7, February, 2019.

[10] Delta Airlines: Training Material ELECTRICAL POWER CH 24 A350-900, January 1st, 2017.

[11] Airbus SAS: ZEROe, Towards the world first zero-emission commercial aircraft, https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html, January 14th, 2021

[12] Wikipedia: Schub, https://de.wikipedia.org/wiki/Schub, January 10th, 2021.

[13] T. Benson: General Thrust Equation, NASA Glenn Research Center, https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/thrsteq.html, January 10th, 2021.

[14] AIAA Journal 52(5):901-911, A.H. Epstein, 2014, Aeropropulsion for commercial aviation in the twenty-first century and research directions needed

[15] Valøen, Lars Ole and Shoesmith, Mark I. (2007). The effect of PHEV and HEV duty cycles on battery and battery pack performance (PDF). 2007 Plug-in Highway Electric Vehicle Conference

[16] IEEE: V. Madonna, Student Member, IEEE, P. Giangrande, and M. Galea., Member, 'Electrical Power Generation in Aircraft: review, challenges and opportunities'

[17] University of Nottingham: Prof. Pat Wheeler, 'The More Electric Aircraft

[18] Moir, I. ; Seabridge, A.: Aircraft System : Mechanical, electrical and avionics subsystems integration. 3th edition. West Sussex, Chichester : John Wley & Sons, Ltd., 2008. – ISBN: 978-0-470-05996-8

[19] Schröter, Torben; Schulz, Detlef: An Approach for the mathematical Description of Aircraft electrical Systems' Load Characteristics including electrical Dependences Validation (IEEE International Conference on Electrical Systems for Aircraft, Railway and Ship Propulsion, ESARS Bologna 2010). IEEE. - ISBN 978-1-4244-9093-6, reviewed paper, Document ID: FP112, pp. 1-6

[20] Schröter, Torben; Benstem, Torsten; Schulz, Detlef: Aircraft Availability and the Optimised Electrical System (3rd International Workshop on Aviation System Technology AST Hamburg 2011). In: von Estorff, Otto; Thielecke, Frank (editors): Proceedings of the 3rd, International Workshop on Aircraft System Technologies. Aachen : Shaker, 2011. - ISBN: 978-3-8322-9904-0, pp. 3-12

[21] Schröter, T.: Power Management on Aircraft, VDE Verlag GmbH, Berlin/Offenbach, 2013, ISBN 978-3-8007-3510-5

[22] D. Schlabe, J. Lienig: Energy Management of Aircraft Electrical Systems - State of the Art and Further Directions, Conference: ESARS, At: Bologna, Italy October 2012,

[23] Airbus Industries: 319/A320/A321 TECHNICAL TRAINING MANUAL MECHANICS / ELECTRICS & AVIONICS COURSE 24 ELECTRICAL POWER

[24] European Union Aviation Safety Agency: 2013-0175: Electrical Power– Generator Control Unit – Inspection, August 8th, EASA AD No.: 2013-0175 2013

[25] Airbus S.A.S.: A380, G MANUAL, MAINTENANCE COURSE - T1 & T2 (RR / Metric), LEVEL III - ATA 24 Electrical Power

[26] Lufthansa Technical: A330/A340 ATA 24 L2E Electrical Power ATA Spec 104 Level 3