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Electric Taxiing System. Kinetic Energy Recovery System as an Electric Taxiing Solution: Economic and environmental analysis Phenom 300 case study

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ABSTRACT

The aviation industry has thrived in recent years, with a significant increase in passenger numbers, leading to the development of larger aircraft fleets and the expansion of airport infrastructure. In 2019, more than 4.5 billion passengers traveled by airplane, which represents an 80% increase compared to 2009. As a consequence, this growth has also resulted in longer taxiing times for aircraft, increasing fuel consumption and operational costs. The industry's CO_2 emissions have quadrupled since the 1960s, with over 1 billion tons released in 2019, contributing to global warming. Given that the improvements being made to current propulsion systems and the production of over 600 million liters of SAF (Sustainable Aviation Fuel) in 2023 do not seem sufficient to meet the ambitious goals set by regulators and operators, the logical solution would be to develop a system capable of moving the aircraft on the ground using alternative, cleaner, and cheaper energies, such as electric power. This paper explores the latest advancements in electric propulsion systems, specifically focusing on external and onboard systems. After the state of the art is established, this paper will cover a case study and propose a new alternative for an onboard system called ETS – Electric Taxiing System. The ETS is a 100% electric system for ground handling operations designed to use only the kinetic energy stored in a battery pack, which is recovered during aircraft landing and braking events. Although there are some studies on this topic, the author considers this paper to be more comprehensive as the results computed here take into account 96 variables, 60 simulations, several flight plans, and real-world data. The case study focuses on the implementation and dimensioning of the ETS, considering electric motor power and torque, and battery capacity for the Embraer Phenom 300. A brief economic and environmental analysis was also conducted, considering the operation of NetJets Europe, the world's leading and largest private jet company.

Introduction

The growing environmental concern led the European Commission to develop the Flightpath 2050 program, which establishes the European vision for the future of aviation. This document forecasts that, by the year 2050, available technologies and procedures will allow, a reduction of 75% in CO_2 emissions per passenger per kilometer, a 90% reduction in NOx emissions, and a 65% reduction in aircraft noise compared to an aircraft manufactured in the year 2000. Additionally, it states that all flights must land with a 1 min margin of error, regardless of atmospheric conditions. Furthermore, the Flightpath 2050 stipulates that aircraft movement on the ground must be completely emission-free during the taxi phase. And this will have a tremendous impact, because the "Airport Carbon Accreditation" estimates that aircraft ground movement accounts between 5-20% of all airport emissions (European Commission, 2011, ACI Europe, 2024).

Combining these factors with the high operational costs and net profit margins of airlines being as low as 2.7%, the operation is pushed to the limit, making it imperative to develop a new system capable of moving aircrafts on the ground using alternative, cleaner, and cheaper energies, such as electric power (Schmidt et al., 2016, IATA, 2023).

The ETS – Electric Taxiing System – aims to revolutionize the ground procedures of aircrafts by changing the taxi operation, traditionally dependent on jet fuel, into an electrically powered process, reducing not only the use of fossil fuels and their associated emissions but also noise levels. This change is attributed to the system's ability to recover and

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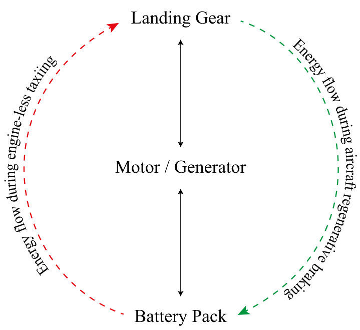

Fig. 1. Schematic of the main ETS components and energy flow.

store part of the kinetic energy from landing and braking during taxi operations. ETS will also allow the aircraft to be autonomous during the pushback phase and parking operation, reducing wait and turnaround times at airports worldwide up to 20 min (Whelltug, 2024).

On top of that, the ETS is designed to be retrofitted and a plug-in, meaning the energy stored in the battery pack can be recharged during the turnaround time using airport sustainable energy sources, allowing the aircraft to perform beyond its original design range without using the aircraft main engines for taxiing.

Fig. 1 shows a schematic of the ETS main components and the energy flow between them.

State of the art

Automotive Industry

For the 2009 Formula 1 World Championship, all cars were equipped with an innovative system - the KERS or Kinetic Energy Recovery Systems. This system stores energy from braking in batteries and reuses it later to increase the engine's power. Although electric cars appeared long before cars with combustion engines, the KERS allowed for the mass adoption of electric cars and this is the basic concept that EV manufactures such as Tesla use in their cars (Car & Driver 2018). In 2020, Tesla's fleet of vehicles, combined with its solar panels, allowed all customers to avoid the emission of more than 5 million tons of CO_2 into the atmosphere. For comparison, an internal combustion engine vehicle from the year 2020 will emit, on average, 69 tons of CO_2 over its lifetime (TESLA, 2020).

The pressure to reduce CO_2 emissions and comply with new regulations enforced by the European Union led several manufactures to reinvent themselves. An example of this is Jaguar Land Rover (JLR), which had to pay a fine of £ 35 million for not meeting the emission targets imposed by the EU (BBC, 2021).

Consequently, the British manufacturer announced that they will invest £ 2,5 billion per year over the next 5 years. By 2030, the same year the UK will ban the sale of new combustion engine cars, JLR predicts, all Jaguars and 60% of Land Rovers sold will be zero-emission vehicles. Not only the United Kingdom but also other countries like France, Norway, and the state of California in the United States have announced the same measure to be implemented as early as 2025 (The Verge, 2021). Currently, there are car manufacturers that equip their vehicles with over 1400 kW of power, 2340 Nm of torque, and 200 kWh batteries with an 800 V architecture capable of supporting fast charging up to 500 kW DC (Electric Vehicle Database, 2024, Rimac Automobili, 2024). More recently, during the 2023 Goodwood Festival of Speed Koenigsegg's R&D team explored the limits of electric propulsion and created the Dark Matter – a 600 kW, 1250 Nm patent-pending Raxial Flux 6-phase e-motor, weighing just 39 kg. Electrification in the automotive industry is a reality and is here to stay (Koenigsegg, "Dark Matter, 2024).

Table 1 shows, for each respective brand and model, the power, torque, battery capacity, and charging power for each electric vehicle.

Aviation Industry

The increasing pressure for environmental responsibility, ambitious objectives set by national and international regulators, and cost-cutting measures by airlines led to the creation of optional operational procedures aimed at reducing primarily CO_2 emissions, noise levels, and fuel consumption during aircraft ground operations. One of these procedures is taxiing using only one of the main aircraft engines in the case of a twin-engine aircraft or using only two engines in the case of a quad-engine aircraft. Currently, this procedure of not using all the aircraft engines for taxiing is not sufficient to meet the objectives of regulators to rapidly reduce emissions of gases such as CO_2, noise, and fuel consumption during aircraft ground operations. On top of that, the improvements being made to current propulsion systems and the production of over 600 million liters of SAF (Sustainable Aviation Fuel) in 2023 do not seem sufficient to meet the ambitious goals set by regulators and operators, the logical solution would be to develop a system capable of moving the aircraft on the ground using alternative, cleaner, and cheaper energies, such as electric power. Therefore, it is imperative to develop a new solution (Airbus, 2004).

This system will be crucial to meet the objectives of Flightpath 2050 and achieve a 40% reduction in turnaround times by 2050, as currently, over 70% of flight delays are caused by issues during the turnaround (Schmidt et al., 2016).

This hybrid or fully electric system, in both dry and wet conditions, will need to operate safely and:

a) Pushback the aircraft to the *taxiway*;
b) Move the aircraft from rest with the intended acceleration;
c) Move the aircraft along the *taxiway* assigned by the ATC;
d) Brake the aircraft until it comes to a full stop;
e) In case of failure, deactivate the taxi system and allow the flight crew to use aircraft's main engines.

These ground propulsion systems for aircraft can be classified into two main groups: external systems that are either connected or disconnected to the aircraft when needed and onboard systems integrated with the aircraft. As an example of external systems, we highlight the TaxiBot, which is currently the only system operational that is certified for commercial use (Postorino et al., 2017). The TaxiBot is available in two

Table 1
EV specifications.

Brand	Rimac (Rimac Automobili 2024)	Koenigsegg (Koenigsegg, "Dark Matter 2024)	Tesla (Electric Vehicle Database 2024)	Aspark (ASPARK 2024)
Model	Nevera	Dark Matter[1]	Roadster	Owl
Power (kW)	1408	600	1000	1480
Torque (Nm)	2340	1250	1200	2000
Battery Capacity (kWh)	120	NA	200	69
Voltage (V)	730	NA	NA	800
Charging Power (kW DC)	500	NA	250	200

[1] Electric motor, not an EV

versions depending on the aircraft category. For narrow-body aircraft, the TaxiBot uses two V8 diesel engines, connected to an electric generator. The maximum power of the TaxiBot is 500 kW, allowing it to tow a Boeing 737 with MTW at 23 knots. For wide-body aircrafts and the generated power increases from 500 kW to 1 MW, meaning the Taxibot is capable of taxiing a fully load A380 up to 20 knots (Simonnet, 2014, Lukic et al., 2019, Lee, 2015, Aschenbrenner, 2015, Hospodka, 2014).

Although the TaxiBot provides lower noise levels around airports, CO_2 emissions and savings in airline fuel consumption, it also requires a significant investment in tow truck fleet. One TaxiBot costs at least 1.5 million dollars, that's three times more expensive than a diesel tow truck. Considering an average European airport with 30 moves per hour, 20 Taxibot are required to achieve higher airport effectiveness. On top of that, added taxiway infrastructure to accommodate increased ground vehicle traffic is also required (Hospodka, 2014, Camilleri & Batra, 2022).

The WheelTug is an onboard system. It consists of two Chorus Motors mounted on the nose wheel of the aircraft, powered by the APU and controlled by the pilot in the cockpit (Re, 2012). The system weighs 137 kg and is capable of taxiing an aircraft weighing over 90,700 kg - well above the maximum takeoff weight of any variation of the Boeing 737 - at a speed of just 9 kts. The WheelTug promises to save up to 20 min for each flight (Lukic et al., 2019, Airbus, 2013, Airbus, 2021, Goldstein, 2020). It is estimated that a single Boeing 737 equipped with the WheelTug can save nearly 379,000 liters of fuel annually. Additionally, carbon dioxide emissions would be reduced by over 650 kg per flight when compared to using two engines during taxiing (Airbus, 2010). WheelTug forecasts that $ 100 could be saved in pushback tractor service fees and $ 95 in engine wear per flight. Considering all the advantages of this system, a Deloitte study concluded that savings for airlines can range from $ 500,000 to $ 6,000,000 per aircraft per year (Airbus, 2021, Goldstein, 2020, Motortrend, 2020). Although this was a very promising project, the team became concerned about traction issues when taxiing due to relying on only two electric motors on the nose wheel. They feared that this configuration might not provide sufficient traction, especially in severe weather conditions. As a result, the project was later refocused for aircraft pushback and parking operations only, which ultimately lead to limited effectiveness (Camilleri & Batra, 2022).

The EGTS, or Electric Green Taxiing System, is developed by Safran, Airbus and Honeywell Aerospace. This onboard system operates in a very similar manner to the WheelTug system, but instead of being applied to the nose wheel, it is installed on the main landing gear of the aircraft. The EGTS is powered by the APU and designed to (Lukic et al., 2019):

- Achieve a maximum taxi speed of 20 knots (37 km/h) over a period of 90 s, resulting in an acceleration of 0.11 m/s^2;
- Reach a speed of 10 knots (18.5 km/h) in 20 seconds during active runway crossings, resulting in an acceleration of 0.26m/s^2;
- Have sufficient torque to move an aircraft at Maximum Takeoff Weight (MTOW) on a 1.5 % taxiway slope.

In terms of performance, the EGTS has 130 Nm of torque available for acceleration and a peak power of 60 kW. Because the EGTS uses the APU as a power source, redesigning the auxiliary power unit to allow the generator to supply electrical power to the in-wheel motors would require costly retrofitting and result in a significant increase in weight. However, even though they had customers waiting, this project is currently suspended. Safran researchers said "As part of a wider technology drive, Safran is studying longer-term autonomous systems that could take over a pilot's job of taxiing or ease the workload so that only one pilot is engaged" (Reuters, 2019). Therefore, it can be concluded that currently, both external and onboard systems, despite reducing fuel consumption, do not completely eliminate it since they are always dependent on other power sources that use fuel, such as the APU, plus they don't allow the aircrafts to be completely emission-free during the taxi phase. In order to comply with EU regulations there is one question remaining: Is it feasible to adapt the kinetic energy recovery technology, commonly found in electric and hybrid automobiles, and apply it to an aircraft?

Methodology

In order to assess the feasibility of implementing an electric propulsion system based on the kinetic energy recovered (ETS) into an aircraft, real-world data from 2015 to 2019 from NetJets Europe, was used. The Embraer Phenom 300 was the aircraft used in this research as it was most popular aircraft averaging 773 flights per year. Adolfo Suárez Madrid–Barajas Airport (LEMD) and Vnukovo International Airport (UUWW) were chosen as baselines due to their notably high taxi-out and taxi-in times, respectively. These times were measured considering the distance from the business aviation terminal to the furthest runway available, thus representing the worst-case scenario for the aircraft. In total, 96 variables were used, and some of them are listed in Table 2. The energy required for taxi-in and taxi-out was computed by using mathematical models, alongside with 60 simulations using Lockheed Martin's Prepar3D flight simulator. Several flight plans, together with real data provided by NetJets Europe and Eurocontrol, were also used to obtain the most accurate results. Subsequently, the ETS equipment to be installed on the aircraft was specified, including the electric motors power and torque, and the battery pack capacity. Average annual savings and emitted emissions were also determined using the simulation results and real-world data from NetJets Europe. (Nick Copley, 2022)

Case study

Taxi-out operation

After all 96 variables were established, we began by studying the ETS performance during the taxi-out operation because the aircraft weight is heavier when compared to the taxi-in phase. Since EASA defines that, for an aerodrome of category C, D, E, or F, a taxiway cannot have a longitudinal slope greater than 1.5% and this value is very negligible, for the following calculations, a flat taxiway is assumed (European Aviation Safety Agency, 2022).

The electric motor power required to put the aircraft in motion P_{start} is given by (1) where F_{start} is the force required to start moving the aircraft and v_{taxi} the linear aircraft velocity during taxiing.

$$P_{start} = F_{start} \cdot v_{taxi} \tag{1}$$

The force required to start moving the aircraft F_{start} is in (2), where m_{out} is the airplane mass when taxing-out, a_{taxi} is the linear acceleration and F_o the opposing force.

$$F_{start} = m_{out} \cdot a_{taxi} + F_o \tag{2}$$

The opposing force F_o is mainly composed by the rolling resistance $F_{rr.out}$ and the aerodynamic resistance F_{ae} as in (3):

$$F_o = F_{rr.out} + F_{ae} \tag{3}$$

Because some aircrafts, including the Phenom 300, are equipped with 2 different tires, it is required to compute the rolling resistance for the 2 main landing gear under the wing $F_{rr.out.wing}$ and for the nose gear $F_{rr.out.nose}$ as in (4). The equation (4) can be calculated from (5) where g is the gravitational constant, W_{wd} is the weight distribution supported by the wing landing gear, N_{wd} is the weight distribution supported by the nose landing gear, f is rolling resistance coefficient, $r_{tire.wing}$ is the tire wing radius and $r_{tire.nose}$ is the nose tire radius.

$$F_{rr.out} = F_{rr.out.wing} + F_{rr.out.nose} \tag{4}$$

$$F_{rr.out} = \frac{m_{out} \cdot g \cdot W_{wd} \cdot f}{r_{tire.wing}} + \frac{m_{out} \cdot g \cdot N_{wd} \cdot f}{r_{tire.nose}} \tag{5}$$

The aerodynamic resistance F_{ae} is determined by (6), where ρ is the air density, A_{wing} the aircraft wing area and C_D the aircraft taxi drag polar coefficient.

$$F_{ae} = \frac{1}{2}\rho A_{wing} C_{D.taxi} v_{taxi}^2 \tag{6}$$

The power required to maintain the aircraft moving with constant speed $P_{taxi\ out}$ is given by (7):

$$P_{taxi\ out} = F_o \cdot v_{taxi} \tag{7}$$

The total energy required for the taxi-out operation $E_{total\ taxi\ out}$ is given by (8) where $n_{stops.out}$ is the total number of times the aircraft will stop, $E_{start\ out}$ is the amount of energy required to start moving the aircraft until v_{taxi}, $E_{taxi\ out}$ is the amount of energy required to maintain the desired taxiing speed and $t_{taxi\ out}$ is the duration of the taxi-out at constant speed.

$$E_{total\ taxi\ out} = n_{stops.out} \cdot E_{start.out} + E_{taxi\ out} \tag{8}$$

Eqs. (8) is equal to (8.1):

$$E_{total\ taxi\ out} = n_{stops.out} \cdot \left[P_{start} \cdot \frac{v_{taxi}}{a_{taxi}}\right] + P_{taxi\ out} \cdot t_{taxi\ out} \tag{8.1}$$

The energy that can potentially be stored in batteries for each time the aircraft breaks and comes to a full stop during the taxi-out $E_{stored\ taxi\ out}$ is given by Eq. (9) composed of three main components, the kinetic energy variation ΔE_C, the energy wasted during breaking E_{wasted} due to the opposing force (F_o) and the system's efficiency $\eta_{breaking}$.

$$E_{stored\ taxi\ out} = \left(\Delta E_C - E_{wasted}\right) \cdot \eta_{breaking} \tag{9}$$

Eqs. (9) is equal to (9.1):

$$E_{stored\ taxi\ out} = \left[-\frac{m_{out}}{2}(v_{taxi})^2\right] - E_{wasted} \cdot \eta_{breaking} \tag{9.1}$$

The energy wasted during breaking E_{wasted} is given by Eqs. (10) that it is equal to (10.1) where t_{break} is the amount of time it takes to stop the aircraft, and $a_{taxi.breaking}$ is the aircraft deacceleration while breaking :

$$E_{wasted} = \int_0^{t_{break}} F_o\left(v_{taxi} - a_{taxi.breaking} \cdot t_{break}\right) dt_{break} \tag{10}$$

$$E_{wasted} = F_o\left[v_{taxi} \cdot t_{break} - a_{taxi.breaking}\frac{t_{break}^2}{2}\right]_0^{t_{break}} \tag{10.1}$$

Taxi-in operation

Landing

A representation for the ETS landing and taxi procedure is shown in Fig. 2.

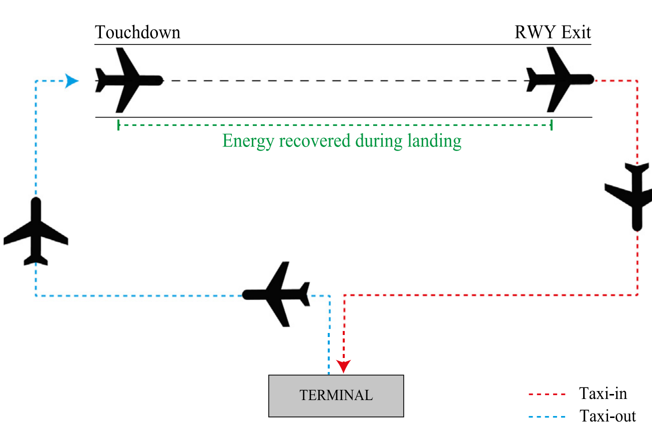

Fig. 2. ETS landing and taxi procedure.

The kinetic energy that can potentially be stored in the battery pack after the aircraft lands and comes to a full stop $E_{stored\ ldg}$ can be computed by using (11) where, $\Delta E_{C.ldg}$ is the kinetic energy variation during landing, $E_{wasted.ldg}$ is the energy wasted due to the opposing force $F_{o.ldg}$ and $\eta_{breaking}$ is the system's efficiency.

$$E_{stored\ ldg} = \left(\Delta E_{C.ldg} - E_{wasted.ldg}\right) \cdot \eta_{breaking} \tag{11}$$

The kinetic energy variation during landing must be calculated using the aircraft mass when it touches the runway m_{ldg} and the aircraft landing speed v_{ldg} as per (11.1):

$$E_{stored\ ldg} = \left[\left[-\frac{m_{ldg}}{2}(v_{ldg})^2\right] - E_{wasted.ldg}\right] \cdot \eta_{breaking} \tag{11.1}$$

The energy wasted due to the opposing force during the aircraft landing ($E_{wasted.ldg}$) can be calculated by using Eq. (12) that it is equal to (12.1), where t_{ldg} is the amount of time it takes for the aircraft to come to a full stop, $F_{o.ldg}$ is the opposing force during landing and a_{ldg} is the aircraft landing deacceleration while breaking:

$$E_{wasted.ldg} = \int_0^{t_{ldg}} F_{o.ldg}\left(v_{ldg} - a_{ldg} \cdot t_{ldg}\right) dt_{ldg} \tag{12}$$

$$E_{wasted.ldg} = F_{o.ldg}\left[v_{ldg} \cdot t_{ldg} - a_{ldg}\frac{t_{ldg}^2}{2}\right]_0^{t_{ldg}} \tag{12.1}$$

The opposing force during landing $F_{o.ldg}$ is mainly composed by the rolling resistance $F_{rr.ldg}$ and by the aerodynamic resistance $F_{ae.ldg}$ as in (13):

$$F_{o.ldg} = F_{rr.ldg} + F_{ae.ldg} \tag{13}$$

The aircraft rolling resistance with landing weight $F_{rr.ldg}$ can be obtained by using (14)

$$F_{rr.ldg} = \frac{m_{ldg} \cdot g \cdot W_{wd} \cdot f}{r_{tire.wing}} + \frac{m_{ldg} \cdot g \cdot N_{wd} \cdot f}{r_{tire.nose}} \tag{14}$$

The aerodynamic resistance is given by using Eq. (15), where $C_{D.ldg}$ is the aircraft landing drag polar coefficient:

$$F_{ae.ldg} = \frac{1}{2}\rho A_{wing} C_{D.ldg} v_{ldg}^2 \tag{15}$$

Taxi-in

The force required to start moving the aircraft after landing ($F_{start.ldg}$) is given by (16):

$$F_{start.ldg} = m_{ldg} \cdot a_{ldg} + F_{o.ldg} \tag{16}$$

The power required to start moving the aircraft $P_{start.ldg}$ is computed by (17):

$$P_{start.ldg} = F_{start.ldg} \times v_{taxi} \tag{17}$$

And the power required to maintain the aircraft moving $P_{taxi.ldg}$ with constant taxiing speed is given by (18):

$$P_{taxi.ldg} = F_{o.ldg} \times v_{taxi} \tag{18}$$

The total energy required for the taxi-in operation ($E_{total\ taxi\ in}$) is given by (19) where $n_{stops.in}$ is the total number of times the aircraft will stop, $E_{start.in}$ is the amount of energy required to start moving the aircraft until v_{taxi}, $E_{taxi\ in}$ is the amount of energy required to maintain the desired taxiing speed and $t_{taxi\ in}$ is the duration of the taxi-in at constant speed.

$$E_{total\ taxi\ in} = n_{stops.in} \cdot E_{start.in} + E_{taxi\ in} \tag{19}$$

Eq. (19) is equal to (19.1):

$$E_{total\ taxi\ in} = n_{stops.in} \cdot \left[P_{start.ldg} \cdot \frac{v_{taxi}}{a_{taxi}} \right] + P_{taxi.ldg} \cdot t_{taxi\ in} \quad (19.1)$$

The energy that can theoretically be stored in the battery pack for each time the aircraft breaks and comes to a full stop during the taxi-in ($E_{stored\ taxi\ in}$) is given by (20) composed of two main components, the kinetic energy variation (ΔE_C), the energy wasted during breaking ($E_{wasted.in}$) due to the opposing force during taxi ($F_{o.in}$) and the system's efficiency ($\eta_{breaking}$).

$$E_{stored\ taxi\ in} = \left[-\frac{m_{in}}{2} (v_{taxi})^2 \right] - E_{wasted.in} \cdot \eta_{breaking} \quad (20)$$

The opposing force during the taxi $F_{o.in}$ is mainly composed by the rolling resistance $F_{rr.ldg}$ and by the aerodynamic resistance F_{ae} as in (21):

$$F_{o.in} = F_{rr.ldg} + F_{ae} \quad (21)$$

The energy wasted during breaking ($E_{wasted.in}$) can be calculated by using Eq. (22):

$$E_{wasted.in} = F_{o.in} \left[v_{taxi} \cdot t_{break} - a_{taxi.breaking} \frac{t_{break}^2}{2} \right]_0^{t_{break}} \quad (22)$$

Electric motor

Taking into account the power required to star moving the aircraft P_{start}, we must now calculate how much power per wheel does the electric motor need to have $P_{motor.wheel}$, taking into account the number of electric motors we need our system to have (n), the motor's efficiency (η_{motor}) and the gear ratio's efficiency (η_{gear}) as given by (23):

$$P_{motor.wheel} = \frac{\frac{P_{start}}{n}}{\eta_{motor} \times \eta_{gear}} \quad (23)$$

The electric motor torque required τ_{motor} is in (24), τ_{wheel} is the torque at the wheel and i is the gear ratio that the ETS will use:

$$\tau_{motor} = \frac{\tau_{wheel}}{i} \quad (24)$$

The wheel torque is composed of the total force applied on the wheel and the tire radius.

These calculations will be done for the moment of maximum effort of the ETS, namely during taxi-out, when the aircraft is at its maximum weight during taxi-out.

For the wing landing gear (25):

$$\tau_{wheel.wing} = \left[\frac{m_{out} \times a_{taxi}}{3} + F_{rr.out.\ wing} \right] \cdot r_{tire.wing} \quad (25)$$

For the nose landing gear (26):

$$\tau_{wheel.nose} = \left[\frac{m_{out} \times a_{taxi}}{3} + F_{rr.out.\ nose} \right] \cdot r_{tire.nose} \quad (26)$$

It is important to notice that the gear ratio has a dual impact on the system. On one hand, increasing its ratio will result in lower motor torque requirement; on the other hand, the required motor rotation speed will increase inversely proportionally. Thus, it is necessary to find an optimal ratio that satisfies these two conditions.

Using the most demanding scenario in terms of angular velocity at which the ETS will operate - the initial landing moment - it is crucial to convert the landing speed into rpm to determine if it falls within the operational limits of the electric motor.

For the wing landing gear, the angular velocity in rpm is given by ω_{wing} (27):

$$\omega_{wing} = \frac{\left(\frac{v_{ldg}}{r_{tire.wing}} \right) \cdot 60}{2\pi} \cdot i \quad (27)$$

For the nose landing gear, the angular velocity in rpm is given by ω_{nose} (28):

$$\omega_{nose} = \frac{\left(\frac{v_{ldg}}{r_{tire.nose}} \right) \cdot 60}{2\pi} \cdot i \quad (28)$$

Battery capacity

The total battery capacity in Ah required for the ETS is given by (29), where $\eta_{baterry}$ is the battery pack system's efficiency:

$$\mathrm{C}_{bat} = \frac{\mathrm{C}_{out} + \mathrm{C}_{in}}{\eta_{baterry}} \quad (29)$$

C_{out} is the battery capacity required during the taxi-out as per (30) and C_{in} the battery capacity required during the taxi-in as indicated in equation (31)

$$\mathrm{C}_{out} = \left[\left(\frac{\mathrm{P}_{start} \times 10^3}{V} \cdot \frac{\frac{v_{taxi}}{a_{taxi}} \cdot n_{stops.out}}{3600} \right) + \left(\frac{E_{taxi\ out}}{V} \right) \right] \quad (30)$$

and

$$\mathrm{C}_{in} = \left[\left(\frac{\mathrm{P}_{start.ldg} \times 10^3}{V} \cdot \frac{\frac{v_{taxi}}{a_{taxi}} \cdot n_{stops.in}}{3600} \right) + \left(\frac{E_{taxi\ in}}{V} \right) \right] \quad (31)$$

Additionally, we should add a safety margin by using a contingency policy, this means we don't want the energy in our battery to be lower than z%, meaning the final battery pack capacity in kWh for the ETS can be computed by (32) where n_{legs} is the number of legs the aircraft needs to do without the ETS being charged using other sources of electric power:

$$\mathrm{C}_{bat.final} = \frac{\left[\mathrm{C}_{bat} + (\mathrm{C}_{bat} \cdot \mathrm{z}\%) \right] \cdot \mathrm{V}}{1000} \cdot \mathrm{n}_{legs} \quad (32)$$

Results

Table 2 shows the main parameters and values that were used to compute the results presented in this chapter. It is important to notice that 96 variables were used to study the ETS, alongside with 60 simulations using Lockheed Martin's Prepar3D flight simulator, several flight plans as well as real-world data provided by NetJets Europe between 2015 and 2019 and Eurocontrol.

The following analysis considers the battery pack to be fully charged for the taxi-out. After applying the variables during this study, it was determined during the taxi-out, where the aircraft weights the most that:

- The taxi-out takes 22 min in total. Taking into consideration, 5 min to allow the engines to warmup prior the apply the takeoff thrust, our system needs to manage 16 min of total taxi-out time and 1 min for pushback. Considering that 10 stops are required, the aircraft will be at constant taxi speed for just under 12 min.
- The power required to start moving the aircraft with m_{out} with an acceleration of 1.39 m/s^2 is approximately 219 kW or 0.68 kWh per cycle.
- The power required to maintain the aircraft with constant taxi speed is approximately 39 kW or 7.53 kWh during the 12 min of constant taxiing speed.

Table 2
Main variables used to study the ETS.

Parameter	Value	Description
Physical Aircraft Specifications		
m_{out} [kg]	8390	Aircraft weight during Taxi-out (EASA 2020)
m_{ldg} [kg]	7730	Aircraft weight during Taxi-in (EASA 2020)
$r_{tire.wing}$ [m]	0.314	Tire Wing Radius (Tires et al., 2021)
$r_{tire.nose}$ [m]	0.189	Tire Nose Radius (Tires et al., 2021)
A_{wing} [m^2]	28.5	Wing area (EASA 2020)
Aircraft Settings		
v_{taxi} [$knots$]	30	Constant taxi speed (maximum aircraft speed during backtrack)
a_{taxi} [m/s^2]	1.39	Taxi acceleration
$a_{taxi.breaking}$[m/s^2]	1.04	Taxi deacceleration while breaking (taking into account pax comfort)
t_{break} [s]	14.8	Amount of time it takes to break the aircraft from v_{taxi}
v_{ldg} [$knots$]	120	Aircraft Landing speed (EASA 2024)
t_{ldg} [s]	38.3	Landing time from v_{ldg} to full stop
a_{ldg} [m/s^2]	1.61	Deacceleration while landing (considering landing safety margins)
$t_{taxi\ out}$ [min]	22	Taxi-out time with 5 min for warmup time (Deonandan & Balakrishnan, 2010)
$t_{taxi\ in}$ [min]	7	Taxi-in time with 3 min for cooldown time (Escapa et al., 2015)
$n_{stops.out}$	10	Number of stops during Taxi-out (considering LEMD airport)
$n_{stops.in}$	3	Number of stops during Taxi-in (considering UUWW airport)
W_{wd} [%]	87	Weight distribution on wing landing gear (Embraer, 2015)
N_{wd} [%]	13	Weight distribution on nose landing gear (Embraer, 2015)
Coefficients		
$C_{D.ldg}$	0.119	Aircraft landing drag polar coefficient (Sun et al., 2018)
$C_{D.taxi}$	0.053	Aircraft taxi drag polar coefficient (Sun et al., 2018)
f [m]	0.008	Rolling Resistance Coefficient (Jazar, 2008)
Physical Constants		
g [m/s^2]	9.81	Gravitational constant
ρ [kg/m^3]	1.225	Air density at 15°C and 1013.25 hPa (International Standard Atmosphere (ISA) 2020)
ETS		
n	3	Number of electric motors
i	3	Gear ratio
η_{motor} [%]	85	Electric motor efficiency (NRDC 2019)
η_{gear} [%]	80	Gear ratio efficiency
$\eta_{breaking}$ [%]	85	Breaking efficiency (NRDC 2019)
η_{system} [%]	85	Overall system efficiency (NRDC 2019)
$\eta_{baterry}$ [%]	90	Battery efficiency
Voltage [V]	800	Battery nominal voltage (Electric Vehicle Database 2023)
z [%]	20	Battery contingency (Burrows, 2024)
n_{legs}	2	Number of flights without ETS being charged using other power sources

- The total energy required for the taxi-out operation is 14.43 kWh (including 0.10 kWh for pushback).
- Each time the aircraft breaks there is 0.168 kWh that can potentially be stored in the battery, this represents 24.7% of the energy required to start moving the aircraft. Combining all 10 stops plus the energy from breaking after pushback the amount of energy recovered adds up to 1.680 kWh this represents 11,6% of the total energy required to taxi-out the aircraft.

Fig. 3 shows the aircraft velocity and energy variation during taxi-out.

During the taxi-in phase:

- The taxi-in phase takes 7 min. Parking takes 1 min. Allowing 3 min for the engines to cooldown, the ETS needs to taxi the aircraft during 4 min in total, of which 1.7 are in constant taxi speed, due to the 3 stops along the way.
- The power required to start moving the aircraft with m_{in} with an acceleration of 1.39 m/s^2 is approximately 202 kW or 0.62 kWh per cycle.
- To maintain the aircraft taxing with constant speed it is required approximately 36 kW or 1.02 kWh over the 1.7 min of constant taxi-in speed.
- The total energy required for the taxi-in operation is 2.98 kWh (including 0.10 kWh for parking).
- From landing the ETS can potentially store just over 8.6 MJ of energy or 2.40 kWh. This represents approximately 80.7% of the total energy required for the taxi-in phase.
- After landing, for each time the aircraft breaks during the taxi-in phase, there is a potential gain of 0.155 kWh, this represents 25.0% of the total energy required to start moving the aircraft. After the 3 stops plus the energy from breaking after the parking operation the amount of energy recovered adds up to 0.465 kWh or 15.6% of the total energy required to taxi the aircraft.

Overall results:

- Considering the parameters on Table 2, for a 17 min taxi-out and a 4 min taxi-in operation the total energy required is 17.41 kWh, from which the ETS can recover 4.55 kWh approximately 26%.

The Table 3 gives the ETS main parameters based on the variables used in the model:

Table 3
ETS main parameters.

Parameter	Value
Electric Motor	
Number of motors	3
Peak Power [kW]	108
Peak Torque [N.m]	503
Nominal Power [kW]	22
Nominal Torque [N.m]	96
Battery	
Nominal Capacity [kWh]	47
Voltage [V]	800
Weight [kg]	230

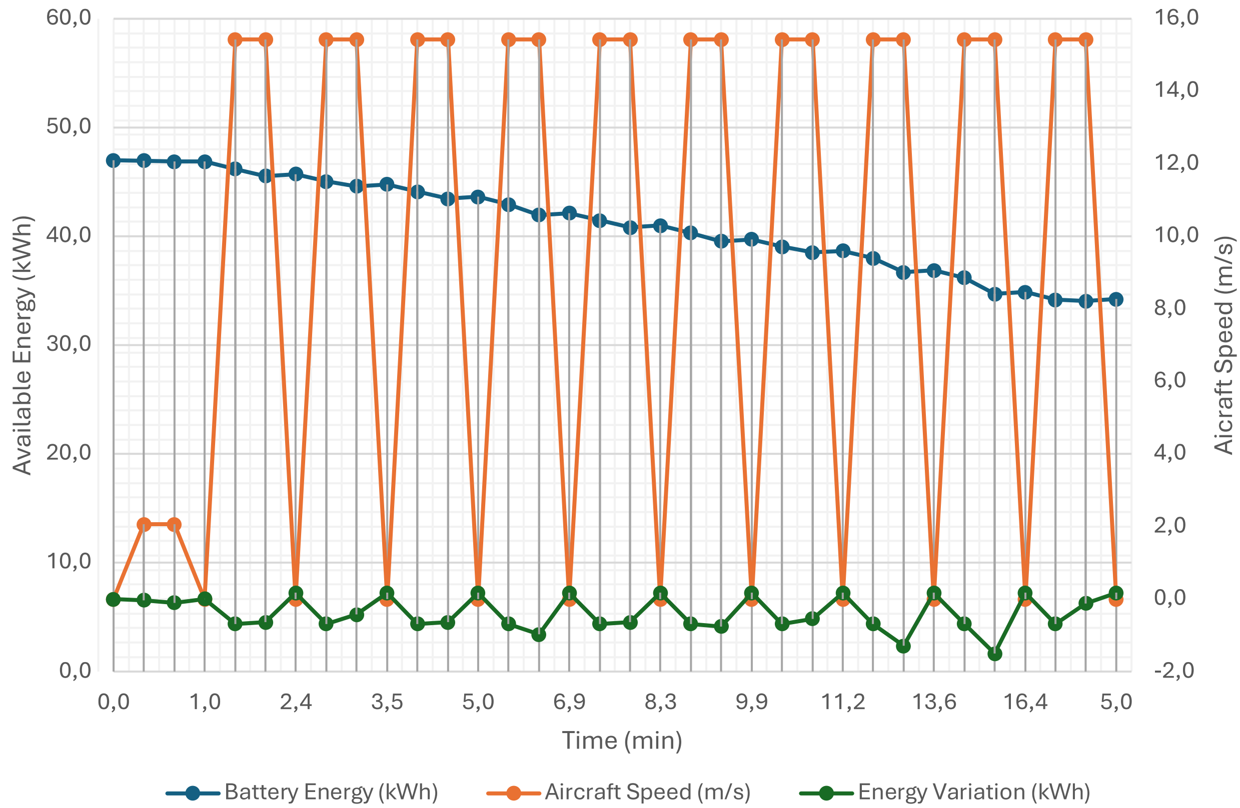

Fig. 3. Aircraft velocity and energy variation during taxi-out.

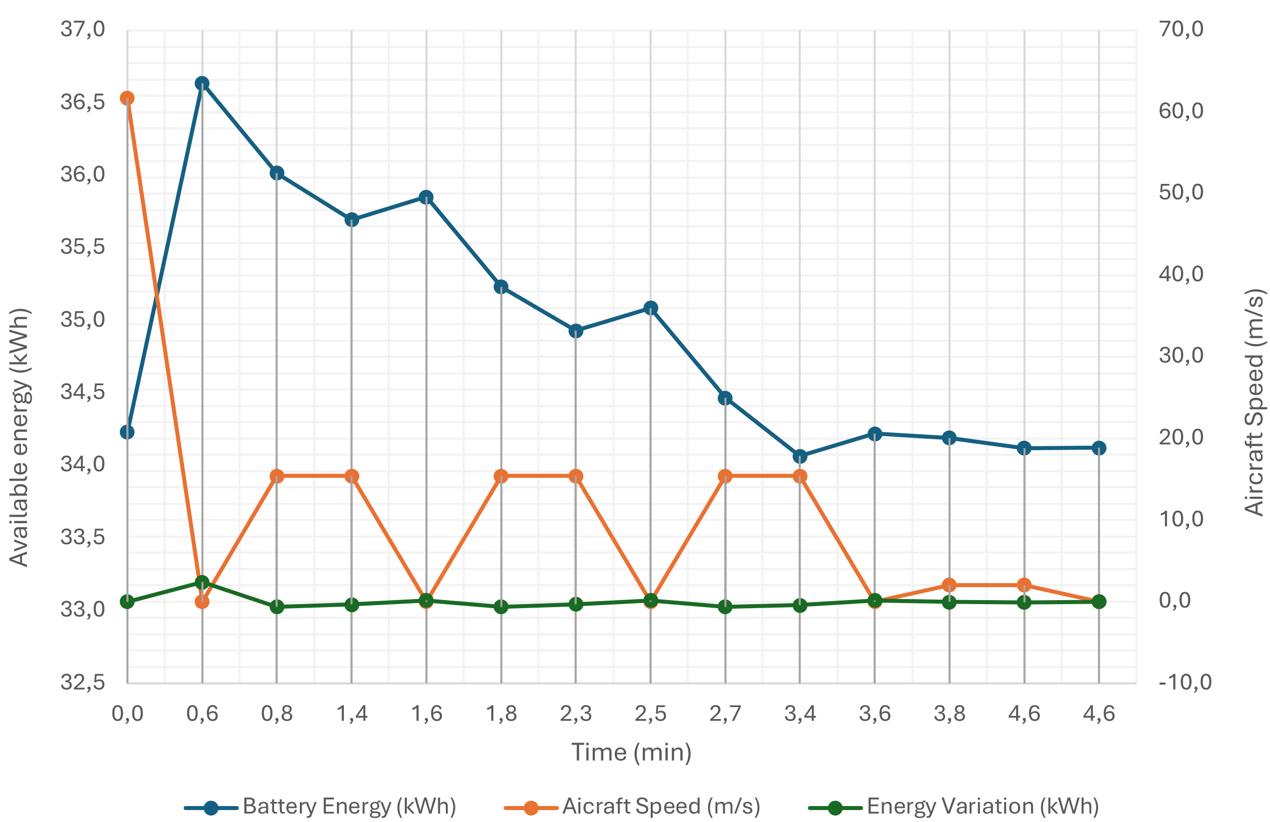

Fig. 4. depicts the aircraft velocity and energy variation during taxi-in.

Fig. 5. TESLA process for recovering batteries.

Potential savings

Table 4 shows the common pollutants emission indices from jet fuel, extensively explain in (Lukic et al., 2019). These indices were used to calculate the amount of pollutants the ETS could save per flight.

During 2018 NetJets Europe made 796 flights with the Phenom 300 CS-PHI and in 2019 the company did 750 flights with CS-PHF, averaging 773 flights per year. According to data from NetJets, IATA and EUROCONTROL, the average taxi-out time was 10 min and 5 min for taxi-in (NetJets, 2020, NetJets, 2019, EUROCONTROL, 2022, EUROCONTROL, 2023). Given this information, by using the ETS it is possible to save up to 21 kg per flight per aircraft (Lockheed Martin, 2024, NetJets, 2019, Jeppesen, 2024). NetJets Europe has 28 Embraer Phenom 300 on their fleet (Flightdb.net 2024) and the average jet fuel price/t in Europe, is approximately 753 €/t (Flightdb.net 2024). Meaning, over a period of 365 days, using the average taxi time and number of flights, ETS could save just more than 454 tons of jet fuel to NetJets Europe's fleet and reduce emissions by 1,457 tons every year. Considering that 48 € could be saved in pushback tractor fees and 88 € in engine wear per flight, if equipped in all aircraft, the ETS can potentially save up to 3,285,860 € to NetJets every year (Motortrend, 2020, CASTELLÓN AIRPORT, 2022).

However, the taxi times used in this case study were the highest registered for NetJets Europe operation between 2015 and 2019. The worst-case scenario was required to properly compute the ETS requirements. This means, under the main conditions and variables presented in Table 2, according to our calculations, simulation results, flight plans and real world data, each Phenom 300 can potentially save up to 62 kg of jet fuel per flight (Lockheed Martin, 2024, NetJets, 2019, Jeppesen, 2024).

Computing the results for the highest taxi times registered and the average number of flights per year, the amount of jet fuel saved by the entire fleet increases to over 1341 tons. Taking into account the costs associated with pushback and engine wear, the company stands to potentially save 3,954,113 € and avoid emissions totaling just above 4,302 tons with the Phenom 300 fleet alone. This means each aircraft can potentially save more than 141,200 € every year.

Besides the financial benefits, using the Electric Taxiing System significantly reduces noise levels, which is particularly important during night operations at airports located in large city centers. Additionally, it provides a more comfortable environment for passengers. (Elliff et al., 2020). Lastly, the Electric Taxiing System (ETS) uses an electric motor that also functions as a generator, reducing the need to use the aircraft brakes. This means brake pads require less frequent replacement, further enhancing the sustainability of this solution.

By using the ETS not only is it possible to save money, but also the environment.

Table 4
Pollutants emission indices from jet fuel.

Pollutants	Jet fuel (g/kg)
HC	3.8
NO_X	9.4
CO	37.6
CO_2	3155

Further considerations

Onboard solutions like ETS have tremendous financial and environmental advantages. Although the ETS is engineered for retrofitting into the aircraft, with its evident benefits during ground operations, a comprehensive analysis into the potential impact of the system's weight during flight is imperative. Using today's technology CATL developed the Shenxing PLUS battery. The system's energy density surpassed the 200 Wh/kg threshold for the first time, reaching 205 Wh/kg. Meaning under this configuration, the battery pack for ETS would weight around 230 kg. Furthermore, the price per kWh in China is 65 €/kWh. CATL dropped that price to 51 €/kWh and the price is expected to be at 33€/kwh as early as next year, meaning the ETS battery pack could cost less than 1551 € per aircraft (CATL, 2024, Wang, 2024). Nevertheless, in the event of weight concerns, mitigating measures such as payload reduction could be considered to offset the additional weight of the ETS Fig. 4.

By using batteries there is also an increase in e-waste. According to the United Nations Institute for Training and Research (UNITAR) worldwide, the annual production of e-waste is rising by 2.6 million tons annually and a record 62 million tons of e-waste was produced in 2022 (United Nations Institute for Training and Research (UNITAR) 2023).

With this concern in mind, Tesla has developed a remarkable process for recovering batteries at the end of their useful life. For every 1000 kWh, it is possible to recover 921 kWh of materials, which will be used in the production of new batteries. This represents a recovery rate of 92.1%, as shown below in Fig. 5 (TESLA 2020).

A final consideration would be to study the ETS described herein either at scale or in a real-world environment in order to validate not only the methodology but also the results presented.

Conclusion

In 2019, the aviation industry quadrupled its emissions, releasing over one billion tons of CO_2 into the atmosphere. To address this, the EU developed the Flightpath 2050 program, aiming for a significant reduction in emissions and a 65% decrease in aircraft noise. On top of that, Flightpath 2050 also stipulates that aircraft movement on the ground must be emission-free during taxiing, leading to the development of external and onboard systems. However, while reducing fuel consumption, both systems still rely on other power sources that use fuel, therefore failing to meet Flightpath 2050′s requirements. This issue led to the development of systems like the Electric Taxiing System (ETS). The ETS is a 100% onboard electric system designed to use only the kinetic energy stored in the battery pack, which is recovered during aircraft landing and braking events during ground handling operations. The ETS is also capable to pushback and parking the aircraft, potentially reducing airport turnaround times by up to 20 min. This reduction is crucial, because over 70% of flight delays are currently caused by issues with aircraft turnaround at airports. Additionally, Flightpath 2050 states that all flights must land with a 1 min margin of error, regardless of atmospheric conditions.

The ETS shows promising results. Each aircraft can save up to 47.9 tons of jet fuel annually, preventing over 153 tons of emissions. Factoring in pushback fees and engine wear, this translates to savings of over 141,200 € per aircraft each year. For NetJets Europe, with its fleet of 28

Phenom 300 aircraft, this translates to potential savings of 3,954,113 € and a reduction in emissions by approximately 4,302 tons annually. It is important to note that the ETS is equipped with an 800V, 47 kWh battery pack capable of handling two flights per day without being charged using other power sources – worst case scenario. This allows the ETS to taxi an Embraer Phenom 300 for a total of 34 min during taxi-out and 8 min during taxi-in.

On top of that, the ETS is designed to be retrofitted and plug-in compatible, meaning the system can be recharged during turnaround time using sustainable airport energy sources. This not only will allow the aircraft to perform beyond its original design without using the main engines for taxiing but also enhances the sustainability of the ETS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Lucas Sampaio: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jorge Costa:** Formal analysis, Validation, Writing – review & editing.

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