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Life Cycle Engineering of future aircraft systems: the case of eVTOL vehicles

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ABSTRACT

This paper introduces the first steps towards a general modelling framework for the integrated life cycle engineering (LCE) of future air transportation systems. The focus of analysis lies on the potential environmental implications of batteries powering electric vertical takeoff and landing aircrafts (eVTOLs), which have emerged as an option for urban air mobility to alleviate automobile traffic in cities. The impact of main influencing factors on the sustainability of eVTOLs is discussed, presenting the main modelling requirements for an LCE framework to accompany the transition towards a more sustainable air mobility.

1. Introduction

The aviation industry accounts for 2.5% of global energy-related CO_2 emissions (Scheffer, 2019) and also contributes to a variety of non-carbon related emissions resulting in further radiative forcing of the climate system (Lee et al., 2009). Given the increasing demand for global air transportation, aviation emissions are growing despite continuing efficiency improvements (ICAO, 2016). In contrast to road transportation, the long life cycle of aircraft technologies implies that by the middle of the century aviation would still be partly powered by fossil fuels. Hence, concerns regarding the future of aviation have increasingly gained relevance. As a response, there is a growing interest towards electric powertrains and alternative fuels (electrofuels and biofuels) for replacing fossil-based combustion engines. Propulsion systems based on batteries, fuel cells and hybrid systems are coming up. Although the underlying new technologies potentially reduce in-flight emissions, the impacts might be redistributed to upstream or downstream stages of the life cycle. Hence, a methodology to assess the environmental implications of these frontier and emerging aviation technologies is necessary. The Life Cycle Assessment (LCA) methodology according to ISO14040 enables a quantification of the environmental burdens of product systems along their life cycle (Hauschild et al., 2017). However, its application often requires high modelling efforts and is limited to the analysis of isolated technologies and specific scenarios, not being able to handle the high data uncertainty and variability of parameters related, for instance, to the regional and temporal differences of electricity grid carbon intensity.

An integrated life cycle engineering (LCE) approach has been proposed for the case of electric vehicles (EVs) (Cerdas et al., 2018). This LCA-based approach allows for the integration of engineering models, addressing the main shortcomings of LCA. Considerably reducing the modelling effort, it enables a better understanding of the implications of emerging technologies by combining different context scenarios and studying the interactions between different designs, product parameters, spatial differences for a better support in design stages. This paper introduces the first steps towards a framework for the LCE of future aircraft technologies. As an example, electric vertical takeoff and landing (eVTOL) aircrafts are the focus of analysis.

2. eVTOL for urban air mobility

Given the increasing congestion in cities and growing concern around high level of air pollution, new mobility technologies and

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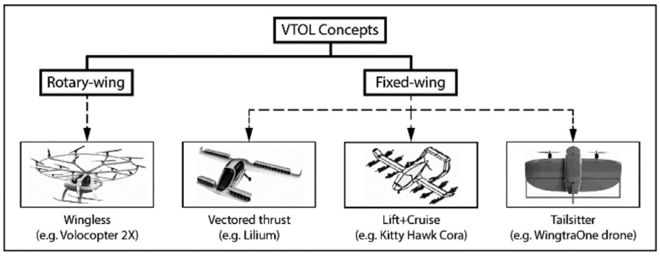

Fig. 1. VTOL aircraft designs from (11) and (12).

business models ranging from micro-mobility (e.g. electric scooters, electric bikes) to long distances (e.g. ride-hailing and car sharing) are emerging as options to cope with these urban transportation challenges (Fredericks et al., 2018). In addition, the increasing interest towards urban air mobility (UAM) and advances in battery technology have posed eVTOL aircrafts as a promising future market in congested areas and limited geographic regions (Kasliwal et al., 2019). eVTOLs are characterized by their ability to vertically takeoff and land, without the need of a runway, which can be combined with an efficient aerodynamic flight of an airplane (Kasliwal et al., 2019). They can achieve an operating range up to 200 nautical miles (nmi) and a cruise speed up to 200 knots (kt), accommodating a maximum of 6 passengers (PAX). There are currently 24 all-electric VTOLs with fixed-wings under development (Gnadt et al., 2019). A key technology is the distributed electric propulsion (DEP), which leads to new optimized designs opportunities, allowing significant reductions in operating costs, noise and emissions.

Two main VTOL groups have been reported in the literature: rotary-wing cruise and fixed-wing cruise (Shamiyeh et al., 2018) (see Fig. 1). The Multirotor design belongs to the rotary-wing category and is efficient in hover, however without a wing for a higher cruise efficiency (e.g. Volocopter 2X). In the fixed-wing group, three main configurations are possible: vectored thrust, lift plus cruise, and tailsitter. Vectored thrust VTOLs use the same propulsion system for hover and cruise flight and have a wing leading to an efficient cruise (Bacchini and Cestino, 2019). They can be divided into tilt-prop (e.g. Joby S2 VTOL), tilt-wing (e.g. Aurora LightningStrike VTOL) and tilt-duct (e.g. Lilium Jet) (Electric VTOL News).

The lift plus cruise design also has a wing but uses two different propulsion systems for hover and cruise segments (e.g. Kitty Hawk Cora, Aurora Flight Sciences VTOL) (Bacchini and Cestino, 2019). Although less efficient in hover flight and with higher noise emissions than multirotors, the fixed-wing forward flight leads to significantly better efficiency in cruise and higher speed (Shamiyeh et al., 2018). In contrast to the aforementioned designs, the tailsitter takes off and lands with a vertical fuselage orientation, tilting the entire aircraft for the horizontal flight.

Finding the best configuration among these various VTOLs design depends mainly on the mission (Bacchini and Cestino, 2019). While multirotor configuration has a higher hover efficiency and low complexity, its range limitation makes it unable to perform long-range missions.

While plenty of research has been conducted on eVTOL configurations (e.g. analyzing cost reduction using Multidisciplinary Design Analysis & Optimization (MDAO) (Duffy et al., 2017), investigating sizing effects and trade-offs between hover and cruise efficiencies (Shamiyeh et al., 2018), evaluating the attractiveness of a hybrid-electric solution for mid-ranges (Finger et al., 2018) etc.), only few studies have assessed their sustainability. Kasliwal et al. (2019) addressed the use stage burdens in terms of primary energy and greenhouse gas (GHG) emissions in comparison with internal combustion engine vehicles (ICEV). Over long distances, eVTOLs outperform cars, however for trips shorter than 35 km, the burden from the highly energy-intensive hover phase dominates the flight profile, leading to higher GHG emissions. Additionally, the burdens are significantly influenced by the area of operation and number of PAX on-board, being important to ensure the maximum seat utilization for the viability of VTOLs. A 3-PAX VTOL outperforms a 1.54 –PAX ICEV and battery EVs (BEVs) on a PAX-km travelled (pkm) basis by 52% and 6%, respectively. Extending these findings, André and Hajek (André and Hajek, 2019) benchmarked the impacts of three eVTOLs concepts by conducting an LCA, including the burdens associated with vehicle production. The results confirm the dependence of carbon emissions on the mission hover share. Considering a hover share of 21% and a maximum seat utilization (PAX = 6), the minimum mission's GWP would range between 160 and 80 g CO_2e per pkm for U.S and Canada grid carbon intensities, respectively. In contrast, BEVs correspond to a potential impact of 58g CO_2e per pkm for the average 1.54 PAX in a vehicle.

While these approaches focused on the key enablers for a more sustainable eVTOL operation (e.g. grid carbon intensity, seat utilization, battery cycles etc.), the influence of different battery technologies on the environmental impact in battery production and operation remains unclear. Additionally, the impact of increasing the battery system size for achieving longer ranges needs to be further explored. For these investigations, a general fixed-wing aircraft is applied.

3. Methods

In order to address the environmental impacts in aviation and to support the engineering of future aircraft systems and UAM concepts, a modelling approach considering the interactions between foreground and background systems is required. Foreground systems comprise all processes specific to the product system (Cerdas et al., 2018). In contrast, background systems, despite not being the focus of analysis, have a significant influence on the foreground system. Data availability is required for building life cycle inventory models, including all material and energy flows employed throughout the entire life cycle of aircraft components. Within the foreground system, this includes defining parameters such as type and mass of materials, manufacturing processes, and the consumption of resources. In the context of background systems, data models for the energy supply, materials supply, temporal and spatial contexts need to be considered. As emphasized by Ploetner et al. (2016), the local electricity mix can strongly influence the life cycle impacts of electric aircrafts, influenced by the share of renewable energy. In addition, materials supply chain within the global market, which are related to different production technologies, the progress forecast in the development of technologies with a long lifetime, the weather and usage scenario (e.g. seat utilization, flight distance, usage intensity, auxiliaries, such as heating, air conditioning) influence the environmental impact.

Following this approach, a methodology for a generic model is presented for estimating the required battery capacity for flying a reference mission and the environmental burdens associated with its operation and production.

3.1. Flight mission profile

The flight mission profile consists of vertical takeoff, fixed-wing climb, fixed-wing cruise, fixed-wing descent and vertical landing. Since there is still no official regulation for VTOLs regarding their energy reserve requirements for emergencies, a reserve of 20% of the battery's capacity is assumed. Each phase of the representative mission is illustrated in Fig. 2. As the taxi phase of VTOLs is generally short and corresponds to low power requirements relative to the flight, it is not considered in the model.

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Table 1
Input parameters

Parameter	Value	Source
Payload mass (m_{pay})	87.5*(PAX+1)	(Kasliwal et al., 2019)
Battery mass (m_{batt})	C_{batt} * (Wh/kg)	(Fredericks et al., 2018)
Empty weight ratio (W_e/W)	0.55	(Fredericks et al., 2018)
Takeoff mass (m)	(m_{pay}+m_{batt})/(1-W_e/W)	(Fredericks et al., 2018)
Gravitational acceleration (g)	9.81 m/s^2	–
Cruise lift-to-drag ratio (L/D)	17	(Kasliwal et al., 2019)
Climb lift-to-drag (L/D_{min})	0.866*(L/D)	(Fredericks et al., 2018)
Disk loading (δ)	450 N/m^2	(Kasliwal et al., 2019)
Air density (ρ)	1.225 kg/m^3	(Kasliwal et al., 2019)
Wing loading (W/S)	63 kg/m^2	(Fredericks et al., 2018)
Zero-lift drag coefficient(C_{D0})	0.03	(Fredericks et al., 2018)
Lift-dependent factor (K)	0.0288	(Fredericks et al., 2018)
Hover system efficiency (η_h)	0.63	(Kasliwal et al., 2019)
Climb/cruise efficiency (η_c)	0.765	(Kasliwal et al., 2019)
Cruise true airspeed (V)	241.4 km/h	(Kasliwal et al., 2019)
Climb rate (ROC)	1000 fpm	(Kasliwal et al., 2019)
Descent rate (ROD)	1000 fpm	(Kasliwal et al., 2019)
Cruise altitude	1000 ft	(Uber 2016)

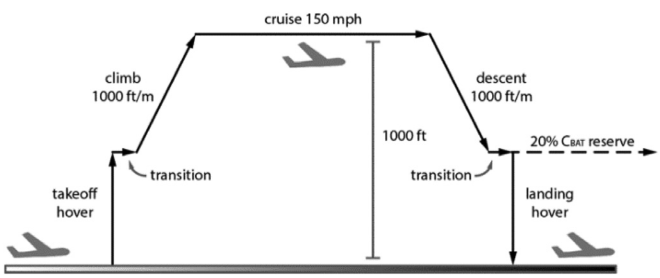

Fig. 2. Flight mission profile

3.2. Power requirement model

The power requirement model used for this study follows the physics-based approach presented by Kasliwal et al. (2019). Table 1 lists the input parameters assumed for the model calculations. For each phase of the mission, average power draw calculations are given by Eqs. (1)–(4). As observed, the requirements are dependent on the takeoff mass (m), which consists of the sum of payload mass, battery mass and structural mass, given by the empty weight ratio (W_e/W). It is assumed a payload mass of 87.5 kg per PAX and the pilot. The battery capacity (C_{batt}) is estimated based on the simulated reference mission range (r); this is further detailed in Section 3.3. Different specific energies (Wh/kg) from cell chemistries were considered for simulation (described in Section 3.4) from which the respective battery mass (m_{batt}) was derived.

Eq. (1) provides the average power draw for takeoff and landing phases. It is assumed that each phase lasts 30 s. The transition duration is set to 60 seconds with hover power (Fredericks et al., 2018).

$$P_{hover} = \frac{mg}{\eta_h}\sqrt{\frac{\delta}{2\rho}} \tag{1}$$

For climb and descent phases, the power draw follows Eq. (2). The corresponding climb/descent velocity profile (V_{climb}) (see Eq. (3)) is determined according to the model presented by Fredericks et al. (2018), where wing reference area (S) is defined by the wing loading (W/S). Additionally, lift-to-drag ratio needs to be adjusted for climb/descent conditions, reducing by 13% as shown in Table 1. Finally, Eq. (4) provides the power required for cruise.

$$P_{climb/descent} = \frac{mg}{\eta_c}\left(ROC + \frac{V_{climb}}{L/D_{climb}}\right) \tag{2}$$

$$V_{climb} = \sqrt{\frac{2mg}{\rho S}\sqrt{\frac{K}{3C_{D0}}}} \tag{3}$$

$$P_{cruise} = \frac{mg}{L/D}\frac{V}{\eta_c} \tag{4}$$

3.3. Battery system modelling

For the power requirement model, an initial estimation of the battery capacity (C_{batt}) is needed, together with an assumed payload and structural mass. Based on a battery pack specific energy (Wh/kg), an initial battery mass can be calculated for the assumed capacity. Having defined the power requirement for each time step, the total energy required (ΔE_{batt}) is calculated by a simple integration of the power (P) over the flight time (t) (see Eq. (5)). Subsequently, the State of Charge (SoC) of the battery is determined according to Eq. (6) and the model verifies whether it lies within the permitted bandwidth. The Depth of Discharge (DoD) is limited to 60%, assuming an additional 20% reserve capacity, complying with the requirements of minimum 20% SoC to preserve the battery cycle life (Uber 2016).

$$\Delta E_{batt}(t_k) = \int_{t_{k-1}}^{t_k} P(t)dt \tag{5}$$

$$SOC(t_k) = E(t_k)/C_{batt} \tag{6}$$

Depending on the SoC at the end of the mission, a new battery capacity is estimated by adjusting the energy needed to complete the mission without running out of energy. The model then recalculates the minimum energy required based on the new capacity estimated (see Fig. 3). It should be noted that these endurance criteria do not ensure that the battery system is able to provide the full hover power demanded by the electric motor. High specific power batteries are required to provide enough power for eVTOLs.

3.4. Environmental impact assessment

As the environmental impact in battery production strongly depends on the cathode material (André and Hajek, 2019), different battery cell chemistries are considered for analysis: Nickel Manganese Cobalt oxide (NMC) using graphite anodes but different cathode active materials ($LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$, $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$, $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$, $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ and $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$),

Table 2
Battery cell specifications for Nickel Manganese Cobalt oxide (NMC), Iron Phosphate (LFP), Nickel Cobalt Aluminum oxide (NCA) and Lithium Sulfur battery (LSB-Li).

Cathode	Energy (Wh)	Spec. energy (Wh/kg)	Expected (Wh/kg)	Life cycles	GWP ($kgCO_2e$)
111-NMC	312.64	145.90	–	1250	36.19
442-NMC	318.90	149.41	–	1250	35.88
532-NMC	325.03	152.89	–	1250	35.34
622-NMC	336.81	159.29	–	1250	35.28
811-NMC	359.08	172.21	302 (Placke et al., 2017)	1250	35.29
LFP	237.98	119.15	–	2000	33.86
NCA	359.08	172.21	–	1284	35.29
LSB-Li	348	290	600 (Fotouhi et al., 2017)	714	24.36

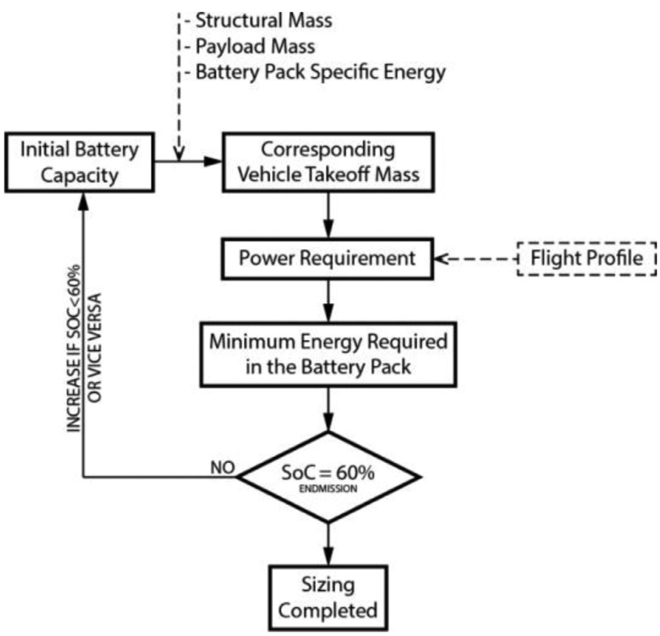

Fig. 3. Flowchart for determining the minimum battery capacity required for powering the eVTOL for a specific distance per charge

Lithium Iron Phosphate battery (LFP), Nickel Cobalt Aluminum oxide (NCA) and Lithium Sulfur with lithium metal foil as anode (LSB-Li).

Regarding the geometry of the cell, the specifications of the Samsung SDI-94 are shown in Table 2. For each cell, the state of the art specific energy, which comes from the project "BenchBatt" (Betz et al., 2019), together with the expected value in future and GWP associated with its production are listed. Additionally, the number of life cycles were retrieved from literature for each of the battery chemistries analyzed NMC (André and Hajek, 2019), LSB (Qiu et al., 2014), LFP (Ioakimidis et al., 2019) and NCA (Popp et al., 2016). In EVs, the share of active mass at a battery pack level has been reported to vary between 60% and 70% (Diekmann et al., 2017, Cerdas et al., 2018, Ellingsen et al., Feb. 2014). We assumed this share to be 90% of the battery pack required, as weight reduction and space optimization is a more critical issue for eVTOLs compared to BEVs. This assumption is tested in a sensitivity analysis.

Based on the required battery capacity for flying a reference mission, the model calculates the number of cells. The cradle to gate GWP impact of the material required for each cell chemistry ($EI_{batt,\ prod}$) is calculated using the computational LCE approach developed in Cerdas et al. (2018). The results are listed in Table 2. For compiling the impact associated with the use stage, grid carbon intensities are taken from ecoinvent. Germany is the country selected for analysis (611 gCO_2e/kWh). Brazil, Australia and China

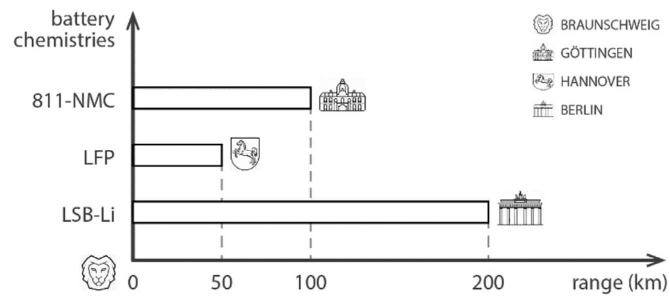

Fig. 4. Maximum range (km) per charge achieved by 811-NMC, LFP and LSB-Li chemistries considering a payload of 175 kg (1 passenger + pilot).

are also chosen for benchmarking purposes with 285 gCO_2e/kWh, 970 gCO_2e/kWh and 1098 gCO_2e/kWh, respectively.

Following a well-to-shaft analysis (André and Hajek, 2019), the total GHG impact consists of battery production ($EI_{batt,\ prod}$) and operation impacts (see Eq. (7)). The operation impact is given by the grid carbon intensity (EI_{grid}) per kWh shaft energy, the energy required for a battery cycle, which depends on the range (r) defined for the reference mission, and the number of cycles (n_{cycles}) assumed.

$$EI_{Batt} = EI_{grid} * \Delta E(r) * n_{cycles} + EI_{batt,prod} \tag{7}$$

4. Results and discussion

As shown in Table 2, the specific energy values of the considered cell chemistries vary significantly, which not only influence their environmental impact but particularly the practical achievable range per charge. As shown by Breguet range equation (Kasliwal et al., 2019), battery specific energy is the main limiting factor for VTOL range. Low specific energy chemistries (e.g. LFP) are insufficient for achieving a practical range of 100 km, since the large battery required makes the system technically unfeasible. Fig. 4 illustrates the effect of the specific energy on the practical range using 811-NMC, LFP, and LSB-Li.

A first analysis is conducted on the influence of different cathode materials on the environmental impact of battery production and operation over its life cycle for a mission of 50 km. Different life cycles are assumed for each chemistry, as listed in Table 2. Fig. 5 (a) shows the lower potential GWP impact of LSB-Li, given its higher specific energy and lower GWP of the cell. In contrast, LFP has the lowest specific energy, which requires significantly larger battery system to perform the same mission, reflecting in the higher emissions from battery production. Another relevant finding concerns the considerably higher share of carbon impact in operation. This results from the higher power demand for eVTOLs with heavier batteries, and larger electricity consumption per charge, which in addition to a longer cycle life leads to a higher life cycle impact. Additionally, the impact of seat utilization on the total emissions is addressed for LSB-Li on a PAX-km travelled basis.

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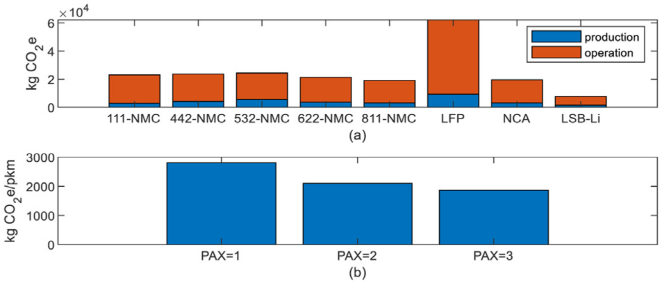

Fig. 5. (a) GHG emissions of battery production and consumption of electric energy during life cycle operation. (b) Total emissions from LSB-Li production and 100 km range for three scenarios (1, 2, 3 PAX) on PAX-km travelled basis.

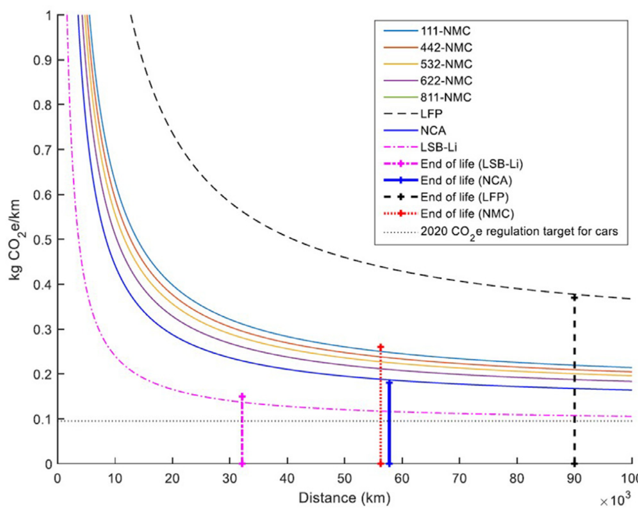

Fig. 6. GHG emissions with respect to the distance travelled during life cycle operation, including battery production and consumption of electric energy. Black dashed line on 0.095 kg CO_2e/km indicates the 2020 CO_2e regulation target for road passenger cars.

[Fig. 5](b) shows the benefit of redistributing the burden over more PAX, reducing the GHG emissions per km travelled.

In order to illustrate the impact of amortizing the fixed burden from the battery production over the distance, the total GHG emissions per km travelled is computed. Fig. 6 shows the tradeoff between emissions and cycle life. Even though LSB-Li presents higher specific energy, resulting in the capability of achieving longer ranges per cycle or requiring less energy for a shorter mission, and consequently lower emissions, the higher degradation rate restricts considerably its lifetime, requiring to be replaced well before the other technologies (as illustrated in Fig. 6, around 32.000 km) and accounting for further battery production burdens. On the other hand, LFP is capable of achieving almost 3 times the total distance of LSB-Li, however significantly higher emissions are associated with it and the less performance in terms of specific energy strongly affects its practical range per charge. Extending the findings on whether VTOLs outperform cars, a comparison of CO_2e emissions from battery technologies for powering eVTOLs against road vehicles is conducted. Fig. 6 shows the 2020 CO_2e regulation for road passenger cars, restricting the emissions to 95 g CO_2e/km. Using current battery technologies, GHG emissions per km do not achieve this target before its replacement.

However, considering the expected development in specific energy of battery technologies, the potential of promising chemistries for powering eVTOLs in the future is assessed. Assuming the same factor of cell energy and GWP (Table 2), results revealed significantly longer total flight distances for the batteries, due to the capability of achieving longer ranges per charge. Total GWP per km for LSB-Li break even with the 2020 target per passenger cars at 100.000 km, before its replacement. On the other hand, 811-NMC achieve a minimum of 0.2 kg CO_2e/km at its current end-of-life. Alongside with enhanced specific energy, improvements in terms of battery cycle life are also expected in the next years (Placke et al., 2017).

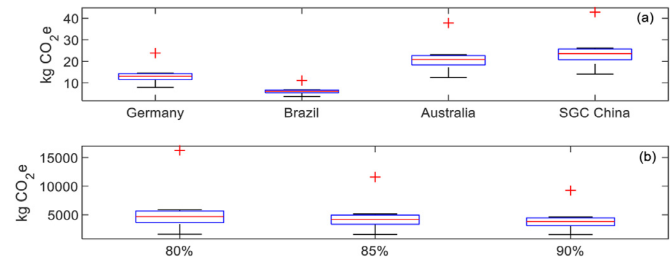

Fig. 7. (a) Variability of GHG emissions per charge from eVTOLs operation (NMC, LFP, NCA and LSB-Li) in Germany, Brazil, Australia and State Grid Corporation China (SGC China). (b) Effect of varying the share of active mass at battery pack on emissions from battery production (NMC, LFP, NCA and LSB-Li). The red cross sign indicates the highest emissions from LFP, whereas the bottom lines correspond to the lowest emission from LSB-Li. The red line in the middle shows the median value of emissions among the chemistries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Furthermore, the impact of different grid carbon intensities on the emissions from eVTOLs operation is addressed. Fig. 7(a) illustrates the variability of emissions from the different battery chemistries under analysis. The lower grid carbon intensity of Brazil, due to its higher share of renewables in the energy mix, results in significantly lower emissions in comparison with the other countries; particularly with China, since most of its electricity comes from coal. Additionally, the effect of varying the share of active mass at a battery pack level is shown in Fig. 7(b). While for most of the chemistries, only a small change in the emissions is observed, emissions from LFP production are largely affected by varying the active mass. This is explained by LFP's lower specific energy, which has a direct implication on its weight and required power, leading to unfeasible battery sizes for achieving the same range as the other chemistries.

5. Conclusions and outlook

This paper introduces an integrated LCE approach for future aircraft systems, which enables a combination of a large number of technologies, mobility scenarios, considering the effects of regional and temporal contexts. This allows for consistent analyses and optimization of design parameters with respect to environmental impacts, supporting engineers, technology developers, and decision makers towards a more sustainable aircraft design and operation. Hence, this modelling approach could contribute to improve the widespread applicability of the LCA methodology in the manufacturing industry, enhancing therefore LCE industry activities.

Our analysis gives a first estimation on potential environmental burdens from production and operation of batteries powering eVTOLs. Even though the GHG emissions from current technologies do not reach the 2020 regulation target of 95 g CO_2e/km, advancements in LSB technology towards higher specific energies and longer lifetime would help to achieve this goal, as more renewable generation is connected to the grid. Alongside with these aspects, consumer adoption is an important factor for the feasibility of eVTOLs.

Hence, given ongoing improvements in LSB, a more promising scenario for eVTOLs to cope with transportation challenges can be expected in the next years. However, for accurate statements regarding their life cycle sustainability, further investigation incorpo-

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rating vehicle production and end-of-life needs to be conducted, benchmarking with electric cars.

CRediT authorship contribution statement

Sofia Pinheiro Melo: Investigation, Conceptualization, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Felipe Cerdas:** Investigation, Conceptualization, Methodology, Writing - review & editing, Project administration. **Alexander Barke:** Conceptualization, Methodology. **Christian Thies:** Conceptualization, Project administration. **Thomas S. Spengler:** Supervision, Funding acquisition. **Christoph Herrmann:** Conceptualization, Resources, Supervision, Writing - review & editing, Funding acquisition.

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References

Scheffer, S., 2019. Aviation: Tracking Clean Energy Progress. International Energy Agency [Online]. Available: https://www.iea.org/tcep/transport/aviation/ .
Lee, D.S., et al., 2009. Aviation and global climate change in the 21st century. Atmos. Environ..
ICAO, 2016. On Board: a Sustainable Future — 2016 Environmental Report.
Hauschild, M.Z., Herrmann, C., Kara, S., 2017. An integrated framework for life cycle engineering. Procedia CIRP 61, 2–9.
Cerdas, F., Thiede, S., Herrmann, C., 2018. Integrated computational life cycle engineering—application to the case of electric vehicles. CIRP Ann..
Fredericks, W.L., Sripad, S., Bower, G.C., Viswanathan, V., 2018. Performance metrics required of next-generation batteries to electrify vertical takeoff and landing (VTOL) aircraft. ACS Energy Lett..
Kasliwal, A., et al., 2019. Role of flying cars in sustainable mobility. Nat. Commun..
Gnadt, A.R., Speth, R.L., Sabnis, J.S., Barrett, S.R.H., 2019. Technical and environmental assessment of all-electric 180-passenger commercial aircraft. Prog. Aerosp. Sci. 105 (November), 1–30.
Shamiyeh, M., Rothfeld, R., Hornung, M., 2018. A performance benchmark of recent personal air vehicle concepts for urban air mobility. In: 31st Congr. Int. Counc. Aeronaut. Sci. ICAS 2018.
A. Bacchini and E. Cestino, “Electric VTOL configurations comparison,” Aerospace, 2019.
“Electric VTOL News,” Vertical Flight Society. [Online]. Available: https://evtol.news/.
“Wingtraone Tailsitter drone.” [Online]. Available: https://wingtra.com/mapping-drone-wingtraone/.
Duffy, M.J., Wakayama, S., Hupp, R., Lacy, R., Stauffer, M., 2017. A study in reducing the cost of vertical flight with electric propulsion. Annu. Forum Proc. – AHS Int..
D. F. Finger, F. Götten, C. Braun, and C. Bil, “Initial sizing for a family of hybrid-electric VTOL general aviation aicraft,” 2018.
N. André and M. Hajek, “Robust environmental life cycle assessment of electric VTOL concepts for urban air mobility,” 2019.
Ploetner, K.O., Miltner, L., Jochem, P., Kuhn, H., Hornung, M., V, B.L., 2016. Environmental life cycle assessment of universally-electric powered transport aircraft. Dtsch. Luft- und Raumfahrtkongress.
Uber, “Uber elevate: fast-forwarding to a future of on-demand urban air transportation,” 2016.
Betz, J., Bieker, G., Meister, P., Placke, T., Winter, M., Schmuch, R., 2019. Theoretical versus practical energy: a plea for more transparency in the energy calculation of different rechargeable battery systems. Adv. Energy Mater..
Y. Qiu et al., “High-rate, ultralong cycle-life lithium/sulfur batteries enabled by nitrogen-doped graphene,” 2014.
C. S. Ioakimidis, A. Murillo-marrod, A. Bagheri, D. Thomas, and K. N. Genikomsakis, “Life Cycle Assessment of a Lithium Iron Phosphate (LFP) electric vehicle battery in second life application scenarios,” 2019.
H. Popp, J. Attia, F. Delcorso, and A. Trifonova, “Lifetime analysis of four different lithium ion batteries for (plug – in) electric vehicle,” 2016.
Diekmann, J., et al., 2017. Ecological recycling of lithium-ion batteries from electric vehicles with focus on mechanical processes. J. Electrochem. Soc..
Cerdas, F., Andrew, S., Thiede, S., Herrmann, C., 2018. Environmental aspects of the recycling of lithium-ion traction batteries. In: Lithorec.
Ellingsen, L.A.-W.W., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O., Strømman, A.H., 2014. Life cycle assessment of a lithium-ion battery vehicle pack. J. Ind. Ecol..
Placke, T., Kloepsch, R., Dühnen, S., Winter, M., 2017. Lithium ion, lithium metal, and alternative rechargeable battery technologies: the odyssey for high energy density. J. Solid State Electrochem..
Fotouhi, A., Auger, D.J., O'Neill, L., Cleaver, T., Walus, S., 2017. Lithium-sulfur battery technology readiness and applications – a review. Energies.