Electric-powered air traffic network with integrated aircraft-battery modelling

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Electric-powered air traffic network with integrated aircraft-battery modelling

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Abstract

In this work, we present an electric-powered air traffic network model based on historical domestic travel demands within Sweden. The hybrid electric aircraft used in the network are designed by retrofitting an existing regional propeller-driven aircraft, which has a passenger capacity of 30 seats. The key advancement of the model is the integrated aircraft and battery modelling capability. This could enable trade-off analysis of electric aircraft designs with different battery technologies and performance characteristics under realistic air traffic conditions. The results presented here include a general assessment of emissions reduction through the adoption of hybrid electric aircraft in the context of Swedish domestic air traffic, and route-specific battery degradation results. While the analysis indicates that regional benefits are anticipated with the advancement of battery technology by 2035, aggressive and radical battery innovations are required to achieve overall environmental benefits. Focusing on a battery pack composed of Lithium Nickel Manganese Cobalt cells, the evaluation of battery degradation poses high challenges to pure electric operations, limits the operational flexibility of hybrid electric aircraft across different routes, and incurs high costs due to frequent battery replacements required to meet mission demands and reserve energy requirements.

Keywords: hybrid, electric aircraft, battery model, degradation, air traffic, emissions

1 Introduction

Approximately 50% of the cumulative CO2 emissions from global aviation 1940-2018 were produced in the last 20 years [1], mainly because the increase in the air traffic volume was more dramatic despite the efforts made to improve the fuel efficiency of aircraft and operation. To achieve the ultimate objective of net-zero greenhouse gas emissions, three key focus areas were identified by Clean Aviation Strategic Research and Innovation Agenda SRIA [2] that will drive the development of future aircraft. They are electric architecture, innovative aircraft architecture and hydrogen-powered architecture. In a previous work studying zero-emission aviation [3, 4], the potential and applicability of adopting sustainable air fuel (SAF), electrical energy and hydrogen for aircraft use within Scandinavia regions have been explored, concluding that Sweden offers very limited opportunities for battery-electric aircraft due to the limited range performance. But battery evolution with higher specific energy density could change this result. Notably, the study was focusing on the comparison of different routines of sustainable aviation technology development, while key battery-related assumptions, mainly specific energy, were obtained from published studies conducted for battery research and applications. As advancements in battery technology are critical for aircraft electrification, considering the wide operation envelope of aircraft and strict requirements on reliability and safety, there are more parameters apart from the specific energy density which need to be analysed for indicating a clear path for application of batteries for aircraft propulsion.

This work aims to investigate the impact of integrating a battery degradation model in a realistic air traffic model for studying electric aircraft conceptual designs with specific battery technology and evaluating the associated environmental impact in the context of Swedish air traffic network. The work involves air traffic modelling of domestic flight conditions within Sweden, targeting Arlanda airport which is the centre of the traffic network. To reflect the realistic demand and consider existing hybrid electric aircraft development, a hybrid electric aircraft was modelled based on the top requirements of Heart Aerospace's ES30 [5]. The considered battery is composed of Lithium Nickel Manganese Cobalt (NMC) cells and a NMC degradation model was used for the assessment of route-specific performance.

2 Methodology

2.1 Air traffic modelling

An in-house air traffic model was created for establishing the air traffic scenarios investigated in this paper. The Swedish domestic flight demands and Arlanda airport were selected for the study. Historical flight data in 2024 published by Transportstyrelsen [6] was used for Scenario 1, which is also the baseline scenario, as listed in Table 1. For the other two other scenarios given in the table, an annual increase of 1.3% in passenger demand has been assumed, following the base prediction given in EUROCONTROL's Aviation Outlook 2050 report [7]. For the assessment of the impact of hybrid electric aircraft within the Swedish air traffic context, three scenarios have been established, resulting in significantly different number of flights, as given as the number of arrivals and departures in Table 1.

Table 1: Air traffic scenarios.

Per year	Scenario 1 2024	Scenario 2 2035	Scenario 3 2050+
Passengers	2031871	2342074	2842773
Arrivals	24742	57531	169775
Departures	25831	46803	174062

For the conventional fleet modelled in scenario 1, the most common aircraft types operating at Arlanda which are published by the airport operator Swedavia in a publicly available environmental report [8], are used. The detailed fleet composition at Arlanda airport is presented in *Table 2*. For simplification, two types of aircraft were selected to cover the majority of operations at the selected airport in Scenario 1. The first type covers the twin-jet narrow body aircraft, including B738, A20N, A320, B38M, A321, A319, A21N, and the second type covers the twin-engine turboprop regional aircraft, AT72 and F50. Representatives of each type were modelled based on A20N and AT72 to represent the categories of jet aircraft and turboprop regional aircraft.

For scenario 2 which is the short-term future 2035 projection, the use of the first-generation hybrid electric aircraft was considered. Range of the first generation of hybrid aircraft followed the development routine set by Heart Aerospace for ES-30 [5], 200 km pure electric and 400 km hybrid, with assumed production initiated from year 2030. While for scenario 3 which is the long-term future 2050+ prediction, with technology development in the aircraft and energy storage system, in particular the battery energy density, doubled ranges were targeted. In scenario 3, it has been also assumed that the use of hybrid and electric aircraft could cover almost all existing flight routines within Swedish domestic air traffic demand. The passenger capacity was assumed constantly at 30 seats for all hybrid electric aircraft.

Table 2: Historical fleet composition at Arlanda airport for year 2023.

Aircraft type	Number of movements
B738	39236
A20N	37839
A320	25798
CRJ9	16130
B38M	10253
AT72	9576
A321	7474
F50	5133
A319	3921
A21N	3422
Other	30473
Total	189255

2.2 Aircraft modelling

As A20N and AT72 were selected representing the existing conventional fleet, the aircraft models of these two aircraft are well supported with publicly available data, i.e. fuel burn and emissions data. The CO2 emissions calculation for the two aircraft followed the methods and tables given in [9] The hybrid electric aircraft, however, has no realistic data for validation. A hybrid electric aircraft retrofitted from Dornier 328 was hence created using commercial aircraft design tool Pacelab APD version 8.1 [10]. Key aircraft design parameters are listed in Table 3, while the hybridization degree was set as 50%, indicating that half of the shaft power of the propulsion unit is from the electric motor.

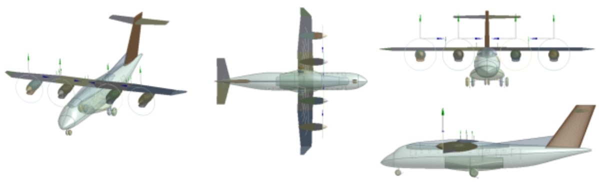

Figure 1: Hybrid electric aircraft model retrofitted from Dornier 328.

Table 3: Hybrid electric aircraft key parameters.

	Scenario 2 2035	Scenario 3 2050+
MTOW *(kg)*	15223	17464
Battery specific energy *(Wh/kg)*	400	600
Battery mass *(kg)*	2265	3107
Fuel capacity *(L)*	1026	1817

With the hybrid electric aircraft created for scenario 2, two flight profiles, Stockholm-Göteborg and Stockholm-Visby, were selected for the investigation of battery degradation. The battery power demand profiles for these two flight routines are plotted in Figure 2, which include standard taxi-out, take-off, climb, cruise, descent, and taxi-in process.

2.3 Battery modelling

The battery model adopted in this study is a NMC battery model published in [11], which is an empirical degradation model considering cycle aging. Although nickel-rich low-cobalt NCM (Ni > 90%) layered cathode has been considered to be the best material with possible energy density higher than 740 Wh/kg [12, 13], the specific energy of around 260 Wh/kg [14] in present-day NMC batteries is still lower than the assumptions used in the aircraft design. Especially for the case in scenario 3 where 600 Wh/kg was assumed, the degradation model may present a higher uncertainty due to the large difference in specific energy. Hence, the cases explored with the battery model are for scenario 2 only in this paper. Whilst the model was built from extensive data of 232 tests for NMC and include key stress factors such as full equivalent cycles (FEC), operating temperature, state-of-charge (SOC), depth-of-discharge (DOC), and charge/discharge current rate, however, calendar aging is not included. The SIMULINK model sketch is shown in Figure 3.

In this paper, the initial state of charge (SOC) of the battery is always set to 100%. The model operates as follows: starting from a fully charged state, the battery is discharged according to the specified flight profiles. At the end of each mission profile, it is recharged at a fixed rate of 1.5 C. This discharge – charge cycle is repeated continuously to assess battery degradation over the aircraft lifetime. The minimum SOC of the battery at the end of the design mission is set to 20%. Flight mission reserves are calculated primarily using extra fuel and the 20% battery capacity remains from the design mission.

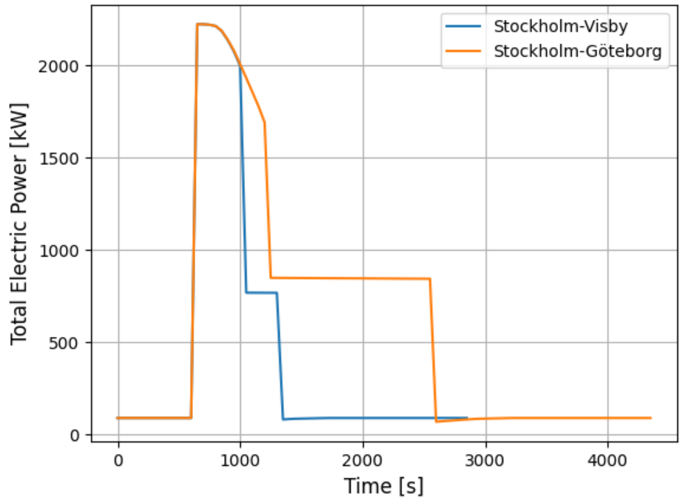

Figure 2: Battery power profiles for the selected flight missions.

Relevant study of using the battery model in electric aircraft application can be found in [15], which investigated the degradation of the battery under different charging rates and initial state of charge.

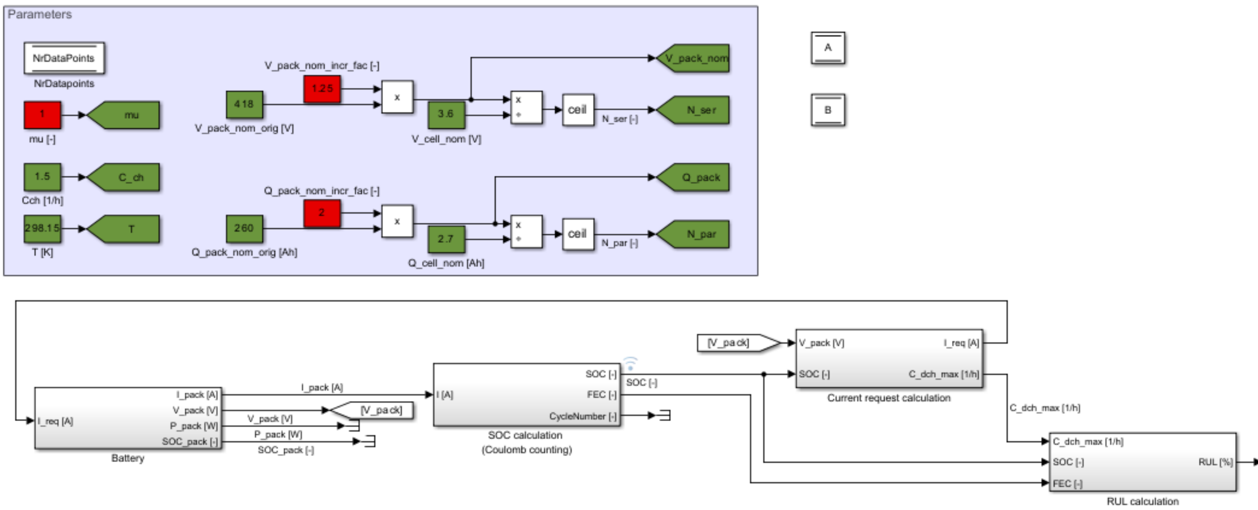

Figure 3: Sketch of the battery SIMULINK model.

3 Results and discussion

3.1 Air traffic modelling results

With the established air traffic model and aircraft model, the annual data of fuel consumption, electrical energy consumption and CO2 emissions are computed for each of the flight routines. As shown in the plots of Scenario 2 in *Figure 4*, the first-generation hybrid electric aircraft can only cover two of the busiest lines, Stockholm-Göteborg and Stockholm-Visby, and a few short routines such as Stockholm-Ronneby and Stockholm-Kalmar. For the rest of the Swedish domestic air travel demand, conventional aircraft will be still dominating, especially the ones with the highest CO2 emissions such as Stockholm-Luleå and Stockholm-Umeå. Nevertheless, the introduction of the hybrid electric aircraft could eliminate a large part of CO2 emissions between Stockholm and Göteborg, although the number of flights increase dramatically due to the smaller passenger capacity. In total, 13% reduction in annual CO2 emissions from operations from domestic flight demand has been observed.

For Scenario 3, while more advanced hybrid aircraft could be used with doubled range compared to the first generation, it is possible for more than 90% of coverage of domestic air traffic demand inside Sweden. The result from this scenario, is a total reduction of 73% annual CO2 emissions from operations. However, if there is no A320 or ATR72 class level hybrid electric aircraft to be built, the number of flights will be 6.8 times as it is of today, which presents an enormous challenge to air traffic management and infrastructure development.

3.2 Battery modelling results

Looking at the two selected flight missions, Stockholm-Göteborg and Stockholm-Visby, in Scenario 2, battery degradation analysis has been done through integrating the battery model with the mission profiles. The results are shown in Figure 5, where the cycle number and state of health (SOH) are plotted against operation time of the aircraft. Give that the flight distance for Stockholm-Visby is less than 200 km, both pure electric and hybrid modes were investigated.

Figure 5 illustrates the number of flights the aircraft can perform before the battery capacity decreases by 5%, corresponding to a state of health (SOH) of 95%. As shown, the aircraft can complete 3,224 flights on the Stockholm–Visby route, 1,543 flights on the Stockholm–Göteborg route, or 1,030 flights on the Stockholm–Visby route in pure electric mode. Among the analysed flight profiles, the pure electric route from Stockholm to Visby results in the highest depth of discharge and the fastest battery discharging rate. After approximately 4346 cycle, the battery system for this route almost reaches the end of its useful life. Indeed, the battery system would be unable to support pure electric flight for Stockholm-Visby route well before reaching this limit. The simulations however neglected the impact of reduced capacity on the aircraft mission level computation.

For the Stockholm-Göteborg routine, after 3307 flights, the SOH of the battery system drops below 90% posing significant risks and challenges in meeting the reserve "fuel" (energy) requirements. In all the simulations, conventional jet fuel has been always considered as the core part of the reserve fuel, while carry heavy batteries as reserve "fuel" without utilizing them is not feasible. In addition, 3,307 flights represent a low utilization level for a regional aircraft over two years, or a high utilization level over one year, particularly for short-range routes with quick turnarounds. The cost associated with replacing the battery system every few years could therefore be prohibitively high. Moreover, the life-cycle emissions associated with battery production and disposal may offset part of the operational emission reductions achieved during service.

Although the state of health (SOH) remains at 92% after 5,335 flights on the Stockholm–Visby route in hybrid mode, this considerable degradation still poses a challenge for the adoption of hybrid-electric aircraft. Due to uncertainties in SOH, an aircraft operating on this route may no longer be suitable for longer missions—such as the Stockholm–Göteborg route, which is close to the maximum hybrid range. This limitation could be mitigated if the degree of hybridization were made flexible, allowing conventional fuel use to compensate for the risk of over-discharging the battery system. Nevertheless, a stepwise utilization strategy—where the aircraft or battery system is progressively reassigned from longer to shorter routes—could help maximize the operational lifespan and economic viability of the system.

4 Conclusion

Though the modelling and analysis of hybrid/electric aircraft introduction in Swedish domestic air traffic scenarios, the results show that:

- Regional benefits are anticipated with the advancement of battery technology by year 2035. A 13% reduction in annual CO2 emissions from operations from domestic flight demand has been observed from deploying the first generation of hybrid electric aircraft.
- Aggressive/radical battery innovations demand to achieve overall environmental benefits, for which a total reduction of 73% annual CO2 emissions from operations can be expected.
- Route-specific battery degradation modelling presents high challenge to pure electric operations, low flexibility of hybrid electric aircraft to be used for different missions and routes, and high cost due to the need of replacing battery systems to meet mission requirement and reserve fuel requirements.
- Hybridization flexibility and step use of the aircraft could be beneficial.

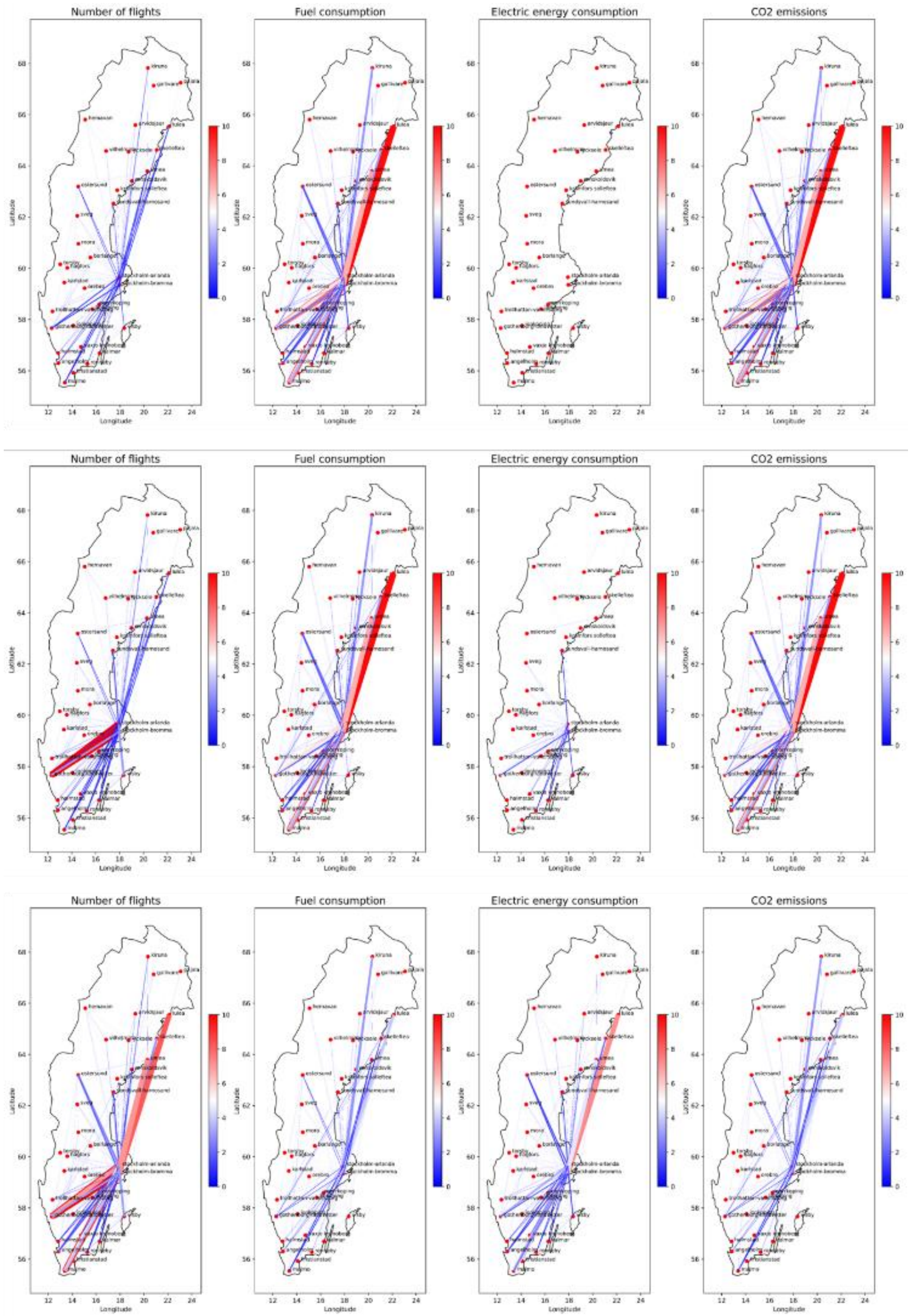

Figure 4: Air traffic modelling results for the studied scenarios: scenario 1 (top), scenario 2 (mid) and scenario 3 (bottom).

Stockholm-Visby
in hybrid mode

Stockholm-Visby
in pure electric mode

Stockholm-Göteborg
in hybrid mode

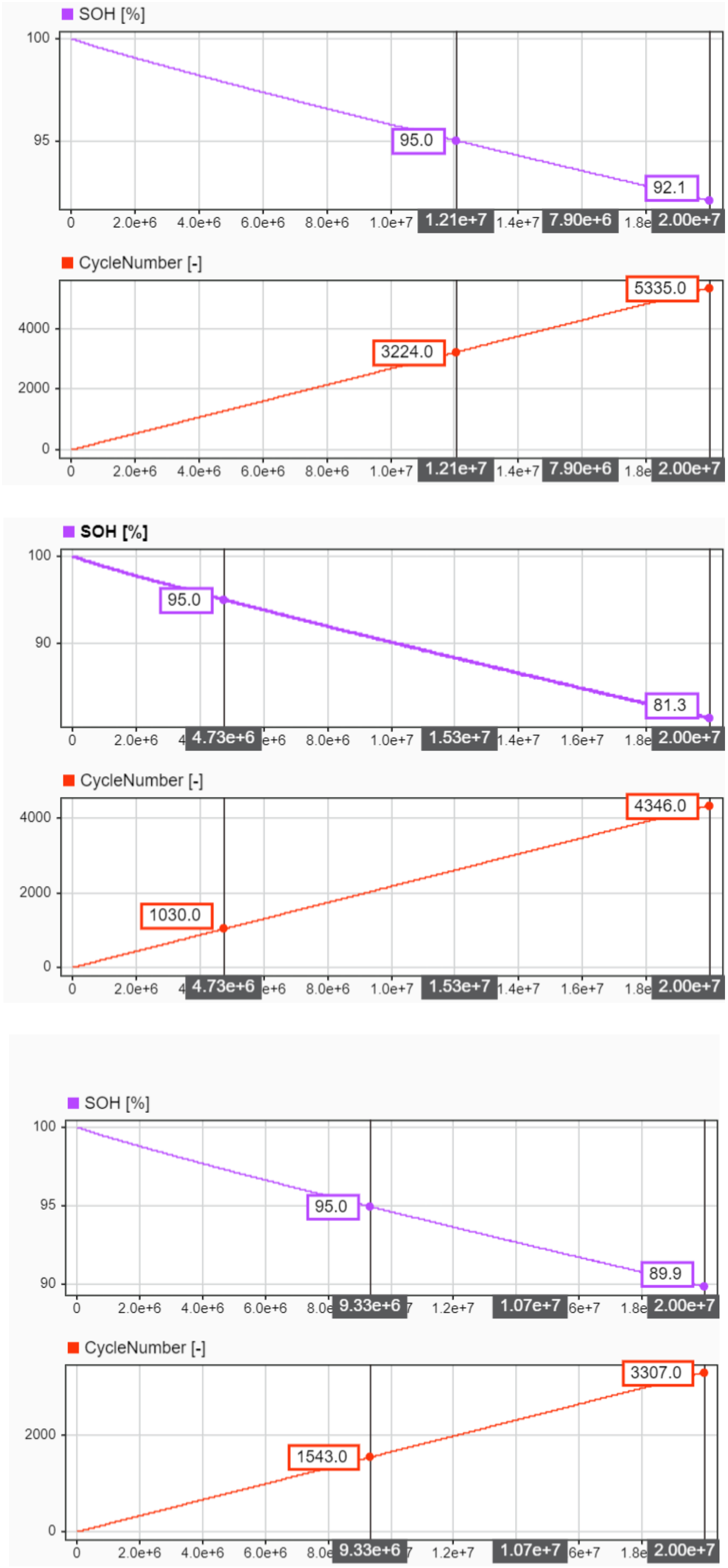

Figure 5: Battery state of health and discharge cycle number charts for 5556 hours operation: Stockholm-Visby in hybrid mode (top), Stockholm-Visby in pure electric mode (mid) and Stockholm-Göteborg in hybrid mode (bottom).

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