Multi Input Multi Output Model of Airport Infrastructure for Reducing CO_2 Emissions

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***Abstract*—Electrification of aircraft presents great potential in achieving long term emission targets of the sector. Electrification of Ground Support Equipment (GSE) also offers significant opportunity for reducing carbon emissions, as well as the air pollution in and around conventional airports. GSE electrification introduces charging and charging scheduling challenges. In this study, a generic Multi Input Multi Output (MIMO) model is developed to understand GSE charging requirements and to investigate GSE charging scheduling for existing turnaround procedures. This will help to quantify the increase in airport electricity requirements and the potential for CO_2 emission benefits from GSE electrification. The model is capable of investigating the trade-off between the number of electric GSE (e-GSE) required and the number of recharges required for different e-GSE battery pack sizes. The model is also capable of sizing e-GSE battery packs of different GSE types specific to their use case. Also, the model is scalable to represent any airport size. A test case of a small airport with seven flights per day has been used to investigate the model performance. Initial results show that GSE electrification could offer around 60% CO_2 savings compared to conventional GSE operations. Also compared to non-scheduled charging of GSE, both magnitude and duration of peak grid loads could be reduced up to 23% and 28%, respectively. This study has a potential for significant contribution to understanding the system-level requirements of electrification of an airport ecosystem.**

Keywords*—aircraft, electric ground service equipment, charging scheduling, grid connected micro-grid, grid balancing

I. Introduction

The aviation sector targets reducing net aviation CO_2 emissions by 50% in 2050 relative to 2005 emission levels [1]. Airports set their own targets for sustainability and emission reduction aligned with targets set by international bodies such as the International Air Transport Association (IATA). London Heathrow Airport (LHR) uses 100% renewable electricity since April 2017 [2]. LHR also introduced an incentive that the first electric aircraft landing to LHR will not be charged for landing fees for a year [3]. Birmingham International Airport (BHX) has set a target to become a zero carbon airport by 2033 [4].

Aircraft operations are accountable for the majority of the aviation carbon emissions. According to [5], aircraft cruise has a contribution of 89%, and Landing and Take-Off (LTO) activities has a contribution of 6% to the carbon emissions in LHR. Hence, there are a significant number of development projects in the industry to achieve technological advancement to introduce low emission aircraft [3][6].

Even though aircraft dominate the carbon emissions in the aviation sector, Ground Support Equipment (GSE) also has a share in LTO activities [6]. GSE are vehicles that service aircraft after landing and before take-off [7]. The set of aircraft ground service operations required after landing and before take-off are defined in turnaround procedures. The Aerospace Technology Institute (ATI) Accelerating Ambition Technology Strategy recommends the optimisation of ground service operations for future airports [8]. Besides their contribution to carbon emissions, GSE are known to have a significant contribution to NO_x pollution. As cited in [9], GSE account for 13% of NO_x in all airports in the US, and electrification of GSE reduces early deaths related to airport emissions by 28% in the UK. Hence, to reduce both carbon and air pollutant emissions from GSE, airports are committing to electrification of GSE [5][4].

A. Problem Definition and Literature Gap

The electrification of aircraft and GSE introduces challenges for charging and charging scheduling within the existing turnaround procedures [3][7][10].

GSE fleet management and availability of sufficient amount of GSE to satisfy airport demand during peak airport traffic is already a problem for ground service providers, airline companies, and airport operators [11]. Hence, electric GSE (e-GSE) charging shall not adversely affect the number of available GSE to service the airport traffic. Moreover, non- scheduled charging of high number of e-GSE may significantly increase the peak grid loads. As a result, understanding the charging requirements of e-GSE and future low emission aircraft, and investigation of the scheduling of GSE charging for existing turnaround services are the key problems to be understood for the full electrification of GSE and the airport ecosystem.

There are existing studies for scheduling of charging of Electric Vehicles (EV), and EV fleets in the literature [12] [13][14][15]. Scheduling of GSE charging problem can be defined as scheduling of charging of EV fleets with a day ahead driving requirements as in [13], and [14]. For GSE, since airline timetables do not change in a sudden or in short term, daily schedule of GSE can be assumed to be known and accurate, when delays are ignored.

Even though the GSE charging management problem can be framed as an EV fleet charging problem in a grid connected

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microgrid, there is a lack of methodology specific to identify GSE charging requirements and the increase in the airport electricity requirements. Moreover, due to variation in airport traffic sizes, GSE types, e-GSE battery pack sizes, and turnaround schedule procedures, there is a gap in understanding how can charging of an e-GSE fleet of different types of GSE be best managed.

II. Methodology

A methodology is proposed to develop a generic Multi Input Multi Output (MIMO) Airport Energy Model (MIMO-AEM) scalable to any size of airport. This will help to quantify the energy requirements and emission benefits of a future airport, where GSE and aircraft are electrified. This study aims to deliver system level results to aid the early decision-making process of stakeholders, with limited access to data.

The model is capable of investigating the trade-off between the number of e-GSE required and the number of recharge required for different e-GSE battery pack sizes and different charging strategies. The model is also capable of sizing GSE battery packs of different GSE types specific to their use case.

In the model, electrification of 16 types of different GSE, electrification of aircrafts, renewable energy plants within the airport micro-grid, utility grid, and a rule-based distributed energy management controller is represented.

A. Generation of Representative GSE Duty-Cycles

GSE duty-cycles that represent the activities before, during, and after aircraft turnaround services for particular types of aircraft are required to estimate the discharge power demand and thus energy usage of GSE during service. Since standardised or real-world duty cycles for GSE are not available in the reviewed literature, a methodology is proposed to generate representative, power vs. time duty-cycles for each type of GSE for turnaround services of different aircraft, which are representative enough to allow a model to be developed.

In Figure 1, the full servicing turnaround time chart representing operation vs. time in minutes for A320 is shown [16] . The power-demand mode identification approach used in [17] for Refuse Collection Vehicles (RCV) is applicable to GSE activities, since GSE are expected to have a similar load profile during the activity categories classified in Figure 1. Table 1 shows the list of GSE activity categories and corresponding power-demand modes. During the generation of the power-demand mode charts, the manufacturer's turnaround time charts are compared with the actual time-in operation results from [7].

B. Aircraft Traffic and Generation of Gate GSE Schedule

Due to variety in aircraft traffic size (e.g. 1300 flights per day at London Heathrow (LHR) [18], 6 flights per day at Teesside (MME) [19]), the model is required to provide the flexibility to be easily scaled up to different aircraft traffic. An algorithm is developed to distribute aircraft traffic among minimum possible number of gates and generate a daily gate GSE schedule for any size of airport traffic.

C. Discharge Power and Energy Usage Estimation of GSE

The methodology in [10], creates the basis for power-demand calculations which requires average of GSE rated power, average of GSE load factor, and duration of GSE use for each GSE and fuel type. Load factor is the ratio of average power demand of a GSE during operation to the rated power of a GSE. For better representation of power-demand modes and obtain a better estimation with the model, GSE are categorised under four classes which are Class A, B, C, and D, according to the similarities between their activities. GSE classes and corresponding GSE types that represented in the model are tabulated in Table 2.

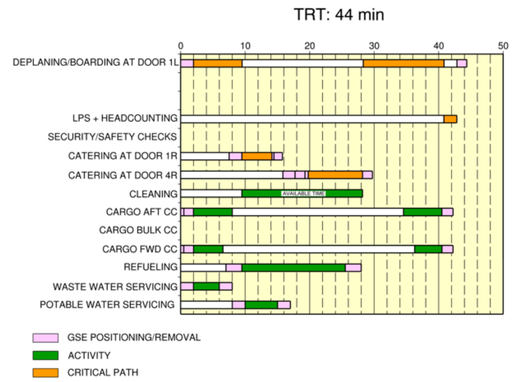

Fig. 1. Aircraft full servicing turnaround time chart [16]

TABLE I. GSE Activity Categories vs. GSE Power-Demand Modes

Category No.	GSE activity category	GSE power-demand mode
1	Activity	High-auxiliary power demand
2	GSE transit between gate and GSE base (Laden)	Laden transit
3	GSE transit between gate and GSE base (Unladen)	Unladen transit
4	GSE removal or positioning	Positioning
5	Idle during operation	Idle, cannot be charged
6	Not servicing an aircraft	Idle, can be charged

TABLE II. List of GSE Classification

GSE class	GSE type
Class A	Pushback tractor
Class B	Fuel tanker
	Catering truck
	Cabin service truck
	Water truck
	Toilet truck
	De-icer
	Cargo loader
	Conveyor belt
	Passenger bus
Class C	Baggage train
	Cargo train
	Passenger stair
Class D	GPU
	ACU
	ASU

Load factors are assigned as a function of GSE power-demand mode and GSE class, as tabulated in Table 3. Average rated power of GSE listed in [10] is used in the model. Energy usage of GSE is calculated using (1) and (2), where $P_{Demand,GSE}$

is GSE power demand in kilowatt, $LF(PDM(t), Class_{GSE})$ is load factor as a function of power-demand mode $PDM(t)$, and GSE class $Class_{GSE}$, and η_{GSE} is lumped efficiency of e-GSE powertrain, $E_{DEMAND,GSE}$ is energy used by GSE in a minute in kilowatt-hours, and t is time in minutes.

In addition to e-GSE, conventional GSE are also represented to identify the level of emissions from conventional GSE with a lumped efficiency for ICE powertrain is replaced with η_{GSE}. The e-GSE battery discharge power, e-GSE energy usage, and conventional GSE energy usage are estimated for each type of GSE servicing each aircraft covering daily airport traffic.

TABLE III. LOAD FACTORS WITH RESPECT TO POWER-DEMAND MODES AND GSE CLASSES

Power-demand mode		Auxiliary: 1	Laden transit: 2	Unladen transit:3	Transit during activity: 4	Idle during operation: 5	Idle: 6
Class	A	0.95	N/A	0.5	N/A	N/A	0
	B	0.3	0.5	0.4	N/A	0	0
	C	0.5	N/A	0.3	0.4	0	0
	D	1	N/A	N/A	N/A	N/A	0

$$P_{DEMAND,GSE}(t)[kW] = P_{RATED}.LF(PDM(t),Class_{GSE}).\eta_{GSE} \quad (1)$$

$$E_{DEMAND,GSE}(t)[kWh] = \frac{\int_{t-1}^{t} P_{DEMAND,GSE}(t)}{60} \quad (2)$$

D. GSE Routing Scenarios

There are two key airport electrification scenarios covered in this study to investigate the trade-off between the number of e-GSE required and the number of recharge required. The first scenario represents the case where conventional GSE is replaced with a minimum number of e-GSE. In this scenario number of e-GSE equals to the number of conventional GSE required in a conventional airport to complete all turnaround services. The second electrification scenario is to use as many e-GSE as required to complete assignments in a day with single full charge. Due to specific energy and energy density limits of batteries [20], maximum battery energy capacity is limited for GSE. In the first scenario limited number of e-GSE with limited battery capacity might require multiple full recharging in a day. In the second scenario limitation in number of recharge and maximum battery capacity might require more e-GSE to complete all operations. Those two electrification scenarios lead to a trade-off between Total Cost of Ownership (TCO) of a e-GSE fleet [21] and operational flexibility [11].

Charging strategy is another aspect of the electrification scenario to quantify the increase in airport system power demand from the grid. The "over-night charging" strategy only allows charging of e-GSE after their last service until their first service of the next day or when their charge is completely depleted. The "continuous intermittent charging" strategy allows charging whenever e-GSE are not servicing an aircraft. Table 4 shows four different cases covering two electrification scenarios and two charging strategies.

TABLE IV. CASES FOR DIFFERENT ELECTRIFICATION SCENARIOS AND CHARGING STRATEGIES

Cases	Electrification Scenario	Charging Strategy
1	1.Minimum no. of GSE	1.After battery depleted or last operation
2	1.Minimum no. of GSE	2.Whenever GSE is not servicing
3	2.Minimum no. of full recharge	1.After battery depleted or last operation
4	2.Minimum no. of full recharge	2.Whenever GSE is not servicing

E. MIMO Aiport Energy Model Development

The MIMO-AEM is developed in Matlab-Simulink to simulate GSE discharging and charging in a grid connected airport micro-grid with renewable energy sources. Figure 2 shows the hardware represented in the model, which are gates, aircraft traffic, GSE fleets, GSE charging stations, renewable energy sources installed to the airport system, Energy Management Controller (EMC) and the utility grid.

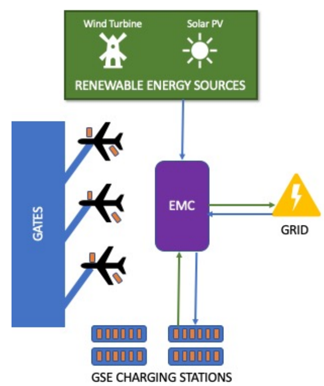

Fig. 2. Multi Input Multi Output airport energy model diagram

F. Energy Management Strategy Development

For energy management in the airport micro-grid GSE fleet is split into GSE sub-fleets that contains the same type of GSE. Each GSE in each GSE sub-fleet is assumed to have a designated charging station. Similar to the distributed algorithm in [15], charging stations and GSE sub-fleet EMC calculate charging power demand and decrease the amount of data required to be transferred between central-aggregator and sub-aggregators.

There are two types of charging power defined in the model, which are essential charging power $P_{ESS,GSE}$, and opportunity charging power $P_{OPP,Demand,GSE}$. P_{ESS} is always supplied to the e-GSE when demanded, disregarding the micro-grid EMC criteria as it is essential for e-GSE to complete next turnaround operations. $P_{OPP,Demand,GSE}$ is only supplied when micro-grid EMC criteria are met as excess renewable energy or cheap electricity is available. Charging station identifies type of charging power that e-GSE demands by using a rule-based algorithm.

Micro-grid EMC collects P_{ESS}, $P_{OPP,Demand}$ from GSE fleet level EMC. and uses a rule -based algorithm to prioritise renewable energy usage when available.

G. GSE Charging Power Estimation

GSE charging stations receives available opportunity power $P_{OPP,Supply,GSE}$, from micro-grid EMC through the distribution of fleet and sub-fleet level EMCs. As a result, charging power for each GSE can be identified for different electrification scenarios and different charging strategies. Consequently, charging power, charge start and charge finish times for each GSE allows understanding the charging requirements of GSE and possible GSE charging scheduling options for existing turnaround procedures. Charging power demand of all GSE in the airport system allows quantification of the increase in airport electricity requirements.

H. e-GSE Battery Sizing

The proposed MIMO-AEM is able to identify e-GSE maximum discharge power $P_{Discharge,Max}$, maximum charge power $P_{Charge,Max}$, and required energy capacity $C_{BAT,Req}$ to complete the routes assigned within electrification scenarios.

e-GSE battery sizing allows evaluation of the suitability of existing e-GSE in different airports. Furthermore, there is a battery database developed by WMG, which contains data of over 300 different cells. The battery database is able to provide battery cell selection suggestions suitable for particular application. The outputs from GSE battery sizing module of the MIMO Airport Energy Model can be used in the battery database to make recommendations to GSE manufacturers about battery cells suitable for particular airport applications.

III. Simulation

Teeside International Airport (MME) traffic on the 4th March 2020 is simulated for the four different electrification cases listed in Table 4. The turnaround servicing of seven aircraft per day for two operation days is simulated.

A. Simulation Results with Different Electrification Cases

Table 5 summarises the simulation results for cases 1 to 4. In the table "Grid – Energy Supplied" is the total energy supplied by the grid, "Grid Mean Power" is the average power demanded from the grid, "Grid Peak Power" is the peak power demanded from the grid, "Grid Peak Duration" is the time at peak demand from the grid in minutes, "GSE Electrification Benefits" is the ratio of well-to-wheel emissions of e-GSE (based on dynamic grid emission intensity) to tailpipe emissions from conventional GSE, "Charge Stations Required" is the minimum number of charge stations required to be used at the same time, "Charge Station Max Charge Power" is the maximum charging power required from charging stations. Figure 3 shows the grid power profile in kilowatts vs the time of the day in "hours:minutes(hh:mm)" format for cases 1 to 4.

Cases 2 and 4 have 15% and 23% lower peak power demand compared to cases 1 and 3, since the GSE can be charged continuously. Case 2 peak power is observed for 28% shorter period. As it can be observed in Figure 3, cases that represent continuous interim charging strategy are successful at grid load balancing as they stay closer to the mean power demanded from the grid. Case 4 requires the lowest charge station maximum charge power, however it requires 2 more GSE compared to cases 1 and 2. Case 2 requires the highest charge station maximum charging power, and mean power demanded from the grid.

TABLE V. Simulation Results for Cases 1 to 4

Airport Electrification Metrics	Case 1	Case 2	Case 3	Case 4
Grid - Energy Supplied [kWh]	3,146	3,351	3,263	3,296
Grid - Mean Power [kW]	55	58	57	57
Grid - Peak Power [kW]	118	100	115	89
Grid - Peak Duration [min]]	1016	735	1016	1016
GSE Electrification Emission Benefits [%]	62.7	60.2	61.6	61.1
Minimum Number of eGSE required [ea]	36	36	38	38
Charge Stations Required [ea]	35	36	38	38
Charge Station - Max Charge Power [kW]	21	27	21	14

B. Simulation Results for GSE Battery Sizing

Results of GSE battery sizing is shown for a catering truck as an example in Table 6 for case 4. The C-rate for charging and discharging were limited to 2C and 10C respectively. The results show that there is headroom for higher power charging. Due to operational reasons the minimum number of conventional catering truck required to service the airport is three and e-GSE is four. The required battery energy capacity is lower than the existing electric catering truck by 65% [22], which is due to sizing the battery for a quiet airport, in which there is a need for four GSE to service only seven flights.

TABLE VI. Simulation Results for Catering Truck Battery Sizing

GSE Type	Catering Truck
Required Battery Energy Capacity [kWh]	34.5
Maximum Discharging Power [kW]	83
C-rate (Discharge - Required) [1/h]	2.4
Maximum Charging Power [kW]	46
C-rate (Charge - Required) [1/h]	1.3
Minimum Required Number of Conventional GSE [ea]	3
Minimum Required Number of Electric GSE [ea]	4

IV. Discussion and Conclusion

The MIMO AEM is able to conduct a preliminary analysis and make estimations for the quantification of the increase in airport electricity requirements, understanding the charging requirements of GSE, and identification of the possible scheduling of GSE charging for existing turnaround procedures. MIMO AEM can be useful for early stage decision making of different stakeholders, such as airport operators, ground service providers, GSE manufacturers, airline companies, and aircraft manufacturers.

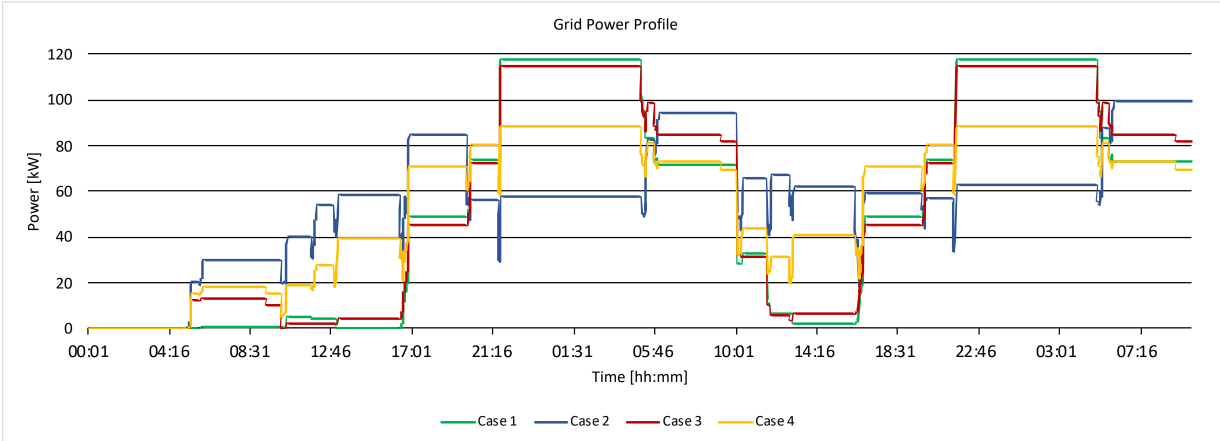

Fig. 3. Power profile demanded from the grid versus time diagram for 4 different simulation cases. Case 1: Minimum number of eGSE with charging after full battery depletion. Case 2: Minimum number of eGSE with continuous interim charging. Case 3: Single full recharge with over-night charging. Case 4: Single full recharge with continuous interim charging

Simulation study using the proposed model indicates that minimum 36 GSE are required to service seven small aircraft on the simulated day at MME. Continuous interim charging could help to reduce the grid peak load and its duration up to 23% and 28%, respectively. The emission benefits from GSE electrification for each case is similar and up to 60% of CO_2 emission could be saved from the electrification of GSE. This result is well aligned with the finding in [10] (CO2 emission saving from GSE electrification was 45% to 65%).

In the next steps, real-world representative GSE duty-cycles shall be obtained for further development of the model. Also, enabling Vehicle-to-Grid operations in the model and optimisation of EMS would reveal a higher potential for emission savings by GSE electrification. At last, a cost-benefit analysis tool for electrification considering the whole airport system would enhance the MIMO AEM would aid the primary goal for recommending the most beneficial electrification scenario of an airport ecosystem.

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