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ScienceDirect

Procedia CIRP 98 (2021) 660–665

www.elsevier.com/locate/procedia

28th CIRP Conference on Life Cycle Engineering

Life cycle sustainability assessment of potential battery systems for electric aircraft

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Abstract

The Flightpath 2050 strategy sets ambitious goals for aviation to reduce its environmental impacts. Therefore, new propulsion concepts that avoid in-flight emissions are being developed. Particular attention is given to (hybrid) electric propulsion systems based on batteries, fuel cells, and synthetic fuels that replace the conventional jet engines. This paper assesses the environmental, economic, and social impacts of eight potential battery systems for short-range aircraft from a life cycle perspective and conducts a pre-selection of suitable technologies. The results indicate that lithium-sulfur batteries are advantageous compared to lithium-ion batteries in terms of environmental as well as social and economic impacts.

Keywords: Life Cycle Sustainability Assessment, Electric Aircraft, Batteries

1. Introduction

The demand for flights has grown considerably over the past decades. It is expected to increase even further due to the continuing globalization and the availability of tickets at moderate fares [1]. Recent studies of Airbus predict that the demand for flights will increase by up to 4.5% annually, which would lead to a doubling of air traffic every 16 years [2]. While this growth is desired from an economic perspective, it is also associated with extensive negative environmental impacts. Especially the emission of greenhouse gases (GHG), such as carbon dioxide (CO_2), is associated with unwanted and long-lasting effects on the climate due to increased global warming [3]. While the aviation sector was responsible for 2.6% of the total global CO_2 emissions in 2017, the projected increase in travel demand would cause the aviation-induced CO_2 emissions to triple until 2050, even if fuel efficiency improvements of approximately 25% would be achieved with each new aircraft generation [4]. Furthermore, it has been demonstrated that the impacts of emissions at high altitudes are more severe than from ground-level emissions [5].

In order to mitigate these impacts, various programs and strategies have been developed. For example, airlines are obligated to participate in the European Union's Emissions Trading System for intra-European flights [6]. Simultaneously, the aviation sector has set itself ambitious goals through the planned introduction of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the development of the Flightpath 2050 strategy. The latter envisages the emission reductions from aircraft by 75% for CO_2, 90% for nitrogen oxides (NO_x), and 65% for noise until 2050 [7].

A first measure to achieve these ambitious goals is the continuous improvement of aircraft fuel efficiency. However, the possible efficiency improvements are finite, and the currently achievable improvement rates of up to 2% annually are not sufficient to achieve the long-term emission

10.1016/j.procir.2021.01.171

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reduction goals [8]. Consequently, radical changes in the propulsion systems of aircraft are required.

Potential approaches to replace the fossil fuel-powered jet engines completely or at least partially include synthetic fuels, battery-electric or fuel cell-based electric propulsion systems, as well as hybrid concepts. While synthetic fuels and hybrid concepts only reduce CO_2 emissions to a certain extent, fuel cell-based propulsion systems eliminate them during flight operation. Nevertheless, none of these three approaches eliminates all of the non-CO_2-emissions, such as water vapor, sulfur dioxide, NO_x, particulate matter, and soot, completely. These emissions represent about 60% of an aircraft's total emissions by mass and have climate-damaging effects as well as other harmful effects on the environment [3,9]. A promising approach that could eliminate both types of emissions during the flight are full-electric propulsion systems. These systems are powered by electricity instead of kerosene and consist of propellers that generate the thrust for flight operation, electric motors that drive the propellers, and batteries used for energy storage [4,9].

However, the specific energy of the currently available battery technologies is still limited. Therefore, the achievable flight ranges with full-electric propulsion systems are much shorter compared to their conventional counterparts. Furthermore, the production of batteries involves energy-intensive processes with negative environmental impacts and rare and critical materials associated with various social risks, such as poor working conditions [4,10].

The ongoing technological developments of battery technologies promise substantial increases in specific energy. It is still difficult to quantify an exact value, but it is conceivable that small passenger aircraft can fly fully electric in the future. In order to develop a propulsion concept that is not only technologically feasible but also sustainable from the environmental, economic, and social perspective, a pre-selection of potential battery systems is necessary and should be carried out in the early development stages.

This contribution aims to carry out this pre-selection based on the current state of research on battery technologies and provide support for decisions regarding potentially suitable battery systems for use in electric propulsion concepts. For this purpose, a Life Cycle Sustainability Assessment (LCSA) approach is used to assess eight alternative battery systems regarding their environmental, economic, and social impacts in the stages of raw materials extraction and production. Based on the assessment results, the most promising battery systems are identified.

The remainder of this article is structured as follows. A brief literature overview on existing sustainability assessment approaches for electric aircraft based on battery systems is presented in Section 2. In Section 3, the framework for the sustainability assessment of this article is described. The results of the sustainability assessment and the pre-selection of potential battery systems are presented in Section 4. In Section 5, the paper concludes with a discussion of the main findings and an outlook on future research.

2. Literature overview

This section provides a brief overview of previous research concerning the sustainability assessment of electric aircraft. It builds on the literature review by Melo et al. [11], in which approaches for the sustainability assessment of emerging aircraft technologies are examined.

A promising study is presented by Ploetner et al. [12]. The authors conduct a sustainability assessment focusing on the GHG emissions of a conceptual electric aircraft, the so-called Ce-liner. Their results show that the production of battery systems for electric aircraft leads to high GHG emissions, which can be compensated during flight operation. It is also shown that the underlying electricity mix is one of the most significant influencing factors here.

A similar study is conducted by Gnadt et al. [4]. The authors analyze a full-electric 180-passenger aircraft based on an Airbus A320neo and compare the performance with a conventionally-powered aircraft. Their results show that an increase of the battery pack's specific energy by the factor of four is required to make electric flying competitive on short-range flights.

Schäfer et al. [9] scrutinize electric aircraft's economic and environmental implications and derive requirements for suitable battery systems. The authors point out that suitable battery systems need higher specific energy and lower production cost. At the same time, the energy sector must undergo a significant transformation towards renewable energies. If these conditions are given, electric aircraft can become a promising alternative on distances up to 1,100 km.

Johanning and Scholz [13] analyze an electric-powered aircraft's potential compared to a conventionally powered aircraft concerning reducing environmental impacts. If the electricity for charging the battery is obtained from renewable energies, the reduction potential is up to 95%. However, a direct comparison of both aircraft types is difficult as the electric aircraft range is reduced by half due to the high battery mass.

In addition to this research, Melo et al. [14] have investigated the use of batteries in vertical take-off and landing aircraft. The authors show that these concepts can be an alternative to cars for short distances of up to 100 km.

Sustainability assessments of battery systems for electric cars and stationary storage applications have been carried out by several researchers, including Ellingsen et al. [15], Deng et al. [16], and Thies et al. [10]. An overview of relevant scientific literature in this field is provided by Peters et al. [17].

This brief literature overview points out that the use of batteries in aviation and the implications for the sustainability of these systems have gained attention in recent years, but detailed sustainability assessments are missing. Moreover, sustainability assessment usually addresses the environmental dimension, while it neglects the socio-economic dimension.

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3. Assessment framework and system definition

This section describes the fundamentals of the assessment framework and the main assumptions concerning the investigated system.

3.1. Life Cycle Sustainability Assessment approach

The sustainability assessment carried out is based on the LCSA methodology, as proposed by Kloepffer [18] or Finkbeiner et al. [19]. It enables the analysis of the three dimensions of sustainability and allows the comparison of different product systems and their supply chains, which is required for the subsequent pre-selection of suitable battery systems [20].

While Environmental Life Cycle Assessment (E-LCA) is used to analyze the environmental impacts of the product system, the Life Cycle Costing (LCC) method is used for the economic analysis and the Social Life Cycle Assessment (S-LCA) method for the social analysis.

The assessment procedure is derived from the ISO 14040/14044 standards, which were initially formulated for E-LCA [21,22]. However, the assessment structure is formulated generically and allows the adoption of LCC and S-LCA [20]. The procedure is divided into four phases: 1. Goal and scope definition, 2. Inventory analysis, 3. Impact assessment, 4. Interpretation.

Due to the wide range of indicators from all three dimensions of sustainability, the decision-makers' preferences, and the underlying uncertainties, a final evaluation is useful. This evaluation can be part of the interpretation phase or can take place afterward.

3.2. Goal and scope definition

This LCSA study aims to analyze and compare eight potential battery systems for electric aircraft (see Table 1). The battery systems are based on different cell chemistries, including five lithium-ion batteries (LIB) based on lithium nickel manganese cobalt oxide (NMC), one LIB based on lithium iron phosphate (LFP), on LIB based on lithium nickel cobalt aluminum oxides (NCA), and one lithium-sulfur battery (LSB). The selection of batteries, as well as their characteristics (material composition, design, specific energy, etc.), are derived from scientific literature. Theoretical battery technologies, which have not yet been developed, are beyond the scope of this LCSA.

The battery systems are characterized by the capability to provide a short-range reference aircraft, developed in the cluster of excellence 'SE²A – Sustainable and Energy-Efficient Aviation' at Technische Universität Braunschweig (Germany), with the required energy for a generic short-range flight with a distance of 1,000 kilometers and a load of 100 passengers including luggage [23]. Based on a rough estimation, this requires a battery capacity of 4.313 MWh (including a 20% safety margin). For a more precise calculation of the battery capacity, an iterative procedure is necessary due to the additional energy demand by the battery's dead weight [14].

The functional unit of the assessment is the production of the described battery system. For this purpose, the stages of raw material extraction, components production, battery cell production, and battery pack production are considered (Figure 1).

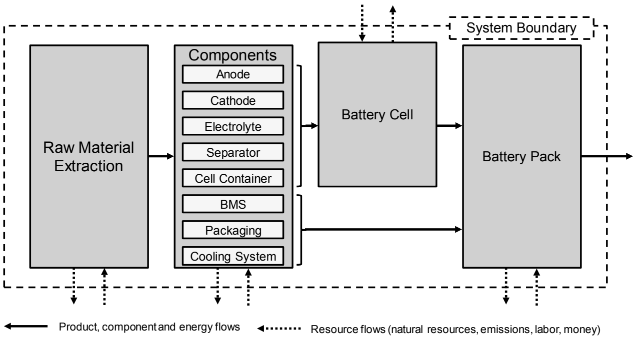

Figure 1. Battery production including product, component, energy, and resource flows

The assessment addresses the environmental, economic, and social impacts associated with each of these stages. Based on the analysis results, a pre-selection of suitable battery systems is carried out to support manufacturers in the further development process for battery-electric aircraft.

An overview of the cell chemistries for the battery systems is presented in Table 1. The number behind the respective LIB variants with NMC describes the ratio of the materials nickel, cobalt, and manganese in the cathode's active material. Based on the energy requirement of 4.313 MWh, the mass, the number of cells, and other characteristics of the battery systems are derived from scientific literature and the Lithium-ion Battery Performance and Cost Model for Electric Vehicles ("BatPaC") [15,16,24].

Table 1. Specification of the investigated battery systems

	Specific energy [Wh/kg]	**Mass [kg]**	**Number of cells [item]**
NMC-111	195	22,115	13,426
NMC-442	202	21,349	13,467
NMC-532	203	21,243	13,467
NMC-622	216	19,965	13,143
NMC-811	222	19,425	13,140
LFP	207	20,833	15,018
NCA	231	18,668	13,393
LSB	290	14,870	23,470

3.3. Inventory analysis

The production processes of the battery technologies constitute the foreground system of this study. This foreground system comprises 19 unit processes for the seven LIB variants and 17 unit processes for the LSB variant. Battery cells are assembled with a battery management system (BMS), the packaging, and the cooling system to produce the final battery pack. The components of the battery cells include the anode (current collector consisting of copper coated with active material), the cathode (current collector consisting of aluminum coated with active

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material), the separator, the electrolyte, and the cell container (pouch bag with aluminum tab and copper tab).

The background system includes data regarding raw materials, electricity, heat, cost, and information about the country-specific production sectors.

Due to the lack of primary data from industrial production processes, secondary data from the Ecoinvent 3.6 database is used to model the raw materials, components, and transports. The extraction and processing of raw materials are assumed to be carried out in the country that accounts for the largest share of global production, according to the U.S. Geological Survey [25]. Component production and battery cell manufacturing are assumed to occur in China, while the battery pack's final assembly takes place in Germany.

The data is modified for the economic assessment by adding current raw material prices based on market data and the country-specific electricity prices. In addition, process-specific costs are determined and added to the unit processes based on the detailed battery production analysis of Schnell et al. [26] and Wentker et al. [27].

For the social assessment, data on the country-specific production sectors from the SHDB are added. The assignment of the raw materials and production processes to specific sectors is necessary to calculate the equivalent work hours at medium risk level for the selected impact categories.

3.4. Impact assessment

The subsequent impact assessment is based on three types of Life Cycle Impact Assessment (LCIA) methods, one for each of the three sustainability dimensions. They are used to transform the life cycle inventory to impact indicators for different impact categories based on category-specific characterization factors. An overview of the selected impact categories and the corresponding units is presented in Table 2.

The environmental impact assessment is based on six impact categories, according to the ReCiPe Midpoint V1.13 method [28]. These impact categories are climate change (CC), terrestrial acidification (TA), human toxicity (HT), freshwater eutrophication (FE), photochemical oxidant formation (POF), and mineral resource depletion (MRD). The selected impact categories are chosen because they allow a comparison to the CO_2 and non-CO_2-emissions of conventional aircraft. Furthermore, they are often used when conducting E-LCA of battery systems [15,16,29].

The economic assessment is based on the life cycle cost (LC) of all unit processes involved in the life cycle of the battery system [30,31].

The social impact assessment is based on the Social Hotspots Database (SHDB) impact assessment method [32]. Selected impact categories are risk of poverty (POV), risk of corruption (COR), and risk of child labor (CHL). The selected impact categories are chosen because they enable the assessment of working conditions in battery pack production. Based on the life cycle cost of the unit process, the sector to which it is assigned, and the country-specific discrete risk level, the equivalent work hours at medium risk level for each impact category are calculated, which are used as an estimate for the social risks related to the product system [14].

The calculation model for inventory analysis and impact assessment is implemented in Python using the Brightway2 framework [33].

Table 2. Selected environmental, economic, and social impact categories with the associated units

Dimension	Impact category	Unit
Environmental	Climate change (CC)	kg CO_2-eq.
	Terrestrial acidification (TA)	kg SO_2-eq.
	Human toxicity (HT)	kg 1,4-DCB-eq.
	Freshwater eutrophication (FE)	kg P-eq.
	Photochemical oxidant formation (POF)	kg NMVOC-eq.
	Mineral resource depletion (MRD)	kg Fe-eq.
Economic	Life Cycle Cost (LC)	USD
Social	Risk of Poverty (POV)	Eq. med. risk hours
	Risk of Corruption (COR)	Eq. med. risk hours
	Risk of Child labor (CHL)	Eq. med. risk hours

4. Results and discussion

In this section, the results of the Life Cycle Sustainability Assessment are discussed. An overview of the impact scores expressed for the 4.313 MWh battery system is presented in Table 3.

4.1. Environmental assessment

Regarding the environmental impacts (CC, TA, HT, FE, POF, and MRD), the LIB based on LFP and the LSB tend to perform better than the LIBs based on NMC and NCA. Here, the LFP variant is advantageous in the categories TA, HT, FE, and MRD, while the LSB is advantageous in the categories CC and POF. On the other hand, the NMC-111, NMC-442, and NMC-532 variants are in each case worst, whereby in the category TA, the NMC-811 is the worst.

For a more detailed analysis of the hotspots, the impact categories CC, POF, and MRD are selected, which correspond to the goals of Flightpath 2050 (CC and POF) and the resource requirements of battery production (MRD). In terms of CC, the cathode's electrode paste is the main contributor to the total impact in all eight cases. While it is responsible for about 30% of the CC impact from LSB production (96 tons of CO_2-eq.), the cathode's electrode paste is responsible for 45-61% in the production of the different LIBs (147 to 233 tons of CO_2-eq.). This is mainly due to a high contribution from the solvent N-methyl-2-pyrrolidone (NMP) in LSB's electrode paste production. For the LIBs, the cathode electrode paste is responsible for a higher percentage of CC since large quantities of LFP, NCA, and NMC are used to produce the cathode electrode paste in addition to NMP.

Concerning the POF, similar results occur. In LSB and LIB production with LFP, the cathode's electrode paste causes 25-46% of the POF impact (306, respectively, 603 kg

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of NMVOC-eq.). This is also primarily due to the high proportion of the solvent NMP. In the production of LIBs with NMC and NCA, the NMC and NCA are mainly responsible for the POF and cause 61-65% of the environmental impact (1,180 to 1,422 kg of NMVOC-eq.). This is due to the share of nickel and cobalt in the NMC respectively cobalt in NCA. The higher the percentage of these materials, the higher the POF.

With regard to the MRD, the current collector of the anode is mainly responsible for the environmental impact during the production of the LSB and the LIB with LFP with a share of approximately 35% of the whole MRD (29, respectively, 21 tons of Fe-eq.). This is due to the collectors' material composition, which consists entirely of copper. For the LIB variants with NMC and NCA, the NMC and NCA are again primarily responsible for the environmental impact with 63-71% (72 to 254 tons of Fe-eq.). The high percentage of MRD is also attributable to the share of nickel, cobalt, and manganese used.

4.2. Socio-economic assessment

For the socio-economic assessment, the impact categories LC, POV, CHL, and COR are examined. It can be observed that the LSB is advantageous in all impact categories when compared to the LIB variants.

Concerning the economic assessment, the LC of LSB with USD 387,000 is between 33-48% lower compared to the other battery technologies. This is mainly due to the cheaper materials and the overall lower material input for the LSB production. The highest share of LC in the case of the different LIB variants is due to the cathode's electrode paste production. The production step accounts for between 47-53% of the total LC and includes the material input and mixing process. The large share of the LC is mainly due to the extraction and processing of nickel and cobalt.

LSB has a 78-90% lower POV, CHL, and COR in terms of social impact categories. This can partially be explained by the different origins of the materials required for production and fewer working hours related to LSB production. The highest social risks of the different LIB variants are again associated with cathode's electrode paste production, with a proportion of 76-92% of the total POV, COR, and CHL. Similar to the LC, this can be explained by the extraction and processing of nickel and cobalt.

4.3. The implication for the pre-selection

The Life Cycle Sustainability Assessment of the various battery systems shows a trend towards promising battery technologies. While LFP and LSB are generally advantageous in terms of environmental impacts during production, and LFP is superior to LSB in some aspects, LSB is beneficial in terms of the socio-economic effects in all impact categories.

Various circumstances can explain this. On the one hand, the material input for the LSB production is lower compared to the production of LIBs, and the materials used are cheaper per unit. On the other hand, different origins of the materials required for production and fewer working hours related to LSB production result in lower social risk. The LCSA also shows that, in addition to its environmental and social advantages, the LSB is an economically promising battery technology for manufacturers of future aircraft propulsion systems due to its 33-48% lower LC.

The development of novel propulsion technologies for electric aircraft should, therefore, primarily focus on LSB. However, LIB variants with LFP, NCA, or NMC-811 should also be further investigated since a specific reference aircraft with a specific flight profile was used for the assessment in the context of this analysis. Under other conditions, these two battery technologies might be advantageous.

5. Conclusions and outlook

This article presents an LCSA of eight potential battery systems for electric aircraft. It assesses the impacts that are related to the materials and the production of the battery systems. Next to the environmental impacts, the assessment also considers socio-economic impacts, which have not yet been investigated in previous studies. The assessment results indicate that LSB is a promising battery technology for electric aircraft. In addition to its environmental and social benefits over competing technologies, it is also advantageous from an economic perspective, which makes it interesting for manufacturers of aircraft powertrains.

Table 3. Environmental and socio-economic assessment results for a battery pack with 4.313 MWh capacity of the respective cell chemistries

Dimension	**Impact category**	**Per battery pack (4.313 MWh capacity)**							
		NMC-111	NMC-442	NMC-532	NMC-622	NMC-811	LFP	NCA	LSB
Environmental	Climate change (CC)	$3.81\cdot10^{5}$	$3.58\cdot10^{5}$	$3.63\cdot10^{5}$	$3.39\cdot10^{5}$	$3.24\cdot10^{5}$	$3.24\cdot10^{5}$	$3.78\cdot10^{5}$	$3.18\cdot10^{5}$
	Terrestrial acidification (TA)	7,268.91	7,268.39	8,958.32	9,118.99	10,271.79	2,000.04	5,860.99	2,148.30
	Human toxicity (HT)	$5.43\cdot10^{5}$	$5.34\cdot10^{5}$	$5.54\cdot10^{5}$	$5.38\cdot10^{5}$	$5.44\cdot10^{5}$	$2.55\cdot10^{5}$	$2.52\cdot10^{5}$	$3.76\cdot10^{5}$
	Freshwater eutrophication (FE)	241.13	233.68	245.77	237.99	240.74	146.89	158.85	174.98
	Photochemical oxidant formation (POF)	2,332.00	2,110.80	2,324.47	2,246.04	2,244.50	1,306.14	1,840.13	1,211.14
	Mineral resource depletion (MRD)	$3.54\cdot10^{5}$	$3.63\cdot10^{5}$	$3.58\cdot10^{5}$	$2.95\cdot10^{5}$	$2.66\cdot10^{5}$	$0.62\cdot10^{5}$	$1.16\cdot10^{5}$	$0.85\cdot10^{5}$
Economic	Life Cycle Cost (LC)	$7.25\cdot10^{5}$	$6.32\cdot10^{5}$	$6.60\cdot10^{5}$	$6.17\cdot10^{5}$	$5.63\cdot10^{5}$	$7.15\cdot10^{5}$	$6.20\cdot10^{5}$	$3.78\cdot10^{5}$
Social	Risk of Poverty (POV)	$5.32\cdot10^{6}$	$4.16\cdot10^{6}$	$4.82\cdot10^{6}$	$4.58\cdot10^{6}$	$4.22\cdot10^{6}$	$4.16\cdot10^{6}$	$4.19\cdot10^{6}$	$0.73\cdot10^{6}$
	Risk of Corruption (COR)	$13.43\cdot10^{6}$	$11.29\cdot10^{6}$	$13.57\cdot10^{6}$	$13.17\cdot10^{6}$	$13.17\cdot10^{6}$	$6.65\cdot10^{6}$	$9.95\cdot10^{6}$	$1.22\cdot10^{6}$
	Risk of Child labor (CHL)	$8.01\cdot10^{6}$	$6.48\cdot10^{6}$	$7.53\cdot10^{6}$	$7.18\cdot10^{6}$	$6.80\cdot10^{6}$	$5.12\cdot10^{6}$	$6.66\cdot10^{6}$	$1.15\cdot10^{6}$

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However, the sustainability assessment has also revealed hotspots in battery production, which are responsible for a large proportion of the environmental and socio-economic impacts. Especially the production of active material for anodes and cathodes is a driver of harmful impacts, which will be analyzed more precisely through sensitivity analysis. Moreover, the analysis carried out so far only assesses the production of batteries. Future research integrates further components of the electric powertrain and carries out a cradle-to-grave assessment.

One key challenge for the further development of the assessment approach is seen in the treatment of the underlying uncertainties. This issue will be addressed in three steps. First, the batteries will be defined more precisely by using electrochemical models of current and future technologies (e.g., lithium-air batteries). Second, the underlying Ecoinvent datasets will be analyzed in detail and updated where necessary. In this way, obsolete datasets are re-modeled based on current production processes and scaled to the industrial production scale. Third, the employed impact assessment methods will be critically reviewed to validate the plausibility of the identified environmental and socio-economic impacts.

Considering these topics in future research will further improve the conducted LCSA analysis in terms of identifying the potential of electric powertrains as an environmentally friendly and sustainable alternative compared to their conventional kerosene-based counterparts.

Acknowledgments

We would like to acknowledge the funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2163/1- Sustainable and Energy Efficient Aviation – Project-ID 390881007.

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This is a resupply of March 2023 as the template used in the publication of the original article contained errors. The content of the article has remained unaffected.