doi:10.3233/ATDE220651

A Design Method to Achieve Decarbonisation in Airports with Battery Operation Algorithm Considering Uncertainties

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Abstract. Decarbonisation of social infrastructures such as airports have attracted wide attention. In commiting to the global decarbonisation target, introduction of renewable energy is important. However, few research has focused on the specifications of renewable energy facilities for airports. Thus, it is vital to enable airport operators to determine the necessary facility specifications for installing renewable energy systems. Moreover, the efficiency of battery operation influences the necessary facility specifications. Yet, many previous studies have proposed linear battery optimisation, even though forecasts for renewable energy supply include uncertainties derived from natural factors, and demand forecasts can also fluctuate due to future uncertainties. This study provides a framework for analysing the cost efficiency of photovoltaic systems, wind systems, and batteries to determine the optimal specifications for each hardware to achieve 100% renewable electricity. Further, it proposes a novel battery operation algorithm considering uncertainties of supply and demand forecasts. A case study on Chubu Centrair International Airport was conducted. The results show practical steps for the airport to achieve decarbonisation. In addition, battery operation based on the proposed algorithm outperformed the linear optimisation in the unpredicted rain weather scenario. It can be said that the proposed method performs well in considering uncertainties.

Keywords. Decarbonisation, renewable energy, zero emission airports, battery operation, uncertainties

Introduction

Recently, decarbonisation of social infrastructures has attracted wide attention. Social infrastructures include harbour facilities, power plants, and airports. According to reports, emissions from the aviation industry account for around 2.5%, and this number has increased faster than the average across all sectors [1][2]. Therefore, decarbonisation of airports is an important issue to be addressed. While there have been transdisciplinary approaches for carbon reduction in buildings such as in [3], focus on creating carbon free airports by decarbonising airport operations is also crucial.

There are research focused on determining the specifications for renewable energy and battery operation algorithms. For example, a mixed integer optimization problem is

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proposed in [4] to determine the optimal size and location of a photovoltaic system with batteries within distributed networks. It aims to minimize the total energy loss to derive a plan when installing battery storage in distributed networks. Using weather data for modelling photovoltaic generation, it tests several different cases of demand load. Similarly, a method to determine the allocation of a battery energy storage system within distribution network is proposed in [5]. While these studies provide the basis of determining the size of renewable energy supply and battery storage, further simulations for airports are necessary.

Simultaneously, operation algorithms of batteries are widely studied in addition to designing the necessary hardware for renewable energy systems. Since the specification determinisation of renewable energy facilities depend on how efficient the battery is used, operation method of batteries to achieve better use of electricity is investigated after planning the optimal size of the whole system such as in [6]. However, many studies have proposed optimisation based on linear forecasts. Optimisation based on linear forecasts can be useful when the forecast is accurate, but consideration on forecast failure is vital.

Setting targets and goals are empirical to companies as they impact its own performance [7]. A practical and a numerical roadmap is without exception important for the aviation industry to achieve decarbonisation and move beyond its current state. Additionally, since forecasts for electricity demand and renewable energy supply cannot be 100% accurate, there is a need to develop a battery operational algorithm which can take uncertainties into account. Thus, the objective of this paper is to establish a framework to evaluate the necessary hardware for installing renewable energy sources for achieving 100% renewable electricity in airports, as well as developing a novel operational algorithm for stationary batteries to consider the predictive distributions of both demand and supply. To fulfil the objective, this paper takes an approach of developing a time series simulator. Further, it implements simulations considering uncertainties with the use of real electricity data.

The structure of the paper is presented as follows. The first chapter describes the proposed framework to design a pathway to achieve practical decarbonisation at airports based on chronological simulations and cost analysis. The second chapter details the structure of the proposed battery operation algorithm considering uncertainty of demand and supply forecasts. The third chapter discusses the applicability of the proposed methods in a case study of an airport in Japan. The fourth chapter concludes the research and provides further prospects.

1. Determining Hardware Specification of Airport Facility to Achieve RE100

1.1. Overview and Flow of Proposed Framework

Decarbonisation of the aviation industry has attracted wide attention in recent years. In this section, a framework to determine an optimal roadmap for airports that seek to decarbonise their facilities by utilising renewable energy is proposed.

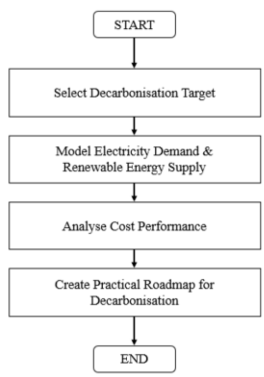

Figure 1. Framework for Determining Decarbonisation Roadmap

The proposed framework is shown in Fig 1. It first starts by defining the decarbonisation target. It is important to consider and define all the possibilities of the destination or outcome. The next step is to model the electricity demand and renewable energy supply. This means to pre-process data so that it can be used for the simulation in the next step. Based on the modelled demand and supply data, a cost performance index is calculated using a simulator. The index shows the financial efficiency of the investment. Lastly, a roadmap is derived by comparing the cost performance with the defined decarbonisation target. Further details of each of these steps are given in the following sections.

1.2. Target of 100% Renewable Energy Supply

The initial step of the proposed framework is setting the decarbonisation target. Here, two targets are considered based on the notion of RE100, a global corporate initiative which aims to supply all electricity usage with 100% renewable energy.

The first target is the widely known RE100 target, which aims at consuming 100% renewable electricity. Hereinafter, this target will be regarded as the strictly defined RE100, meaning there will be no electricity procurement from the grid which its supply is mainly fossil-fuel oriented electricity. While the strictly defined RE100 goal is an ideal target, a drastic change may be required for achieving it, which will be a burden on companies. Therefore, the second target - a possible alternative - is considered: the broadly defined RE100. The objective of the broadly defined RE100 goal is to supply 100% renewable electricity only on days when the weather conditions are desirable such as sunny days. Although it is not a complete form of RE100, it will be a steppingstone to the strictly defined RE100, which is the desire for all institutions in the future.

1.3. Modelling Demand and Supply

The second step is modelling of demand and supply, which is enables the calculation of the necessary facilities for achieving the RE100 targets. Demand modelling can be done by acquiring time series data from airports, and supply modelling can be done by extracting time series data from power companies. To assess the RE ratio for a combination of photovoltaic supply, wind supply, and utility scale battery capacity, a linear optimization problem is structured. The RE ratio indicates how much percentage of the total demand was supplied by renewable electricity. The objective function of the linear optimisation problem is to minimize the total amount of electricity procured from the grid.

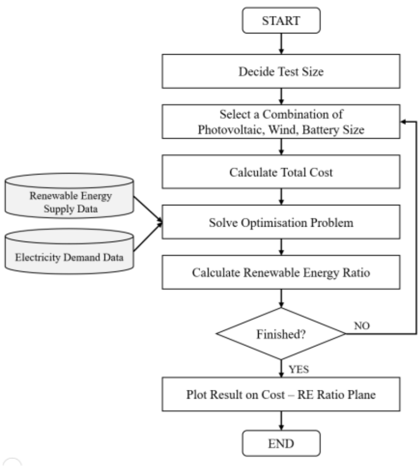

Figure 2. Simulator for Price-Perfomance Evaluation.

1.4. Optimal Energy Portfolio

The third and fourth step is evaluation and determination of the roadmap based on the outcomes. Evaluation of price-performance ratio is crucial when determining actions. Thus, a simulator to assess the relationship between cost and RE ratio is developed using the optimisation problem defined in the previous section, which is shown in Fig 2.

First, the list of hardware specifications for testing is decided. The hardware includes photovoltaic power facility, wind power facility, and battery. In the next step, a size of photovoltaic power facility, a size of wind power facility, and a size of battery is selected from the list provided in the first step. When the combination is selected, the total cost of the whole hardware or facility installed is calculated. Next, the simulator solves the linear optimisation problem with the input of the selected specifications, and returns the RE ratio, which is the percentage of the demand load supplied by renewable electricity. At this point, the total cost and the achievable RE ratio is known for the selected combination. By running the simulation for various kinds of combinations, numerous plots that represent the combination of facilities can be mapped to the cost-RE ratio plane. After a decent number of tests, a Pareto set, the plots where the cost or the RE ratio cannot be improved without worsening the other, is derived. This will enable airports to develop a practical roadmap of renewable electricity consumption by following the Pareto set.

1.5. Importance of Battery Operation

In this chapter, the specifications for the necessary renewable energy facilities were investigated. Using this framework, the hardware specification can be determined using real supply and demand data. However, determination of specification will differ by what kind of battery operation algorithm is used. If the battery is not operated in an ideal way, generated renewable energy might be wasted or there might be energy shortage. In short, the battery operation has a close relationship with the hardware specifications, which further affects the practical roadmap toward decarbonisation. Thus, it is important to develop an optimal method to operate the battery. In the next chapter, a novel battery operation algorithm considering uncertainties is proposed.

2. Battery Operation Algorithm Considering Uncertainties

2.1. Uncertainties of Renewable Energy Supply and Demand

Many studies have investigated methods to improve the accuracy of demand and supply forecasting. However, it is extremely difficult to provide a forecast with 100% accuracy. Errors should be expected for any forecasts and even forecasts totally off reality can be expected in times of harsh weather conditions such as typhoons. Fig 3 illustrates forecast failure. The predicted photovoltaic supply is

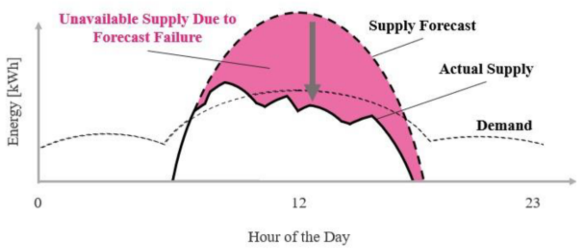

Figure 3. Unavailable Supply Due to Forecast Failure.

shown in a thick dotted line, and the actual photovoltaic supply is shown in a thick solid line. In this figure, photovoltaic generation was expected to fully operate generating surplus energy to be charged to the battery during the daytime. If the amount of insolation was as forecasted, the daytime electricity demand would have been supplied from photovoltaic generation, and electricity usage during other times of the day would have been provided from the surplus energy stored in the battery. However, due to the failure in weather forecasting, the actual supply was much smaller than expected. The difference between the forecast and the actual observation derives issues of energy shortage. The larger the difference, the greater the amount of electricity necessary to procure from the grid. Further, if the whole system were not to be connected to the grid, such forecast failures can lead to severe consequences such as blackouts.

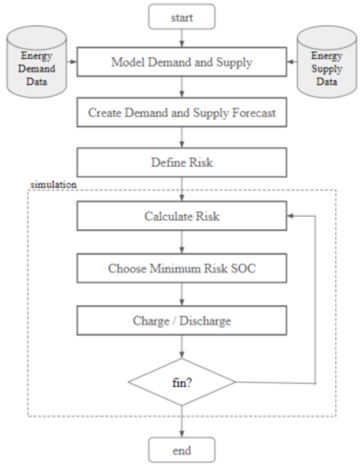

Figure 4. Battery Operation Algorithm Considering Uncertainties.

Therefore, it is vital to take a standpoint based on the idea that forecasts can prove to be wrong and that measures to mitigate the effects of errors should be developed. The study proposes an operational algorithm for batteries considering such uncertainties.

2.2. Proposed Battery Algorithm

The proposed battery operation algorithm is shown in Fig 4. First, the electricity demand and supply are modelled. Next, using the model, the predictive distribution for both demand $\boldsymbol{P_d}$ and supply $\boldsymbol{P_s}$ is derived. The algorithm aims to minimise the risk $\boldsymbol{r}$ by using those predictive distribution. The risks are defined as follows:

$$\boldsymbol{r = r_{loss} + r_{buy}} \tag{1}$$

$$\boldsymbol{r_{loss} = \sum_{t_{sur}} \int_0^\infty \left\{x_s - \left\{1 - \frac{soc(t)}{100}\right\} \cdot bat\right\} P_s(t, x_s) dx_s} \tag{2}$$

$$\boldsymbol{t_{sur} = t \in T | t > t_\alpha, x_s(t) > x_d(t)}$$

$$\boldsymbol{r_{buy} = \sum_{t_{short}} \int_0^\infty P_s(t, x_s) \int_\theta^\infty max\left(0, x_d - x_s - \frac{soc(t)}{100} \cdot bat\right) \cdot P_d(t, x_d) dx_d dx_s} \tag{3}$$

$$\boldsymbol{\theta = min\left(x_s + \frac{soc(t)}{100} \cdot bat, bat\right)}$$

$$\boldsymbol{t_{short} = \{t \in T | t > t_\alpha, x_d(t) > x_s(t)\}}$$

The opportunity cost risk r_{loss} is the risk of disposing surplus photovoltaic energy due to insufficient capacity left in the battery, shown in Fig 5. On the other hand, the grid electricity procurement risk r_{buy} is the risk of procuring electricity from the grid due to insufficient energy charged in the battery, shown in Fig 6. x_s and x_d represents the amount of supply and demand, respectively. $soc(t)$ is the state-of-charge (SOC) at time t, and bat is the battery capacity. t_α is the switch time, defined as the closest time from the current time when the plus and minus of the net photovoltaic generation is expected switch.

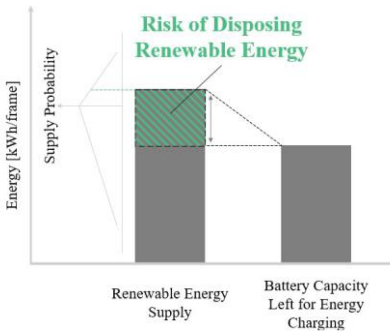

Figure 5. Opportunity Cost Risk at Switch Time.

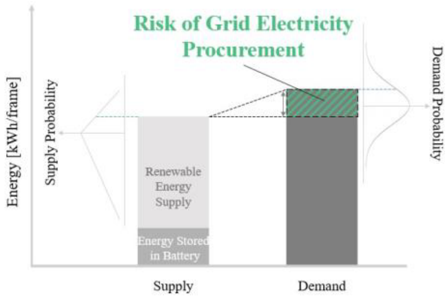

Figure 6. Grid Electricity Procurement Risk at Switch Time.

A simulator based on the proposed operation algorithm was developed using Python. The simulator runs for all time $t\ (1, 2, 3, \cdots, T)$ from the start to end of the test period. At each time t, the battery would decide the SOC at a switch time t_α based on risk. The target time is the predicted time when the relation between the forecasted demand and forecasted supply switch. If the demand load is larger than the supply, the target time will be the time when the demand load becomes smaller than the supply, and vice versa. The risk is calculated based on the demand and supply forecast at that point. The SOC that has the minimum value of risk is selected as the target SOC at time t_α. The battery will operate to charge energy if the current SOC is lower than the target SOC, and to discharge if the target SOC is higher. The amount of charging or discharging at each time is inversely proportional to the grid electricity price.

3. Case Study

A case study is presented in this chapter to show how the proposed framework and battery operation algorithm can be applied to real world cases. The case of Chubu Centrair International Airport, located in Aichi, Japan, will be investigated.

3.1. Determining Hardware Specification for Achieving RE100

In this section, the proposed framework is applied to the airport. Real time series data of the electricity demand collected at airport K (a hub airport in Japan) from January 2018 to December 2018 was scaled and used to alter the data for Chubu Centrair International Airport since such data was not available. For renewable energy generation data, the data provided by Chubu Electric Power from January 2018 to December 2018 was used [8].

From data analysis using the weather data in Tokoname, 144 days were in good weather conditions while 223 days were in undesirable weather conditions. Thus, the broadly defined RE100 means to achieve renewable supply at each timesteps during those 144 sunny days.

Combinations of photovoltaic facility size, wind facility size, and battery capacity were tested to evaluate how much demand could be supplied by renewable energy. A total of 14,400 combinations were tested including photovoltaic and wind facility size of 0~60 MW output and 0~700 MWh battery capacity. The cost values used in for this simulation is given in Table 1 [9][10][11].

Table 1. Equipment Cost Used for Calculation.

Equipment	Cost
Photovoltaic System	940 [USD/kW]
Wind System	850 [USD/kW]
Utility Scale Battery	275 [USD/kWh]

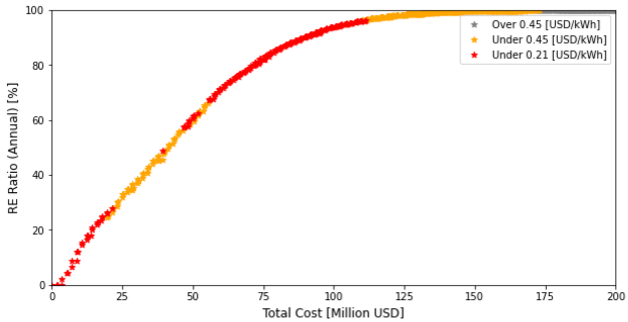

Figure 7. Annual Economic Efficiency of Battery for Each Pareto Efficient Combination of Photovoltaic System, Wind System, and Battery.

Fig 7 shows the cost per 1 kWh charge for each combination of the Pareto set in the case of the strictly defined RE100. This indicates how efficiently the battery is used over the life. The depreciation period is set as 6 years [12]. The dots where plotted red indicate the most efficient with just under 21 cents/kWh, which is equivalent to the typical electricity price per kWh in Japan [13]. The orange dots represent the combinations where charging and discharging 1 kWh of energy from the battery has an equivalent cost of under 45 cents/kWh, which is the price level of using hydrogen for energy storage [14]. To achieve the strictly defined RE100 with the minimum cost, the necessary equipment combination is 50MW photovoltaic power facility, 56MW wind power facility, and 300MWh utility scale battery. In this case, the total cost is $177 million.

Fig 8 shows the cost per 1 kWh charge for each combination of the Pareto set for the broadly defined RE100 target. It indicates how efficiently the battery is used over the life. The red and orange dots indicate combinations where energy from the battery can be used under 21 cents/kWh and 45 cents/kWh, respectively. The blue dots indicate plots which have much cheaper cost level of below just 4 cents. This is enabled by the high battery cycle count.

The minimum cost required to achieve the broadly defined RE100 target is $131.5 million, by introducing 38MW photovoltaic power facility, 48MW wind power facility, and 200MWh utility scale battery.

From these results, it can be said that the investment necessary for achieving the strictly defined RE100 may not be cost effective, but making efforts toward the broadly defined RE100 target may be a practical solution in the near future.

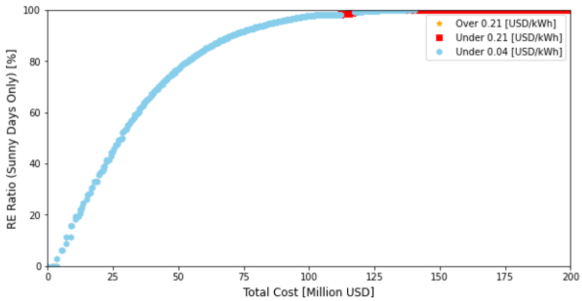

Figure 8. Economic Efficiency of Battery for Each Pareto Efficient Combination of Photovoltaic System, Wind System, and Battery on Sunny Days.

3.2. Battery Operation Algorithm Considering Uncertainties

In this section, the proposed charging algorithm is applied to a week in August. The same demand data is used as the previous section, and the scaled photovoltaic generation data is used for the supply data. The elctricity price differs throughout the day, with the night-time price being the cheapest and the price from noon until afternoon being the most expensive.

Data for August 1 to August 24 was used as training data, and data for August 25 to August 31 was test data. The ARIMA model predicts the last seven days of the month using data until the previous day. In creating the demand forecast data, an assumption was made that the forecast data will follow a normal distribution. While the standard deviation at 0:00 is small because it is the most chronologically nearest forecast, the standard deviation becomes larger at other points of time since there are more uncertainties. Likewise, the forecast data for photovoltaic generation was created using triangular distribution.

By creating and using the distribution of demand and supply, the simulator was run using the proposed method. First, the fine weather scenario was considered. In this scenario, the weather condition for the week was good enough for photovoltaic and wind generation systems to operate. The proposed algorithm was compared in the same one-week scenario with a base case and two other battery operation algorithms: the *perfect* algorithm and the *linear* algorithm. The base case was set as battery operation with no batteries installed and hence, the generated photovoltaic electricity is consumed or disposed at the point of production. When photovoltaic generation cannot meet the demand, electricity is purchased from the grid. The *perfect* algorithm optimises the battery operation to minimize the purchase cost from the grid by using actual demand and supply data instead of predicted data. In other words, the amount of energy demand and supply in the future is assumed to be known at the present time. Thus, the theoretical minimum cost can be calculated using this algorithm. The *linear* algorithm optimises the battery operation to minimize the purchase cost from the grid by using linearly forecasted data which does not have a predictive distribution. The comparison result of purchased electricity cost between the base case and the three different algorithms is shown in Fig 9. The costs are scaled so that the cost for buying electricity in the case with no battery is expressed as 100. The costs for the other algorithms are shown in relative values. The perfect algorithm requires no electricity from the grid, since it can optimise the battery operation using real data. The purchased electricity cost from the grid using the linear algorithm and the proposed algorithm were 2.5% and 4.0% of that without batteries, respectively.

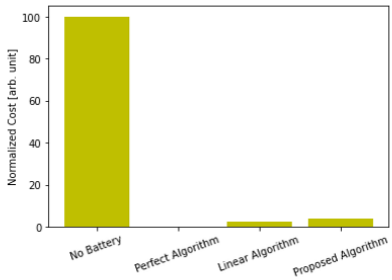

Figure 9. Comparison of Electricity Procurement Cost in Fine Weather Scenario.

Next, an unexpected rain weather scenario was considered. This scenario includes one day in the week when rain poured despite a fine weather forecast. Hence, the supply forecast mean of photovoltaic generation is the same as in the case of a fine day, but there is no actual photovoltaic generation throughout the day. The proposed algorithm was operated in the same condition as the previous fine weather scenario except that the bad weather condition on the fifth day was unforeseen.

The battery operation algorithm succeeds in minimising the risk of buying electricity from the grid on the fifth day, when there is no surplus photovoltaic generation due to bad weather conditions.

The comparison with other algorithms is shown in Fig 10. The perfect algorithm has the best performance with just 21.8% of electricity purchased from the grid compared to the base case. This is followed by the performance of the proposed algorithm with 28.8%. Battery operation using the linear algorithm, which does not consider uncertainties, requires the highest electricity cost of 30.8% from the grid. Theoretically, the minimum cost that can be achieved in this case study is the cost derived from the perfect algorithm. The result of this simulation shows that the proposed method effectively considers uncertainty derived from forecast failures.

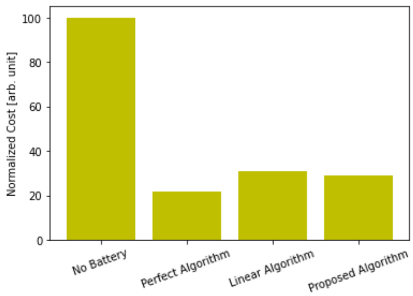

Figure 10. Comparison of Electricity Procurement Cost in Unexpected Rain Weather Scenario.

4. Conclusion

As the world strives to achieve decarbonisation, the spotlight to commit to the global decarbonisation target is with no exception put on the aviation industry to aim for green airports. This research showed a framework to quantitatively analyse the effects of introducing renewable energy generation for supplying clean energy to the airport electricity usage. Additionally, it proposed a novel battery operation algorithm considering uncertainties derived from natural factors.

Yet, the evaluation of the necessary renewable energy systems and the development of operation systems for batteries have much more to be investigated. Here, three possible facets for future studies are described:

1. The impact of the optimal battery operation algorithm toward determining the optimal renewable energy system may be an area left for future studies.
2. The proposed battery operation algorithm considering uncertainties may be enhanced by defining return in addition to risk to meet various risk preferences of users.
3. Further research on the effectiveness can be tested using various weather scenarios as well as implementing comparison between other algorithms.

In approaching decarbonisation, the importance of quantitatively assessing introduction of renewable energy as well as developing a reliable battery operation method is greater than ever before. Especially, forecasting can never be 100% accurate, which therefore makes considering uncertainty highly essential. Continuous exploration on these issues should be addressed.

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