Electric Power Systems Research 211 (2022) 108242

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Airport electrified ground support equipment for providing ancillary services to the grid

Mohammed Alruwaili [a,b,*], Liana Cipcigan [a]

[a] School of Engineering, Cardiff University, Cardiff, UK
[b] Department of Electrical Engineering, College of Engineering, Northern Border University, Ar'Ar 73222, Saudi Arabia

ARTICLE INFO

Keywords:
Airport
Electrified ground support equipment
Vehicle to grid
Ancillary services
Aggregators

ABSTRACT

The ground handling operations are used in airports for handling activities and processing passengers with the help of specially designed vehicles known as ground support equipment. The ground support equipment (GSE) is being parked after serving a flight until the next flight. The GSE idle duration between flights is depending on the flight schedule and can be turned into a profit source. This paper is presenting a methodology for electrified ground support equipment (EGSE) for providing frequency regulation ancillary services to the grid through an aggregator. The passengers flight schedule is considered to increase the vehicles' availability to participate in the frequency regulation ancillary services market. The optimization model is formulated to maximize the airport profitability by using aggregation of EGSE in frequency regulation market. The results show that the EGSE provides a significant profit by participating in frequency regulation ancillary service with the use of V2G mode.

1. Introduction

Aviation is recognised as the most carbon-intensive sector and at the same time the most difficult of decarbonise accounting for 12% of all transport CO_2 emissions and 2% of global carbon emissions [1]. Year 2020 is excepted from recent statistics due to COVID-19. The recent plan to decarbonise UK aviation [2] set the commitment to net-zero emissions by 2050 through some interim decarbonization targets for example 15% reduction in net emissions relative to 2019 by 2030 and 40% reduction by 2040.

The European Commission (EC) adopted in July 2021 a number of legislative proposals to achieve climate-neutral by 2050. As part of this effort is the decarbonization of aviation sector who accounted for 3.85% of total CO_2 direct emissions in 2017. Also, it is the second source of transport greenhouse gas emissions (GHG) after road transport [3]. An important measure adopted to address the climate change is EU Emissions Trading System (EU ETS) seen as a key tool to limit GHE [4]. EU ETS is the first international emission trading system covering commercial aviation within the European Economic Area along with electricity generation, heat generation and energy-intensive industries. Moreover, in 2018, aviation generated around 3% of the total U.S. CO_2 emissions and around 9% of GHG emissions from the U.S. transportation sector [5]. The U.S commercial civil aviation were responsible for 24% of global civil aviation CO_2 emissions [6]. Thus, in January 2021, The U. S. Environmental Protection Agency launched the first federal policy to regulate GHG emissions from commercial aircraft [7].

At an airport ecosystem the pollution is coming from different sources, and these are classified as direct emissions airport-own sources and indirect emission from non-airport-own sources. Some examples of direct emissions are aircraft engines, ground support equipment (GSE), electricity consumption in buildings, vehicle fleets, generators, airport-own power plants that burn fossil fuels. Indirect emissions are coming from shuttle busses, taxis, passenger vehicles arriving or departing the airport.

One path to cut airport related GHG is to use low or zero-emission GSE and provide the infrastructure provision for supporting decarbonization solutions since many of these ground handling equipment are at present powered by diesel or petrol fuel. This paper is focusing on exploring the environmental opportunities for the electrification of GSE and the provision of frequency regulation ancillary services to the grid by the aggregation of EGSE vehicles.

2. Electrified ground support equipment

GSE are designed to support aircraft operations at ground between flights or maintenance operations [8]. Most of the GSEs are mainly operated on the airside to provide services to the aircraft for example

* Corresponding author at: College of Engineering, Northern Border University, Saudi Arabia.
E-mail address: alruwailim2@cardiff.ac.uk (M. Alruwaili).

https://doi.org/10.1016/j.epsr.2022.108242
Received 8 January 2022; Received in revised form 3 May 2022; Accepted 29 June 2022
Available online 13 July 2022

Nomenclature

Indices

$k \in K$	sets of EGSE type.
$i \in I$	number of EGSE of each type.
$t \in T$	sets of time.

Parameters

Ru_t	regulation up available capacity (kW).
Rd_t	regulation down available capacity at time *t* (kW).
pu_t	regulation up capacity price at time *t* (€/kW-h).
pd_t	regulation down capacity price at time *t* (€/kW-h).
$E^{ch}_{k,i,t}$	dispatched energy for regulation down (kWh).
$E^{dis}_{k,i,t}$	dispatched energy for regulation up (kWh).
p_t	energy price at time t (€/kWh).
$pdis_t$	selling energy back price at time t (€/kWh).
ϕ	battery degradation cost (€/kWh).
β_t	energy price (€/kWh).
$n_{EGSEk,t}$	required number of EGSE to serve airplanes of each type *k* at time *t*.
$SOC^{max}_{k,i,t}$	minimum state-of-charge (%).
$SOC^{min}_{k,i,t}$	maximum state-of-charge (%).
α_{up}	dispatched ratio for regulation up.
α_{down}	dispatched ratio for regulation down.
$Ereq_{k,i,t}$	hourly required energy (kWh).
$Rd, offered_t$	offered regulation down capacity (kW).
$Ru, offered_t$	offered regulation down capacity (kW).
LD_t	number of landing and departing flights.
Pch_{max}	maximum charging power rate (kW).
$Pdis_{max}$	maximum discharging power rate (kW).
C_{ch}	EGSE aggregator charging energy cost (€).
C_{deg}	EGSE aggregator degradation cost (€).
$A_{EGSE,k,t}$	all available EGSE of type k at time t.

Variable

$P_{k,i,t}$	available regulation down capacity (kW).
$P^{-}_{k,i,t}$	available regulation up capacity (kW).
$PR^{-}_{k,i,t}$	regulation up capacity prediction (kW).
$PR_{k,i,t}$	regulation down capacity prediction (kW).
$available_{k,i,t}$	binary variable for EGSE availability state.
$Em_{k,i,t}$	binary variable for regulation Up or Down states of EGSE.
$C1_t$, $C2_t$, $a1_t$, $a2_t$, $d1_t$ and $d2_t$	Binary indicators to control regulation bids.

refueling, loading luggage, passenger transport, loading food and portable water, de-icing airplanes. There are different providers in charge with airport ground operations. There are several types of GSEs, and among those types, the most used GSE which used in this study are [9]:

(i) Aircraft push-back known as aircraft tractor. It is used to push back the airplane from the gate to the aircraft movement area such as a taxiway or to tow the aircraft to another location such as a maintenance hangar. It is used when the airplane is not under its own engine power [10].
(ii) Baggage Tractor is used to tow train of baggage carts or cargo between the aircraft and the airport facilities. They are one of the most GSE vehicles used in the airport [11].
(iii) Belt Loader: is used to load and unload baggage and cargo between the airplane baggage and cargo compartments and the baggage and cargo carts.
(iv) Container Loader: is used to load and unload cargo containers, pallets, and other payloads into and off the airplane.

Similar with road electric vehicles (EVs), EGSE could offer frequency regulation ancillary services to the grid. Road EVs can be seen as mobile batteries which in aggregation could offer significant storage capacity through vehicle-to-grid (V2G). Vehicle-to-grid system was trailed to manage the impact of EVs on the power grid [12]. The concept of V2G is that EVs can charge during off-peak hours and discharge power into the electric grid when power is required via a bidirectional power charger [13]. So, both of the power grid and the EV owners whom become active prosumers rather than being passive customer could make profits while the EVs are not in use [14]. The charging and discharging process of EVs should be optimally controlled to reduce the negative impacts on the power system [15]. So, V2G is a proper technology that quickly responds to mitigate the fluctuation in the grid rather than the conventional technologies since EVs are treated as controlled load.

The ancillary service market is providing flexible solutions to the power grid to overcome many challenges that are facing Transmission System Operator (TSO) for a reliable power grid operation. In particular, the ancillary services such as frequency and voltage regulation are provided through an aggregator that interacts between the electricity market and aggregated EVs [16]. The aggregator interacts between EVs owner and electricity market to ensure the available power capacity is ready when is needed by the market operator. The EVs aggregator act as an electricity retailer that participate in electricity market on behalf of EVs owners and satisfy their charging needs under a signed agreement [17]. This business model includes several benefits such as more reliable and effective EV fleet management, higher customer confidence, and faster response to electricity market [18]. However, in real-world situations, the uncertainties relating to market pricing and EVs owners behavior make the aggregator model/ challenging [18]. Many studies have been conducted to find the best participation strategies of EV aggregators in the electricity market. These studies aim to optimize the EVs operation for optimal bidding in the day-ahead and real-time electricity market including robust [19,20], stochastic [18,21,22], deterministic [23,12]. In [23], a deterministic optimization model is developed for an EV aggregator to participate in the secondary frequency response market. Three different charging preferences for EVs owners are considered by the aggregator while defining bids. The objective of the proposed model is to maximize the EVs aggregator profit with and without consideration of V2G. Because of the considered flexibility from EV consumers, the model does not present considerable benefits for regulation up, both with and without the V2G mode. However, the study is not considering the EV state-of-charge. The authors of [18] proposed a two-stage risk-constrained stochastic programming method for EV aggregators to determine the optimal biding strategy in the day-ahead and real-time energy, and frequency regulation markets. The study considers the uncertainty of real-time energy prices and regulation service deployments, as well as EV owners associated uncertainties. A stochastic robust optimization model is introduced in [20] where day-ahead market prices and EVs driving requirements uncertainties are considered. The proposed approach allows the aggregator to cut charging expenses when compared to other charging strategies. The participation of EV aggregator in the frequency regulation ancillary services market was not considered in this paper. An optimal scheduling strategy using V2G is applied to optimize the energy and provide ancillary services [12], e.g., load regulation and spinning reserves. A deterministic algorithm was developed to be used by an aggregator to maximize profits by buying and selling energy, spinning reserves, and regulation in a day-ahead electricity market. The study also considers the unexpected EV departures during the contracted time. The proposed model is simulated using a hypothetical group of 10,000 EVs which revealed a potential yearly profit of $6 million for the aggregator. In addition, in [24], the use of the plug-in EVs to provide frequency response services based on a real-time greedy index is introduced. The proposed method transforms the multi-dimensional problem of optimal dispatch into a one-dimensional problem while satisfying the optimal solution. The author of [25] introduced a robust optimization model for the EV aggregator bidding strategy in real-time electricity pricing considering battery degradation uncertainty. The uncertain parameters worst case scenario is used to determine the bids. However, due to the robust optimization algorithm nature, the model results might be over-conservative. A day ahead optimization formulation to minimize the cost of operation of EVs fleet participating in the regulation market was developed on [26]. A hierarchical control system that optimizes the charging, market bidding, and response to the system operator is developed to minimize the operation cost and maximize the regulation services revenue. The results show that bidding strategy is significantly sensitive to various parameters, e.g., retail demand charge, high SOC reserve, and large difference in regulation up and down prices. However, the associated monetary value regarding EVs battery degradation is not considered.

Many studies are discussing solutions to facilitate the road EVs participation in the frequency regulation ancillary services market, but from the authors' knowledge there is no research work considering the use of off-road EVs like EGSE to participate in the frequency regulation market. In addition, in the above literature survey, the daily average energy consumption of EV is used. While, in this work, the hourly energy consumption of EGSE is used instead offering higher granularity of data. Accordingly, this paper proposes mixed-integer linear programming (MILP) to help aggregators utilizing the EGSE to participate in the frequency regulation market. The main contributions of this research compared to the previous work are as follows:

(i) Formulate an innovative aggregator model for providing frequency regulation ancillary services using airport EGSE aggregation based on the passenger flight schedule.
(ii) Study the EGSE aggregator profitability from providing frequency regulation services using real data of Ostend–Bruges Airport as a case study.
(iii) Formulate the optimal participation of the EGSE aggregator in the day-ahead frequency regulation market as a MILP model. The developed model is able to satisfy the EGSE fleet energy needs and obtain optimal bids for the EGSE aggregator in the day-ahead market.

3. Frequency regulation ancillary services

The changes in the traditional vertical power system paradigm unbundled the power system into generating units, TSO, and distribution system operators (DSO). For a transparent and cost-effective energy trading, electricity markets have been established. Through the liberalization of the electricity markets, certain services linked to power generation, transmission, and distribution were separated. The power system has recently seen a massive transformation and the decarbonization of the electricity system requires investment in low-carbon energy sources resulting in an increased share of distributed energy resource (DER). With reduction in operating hours of conventional large-scale fossil fuel generators there is a need for emerging technologies to provide flexibility through ancillary services [27]. Ancillary services include various services related to power system characteristics such as frequency control, voltage control, congestion management, black start, and loss compensation [28–30]. The frequency control market is more commercialized globally since it is related to active power supplying which can be promptly priced [23]. Whereas for example, the voltage control market is linked with reactive power which has local influence and is hard to trade [31,23].

The research work in this paper focuses on the frequency regulating opportunity. There is no unified universally market structure for frequency control in most countries. However, the common feature is that the frequency control ancillary service market is designed based on bidding and contracting structure [32,23]. In addition, the frequency control ancillary service nomenclature and functionality differ locally and globally. For example, in the USA, frequency control ancillary services termed as regulations and reserves for Pennsylvania, New Jersey, and Maryland Interconnection area (PJM) [33], regulation for New York Independent System Operator (ISO) [30], and regulation up, regulation down, spinning reserve and non-spinning reserve for California ISO [34]. In addition, frequency control ancillary services in Australia include contingency, and regulation [35]. In the European Union countries, the frequency control services known as frequency containment reserves (FCR) (i.e., primary control), frequency restoration reserves (FRR) (i.e., secondary control) and replacement reserves (RR) (i.e., slow tertiary control) [36,37,27].

The FCR or primary control is the first type of control that automatically respond within seconds to a frequency deviation following a disruption. The available reserve of active power is used to contain the mismatch between generation and demand to stabilize the system frequency within seconds [38,39]. Later, the FRR is activated to set back the system frequency to its nominal value. The active power reserve available is used to restore power balance between control areas. The area control error (ACR) is reduced to zero by restoring unscheduled power flow between different areas to original values by the automatic generator control (AGC). The AGC adjust raise or lower set points of active power of various regulation resources, including EVs fleet, to provide required response to minimize ACE. The minimization of ACE includes signals for frequency regulation up and down. Regulation up is required when the system frequency is under reference frequency, and this can be done by discharging EV battery. Whereas regulation down is required when the system frequency is above reference frequency, and this can be done by increasing EV charging power rate. The FRR requirements are established based on day-ahead or real-time (one hour prior). In addition, the FRR activation starts from a few seconds (typically 30 s) and lasts a few minutes (typically 15 min) to make FCR available for any other system disturbance and can be either automatic or manual [38,40]. Finally, the RR or tertiary control is manually activated to restore and support the required level of FRR for further system disturbance using available reserve active power.

4. Methodology for EGSE frequency regulating provision

The main aim of this work is to propose a methodology for using EGSE to participate in a day-ahead frequency regulation market through an aggregator based on the flight schedule. Since the flight schedule is known in advance, the uncertainty of V2G status could be eliminated.

The main aim of the proposed EGSEs aggregator is to maximize the profit, which is based on an optimization problem subjected to various constraints. The EGSE aggregator profits are like any other investment where the revenue and cost functions should be formulated. The EGSE aggregator profits are defined as:

$$Pro = Rev - C \quad (1)$$

Where the EGSE aggregator sources of revenue (Rev) are capacity payment and energy payment. The capacity payment represents the payment for the contracted capacity of the regulation up and down regardless this capacity is used or not. This is only paid if the EGSE is plugged in and available for the contracted hour. The energy payment is the payment of selling energy to the EGSE owner to charge the EGSE fleet and selling energy back to the grid. The revenue can be expressed as:

$$Rev = \sum_{t\in T} Ru_t \cdot pu_t + Rd_t \cdot pd_t \cdot \Delta_t + \sum_{t\in T}\sum_{k\in K}\sum_{i\in I}\left[E^{ch}_{k,i,t}\cdot p_t\right]$$

$$+ \sum_{t\in T}\sum_{k\in K}\sum_{i\in I}\left[E^{dis}_{k,i,t}\cdot pdis_t\right] \quad (2)$$

Where:

Ru_t: Available capacity of the regulation up at time t (kW).
Rd_t: Available capacity of regulation down at time t (kW).
$E^{ch}_{i,t}$: Regulation down dispatched energy (kWh).
$E^{dis}_{i,t}$: Regulation up dispatched energy (kWh).
pu_t: The capacity price of regulation up at time t (€/kW-h).
pd_t: The capacity price of regulation down at time t (€/kW-h).
p_t: energy tariff at time t (€/kWh).
$pdis_t$: selling energy back price at time t (€/kWh).
Δ_t : Time interval.

Note that the capacity price for regulation up and down (€/kW-h) means € per kW available for regulation up or down whether used or not for the hour t. The first part in Eq. (2) represents the capacity payment revenue, while the second and third parts represent the energy payment that results from either charging or discharging EGSEs.

The EGSE aggregator source of costs includes the cost of energy to charge EGSE and the cost of battery degradation, which is related to discharging the EGSE battery in the V2G mode.

$$C = C_{ch} + C_{deg} \quad (3)$$

Where:

C_{ch} is the cost of energy that is needed to charge all the EGSE. This cost is paid by the aggregator to the utility.

C_{deg} is the cost of battery degradation which is associated from discharging the EGSE battery in the V2G mode. The cost of energy and degradation are represented as follow:

$$C_{ch} = \sum_{t\in T}\sum_{k\in K}\sum_{i\in I} E^{ch}_{k,i,t} \cdot \beta_t \quad (4)$$

$$C_{deg} = \sum_{t\in T}\sum_{k\in K}\sum_{i\in I} E^{dis}_{k,i,t} \cdot \varphi \quad (5)$$

Eq. (4) illustrates the positive power draw by ith EGSE at time t to charge it. It multiplies by the energy price (β_t) at time t. While Eq. (5) shows the degradation cost of the ith EGSE at time t that is resulted from discharging the energy (E^{dis}) to the utility grid. This cost is paid by the aggregator to the EGSE owner when the EGSE supply the grid by discharging the EGSE battery. ϕ is the degradation cost per kWh.

The revenue and cost both depend on the EGSE status; whether it is charging or discharging so, the aggregator must take the i^{th} EGSE availability into account. Airport electric ground vehicles equipment availability is mainly depending on flight schedule. The flight schedule is already known in advance, which eliminates the uncertainty of the unexpected departure of EGSE.

There is a significant difference between road EVs and EGSE to participate in frequency regulation ancillary services. The EVs participation is dependent on the customer behavior. However, the EGSE charging and discharging pattern are well known in advance since it depends on the flight schedule. Therefore, the provision of frequency regulation ancillary services can be set in advance based on this well-known schedule.

The required number of electric ground support equipment to serve all flights at time t can be calculated as following [41]:

$$n_{EGSE\ \ k,i,t} = \frac{LD_t}{n_{\ TE_{k,i}}} \quad (6)$$

Where:

LD_t: is the number of landing and departing flights at hour t.
$n_{\ TEk,i}$: is the number of turnaround events that each vehicle i of type k can perform per hour.

The number of required EGSE ($n_{EGSE\ k,i,t}$) is round towards $+\infty$. The number of available EGSE to perform frequency regulation service at time t is:

$$A_{EGSE_{k,t}} = Tot_{EGSE_k} - n_{EGSE_{k,i,t}} \quad (7)$$

Where $Tot_{EGSE\ k}$ is the total number of EGSE of type k.

The hourly energy required by each vehicle i to perform its task is the multiplication of the energy used per turnaround event and the total number of turnarounds per hour and is represented as:

$$Ereq_{k,i,t} = n_{TE_{k,i,t}} \cdot E_{TE_{k,i}} \quad (8)$$

Where $E_{TE_{k,i}}$ is the required energy of each turnaround event (kWh).

Turnaround event is defined as the EGSE left its parking slot to serve an aircraft and back to the same spot after finishing the required work. The time and distance from the parking slot and to the airplane are measured to calculate the required energy per turnaround event. The turnaround time is calculated as follows [41].

$$t_{TA,i} = t_{to\ \ airplain,i} + t_{from\ \ airplain,i} + t_{task\ \ airplain,i} \quad (9)$$

Where:

$t_{TA,i}$ is the required total time of vehicle i to perform one turnaround event in (min).
$t_{to\ airplain,i}$ is the required time of vehicle j to arrive to the airplane from its parking in (min).
$t_{from\ airplain,i}$ is the required time of vehicle j to arrive to its parking again from airplane in (min).
$t_{task\ airplain,i}$ is the required time of vehicle j to complete its task at the airplane in (min).
Then, the number of turnaround events of each vehicle i of type k in one hour is calculated as follow:

$$n_{TE_{k,i,t}} = RES * 60 / t_{TA,i} \quad (10)$$

Where Res is the reserved time factor for each vehicle in each hour for different works such as driver changes. The number of turnaround events $n_{TE_{k,i,t}}$ is round towards zero. Turnaround event across two consecutive hours is considered since each landing or departing flight is considered separately. For example, flights from 9:00 to 9:59 are inputs for $t = 9$ and flights from 10:00 to 10:59 are inputs of $t = 10$. So, if a flight land at 9:50 am and departs at 10:20 am, it will count as two flights one at $t = 9$ and one at $t = 10$. EGSE will be unavailable from 9 am, not from 9:50 am, and for the next hour, EGSE will be reserved from 10:00 am to 10:59 am, not 10:20 am.

Moreover, the maximum power that each EGSE can provide for regulation down or up in case of charging or discharging is limited by the stored energy in the battery and the required time to response for regulation service. The maximum power that EGSE can provide for regulation up at time t is:

$$P^{-}_{k,i,t} = \left(Es_{k,i,t} - SOC^{min}_{k,i,t} * t_{dispatch}\right) \quad (11)$$

And the maximum power that EGSE can provide for regulation down is:

$$P_{k,i,t} = \left(SOC^{max}_{k,i,t} - Es_{k,i,t} * t_{dispatch,ch}\right) \quad (12)$$

Where the maximum discharge power $P^{-}_{k,i,t}$ and the maximum charge power $P_{k,i,t}$ in kW and $Es_{k,i,t}$ is the stored energy in kWh. Also, $t_{dispatch}$ and $t_{dispatch,ch}$ are the time needed to dispatch the required energy in hours to

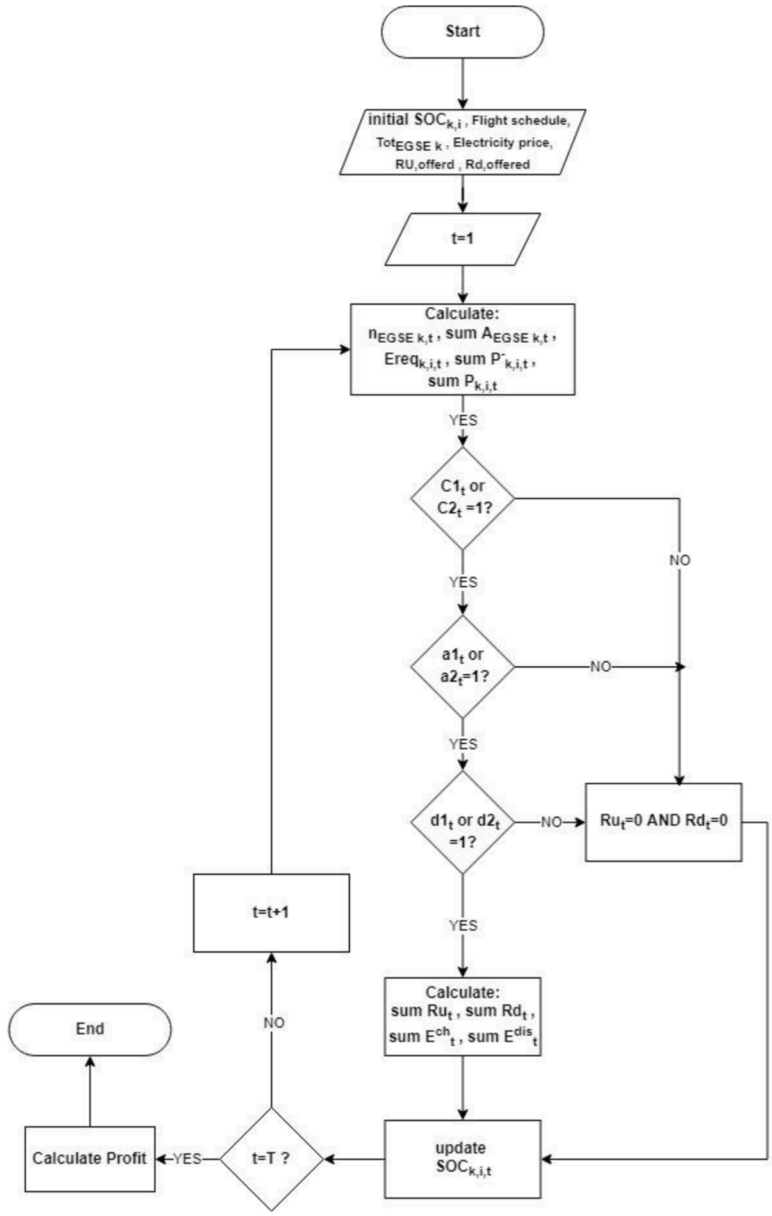

Fig. 1. Proposed frequency regulation flowchart.

response to a regulation call. It depends on the used bidirectional charger technology. The aggregator offered power for regulation up or down at a given time is the sum of the maximum power of all EGSE for regulation up or down.

The actual power draw of EGSE for regulation up and down is not known because the aggregator optimizes the EGSEs fleet in advance. Consequently, the expected drawn power of EGSE is described as a fraction of the total contracted power for regulation services. The predicted dispatch power ratio for regulation up and down respectively are [13]:

$$E^{dis}_{k,i,t} = P^{-}_{k,i,t} \times t_{plug} \times \alpha_{up_{k,i,t}} \tag{13}$$

$$E^{ch}_{k,i,t} = P_{k,i,t} \times t_{plug} \times \alpha_{down_{k,i,t}} \tag{14}$$

Where $\alpha_{up_{k,i,t}}$ and $\alpha_{down_{k,i,t}}$ are the average dispatched to contract ratio for regulation up and down, respectively. t_{plug} indicates the time in hours that EGSE is plugged in and available. The optimization model is formulated to maximize the profits by participating in frequency regulation market and the following assumptions are used:

1 The cost of bidirectional charger installation is not considered.
2 The charging and discharging process is assumed to be linear for simplicity.
3 The degradation cost is only considered with discharging cycle, which represents V2G mode.
4 Flights delay or cancelation is neglected.

The objective function can be written as follows:

$$Maximize\ Pro = Rev - C \tag{15}$$

And the objective function in (15) is subjected to the following constraints:

$$SOC^{min}_{k,i,t} \leq SOC_{k,i,t} \leq SOC^{max}_{k,i,t} \tag{16}$$

$$SOC_{k,i,t} = SOC_{k,i,t-1} + \left(E^{ch}_{k,i,t} - E^{dis}_{k,i,t}\right) - Ereq_{k,i,t} * \left(1 - available_{k,i,t}\right) \tag{17}$$

$$P^{-}_{k,i,t} \leq PR^{-}_{k,i,t} \tag{18}$$

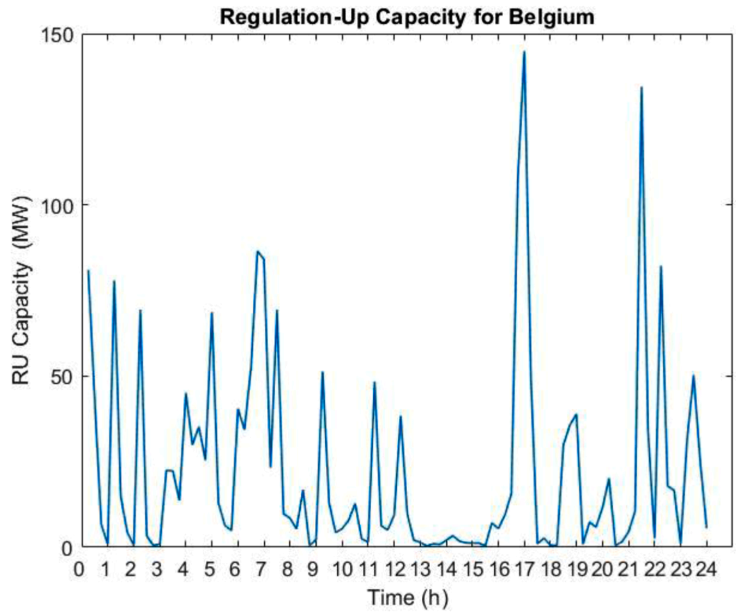

Fig. 2. Regulation-up capacity.

$$0 \le P^{-}_{k,i,t} \le Pdis_{max} * available_{k,i,t} \tag{19}$$

$$PR^{-}_{k,i,t} - P^{-}_{k,i,t} \le \left(1 - available_{k,i,t}\right) * Pdis_{max} \tag{20}$$

$$P_{k,i,t} \le PR_{k,i,t} \tag{21}$$

$$0 \le P_{k,i,t} \le Pch_{max} * available_{k,i,t} \tag{22}$$

$$PR_{k,i,t} - P_{k,i,t} \le \left(1 - available_{k,i,t}\right) * Pch_{max} \tag{23}$$

$$Em_{k,i,t} * Pch_{min} \le P^{-}_{k,i,t} \le Pch_{max} * Em_{k,i,t} \tag{24}$$

$$\left(1 - Em_{k,i,t}\right) * Pdis_{min} \le P_{k,i,t} \le Pdis_{max} * \left(1 - Em_{k,i,t}\right) \tag{25}$$

$$\sum_{t=T}\sum_{k\in K}\sum_{i\in I} available_{k,i,t} = A_{EGSE,k,t} \tag{26}$$

$$d1_t * Ru, offered_t \le Ru_t \le d1_t * \sum_{k=1}^{k}\sum_{i=1}^{AEGSE} P^{-}_{k,i,t} \tag{27}$$

$$d2_t * Rd, offered_t \le Rd_t \le d2_t * \sum_{k=1}^{k}\sum_{i=1}^{AEGSE} P_{k,i,t} \tag{28}$$

$$C1_t = \left\{ \begin{matrix} 1, \ Ru, offered_t > 0 \\ 0, \ else \end{matrix} \right\} \tag{29}$$

$$a1_t = \left\{ \begin{matrix} 1, \ Ru, offered_t \le \sum_{k=1}^{k}\sum_{i=1}^{AEGSE} P^{-}_{k,i,t} \\ 0, \ else \end{matrix} \right\} \tag{30}$$

$$d1_t = \left\{ \begin{matrix} 1, \ C1_t + a1_t > 1 \\ 0, \ else \end{matrix} \right\} \tag{31}$$

$$C2_t = \left\{ \begin{matrix} 1, \ Rd, offered_t > 0 \\ 0, \ else \end{matrix} \right\} \tag{32}$$

$$a2_t = \left\{ \begin{matrix} 1, \ Rd, offered_t \le \sum_{k=1}^{k}\sum_{i=1}^{AEGSE} P_{k,i,t} \\ 0, \ else \end{matrix} \right\} \tag{33}$$

$$d2_t = \left\{ \begin{matrix} 1, \ C2_t + a2_t > 1 \\ 0, \ else \end{matrix} \right\} \tag{34}$$

Eqs. (16) and (17) control the state-of-charge (SOC) of each EGSE to ensure that SOC stays within its assigned limits. Constraints (18)–(23) are used to determine the fleet total available power capacity for regulation up and down. $available_{k,i,t}$ is a binary variable that represents the availability state of EGSE. It equals to 1 when EGSE available and not in use to serve an aircraft and vice versa. Binary variable $Em_{k,i,t}$ in constraints (24) and (25) is used to guarantee that each vehicle is only providing regulation up or down at the same time. Moreover, Eq. (26) is used to ensure that the number of available EGSE of the same type at time t is equal to the number of available EGSE of each class which is calculated based on the flight schedule by using Eq. (7). Constraints (27) and (28) are used to guarantee that the bid capacity for regulation up and down is between the fleet available power capacity for regulation and offered regulation capacity by the system operator. Indicator constraints in (29)–(34) are used to ensure regulation bids take a place when offered regulation is larger than zero and EGSE total capacity for regulation is larger than offered regulation. This depends on the market policy where EGSE are participating where a minimum capacity should be reserved to perform regulation up or down. For example, if the minimum required regulation capacity is 1MW so, the aggregator can only make a bid at time t if the total fleet available capacity at the same time t is 1MW or more. Suppose the total available capacity is lower than 1MW, so the aggregator cannot make a bid.

The proposed methodology of the frequency regulation ancillary services participation flowchart is shown in Fig. 1.

5. Case study, Ostend-Bruges airport

The aircraft push-back, baggage tractor, belt loader and container loader EGSE are used to demonstrate the performances of the optimization model. These types of EGSE are selected because they are the most used in airports, and they are mature technologies that already have an electric model available in the market [11]. The specification data of EGSE used in the analysis could be found in [42]. Challenger 280e is an electric aircraft tractor equipped with two 96V-875Ah lead-acid batteries, and it is capable of towing an aircraft wight up to 300 tons. Moreover, CH70We Neo is an electric container loader that can lift up to 7 tons and comes with an 80V-810Ah battery. The

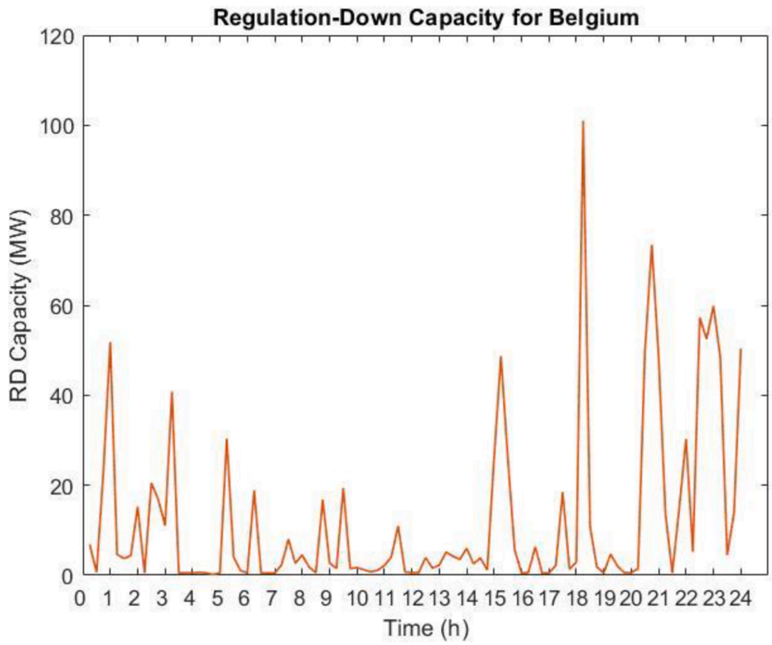

Fig. 3. Regulation-down capacity.

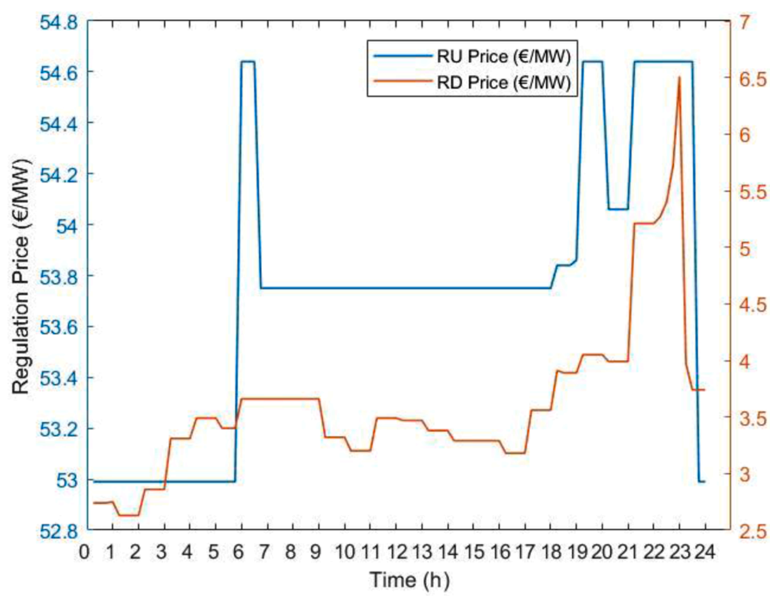

Fig. 4. Regulation prices.

considered EGSE fleet also contains TLD Jet-16 electric baggage tractor and CBL-150E electric belt loader. The zero-emission baggage tractor and belt loader are equipped with batteries with 80V-620Ah and 48V-500Ah, respectively.

The case study is considering Ostend–Bruges Airport with pre-Covid flight schedule on Monday of August 2019. The flight schedule in most cases is fixed and has only minor changes from year to year only if a new route is added or an old route canceled.

There are 17 aircrafts stands for commercial flights located in Ostend–Bruges airport [43], and each aircraft stand is assumed that has baggage tractors, belt loader, aircraft push-back tractor, and container loader [9]. Consequently, it is assumed that EGSE types k and EGSE number i are equal to 4 and 17, respectively. The regulation data and energy prices from Elia group are used to validate the model [44] due to their availability of data. Elia group is responsible for operating the Belgium grid and control the frequency. They publish data of submitted and awarded bids of local balancing auctions. 1MW minimum volume offered is required, but for the scale down of the case study, the minimum threshold is reduced to 0.5MW. The regulation data provided by Elia group are online available in [44]. These data are input data used to validate the proposed model, which can be changed based on the market data. The 15 min data of upward secondary reserve which used in this model are shown in Fig. 2.

The 15 min data of downward secondary reserve used in this model are shown in Fig. 3.

The regulation prices for both regulations up and down are shown in Fig. 4.

The expected dispatch ratios used in the modeling are 0.28 for regulation up and 0.1 for regulation down based on the average ratio of the actual activated data for the same day of offered regulation capacity

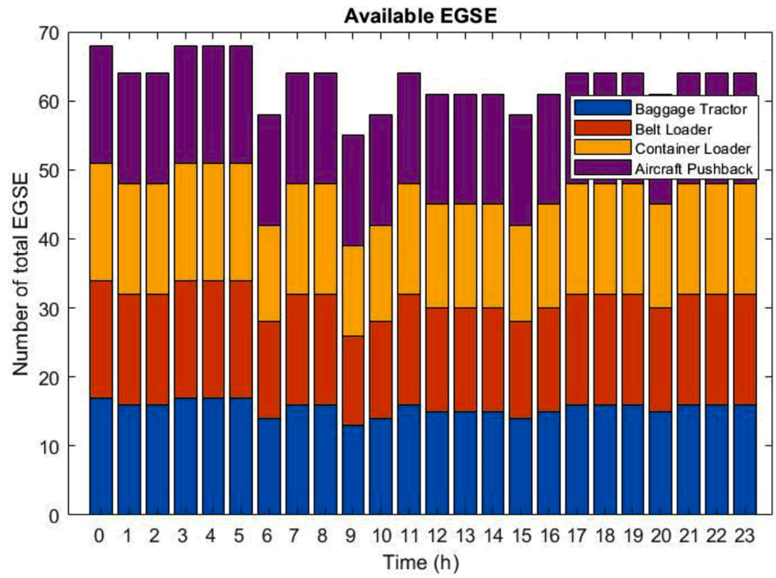

Fig. 5. Total number of available EGSE.

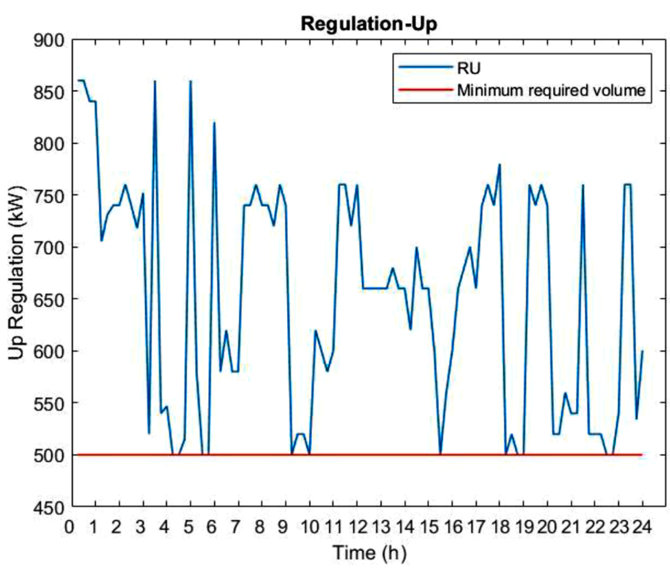

Fig. 6. Regulation Up awarded bids.

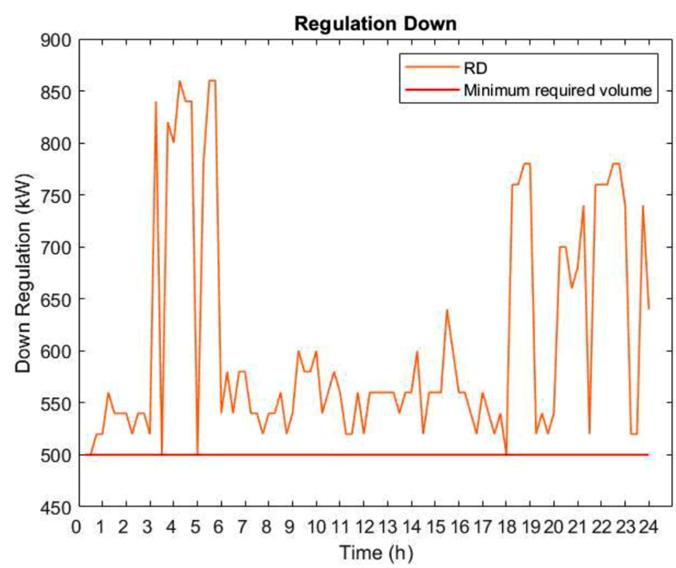

Fig. 7. Regulation down awarded bids.

data. The Mixed-integer linear programming (MILP) optimization model was solved using GUROBI optimization solver [45]. The time horizon of optimization is 24 h. It is assumed that the initial SOC of EGSEs was 50% of the battery capacity at the beginning of the day.

6. Simulation results

First, Eqs. (6)–(10) are used to calculate the total available EGSEs for 24-h. The reserved time factor *Res* is assumed to be 0.75, which means 15 min each hour is reserved for each EGSE for the driver change, plugging or unplugging the charger, and time delay that might occur [41]. The number of available EGSEs of each hour is shown in Fig. 5.

The optimization simulation result of regulation up is shown in Fig. 6. The results show that the aggregator was able to offer a bid for all the time and successfully submit the minimum required capacity. The maximum bids are during the airport off-peak hours, where the number of flights is low.

Fig. 7 illustrates the hourly regulation down capacity. The results show that the EGSE aggregator successfully achieves the minimum capacity of bid requirements. It is also noted that regulation down which correspond to adjusting charging rate is during airport off-peak time where most of EGSEs are available. The aggregator participates in both regulations up and down at the same time because the availability of EGSE, which is based on the flight schedule, has been taken into account, and that increased the plugged-in time certainty. This means, part of the total EGSEs are used to provide regulation up, and the rest are selected to participate in regulation down. The EGSE state of charge was considered to make sure that all EGSE operate within the acceptable SOC limits.

Fig. 8 represents samples of EGSEs state of charge for the studied period. Eq. (11) is used to calculate the SOC of each EGSE after each time step to update the SOC to be considered in the next time step. The results show that all EGSEs have not violated the maximum or minimum SOC because it is assumed that each EGSE is plugged in during the availability time and providing either regulation up or regulation down. As a result, each EGSE has access to a charging point all the time.

The aggregator total profits of participating in the selected day of frequency regulation ancillary service market is shown in Table 1.

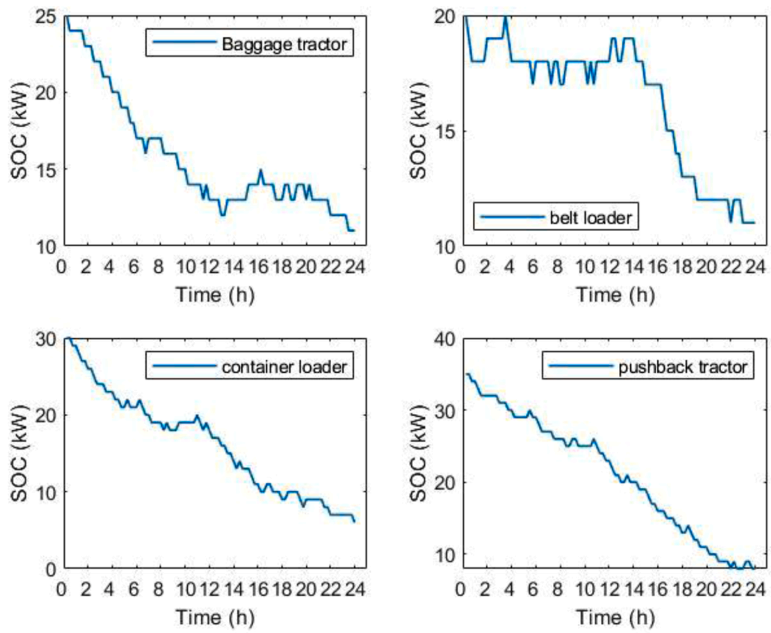

Fig. 8. Sample of EGSE SOC.

Table 1
Aggregator revenue and cost.

Regulation Down Revenue	199.9 €/day
Regulation Up Revenue	3298.1 €/day
Total Revenue	4090 €/day
Charging Cost	49.9 €/day
Degradation Cost	65.5 €/day
Total Profit	3975.1 €/day

Table 1 breakdown the incomes and expenses of participating in the regulation market. The aggregator net revenue is 4090 €/day, which includes the income from providing regulation services and selling the required charging energy to the EGSE fleet. The highest source of income is frequency regulation up which resulted in over 3000 €/day of profits. The regulation up revenue share is around 80% of the total revenue The quarter-hourly average committed regulation up capacity and price are 650 kW and 0.052€/kWh, respectively. Moreover, the remain 20% of earnings come from selling energy to the EGSE fleet for charging and regulation down which are 592 €/day and 199.9 €/day, respectively. The quarter-hourly average committed regulation down capacity and price are 606 kW and 0.0033€/kWh, respectively. The quarter-hourly average expected dispatched energy for regulation up is 182 kW at average price of 0.025€/kW. While regulation down quarter-hourly average expected dispatched energy is 60 kW at average price of 0.02€/kW. However, the aggregator total daily cost is 115 €/day, which includes the charging and degradation cost. The cost of energy purchase from the utility, which is the daily required EGSE energy to serve airplanes is 49.96 €/day. At the same time, the associated cost of discharging EGSE fleet batteries is 65.5 €/day. The net profit that the aggregator can earn from participating in the ancillary market is around 4000 €/day over the studied period.

The benefit of considering the flight schedule is clearly seen where the aggregator effectively manages the EGSE fleet participation in the frequency regulation ancillary service market. Besides the positive impact on the environment, electrifying the GSE fleet is a profitable business that can accelerate aviation sector electrification. The calculation results show that the aggregator primary profitable source is regulation up. This is because regulation up capacity prices are higher than the regulation down prices. The regulation up prices are about €50/MW while regulation down prices lay around €4/MW. Moreover, the capacity of available power which aggregator can control is high because the uncertainty of EGSE availability is very low. Also, it is assumed that all the offered bids by the aggregator are winning bids so, the capacity payment is guaranteed. The number of EGSE compared to the number of flights is also providing an advantage where most of the EGSE are always available.

However, the cost only includes charging and degradation cost. The charging cost and cost of battery degradation are low since EGSE is charging and discharging in a controllable manner based on a fixed usage. Also, the charge and discharged power is a small percentage of the total contracted capacity for regulation-down and regulation-up so, increasing this percentage will reduce the total revenue. Moreover, the regulation-up price, which is supply energy to the grid, is much higher than the regulation down price; thus, the aggregator income is high. The EGSE availability certainty level has obviously increased the profits where aggregator successfully submitted regulations bids for the whole time. Comparing EGSE with on road EVs, EGSE prove to be a more confident source of providing frequency regulation services and could be more beneficial because the EGSE operates in a closed operation environment. These are of road vehicles, operating in a controlled environment where travel distance is scheduled in advance and speed is controlled, which preclude traffic congestion and guarantee EGSE availability.

7. Conclusion

Electrifying airport ground handling vehicles is a major step in reducing airport carbon footprint. The benefits of using EGSE are not only limited to environmental purposes, but it also can support the power grid offering flexibility services. EGSE fleet can relieve the power grid by adding more flexible sources and take part in ancillary services. In this work, an optimal approach of electric ground support vehicles participation into the ancillary service market to provide frequency regulation services was developed. The flight schedule consideration for V2G mode was presented. The uncertainties of vehicle availability to participate in V2G mode is eliminated because EGSEs availability depends on the number of airplanes that are being served, which is scheduled in advance. The EGSE aggregator maximizing profits model was considered. The optimization model results showed that the aggregator could make a good profit by participating in the frequency regulation ancillary services market. It is clear that, the impact of flights delay prediction on EGSE operation should be considered to help determine the most feasible option for investment choices. This prediction issue as an open research area will be discussed in future work.

CRediT authorship contribution statement

Mohammed Alruwaili: Conceptualization, Methodology, Software, Writing – original draft, Validation. **Liana Cipcigan:** Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Acknowledgement

We are grateful for support from the Decarbonising Transport through Electrification (DTE) Network+ funded by EPSRC Grant Ref. EP/S032053/1. The corresponding author would like to thank Northern Border University, Saudi Arabia, for sponsoring his post-graduate study at Cardiff University, UK.

References

[1] International Council on Clean Transportation, Aviation. https://theicct.org/aviation, 2020 (accessed 14 September 2021).
[2] Sustainable Aviation. Decarbonisation Road-Map: A Path to Net Zero. 2020. Available online: https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf (accessed Sep. 14, 2021).
[3] European Commission, Reducing emissions from aviation. https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-aviation_en, 2021 (accessed 14 September 2021).
[4] European Commission, EU Emissions Trading System (EU ETS). https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en#Main_legislation, 2021 (accessed 14 September 2021).
[5] United States Environmental Protection Agency (EPA), Inventory of U.S. Greenhouse Gas Emissions and Sinks. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks, 2020 (accessed 14 September 2021).
[6] B. Graver, K. Zhang, D. Rutherford, CO2 emissions from commercial aviation, 2018, Int. Counc. Clean Transp. 16 (September) (2019) 13.
[7] X. S. Zheng and D. Rutherford, Reducing aircraft CO2 emissions: The role of US federal, state, and local policies, *Brief. note. Washingt. DC ICCT (https//theicct. org/publications/aviation-CO2-US-feb2021)*, 2021.
[8] The International Civil Aviation Organization (ICAO), Glossary. https://www.icao.int/cybersecurity/Lists/Glossary/DispForm.aspx?ID=111, 2016 (accessed 14 September 2021).
[9] EPRI, Electric Ground Support And Gate Electrification Equipment For Airports, EPRI, 2020.
[10] The national academies of sciences engineering medicine and national academies of sciences engineering medicine, Improving Ground Support Equipment Operational Data for Airport Emissions Modeling, The National Academies Press, Washington, D.C., 2015, https://doi.org/10.17226/22084.
[11] EPRI, Austin-Bergstrom International Airport Electrification: landside Vehicle and Airside Equipment Operations, EPRI, 2011.
[12] E. Sortomme, M.A. El-Sharkawi, Optimal scheduling of vehicle-to-grid energy and ancillary services, IEEE Trans. Smart Grid 3 (1) (2012) 351–359, https://doi.org/10.1109/TSG.2011.2164099.
[13] W. Kempton, J. Tomić, Vehicle-to-grid power fundamentals: calculating capacity and net revenue, J. Power Sources 144 (1) (2005) 268–279, https://doi.org/10.1016/j.jpowsour.2004.12.025.
[14] A. Aldik, T. Khatib, EV aggregators and energy storage units scheduling into ancillary services markets: the concept and recommended practice, World Electr. Veh. J. 11 (1) (2020), https://doi.org/10.3390/WEVJ11010008.
[15] Z. Luo, et al., Economic analyses of plug-in electric vehicle battery providing ancillary services, in: Proceedings of the IEEE International Electric Vehicle Conference IEVC, 2012, pp. 1–5, https://doi.org/10.1109/IEVC.2012.6183272.
[16] C. Guille, G. Gross, A conceptual framework for the vehicle-to-grid (V2G) implementation, Energy Policy 37 (11) (2009) 4379–4390, https://doi.org/10.1016/j.enpol.2009.05.053.
[17] R.J. Bessa, M.A. Matos, Global against divided optimization for the participation of an EV aggregator in the day-ahead electricity market. Part I: theory, Electr. Power Syst. Res. 95 (2013) 309–318, https://doi.org/10.1016/j.epsr.2012.08.007. Feb.
[18] R. Habibifar, A. Aris Lekvan, M. Ehsan, A risk-constrained decision support tool for EV aggregators participating in energy and frequency regulation markets, Electr. Power Syst. Res. 185 (2020), 106367, https://doi.org/10.1016/j.epsr.2020.106367. Aug.
[19] U. ur Rehman, M. Riaz, M.Y. Wani, A robust optimization method for optimizing day-ahead operation of the electric vehicles aggregator, Int. J. Electr. Power Energy Syst. 132 (2021), 107179, https://doi.org/10.1016/j.ijepes.2021.107179. Nov.
[20] L. Baringo, R. Sánchez Amaro, A stochastic robust optimization approach for the bidding strategy of an electric vehicle aggregator, Electr. Power Syst. Res. 146 (2017) 362–370, https://doi.org/10.1016/j.epsr.2017.02.004. May.
[21] J.P. Iria, F.J. Soares, M.A. Matos, Trading small prosumers flexibility in the energy and tertiary reserve markets, IEEE Trans. Smart Grid 10 (3) (2019) 2371–2382, https://doi.org/10.1109/TSG.2018.2797001. May.
[22] J. Iria, F. Soares, M. Matos, Optimal bidding strategy for an aggregator of prosumers in energy and secondary reserve markets, Appl. Energy 238 (2019) 1361–1372, https://doi.org/10.1016/j.apenergy.2019.01.191. Mar.
[23] J.M. Clairand, Participation of electric vehicle aggregators in ancillary services considering users' preferences, Sustainability 12 (1) (2020) 1–17, https://doi.org/10.3390/SU12010008.
[24] X. Ke, D. Wu, N. Lu, A real-time greedy-index dispatching policy for using PEVs to provide frequency regulation service, IEEE Trans. Smart Grid 10 (1) (2019) 864–877, https://doi.org/10.1109/TSG.2017.2754241.
[25] M.A. Ortega-Vazquez, Optimal scheduling of electric vehicle charging and vehicle-to-grid services at household level including battery degradation and price uncertainty, IET Gener. Transm. Distrib. 8 (6) (2014) 1007–1016, https://doi.org/10.1049/iet-gtd.2013.0624. Jun.
[26] N. DeForest, J.S. MacDonald, D.R. Black, Day ahead optimization of an electric vehicle fleet providing ancillary services in the los Angeles air force base vehicle-to-grid demonstration, Appl. Energy 210 (2018) 987–1001, https://doi.org/10.1016/j.apenergy.2017.07.069.
[27] A. Kaushal, D. Van Hertem, An overview of ancillary services and HVDC systems in European Context, Energies 12 (18) (2019) 3481, https://doi.org/10.3390/en12183481. Sep.
[28] TenneT, Dutch Ancillary Services. https://www.tennet.eu/electricity-market/dutch-ancillary-services/, 2022 (accessed 28 March 2022).
[29] PJM, Ancillary services. https://www.pjm.com/markets-and-operations/ancillary-services, (accessed 30March 2022).
[30] NYISO, Ancillary services. https://www.nyiso.com/ancillary-services, 2022 (accessed 2 March 2022).
[31] A. Gómez Expósito, A.J. Conejo, C. Cañizares, Frequency and voltage control, in. Electric Energy Systems, 2nd ed., CRC Press, 2018, pp. 373–434, https://doi.org/10.1201/9781315192246-9. Chapter 9.
[32] U. Helman, H. Singh, P. Sotkiewicz, RTOs, Regional Electricity Markets, and Climate Policy, 1st ed., Elsevier Inc., 2010 https://doi.org/10.1016/B978-1-85617-655-2.00019-5.
[33] PJM, Ancillary services market. https://learn.pjm.com/three-priorities/buying-and-selling-energy/ancillary-services-market.aspx, (accessed 30 March 2022).
[34] California ISO, Market processes and products. http://www.caiso.com/market/Pages/MarketProcesses.aspx (accessed 30 March 2022).
[35] Australian Energy Market Operator (AEMO), Settlements Guide To Ancillary Services Payment And Recovery, 2020. [Online] Available, https://aemo.com.au/-/media/files/electricity/nem/data/ancillary_services/2020/settlements-guide-to-ancillary-services-payment-and-recovery.pdf?la=en.
[36] European Commission. Commission Regulation (EU) 2017/2195 of 23 November2017 establishing a guideline on electricity balancing; 2017.
[37] Dries Lamont, Flexible power balancing on the Elia grid. https://www.egssis.com/flexible-power-balancing-on-elia-grid/, 2020 (accessed 30 March 2022).
[38] A. Janjic, L. Velimirovic, M. Stankovic, A. Petrusic, Commercial electric vehicle fleet scheduling for secondary frequency control, Electr. Power Syst. Res. 147 (2017) 31–41, https://doi.org/10.1016/j.epsr.2017.02.019. Jun.
[39] Elia, Flexible Demand Management Products, Elia, 2017.
[40] F. Teng, M. Aunedi, D. Pudjianto, G. Strbac, Benefits of demand-side response in providing frequency response service in the future GB power system, Front. Energy Res. 3 (2015), https://doi.org/10.3389/fenrg.2015.00036. Aug.
[41] F. Jarnehammar, Asset management of electrical transportation systems using alternative charging technologies: case study Stockholm Arlanda Airport, Dissertation (2018).
[42] Trepel Airport Equpement, Trepel Airport Equpement: Product overview. [Online], Available: https://trepel.com/download/trepel-products.pdf.
[43] Ostend-Bruges International Airport, All Flights. https://www.ostendbruges-airport.com/flightdates/, (accessed 15 September 2021).
[44] Elia Group, Data download. https://www.elia.be/en/grid-data/data-download-page, (accessed 13 March 2021).
[45] Gurobi Optimization, LLC, Gurobi Optimizer Reference Manual. 2021. [Online]. Available: https://www.gurobi.com.