AN OPTIONAL APU FOR PASSENGER AIRCRAFT

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ABSTRACT

Most passenger aircraft do not need an Auxiliary Power Unit (APU) to provide them with extra electric, pneumatic, and hydraulic power. Nevertheless they are equipped with one, although use of the APU at airports gets restricted more and more. It is proposed here to offer the APU only as an option. The hypothesis of this research is that an aircraft type with an optional APU (with the option not selected when the aircraft is ordered) has economical and ecological advantages in operation compared to an aircraft not offering an opt-out from the APU. Others have only looked at replacing the gas turbine based APU of today with some other device and have mostly increased mass and costs with their proposal. However, eliminating the APU will clearly reduce mass and costs. Literature and the Internet was reviewed and simple calculations were made. It was found that ordering APU-like services from the airport (electric supply, conditioned air supply, engine start with air starter unit) tends to be more costly due to the need for additional labor. As long as it is still allowed to operate the noisy and polluting APUs at airports, a financial benefit can be obtained from an aircraft without an APU only for long range flights where APU mass is replaced by additional payload.

1 INTRODUCTION

All modern passenger aircraft are equipped with an Auxiliary Power Unit (APU). Its main purpose is to provide the aircraft on the ground with electric, hydraulic and pneumatic power. Either the APU provides all three forms of power directly, or conversion of power takes place with additional on board equipment. The APU often provides only electric and pneumatic power, but no hydraulic power. Hydraulic power can in this case e.g. be provided from an electric motor driven pump. The three power forms are called secondary power. Secondary power is used to drive all aircraft systems (avionics and utility systems). Secondary power is contrasted by propulsive power used to move the aircraft forward. Any device that produces secondary power could be an APU. Traditionally APUs are small gas turbines because of their high power-to-mass ratio. When at least one of the aircraft engines is running (as in flight and during taxiing) it can provide necessary secondary power and the APU is not needed. On the apron Ground Service Equipment (GSE) is available to provide secondary power to the aircraft. [1]

On the apron the APU is needed only if GSE is not available or not ordered. Without an APU an aircraft would depend on GSE only for starting one engine with pressurized ground supplied air. Aircraft are allowed in general to fly without an APU. Exceptions are flights with two-engined aircraft and long routes over water or terrain without an alternate airport – so called ETOPS flights. ETOPS stands for Extended Twin Operations. Another exception where an APU is needed could be an aircraft with safety architecture depending on an available APU. Airports prefer if the APU is not operated due to environmental and financial reasons.

For all these reasons, the idea is to certify an aircraft type with means for APU installation without actually installing it for every aircraft. The APU should be offered only as an option. An aircraft without an APU should have a reduced purchase price, no depreciation on the (non existing) APU, reduced maintenance costs, no spare holding costs for APU parts, reduced aircraft empty mass and therefore reduced fuel burn. If the aircraft is resold the new owner has the option to have an APU installed, if deemed necessary. In this way the "missing" APU should not reduce the residual value of the aircraft beyond the price of an APU (which should be close to the amount saved initially on the purchase price). In short: An aircraft without an APU is expected to have lower Direct Operating Costs (DOC).

The hypothesis of this research is that an aircraft type with an optional APU has economical and ecological advantages in operation. The comparison is made with the aircraft not offering an opt-out from the APU as it is the standard today. This paper tries to test the hypothesis by examining the feasibility of the idea based on a literature and Internet review. The potential of reducing fuel burn (and hence environmental impact) is calculated. Economical advantages are estimated. General conclusions are drawn for a generic "typical" passenger aircraft. Calculations are based on the Airbus A320. Before concluding, a brief comparison is also made with the most prominent APU alternatives to the gas turbine APU.

2 APU DESCRIPTION

The APU of passenger aircraft is usually installed in the tail cone. It is isolated from the rest of the aircraft by a firewall. Installation details of the APU of the Airbus A320 are given in Figure 1.

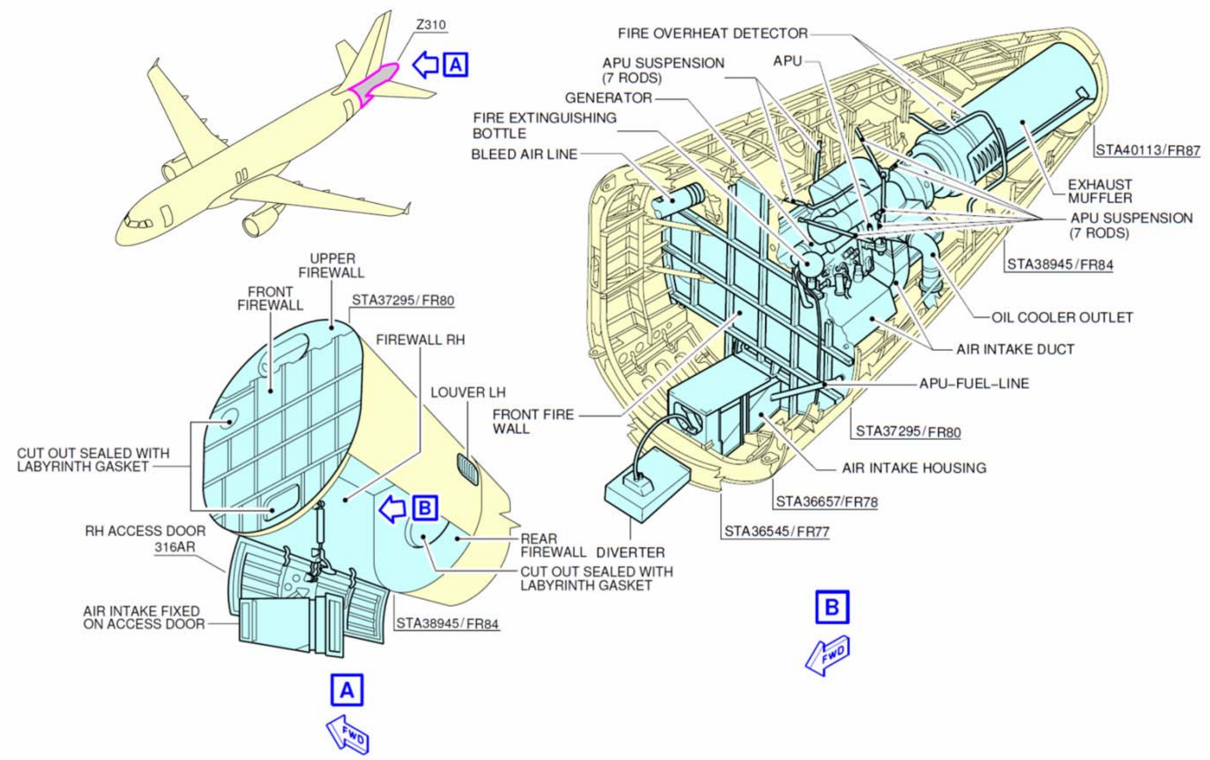

Figure 1: APU installation of an Airbus A320 [2]

The APU can be started by an electrical starter powered by the aircraft on-board batteries. Figure 2 shows the main parts of an APU as it is installed in the Airbus A320. The APU is started after an electric flap motor opens the air intake. The compressor, combustion chamber, and turbine form the gas turbine of the APU. It is producing shaft power to drive a) the load compressor to generate compressed air (so called bleed air) and b) the APU generator via a gear box to generate electric power for the aircraft systems. APU bleed air can be shut off by a valve. The combustion products are leaving the aircraft via an exhaust pipe. [1]

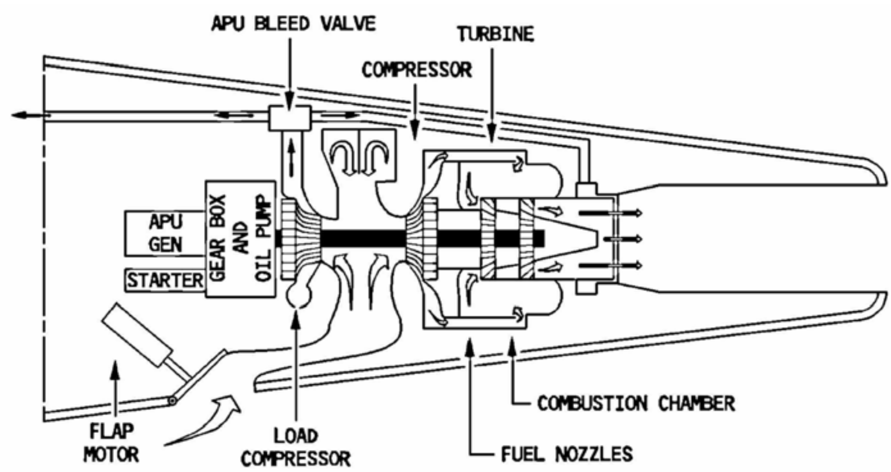

Figure 2: APU installation of an Airbus A320 [1]

3 APU HISTORY

The **Boeing 727** was the first aircraft that was equipped with an APU, and this was due to the fact that it was intended to be operated on shorter routes to smaller airports where ground services would not always be available. So while the Boeing 707 always could rely on ground services the 727 entered the market trying to reach new destinations that did not have these ground services [3]. In the Boeing 727 the APU only provides power on ground and cannot be started while airborne. And since it has 3 engines the extra redundancy of the APU was not needed [4]. The APU in the 727 is placed in the belly of the aircraft and the air-intake is placed in the wheel well. Which means once the landing gear has been raised the APU has no access to air and will flame out [5]. The **Boeing 737** uses the APU both on ground and in air. This is mainly due to the two engine design, and the fact that the aircraft (until the 737 max) lacks a RAT Ram Air Turbine (RAT). The more common case is having the APU as a back-up unit [6]. The early **Boeing 747** had an APU that was only certified for ground use, this is due to the fact that it has 4 engines providing sufficient redundancy [4]. Today, the 747 is certified to run up to 6100 m [7]. The APU of the **Boeing 767** is used for ground power and as emergency backup power in flight (Janes 2008). The **Boeing 777** has an APU that can be run both on ground and in flight, due to the ETOPS regulations [7].

The **Airbus A300** is equipped with an APU that can run both on ground and in the air in case of a failure [8]. If maximum take-off thrust is needed the APU can operate to supply bleed air for air conditioning and wing anti-icing [9]. The **Airbus A320** has an APU that is used for ground operation but can be run also in flight and during take-off if needed [7]. The **Airbus A340** APU runs on ground and as backup in the air [7].

The APU **Honeywell 131-9A** can be used in aircraft in the size of the Airbus A320 or the Boeing 737. It produces around 90 kW and is equipped with an Electronic Control Box (ECB) that integrates advanced "plain-English" trouble shooting logic and health-monitoring capabilities [10].

Pratt & Whitney AeroPower APS 3200 (formerly **Hamilton Sundstrand**) is also an APU for single aisle aircraft such as the Airbus A320. It weighs 140 kg, which is a bit lower than its Honeywell counterpart, and delivers about the same power output. It is certified for 120 minutes of ETOPS operation and equipped with a Full Authority Digital Electronic Control Unit [11].

4 APU OPERATION

4.1 Ground Operation

On airports without ground supply of electricity, conditioned air, or compressed air the APU may be started some time before boarding. The APU´s first task is to cool down or to heat up the cabin to the selected temperature to make sure the passengers can board in a pleasant environment. During boarding the APU provides also electricity for all cabin systems [12]. Subsequently, the APU can supply bleed air to start at least one of the main engines. Other engines can be started from bleed air of the first running engine or also from the APU. Once the engines are running, the APU is switched off. When the aircraft taxies in, the APU can be started before the engines are shut off to take over the supply with secondary power.

On airports with ground supply of electricity the APU can be switched off for most of the turn around time and may only be necessary shortly before the flight (to cool down or to heat up the cabin and) to start the engines.

4.2 In-flight Operation

In-flight operation can become compulsory during **ETOPS flights.** The FAA ETOPS certification rules [13] specify necessary checks for a reliable use of the APU during ETOPS flights:

"(1) If the airplane type certificate requires an APU but does not normally require the APU to operate during the ETOPS portion of the flight, the certificate holder must develop an in-flight start and run reliability program to ensure that the APU will continue to provide the performance and reliability established by the manufacturer."

"(2a) In-flight APU starts do not need to be performed on ETOPS flights; however, the APU must be in the ETOPS configuration."

The Minimum Equipment List for the Airbus A330 shows that it is certified to fly ETOPS missions up to 120 minutes with the APU inoperable [14]. In comparison, the maximum ETOPS rating of the A330 with APU is 240 minutes [15] This means that without an operable APU the A330 can still fly half of it ETOPS rating. With 120 minutes of ETOPS it would still be possible for example to fly from Hamburg to San Francisco as shown in Figure 3.

Figure 3:
Example of ETOPS flight (Hamburg to San Francisco) with the Airbus A330 without an APU based on 120 minutes of ETOPS [16]

5 STAKEHOLDER VIEWS OF THE APU

For the detailed Internet review on this topic please see Peterson [17] The following paragraphs just give the conclusion of each stakeholders view.

5.1 Pilot's View

Pilots need the APU to perform a specific function that is to supply the aircraft with hydraulic power, pneumatic power and electrical power while on ground, and they don't want to have to do anything extra to get to this function, like keeping the main engines running for a little longer or waiting for the ground crew to provide secondary power as a ground service.

5.2 Airline's View

Airlines are interested in keeping their schedules and making a profit. The APU is just a cost factor for the airlines and could be replaced by ground service equipment if this is possible at lower costs and same reliability. The airline welcomes more ecological alternatives to the APU as this can help to emphasis their "green image".

5.3 Manufacturer's View

The aircraft manufacturer's primary focus is getting the aircraft certified and sold. Today the APU is a default part of the aircraft, because the airlines takes it for granted that the aircraft comes equipped with an APU even if they do not need it for every type of operations. If the airlines would start requesting aircraft without APU manufacturers would certainly acknowledge this request.

5.4 APU Manufacturers 's View

The APU manufacturers see the APU as a necessity for aircraft of today. Selling APUs is their way of generating their income. Ground Service Equipment (GSE) is a competitor to the APU. Honeywell [18] takes pride in their product and writes on the homepage: "When US Airways Flight 1549 was forced to ditch in the Hudson River in 2009, a Honeywell 131-9A provided the power required to keep flight controls and displays operable. This enabled Captain Chesley Sullenberger to touch down in control and at the lowest possible airspeed." This is true, because with only power from the Ram Air Turbine (RAT) and batteries performance would have been degraded compared to the situation with APU. E.g. flaps would not have been extended.

5.5 Airport's View

Airports face much criticism from neighbors with respect to noise and pollutant emissions (air quality). For this reason, airports have a natural tendency to listen to any proposals to improve their situation. Many airports have set regulations on how long the APU is allowed to run, both before take-off and after landing. London Heathrow [19] and Zürich [20] are just two examples. If the airport delivers ground power it can often be done in a more environmentally friendly way compared to power generation on board an aircraft.

Airports can also see a benefit providing ground service rather than the airlines helping themselves with an APU burning fuel and polluting the airport. So, there is a double benefit for airports to regulates and/or forbid APU usage.

An important question to airports (especially to smaller airports) was during the study, if they have sufficient ground service equipment available to start aircraft engines and provide aircraft with conditioned air. A review of smaller German airports showed: Necessary equipment is available, but it has its price.

5.6 Resident's View

Aircraft without an APU, introduced in the long run, would improve air quality around airports and would reduce the noise the level.

6 APU CHARACTERISTICS

Table 1 shows selected passenger aircraft and their APUs together with parameters on mass and power.

Data from Table 1 is depicted in Figure 3. Short/medium range single aisle aircraft show with about 0.2 % APU mass to Maximum Take-Off Mass (MTOW) twice the specific mass compared to long range aircraft with only 0.1 %. Without an APU, operation (i.e. fuel burn) benefits for single aisle aircraft from the saved high specific mass and for long range aircraft from the large flight distance flown with reduced mass.

Table 1: Passenger aircraft and their APUs. Based on [21]

aircraft type	MTOW [kg]	range [km]	APU Type	APU dry mass [kg]	shaft power [kW]	power-to-mass ratio [kW/kg]	APU dry mass/MTOW [%]
B737-600	66.000	5970	Honeywell 131-9B	145	447	3,09	0,22
B737-700	70.080	6370	Honeywell 131-9B	145	447	3,09	0,21
B737-800	79.010	5765	Honeywell 131-9B	145	447	3,09	0,18
B777-200	247.200	9700	Honeywell 331-500B	310	895	2,89	0,13
B777-300	299.370	11120	Honeywell 331-500B	310	895	2,89	0,10
B787-8	227.930	14500	Hamilton Sundstrand APS5000	245	820	3,35	0,11
B787-9	252.651	15327	Hamilton Sundstrand APS5000	245	820	3,35	0,10
B787-10	252.651	13000	Hamilton Sundstrand APS5000	245	820	3,35	0,10
A318	68.000	5780	Honeywell 131-9A	145	447	3,09	0,21
A319	75.500	6850	Honeywell 131-9A	145	447	3,09	0,19
A320	78.000	6100	Honeywell 131-9A	145	447	3,09	0,19
A321	93.900	5950	Honeywell 131-9A	145	447	3,09	0,15
A330-200	242.000	13400	Honeywell 331-350	250	745	2,98	0,10
A330-300	242.000	11300	Honeywell 331-350	250	745	2,98	0,10
A340-500	380.000	16670	Honeywell 331-600	307	895	2,91	0,08
A340-600	380.000	14600	Honeywell 331-600	307	895	2,91	0,08
A350-800	248.000	15300	Honeywell HGT1700	335	1268	3,78	0,14
A350-900	268.000	14350	Honeywell HGT1700	335	1268	3,78	0,13
A350-1000	308.000	14800	Honeywell HGT1700	335	1268	3,78	0,11
A380-800	569.000	15200	P&W CANADA PW980A	447	1342	3,00	0,08

For the overall aircraft system safety concept it makes a difference if the APU is dependable or not. If overall safety depends on the APU, then the APU is essential; otherwise it is non-essential.

"Essential APU" means an APU which produces bleed air and/or power to drive accessories necessary for the dispatch of the aircraft to maintain safe aircraft operation. [22]

"Non-essential APU" means an APU which may be used on the aircraft as a matter of convenience, either on the ground or in flight, and may be shut down without jeopardising safe aircraft operations. [22]

An essential APU is necessary for dispatch. For the pilot this is indicated on the Minimum Equipment list (MEL).

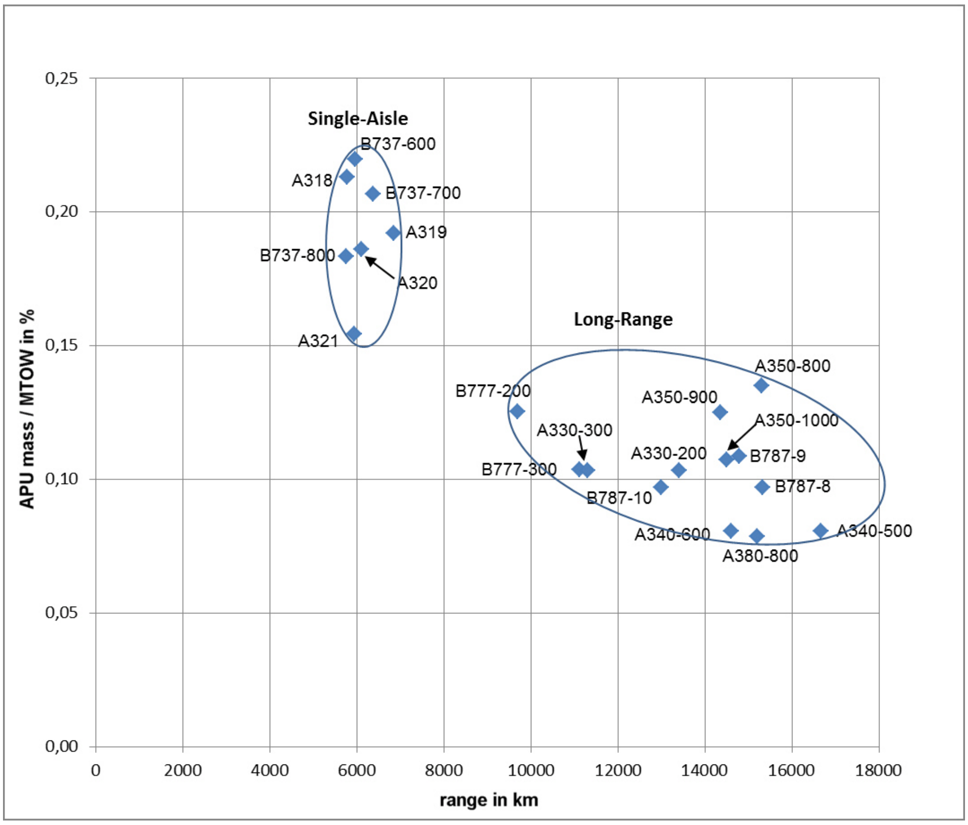

Figure 3: APU relative mass versus aircraft range [21]

7 POTENTIAL SAVINGS WITHOUT AN APU

7.1 Saving Mass without an APU

Table 2 shows the estimated mass of all components from the APU system including the dry mass of the APU itself and all attached components, tubes, ducts, and wires. Three different cases are considered:

A: Deinstallation of the APU and all Line Replaceable Units (LRU). This option allows for a quick reinstallation of the APU and offers the greatest flexibility. Deinstallation or reinstallation of the APU can be done by two workers in one shift. Prerequisite is to insert a "APU substitution kit" when the APU is deinstalled to hold all tubes, ducts, and wires in their proper position and to cover openings.

B: Deinstallation as in case A plus deinstallation of almost all components, tubes, ducts, and wires only in the tail cone. This would also eliminate the "APU substitution kit". Problematic are the generator wires that have no coupling at the fire wall. They are either left in place (as considered here) or could also be totally removed.

C: Deinstallation as in B plus deinstallation of all remaining components also in the rest of the aircraft.

Table 2: Estimating the mass of the total APU system [21]

sub system	component	mass [kg]	case
APU	APU dry mass	-145,0	A
	dummy	15,0	A
	APU installation (structure)	-40,0	B
fuselage	tail cone (more lightweight design)	-60,0	C
air intake	air inlet ducts	-2,0	C
	air vane	-2,0	C
	air inlet with flap	-10,0	C
	flap actuator	-2,0	B
	possible dummy for flap actuator	0,5	B
exhaust	exhaust pipe and muffler	-10,0	C
fuel system	fuel pump	-15,0	A
	fuel lines inside the tail cone	-3,0	B
	fuel lines up to the cross feed valve (including shroud & fasteners)	-60,0	C
oil system	oil	-5,0	A
engine control	Electronic Control Box (ECB)	-3,0	A
	ECB rack & electrical wires (incl. fasteners and structure)	-15	C
starter	-	-10,0	A
ignition	integrated		
fire detection and extinguishing	1 fire extinguisher (one-shot-system)	-5,0	B
	fire pneumatic continuous loop detector	-3,0	B
bleed air system	ducts in tail cone	-5,0	B
	ducts up to cross bleed valve (including insulation, overheat electric continuous-loop detector and structure)	-120,0	C
electrical system	generator	-25,0	A
	wiring from avionic compartment to starter and generator	**-90,0**	C

Savings are for the APU deinstallation and for the three different cases from Table 2:

Only APU deinstallation:	-145 kg (for reference)
Case A deinstallation:	-188 kg (1.3 times APU dry mass)
Case B deinstallation:	-261 kg (1.8 times APU dry mass)
Case C deinstallation:	-630 kg (4.3 times APU dry mass)

Potential savings can also be estimated for all aircraft from Table 1, assuming the factors of 1.3, 1.8, and 4.3 would come out similarly also for APU installations of other aircraft.

Mass savings can be used for different options:

1. fly lighter and save fuel
2. put in more fuel and fly further
3. put in more payload and earn more (this option is only possible when flying ranges longer that range at maximum payload, otherwise payload is limited by maximum zero fuel mass, MZFW)

Applying option 3 and Case A means payload could be increased by 2 passengers (including luggage)!

7.2 Saving Fuel without an APU

APU Operation: An APU of the size as used for the Airbus A320 consumes 2 kg of fuel per minute [23]. Without an APU this fuel is saved and the environment is by this amount less polluted with benefits to the air quality in the vicinity of the airport. For a short turn around of 30 minutes achievable with a single aisle aircraft **60 kg** of fuel can be saved for each flight. Fluctuating fuel cost during the last years can be averaged to 1 USD/kg. So, financial savings are **60 USD**.

Aircraft Operation: The Aircraft is lighter without an APU. Fuel consumption is proportional mass and almost proportional to flight time (or distance).

$$m_F = m\,(e^{t_f \cdot k_E} - 1) \quad , \quad k_E = \frac{c\,g}{E} \tag{1}$$

m_F: fuel mass to transport fixed mass m
m : mass to be transported (or saved)
t_F : flight time
c : specific fuel consumption e.g. 16 mg/N/s
E : glide ratio $E = L/D$ e.g. $E = 15$
g : earth acceleration, 9.81 m/s²

For a typical stage length (range) for a DOC calculation which is 50 % of the range at maximum payload (755 NM for the A320 flown in the stratosphere with M_{CR} = 0.76 yields 6235 s flight time) and mass saving for a Case A deinstallation (188 kg) results in fuel savings of **13 kg**. Financial savings are just **13 USD**.

7.3 Saving Money without an APU?

Money saved without an APU is calculated with the method for Direct Operating Costs for aircraft systems (DOCsys) [24]. For a flight time of 6235 s = 1.73 h DOCsys calculates 1010 flights per year.

Depreciation is calculated over 15 years with a residual value of 10 %. System purchase costs are estimated based on system mass with 2000 kg/USD. Eliminating 188 kg (Case A) would save 376000 USD which is equivalent to depreciation of 22560 USD per year or **22 USD** per flight.

Maintenance parameters are estimated from [25] for ATA 49:
Maintenance Man Hours per Flight Hour (MMH/FH) for on aircraft maintenance: 0.00290 1/FH
Maintenance Man Hours per Flight Hour (MMH/FH) for off aircraft maintenance: 0.02090 1/FH

Material Costs per Flight Hour (MC/FH): 2.85 USD/FH
Burdened labor costs are 69 USD/ based on the year 1989.
Burdened labor costs corrected with 2.5 % per year up to 2015 increase to 131 USD.
Maintenance cost savings are 10400 USD per year or **10 USD** per flight.

All together savings are: 60 USD + 13 USD + 22 USD + 10 USD = **105 USD** per flight.

This so far looks quite good, but it is unfortunately not the end of the story. If there is no APU on board at least the service for starting the engines needs to be purchased at the airport. Some airports show there service charges online. We look here at the small international airport Münster-Osnabrück (FMO) [26] and convert 1 EUR = 1 USD. Minimum duration for these charges are 30 minutes.

- One ground handler acting is 22.50 USD for 30 minutes.
- Cabin heating is 84.50 USD for 30 minutes without labor.
- A Ground Power Unit for electrical supply 400 Hz, 90 kVA is 46 USD per 30 minutes without labor.
- For an air starter charges are 152.50 USD without labor for one aircraft start.
- This yields **175 USD** to get the aircraft started and is adding costs for equipment and labor.
- Let's assume if the worker is paid 30 minutes for aircraft starting the remaining time can be used to get also other services in place (if needed).

It turns out there is no financial benefit. Money spent for ground services (at least to German expensive standards) more than compensates the savings earned by flying without an APU on a typical mission of a single aisle aircraft.

Here is an **alternative reasoning** with less numbers: Air starters are often built by mounting an aircraft APU on a truck. Eliminating the APU on board and replacing it with an APU on the ground has the advantage of not keeping the APU's mass airborne, other wise with respect to fuel usage of the APU, depreciation and maintenance costs there are little differences if we assume usage of the APU on board and on the ground is the same. But applying an APU on the ground has the disadvantage to pay for an additional ground handler (whereas the pilot is operating the APU by pressing some buttons as part of the job of flying the aircraft). We calculated above fuel savings of 13 USD for a 1.73 hour flight. That is 7.5 USD savings for each hour of the flight. If a ground handler charges 22.50 USD to get the APU related jobs for a turnaround done, **we would need to fly here at least 3 hours to break even for the aircraft without an APU**. In countries with lower wages required flight time to break even will be lower.

7.4 Saving Money without an APU Considering the Payload-Range Diagram

So far we only considered Option 1. "fly lighter and save fuel" to exploit the benefits of flying without an APU. Option 3. (from Section 7.1) "put in more payload and earn more" will show more benefits, but works only for longer flights where payload becomes limited through the payload-range diagram. This is more likely when seating 180 passengers in the A320. However these long distances the aircraft generally operates less frequently. Figure 4 shows the details.

The payload increase expressed in % is given in Figure 5. We consider the variant of the A320 with a Maximum Take-Off Mass (MTOW) of 77 t. This variant has a maximum payload of 21000 kg. When flying a distance of e.g. 1800 NM, Case A would allow a payload increase – due to a reduced Operating Empty Weight (OEW) – equivalent to 2 passengers which is almost 188/21000 = 1 %.

How much can be gained from payload increase? The revenue from the ticket should be higher than the costs. The costs can be estimated from a Direct Operating Costs (DOC) calculation. The DOC method of the Association Of European Airlines for Short- Medium Range Aircraft from 1989 [27] is applied and the results given in 2015 USD calculated with 2.5 % inflation. For the flight considered above costs of 130 USD can be estimated. Payload can be increase by 188 kg (Case A) or two passengers including their luggage with costs of roughly **260 USD**. Revenue should be higher that this and more revenue is even possible with higher mass savings with Case B or Case C. Now finally, the financial benefits are higher than the fees for the ground support equipment.

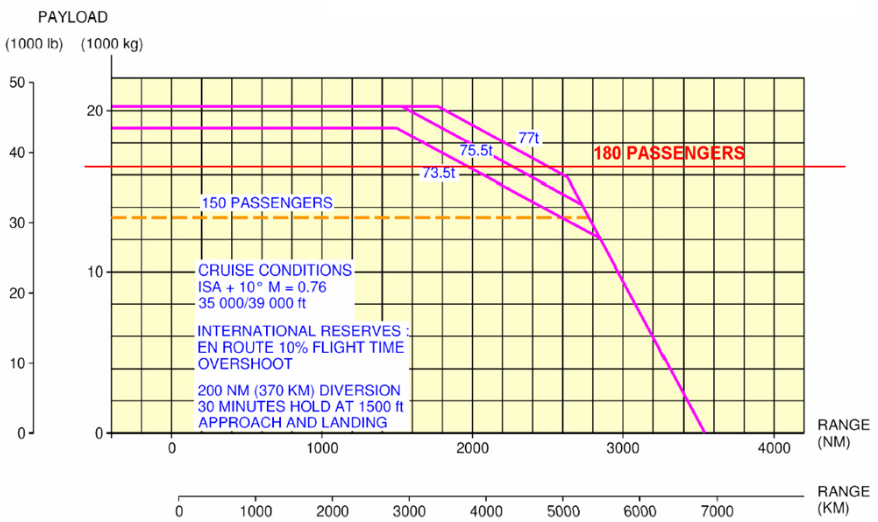

Figure 4: Airbus A320 Payload-Range Diagram. Only at longer ranges where the purple lines fall below the red line (for 180 passenger) can the aircraft without APU show its increased payload capabilities [2]

8 SUMMARY AND CONCLUSIONS

Most aircraft do not need an APU; nevertheless they are equipped with one. This raises the question, why APUs have not been eliminated in a competitive environment like the airline business. The fact that APUs have not been eliminated indicates that there must be good reason for it! The various stakeholders in aviation have been considered. No show stoppers where found why an APU should not be eliminated for an aircraft. Especially airports are pressing for the use of their ground service equipment instead of using the APU. This has ecological reasons mixed with financial reasons. It was found, eliminating an APU has a considerable weight saving potential. However, it shows only limited financial savings if compared with the high costs charged for equipment and labor at the airport. Charges are necessary for ground service equipment that replaces the APU. Calculations show, eliminating an APU would benefit the airline best if the aircraft is operated on quite long range routes beyond the range at maximum payload. Increasing payload has clear financial advantages over reducing weight and saving fuel. Only in this way an aircraft without APU could show its economic and ecologic benefit over its benchmark. The hypothesis of this research that an aircraft type with an optional APU has economical and ecological advantages in operation was only proven for long range operations (long range with respect to each aircraft's capabilities).

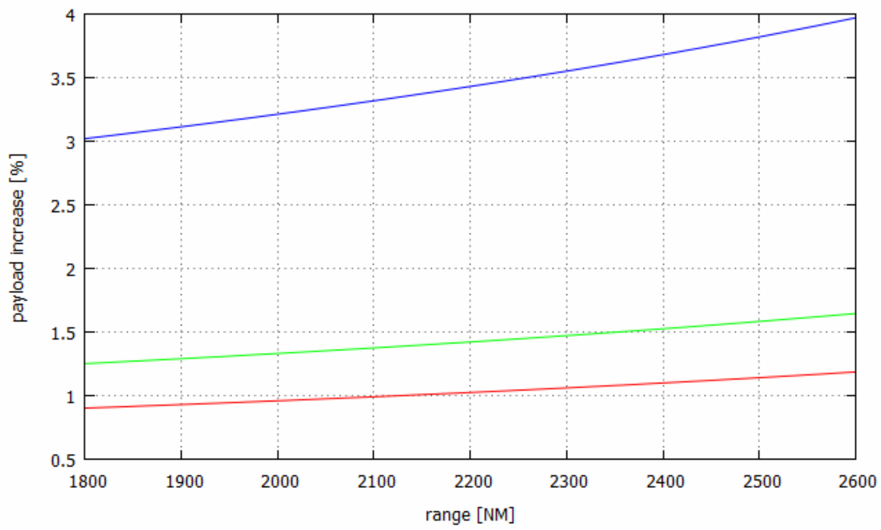

Figure 5: Airbus A320 payload increase due to OEW reduction achieved by APU elimination with Case A (red), B (green), C (blue). Shown is here the range allowing take-off with MTOW between 1800 NM and 2600 NM.

9 ACKNOWLEDGMENTS

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