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Towards Carbon Neutral Airport Operations Through the Use of Renewable Energy Sources: The Case of Chhatrapati Shivaji Maharaj and Indira Gandhi International Airports, India

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Abstract**—***A very significant development in the global airport industry in recent times has been the introduction and use of green renewable energy systems, such as solar and wind powered hybrid systems. Airports are very energy intensive and have a significant carbon footprint. Thus, the use of renewable green energy is enabling airports to reduce their carbon footprint thereby mitigating their environmental impact. Using an in-depth instrumental case study research design, this study has examined the use of renewable green energy systems by Delhi's Indira Gandhi Airport and Mumbai's Chhatrapati Shivaji Maharaj International Airport. The case study revealed that Chhatrapati Shivaji Maharaj International Airport has entirely switched to green sources for its energy consumption needs, thereby making it one of India's 100 per cent sustainable airports. In April 2022, Mumbai Airport enhanced its usage of green energy when it deployed a 10Kwp Hybrid SolarMill consisting of 2Kwp TurboMill (three Savonious vertical axis type wind turbine (VAWT) and 8Kwp Solar PV modules. The new system has enabled Chhatrapati Shivaji Maharaj International Airport to reduce its carbon footprint as the new system will reduce its carbon dioxide (CO_2) emissions by 120,000 tonnes per year. In 2022, Delhi's Indira Gandhi Airport became the first airport in India to be powered entirely by hydro and solar energy sources. This energy-related measure is one of the airport's key actions to realize its 2030 objective of being a Net Zero Carbon Emission Airport. By moving to renewable sources for its energy requirements, the airport is expected to reduce its carbon footprint by around 200,000 tons of carbon dioxide (CO_2) emissions per annum. The use of green energy sources has helped the airports to mitigate the harmful environmental impact from the use of fossil-based fuels.*

Keywords**— *Airports, Airport photovoltaic (PV) systems, Airport hybrid renewable energy systems, Carbon footprint mitigation, Sustainable airport energy management.***

I. INTRODUCTION

Airports play a vital role in the global air transport industry. The increase in both passenger and air cargo traffic has led to an increase of energy requirements. In response to the growing energy consumption, airports have introduced a wide range of energy saving procedures (O'Meara et al., 2020), as part of their sustainability policies and strategies. Indeed, sustainability is gaining more importance in the air transportation industry (Koç & Durmaz, 2015). Airports have been considering their impact upon the environment and as a result many airports have sought to green their operations, with the goal of becoming a green airport (Korba et al., 2022). A "green airport" is an airport which has a minimal impact on the environment and is one that endeavors to become a carbon neutral facility in terms of carbon emissions, with the aim to ultimately produce zero greenhouse gas emissions (González-Ruiz et al., 2017). The concept underlying a "green airport" is for the airport to create a centre of sustainable practices (Sumathi et al., 2018). Furthermore, many airports have increased their focus on energy efficiency as part of their efforts to reduce their impact on the environment (Preston, 2015). The increased focus by airports on their energy efficiency is because airports are extremely energy intensive (Bujok et al., 2023; de Rubeis et al., 2016; Ortega Alba & Manana, 2017). Airports are sites that have high and intense energy consumption (Akyuz et al., 2019). The improvement in energy efficiency and environmental performance of buildings is increasingly viewed as being one of the major priorities for airports all around the world (Fesanghary et al., 2012). In recent years, there has been a growing interest in targeting energy efficiency as a roadmap for carbon mitigation strategies and measures, limiting energy use, improving buildings' energy performance, and reducing energy consumption for achieving sustainable buildings (Hafez et al., 2023). One of the most significant trends in the global airport industry in recent times has been the introduction and use of green renewable technologies. Many airports around the world have now installed photovoltaic (PV) solar systems as a key environmental measure (Baxter, 2022b; Smagulov et al., 2021; Wybo, 2013).

The Indian air transport industry is among the top ten in the world in terms of its size (Choudhuri et al., 2015). In recent times, India has emerged as the ninth largest aviation market globally, with the country now having more than 120 operational airports. India now has 34 international airports in operation (Thummala & Hiremath, 2022). India's aviation industry has evolved since the first flight in 1911. Prior to 1953, there were nine airlines, including Air India, and Indian Airlines, serving the market. An important development occurred in 1953, when the airlines were nationalized and merged into Indian Airlines. In 1986, private companies were permitted to operate as air taxis (Choudhuri et al., 2015). In August 2003, Air Deccan commenced operations as India first low-cost carrier (LCC) (Shukla, 2013). In 2005, GoAir, Indigo, Kingfisher, Paramount, and SpiceJet launched their operations (Zhang & Zhang, 2017). The industry witnessed some consolidation in 2007 when Jet Airways acquired Sahara, Kingfisher acquired Air Deccan, and Air India acquired Indian Airlines (Choudhuri et al., 2015; Zhang & Zhang, 2017). In 2006, the Indian Government approved the restructuring of Mumbai and Delhi Airports through public-private partnerships (Zhang & Zhang, 2017).

An important development in India's airport industry in recent times has been the increasing use of renewable and green energy. Nowadays, airports' interest in solar photovoltaics (PVs) is growing and many Indian based airports now use photovoltaic (PV) solar systems as one of their key energy sources. These systems provide a way to lower the burden of energy costs and to show environmental stewardship by airports (Sreenath et al., 2020a). The solar photovoltaic cells have received special attention during recent times due to their rapid renewability consideration, particularly in international airports because of airport sustainability goals and the high cost of fossil fuel (Sher et al., 2021). Furthermore, solar energy is viewed as being one of the most suitable renewable energy options in India (Kalita et al., 2019).

The objective of this study is to examine the green renewable technologies implemented by Mumbai International Airport (Chhatrapati Shivaji Maharaj Airport) and Delhi International Airport (Indira Gandhi International Airport). A secondary objective is to examine the environmental-related benefits that the airports will achieve from the implementation of the green renewable technologies. A third objective is to examine the impact that these new renewable technologies will have on the airport's footprint and their goal to become carbon neutral airports. Airports consume energy, and hence, their carbon footprint should be considered (Bahadir, 2022). Chhatrapati Shivaji Maharaj Airport has entirely switched to green sources for its energy consumption needs, thereby making it one of India's 100 per cent sustainable airports (International Airport Review, 2022; Loreng, 2022). In 2022, Delhi's Indira Gandhi Airport became the first airport in India to be powered entirely by hydro and solar energy sources (Airports Council International, 2022a). Importantly, both airports are committed to reducing their carbon dioxide (CO_2) emissions and maintaining their Airport Carbon Accreditation (ACA) carbon neutral certification.

The remainder of the paper is organized as follows: the literature review is presented in Section 2 and this establishes the context for the in-depth case study. The research method used in the study is described in Section 3. The case study is presented in Section 4. The key findings of the study are presented in Section 5.

II. BACKGROUND

2.1. Energy Usage at Airports

Airports and their key stakeholders require power to operate their equipment, systems, heating, ventilation, and air conditioning (HVAC) systems, as well as for the lighting of their buildings. In addition, airports require power for their airfield infrastructure, for example, runway and taxiway lighting. Airport energy usage also includes the fuel necessary to power ground support equipment (GSE) (Nam, 2019). The primary areas of energy consumption at an airport are heating, cooling, lighting, and the energy required for operating the airport's facilities and systems (Janić, 2011; Radomska et al., 2018). Electrical energy is also used at airports for powering the aids that are used to facilitate air transport operations, and for airport buildings, aircraft hangers and other airport facilities (Kazda et al., 2015). At many airports, crude oil is often used for producing the fuel used to power the ground service equipment (GSE) and vehicles that are used in an airport's airside and landside areas, especially in the aircraft ground handling process (Janić, 2011). Fuel is also used for airport's heating boiler systems and emergency generators (Ortega Alba & Manana, 2016). The airport terminal's heating, ventilation, and air conditioning (HVAC) systems use the largest amount of energy (Akyüz et al., 2017). Fuel is also used for airport's heating boiler systems and emergency generators (Ortega Alba & Manana, 2016). Airports consume large quantities of electricity (Sreejaya et al., 2020). Typically, airport terminal buildings consume more energy than other buildings that are located within the airport precinct due to the terminal building's functional and operational characteristics (Yildiz et al., 2022). The airport terminal's heating, ventilation, and air conditioning (HVAC) systems use the largest amount of energy. It has been estimated that around 70% of the energy consumed in airport terminal buildings is used for heating, cooling, and air conditioning purposes. This energy consumption rate is higher in those countries that have a cold climate (Akyüz et al., 2017). Indeed, airport terminals have a high level of energy consumption for space heating in cold climate zones (Liu et al., 2021). Airport terminal buildings also have a high energy demand due to their cooling demand. This is especially so in hot arid climates, where airports cool their terminal buildings to achieve passenger thermal comfort (Abdallah et al., 2021).

The operation of more efficient heating and cooling systems and the performance of the building envelope can result in significant reductions in energy consumption. This can be achieved without compromising comfort conditions in the airport terminal buildings (Akyüz et al., 2018). To ensure that energy demand can be met when the needs arise, airports are increasingly focusing on energy-conservation measures in the design (and operations) of terminal buildings and infrastructure (Thomas & Hooper, 2013).

2.2. The Factors that Influence an Airport's Energy Consumption

An airport's energy consumption is influenced by a range of factors, which include:

- The airport's size.
- The airport's architecture (compact, finger passenger terminals, satellite passenger terminals, and remote satellite passenger terminals).
- Location and climate.
- Airport operational hours.
- Insulation level of terminal(s) building(s),
- Heating, ventilation, air conditioning (HVAC) system.
- Airport energy actors' energy usage behavior.
- Energy management.
- Level of airport maintenance.
- Capacity of aircraft maintenance facilities.
- Daylight utilization.
- Solar heating.
- Traffic density.
- Number of passengers handled at the airport.
- Smooth operations of electrical and mechanical systems (Akyuz et al., 2019, p. 28).

2.3. Airports Growing Use of Solar Photovoltaic (PV) Systems

Consumption of fossil fuel generated electrical energy can be reduced substantially through the application of renewable energy systems in transportation-related facilities such as airports (Choudhary et al., 2021). The integration of solar energy systems is now viewed as being crucial to achieving the global goals for sustainability as well as the reduction of greenhouse gases and pollutants emissions, which have an adverse impact upon the environment (Lykas et al., 2022). Renewable energy has become an increasingly cost-effective commerce preference for airports due to technological advancement, market ripeness, together with the public-sector investment (Emeara et al., 2021). Photovoltaic power (PV) has now become the fastest-growing source of renewable electricity. Renewable electricity sources are anticipated to play a crucial role in the transition towards a net-zero emission energy system (Bosmans et al., 2022). A key environmental-related trend in the global airport industry in recent times has been the use of renewable energy sources, such as, photovoltaic (PV) solar systems, by airports (Figure 1). The use of renewable energy resources has provided airports with several favorable environmental related advantages. Green energy produces no greenhouse gas emissions from the combustion of fossil fuels. As a result, this reduces some forms of harmful air pollution (United States Environmental Protection Agency, 2022). Furthermore, renewable energy systems provide the airport with an alternative clean source of power (Kramer, 2010). An airport normally occupies a large area, has no obstructions and so there is potential for development of solar energy within its precinct (Hermawan, 2017). Solar energy and wind energy can be combined to form Solar-Wind Hybrid Power System (SWHPS), which will enhance the qualities and environmental benefits of each other (Vasant & Pawar, 2017).

Fig.1: Photovoltaic PV Solar System at Denver International Airport

Photograph Provided Courtesy of Denver International Airport

3.1. A Brief Overview of Photovoltaic (PV) Solar Systems and the Key Issues for Airports

Nowadays, there has been an increased interest by airports in solar photovoltaics (PVs) systems (Sreenath et al., 2020a). An airport's carbon footprint can be reduced through the substitution of the conventional source of energy with solar PV based power generation (Sukumaran & Sudhakar, 2017a). This is because the atmospheric pollution from airport operations can be decreased through the consumption of renewable energy (RE)-based electricity generation (Sreenath et al., 2019). Passenger terminal buildings and car parking lots are ideal locations for photovoltaic (PV) installation. The future trend towards the electrification of the aviation and automobile industries will increase the electricity demand at airports and this could potentially involve the integration of photovoltaic (PV) systems with airport infrastructure (Jiang et al., 2021). Considering this concern as to the adverse impact of their carbon footprint on the environment, many airports around the world have installed photovoltaic solar (PV) systems (Baxter, 2021; Sreenath et al., 2020b, 2021a, 2021b; Sukumaran & Sudhakar, 2017b). The solar photovoltaic (PV) systems being installed at airports are normally customized so that they optimize the use of the selected site (Baxter et al., 2019).

Solar photovoltaic (PV) systems are customized depending upon the requirements of the site. There are different environmental factors at each site. These factors will influence the type of system required and its level of performance. PV systems include the following components:

- The solar resource – the sun is the power source for all PV systems.
- Photovoltaic cells – when treated with chemical impurities (this process is referred to as doping), these thin sections of semi-conductor material react to sunlight, creating voltage and current.
- Panel or module.
- Array – an array is comprised of multiple panels wired together in series and in parallel to provide specified voltages and current (The array is typically fastened to a mounting structure).
- Battery – a battery can be defined as a direct current (DC) electrical energy storage device.
- Inverter – the DC-AC inverter converts direct current (DC) power into alternating power (AC).
- Charge controller – a charge controller regulates, charges, and maintains battery voltage.
- Electrical load – this includes the appliances and other devices that use the energy generated by the PV system.
- Wiring – the PV system wiring includes the wires that are known as conductors that connect the system components to complete circuits; and
- Surge protector – this is a device that safeguards against electrical shock from short circuits and damaging power fluctuations (Balfour et al., 2013, pp. 4-5).

Solar systems can be installed either fixed or adjustable to increase the amount of solar energy (Emeara et al., 2021). Importantly, there are different environmental factors that will be applicable for each site. Consequently, these factors will influence the type of photovoltaic (PV) system that is required, and they will also impact its level of performance. Photovoltaic (PV) systems are comprised of the solar resource, photovoltaic cells, panel or module, array, battery, inverter, charge controller, electrical load – this includes the appliances and other devices that use the energy generated by the PV system, wiring and the surge protector – this is a device that safeguards against electrical shock from short circuits and damaging power fluctuations. The photovoltaic (PV) system wiring includes the wires that are known as conductors that connect the system components to complete circuits (Balfour et al., 2013). Quite often photovoltaic solar systems are collective in nature, that is, they are centralized systems that provide electricity to a group of users. These users include commercial customers (Bhattacharyya, 2015).

However, there are several key issues that airport's need to be cognizant of when considering the installation and use of a photovoltaic (PV) solar system (Baxter et al., 2019). Solar photovoltaic (PV) systems are required to be installed at a sufficient distance from the airport's runway(s) and these systems should adhere to all relevant safety and fire measures applicable at the airport (Kandt & Romero, 2014). If inappropriately located at the airport, then there is a risk that the solar photovoltaic (PV) systems at airports can impact pilots, air-traffic controllers, aircraft, and air navigation systems due to the glare reflection (Mostafa et al., 2016). The solar system could cause either glint or glare, or possibly a combination both. This could potentially result in a brief loss vision, which would be an important safety concern for aircraft pilots (Anurag et al., 2017). Consequently, glare due to the reflection of sunlight from the metal parts of a solar PV panel could potentially provide a risk that may result in an adverse impact on aviation safety (Mostafa et al., 2016). There are several measures that an airport can use to mitigate the glare from their solar system. The first measure involves the application of anti-reflective coatings (Solanki & Singh, 2017). The second measure involves the surface texturing of the systems panels (Ahmed et al., 2017). Neither of these measures should have a noticeable impact on the solar PV system performance but will greatly assist in minimizing reflection from the PV system (Kandt & Romero, 2014).

The performance of a photovoltaic (PV) solar system is highly dependent on the amount of solar penetration to the solar cell, the type of climatic season, the temperature of the surroundings, and the environmental humidity present at its location (Mohamad Radzi et al., 2023). The amount of power that can be produced by these systems is dependent upon the type of photovoltaic (PV) solar system used at the airport, the PV system's orientation, and the available solar resource (Kandt & Romero, 2014). Many airports quite frequently have large tracts of open space that could be potentially used for the installation and operation of a solar photovoltaic (PV) system (Baek et al., 2016; Curran, 2016). Consequently, many airports who meet the spare land use requirement are now installing or plan to install large surfaces of PV panels (Wybo, 2013).

2.3.2. The Environmental Related Benefits of Photovoltaic (PV) Solar Systems for Airports

Solar power is a clean and abundant energy source, and it is an environmentally friendly energy solution (Moukhtar et al., 2021). Solar power photovoltaic (PV) systems lower the airport's ground emissions (Sukumaran & Sudhakar, 2017b). The airport's carbon footprint (carbon dioxide CO_2 emissions) can also be reduced by substituting solar PV based power generation for traditional, more heavily polluting, fossil-fuel based energy sources (Sukumaran & Sudhakar, 2017a; Wybo, 2013). In addition, the use of green or renewable energy sources provides the user with an important opportunity to optimize energy efficiency (Arman & Yuksel, 2013). Another advantage is that renewable energy sources normally have very little waste (Yerel Kandemir & Yayli, 2016). Other advantages of solar power are that they do not emit any greenhouse gases, such as carbon dioxide (CO_2) into the atmosphere, there are no releases of toxic gases, such as sulphur dioxide (SO_2), photo-voltaic (PV) solar systems can make use of barren land, the systems allow for individual installation and use, and they can decrease transmission line costs in existing electricity grids. The disadvantages of solar power are the electrical energy produced by the system may be intermittent and unstable (Aktaş & Kirçiçek, 2021; Alotto et al., 2014; Muhammed & Baladraf, 2021), the generation of electrical energy is reliant on natural events, large powerful photovoltaic solar systems require large tracts of land for their installation, and the surfaces of the solar panels must be cleaned periodically in order not to reduce system efficiency (Aktaş & Kirçiçek, 2021). Thus, solar is an uncertain energy sources, since it varies throughout the day, season, and geographic location (Correia & Ferreira, 2021).

2.4. An Overview of the Environmental Benefits of Hydropower

Hydropower has important environmental benefits. Hydropower is a clean, renewable, and environmentally friendly source of energy (Berga, 2016; Tong, 2019; Wagner & Mathur, 2011). As hydropower is a renewable source of energy, the energy produced through hydropower relies on the water cycle, which is driven by the sun, making it a renewable energy source. Hydropower is fueled by water, and this therefore makes it a clean source of energy. Hydropower provides low-cost electricity and durability over time when compared to other sources of energy. Importantly, hydropower complements other renewable energy sources (Office of Energy Efficiency and Renewable Energy, 2022). Hydropower does not pollute the air, thereby providing a reduction in carbon dioxide (CO_2) emissions (McKinney et al., 2007; Wagner & Mathur, 2011; Walsh et al., 2020) unlike power plants that burn fossil fuels, such as, coal or natural gas (Spellman, 2022; Tong, 2019). Furthermore, hydro power does not produce any toxic, hazardous, or radioactive waste (McKinney et al., 2007). Hydropower does have some disadvantages: large land disturbance and the potential relocation of people, high methane (CH_4) emissions from rapid biomass decay in shallow tropical waters, and the disruptions to downstream eco-systems (Tyler Miller & Spoolman, 2012). Hydropower may also affect marine life (Majumdar, 2016), as fish populations can be impacted if they are unable to swim upstream to spawning grounds or to the ocean (Spellman, 2022).

2.5. Hybrid Renewable Energy Systems (HRES)

The renewable energy sources such as solar energy and wind energy are complementary in nature. The use of these natural resources to produce power reduces the power demand on the conventional power generation sector (Kumar et al., 2015). The sun and wind-based generation are increasingly being considered alternate source of green power generation which can be used to mitigate power demand issues (Saidi & Chellali, 2017). Accordingly, Hybrid Renewable Energy Systems (HRES) are becoming popular as stand-alone power systems for providing electricity (Kumar & Garg, 2013; Shirsath et al., 2016). Indeed, amongst the various renewable energy sources, photovoltaic (PV) and wind turbines (WT) have become very attractive due to the abundant local availability in nature, technological progress, and economic benefits provided from such a system (Malik et al., 2020). A hybrid energy system, or hybrid power, normally consists of two or more renewable energy sources which are used in tandem to provide increased system efficiency as well as a greater balance in energy supply (Shirsath et al., 2016). The hybrid combination of both distributed energy resources eliminates mutual intermittences due to their adverse nature; therefore, the reliability of the system will be improved. The basic key objective of these hybrid systems is to generate electrical energy by using renewable and clean energy with minimum pollution (Malik et al., 2020). A typical wind-PV hybrid system is comprised of a small wind turbine, a photovoltaic (PV) generator and an appropriate storage system together with the corresponding electronic equipment (Godson et al., 2013; Kosmas & Panagiotis, 2022).

A wind-solar hybrid system is a reliable alternative energy source because it utilizes solar energy combined with wind energy to create a stand-alone energy source that is both dependable and consistent. Solar power or wind power alone can fluctuate, however, when they are used together, they can provide a reliable source of energy. Thus, an ideal solution is to combine these two forms of energy sources to create a constant energy flow (Dalwadi et al., 2011).

III. RESEARCH METHODOLOGY

3.1 Research Method

This study used a qualitative instrumental case study research approach (Janis, 2022; Miller, 2022; van Vreden, 2022). An instrumental case study is the study of a case. An instrumental case study can study a firm(s). This research approach provides insights into a specific issue, enables researchers to redraw generalizations, or builds theory (Stake, 1995, 2005), whilst also facilitating the understanding of a specific phenomenon. An instrumental case study is designed around established theory (Grandy, 2010). The present study was designed around the established theory of airport energy management (Akyuz et al., 2019; Thomas & Hooper, 2013), green energy (Aswathanarayana, 2010; Bhowmik et al., 2017; Kalyani et al., 2015), the use of solar power by airports (Baxter et al., 2019; Sreenath et al., 2020b, 2021a, 2021b; Sukumaran & Sudhakar, 2017a), and wind power (Gipe, 2004; Maegaard et al., 2013; Manwell et al., 2009).

3.2 Data Collection

Data for the study was obtained from a variety of documents, airport industry-related journals, annual reports, press releases, company materials available on the internet and records as sources of case evidence. Documents included Delhi International Airport (Indira Gandhi Airport) and Mumbai International Airport (Chhatrapati Shivaji Maharaj International Airport) environmental policies, industry publications, and the airport’s websites. Thus, this study used secondary data. The study followed data collection guidance of Yin (2018), that is, multiple sources of case evidence were used, a database on the subject was created, and there was of a chain of case evidence.

3.3 Data Analysis

Document analysis was used to analyze the documents gathered for the study. Document analysis focuses on the information and data from formal documents and company records that are gathered by the researcher(s) when conducting their case study (Andrew et al., 2011; Oates, 2006; Yin, 2018). The documents gathered for the study were assessed for their authenticity, credibility, representativeness and meaning (Scott, 2014; Scott & Marshall, 2009).

In this study, significant information was extracted from the secondary data collected using thematic analysis (Braun & Clarke, 2022; Guest et al., 2012; Terry et al., 2017). The thematic analysis was performed five discrete stages. First, the collected data was arranged according to its relevance to the study. In the second stage, the organized data was coded and recoded and was subsequently classified into meaningful groups. In the third stage, the most relevant themes were searched and extracted from the classified data. In the fourth stage, the themes that had been produced were checked to ensure that they appropriately represented the meanings found in the data set as a whole. In the fifth and final stage, the themes were defined, named, and presented in the case study (Ojogiwa, 2021).

All the documents collected for the study were stored in a case study database (Yin, 2018). All the study's documents were in English. Each document was carefully read, and key themes were recorded in the case study (Baxter, 2022a).

IV. RESULTS

4.1. Chhatrapati Shivaji Maharaj International Airport

4.1.1. An Overview of Chhatrapati Shivaji Maharaj International Airport

Mumbai International Airport was privatized in 2006. At that time India's Ministry of Aviation contracted the management and operation of the airport to GVK, a private firm. As part of the agreement between the two parties, the land that belonged to the Airport Authority of India was leased out for thirty years (Ren, 2017). In November 2019, the Competition Commission of India granted its approval for Adani Properties Private Limited to acquire a shareholding in Mumbai International Airport Limited (Kumari & Aithal, 2020). Mumbai International Airport Limited (MIAL) is managed by Adani Airport Holdings Limited (AAHL), which is a subsidiary of Adani Enterprises. MIAL is a Public-Private Partnership (PPP) venture between AAHL, who holds a majority shareholding of 74%, and the Airports Authority of India, holding the remaining 26% of the company's shares (Chhatrapati Shivaji Maharaj International Airport, 2021). The initial Public Private Partnership agreement was for a term of 30 years, which took effect from May 3, 2006, and the agreement is extendable by a further 30 years subject to the terms of "Operations Management and Development of Agreements" (OMDA) signed between the Airports Authority of India (AAI) and Mumbai International Airport (MIAL). Mumbai's Chhatrapati Shivaji Maharaj International Airport is India's second busiest airport (Dan et al., 2017; Jaffe, 2015, Gaonkar 2013). The airport can handle around 50 to 52 million passengers per annum (Sharma, 2022).

The airport has three passenger terminals: Terminal 1 is used for domestic flights, Terminal 2 is used for both domestic and international flights, and the General Aviation terminal, which is used for private and non-scheduled flight operators. Mumbai airport is equipped with two crossing runways which are designated 09/27 and 14/32. Runway 14/32, (2,925m, 9,596ft) is the runway that runs between Terminals 1 and 2. The main runway 09/27 (3,445m, 11,302ft) intersects runway 14/32 just south of the terminal buildings (Airport Technology, 2020).

Chhatrapati Shivaji Maharaj International Airport is an ISO 50001:2018 (Energy Management System) and ISO 14001:2015 (Environmental Management System) certified company (Loreng, 2022). ISO 14001 is a worldwide meta-standard for implementing Environmental Management Systems (EMS) (Dentch, 2016; Grover & Grover, 2017; Heras-Saizarbitoria et al., 2011). Introduced in June 2011, the ISO 50001 International Standard was developed to provide a unified framework for energy management efficiency (Dzene et al., 2015; Gopalakrishnan et al., 2014; Yuriev & Boiral, 2018). The ISO 50001 Energy Management System standard also provides a basis for energy management improvement by a firm (Jovanović & Filipović, 2016).

The airport has been accredited at the Airports Council International Airport Carbon Accreditation (ACA) Level 4+, which signifies that it is a carbon neutral airport (Naik, 2022). Through the implementation of a certified ISO 50001 Energy Management System, the airport has developed a policy for the efficient use of energy, set goals and targets for the forthcoming years and adopted a robust mechanism to review its progress (Chhatrapati Shivaji Maharaj International Airport, 2020).

4.1.2. Chhatrapati Shivaji Maharaj International Airport Environmental Policy

Mumbai International Airport (Chhatrapati Shivaji Maharaj International Airport) defined and implemented a very comprehensive environmental policy in 2022. In accordance with the policy, Mumbai International Airport, while developing, maintaining, managing, and operating the airport, the airport is committed to achieving excellence and sustainability in the quality of its facilities and services, and the company manages the impact of its business on the environment (Chhatrapati Shivaji Maharaj International Airport, 2022).

Mumbai International Airport aims to continually improve is environmental performance by:

- Ensuring compliance with applicable legal and other requirements, including civil aviation safety legislation and standards.
- Provision and optimal use of resources whilst promoting re-use, recycling, and re-purposing.
- Protection of the environment by pollution prevention and waste minimization.

- Nurturing sustainability initiatives and development, including effective climate change and greenhouse gas (GHG) management (Chhatrapati Shivaji Maharaj International Airport, 2022).

Chhatrapati Shivaji Maharaj International Airport has historically placed a high focus on carbon neutrality, energy savings, emissions reduction, and climate action since its inception. The airport employs a holistic approach towards its sustainable operations and has carried out various initiatives under environment management. These include airport carbon management system, airport carbon neutrality, sustainability reporting, renewable energy installations, wastewater recycling, effective waste management system, and organic waste treatment, amongst others. Furthermore, the airport closely monitors its noise management, air quality monitoring, waste management and climate change, which helps minimize its environmental impact (Airports Council International, 2022c).

Chhatrapati Shivaji Maharaj International Airport's green policies focus on continuous energy reduction through the adoption of energy efficient products, operational efficiency, and the application of innovative technology to address the challenges associated with climate change (Airports Council International, 2022c).

A share of the airport's purchased electricity is used by concessionaires, government authorities and other stakeholders, which have operations at the airport. Hence, the electricity purchased by the airport also includes electricity is also consumed by other key stakeholders (Chhatrapati Shivaji Maharaj International Airport, 2020).

4.1.3. Chhatrapati Shivaji Maharaj International Airport Energy Sources

To sustain its operations and airport infrastructure, Chhatrapati Shivaji Maharaj International Airport uses a mix of energy sources. These energy sources are compressed natural gas, diesel, electricity, petrol, and solar energy (Chhatrapati Shivaji Maharaj International Airport, 2020)

4.1.4. Chhatrapati Shivaji Maharaj International Airport Hybrid Solar Mill System

As previously noted, Mumbai International Airport has shifted totally towards the use of green energy for its consumption needs. Out of the total 100 per cent, the airport procures around 95 per cent from green sources, such as, hydro and wind energy (International Airport Review, 2022; Loreng, 2022). Mumbai International Airport achieved 100% use of green energy sources in August 2022. The airport is committed to continuous reduction in energy consumption, and hence, a reduction in its carbon footprint. Mumbai Airport has installed a 1.06MW rooftop solar power plant, which can be increased to 4.66MW (International Airport Review, 2022).

Figure 1 presents Chhatrapati Shivaji Maharaj International Airport annual solar power generation and the year-on-year change for the period covering the 2016-2017 to 2019-2020 financial years. Figure 1 shows that there has been an upward trend in the airport's annual solar power generation during this period. Figure 1 shows that there was a very pronounced spike in this metric in the 2017-2018 financial year, at which time it increased by 110.91% on the 2016-2017 levels. This large increase was followed by two further significant annual increases in the airport's solar power generation, when it increased by 22.36% in the 2018-2019 financial year and by 27.80% in the 2019-2020 financial year (Figure 1) This upward trend is very favorable and highlights the importance of renewable energy usage by the airport operator.

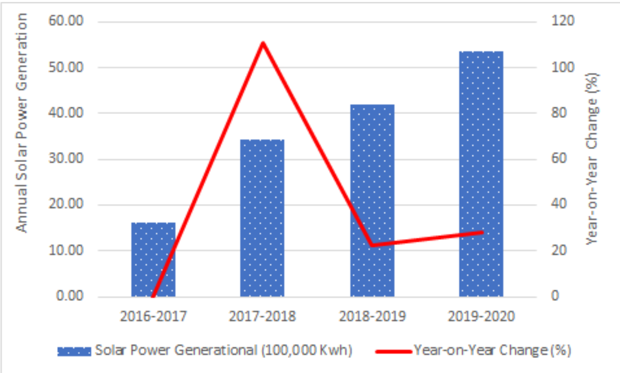

Fig.1: Chhatrapati Shivaji Maharaj International Airport Annual Solar Power Generation and Year-on-Year Change: 2016-2017 to 2019-2020 Financial Years

Source: Data derived from Chhatrapati Shivaji Maharaj International Airport (2020).

In April 2022, Mumbai Airport enhanced its usage of green energy when it deployed a 10Kwp Hybrid SolarMill consisting of 2Kwp TurboMill (three Savonious vertical axis type wind turbine (VAWT) and 8Kwp Solar PV modules, with an estimated minimum energy generation of 36 kWh/day. This first-of-its-kind, fully integrated, hybrid renewable energy product, harnesses both solar and wind energy that are combined to generate electricity at the airport (International Airport Review, 2022; Loreng, 2022). Importantly, wind energy (WE) is increasingly emerging as a green and clean energy source (Chawda et al., 2023). In addition, the development of modern photovoltaic thermal systems (PV/T) is regarded as being one of the most important steps in the application of using solar energy to produce both electricity and heat (Chaichan et al., 2022).

4.1.5. The Environmental Benefits of Chhatrapati Shivaji Maharaj International Airport Hybrid Solar Mill System

The new green energy powered system will enable Chhatrapati Shivaji Maharaj International Airport to reduce its carbon footprint as the new system will reduce its annual carbon dioxide (CO_2) emissions by 120,000 tonnes (The Economic Times, 2022). The reduction in carbon dioxide emissions (CO_2) is contributing to the airport's goal of Net Zero emissions by 2029. As noted earlier, a very important benefit of the use of photovoltaic (PV) solar systems by airports is that these systems lower the airport's ground emissions, and hence, the airport's carbon footprint (Sukumaran & Sudhakar, 2017a; Wybo, 2013). Reducing the use of fossil fuels considerably reduces the amount of carbon dioxide (CO_2) produced, as well as reducing the levels of the pollutants released into the atmosphere (Demirbaş, 2006). This is especially important for airports because the global aviation industry generates a substantial carbon footprint which is predicted to increase in the future (Filimonau et al., 2018). The aviation industry has set a goal of net zero emissions by 2050 (Amankwah-Amoah et al., 2023; Bergero et al., 2023; Serafimova & Finger, 2022). Airports can play a key role in achieving this goal by deploying and using green energy.

A further environmental-related benefit of the renewable energy system is that reduces the negative effects of fossil fuel-based energy (Midilli et al., 2006). Indeed, the transition towards more renewable sources reduces a firm's dependence on fossil fuels (Mutezo & Mulopo, 2021; Omer, 2008). Fossil fuels produce harmful emissions that negatively impact the environment (Ağbulut & Sarıdemir, 2021).

In addition, the use of green or renewable energy sources provides the user with an important opportunity to optimize energy efficiency (Arman & Yuksel, 2013). Indeed, this is a very important advantage of Chhatrapati Shivaji Maharaj International Airport new renewable green technology system as the new system is very energy efficient.

4.2. An Overview of Indira Gandhi Airport

4.2.1. An Overview of Indira Gandhi Airport

Indira Gandhi Airport is located 16 kilometres from the centre of Delhi. The airport has three passenger terminals and three runways. Runway 11-29 has a length of 4,430 metres, whilst the airport's Runway 10-28 has a length of 3,810 metres. The airport's third runway, Runway 09-27, is 2,813 metres in length. Terminal 3 is an integrated terminal, and thus, it handles both domestic and international passenger traffic (Delhi Indira Gandhi Airport, 2022). Delhi's Indira Gandhi Airport handled 37,139, 957 passengers in 2021, making it the world's 13th busiest passenger airport in 2021(Airports Council International, 2022b). Indira Gandhi Airport is now amongst the twenty busiest airports in the world (Ganguly, 2019). The airport is India's busiest airport (Agarwal et al., 2018; Zhou et al., 2019).

On January 31, 2006, a consortium that was led by GMR Infrastructure, and including Germany headquartered Fraport AG, and others, won the contract to modernize Delhi Airport (Pratap & Chakrabarti, 2017). Following the privatization of the airport in 2006, Delhi International Airport Private Ltd. (DIAL) was formed with the key objectives of operating, maintaining, developing, designing, constructing, upgrading, modernizing, financing, and managing the Indira Gandhi International Airport (Chaudhuri & Chaudhuri, 2017).

Delhi's Indira Gandhi Airport has placed a very high focus on sustainability and, as a result, the airport has implemented various initiatives such as renewable energy development and usage, energy efficiency, green building, programs with airlines, operational efficiency measures, green transportation, tree plantation, and management of greenhouse gases (GHG) in accordance with the Airport Council International's (ACI) Airport Carbon Accreditation program (Delhi Airport, 2022; Gandhiok, 2022). In 2020, Delhi Airport became the first airport within the Asia-Pacific region to achieve "Level 4+" under ACI's Airport Carbon Accreditation program (Delhi Airport, 2022). This indicates that besides being a carbon-neutral airport, Delhi International Airport has adopted long-term absolute emission reduction goals in line with the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) 1.5-degree scenario (Airports Council International, 2022a).

4.2.2. Indira Gandhi Airport Environmental Policy

Delhi International Airport has defined and implemented a comprehensive environmental policy. Delhi International Airport is committed to conducting its business in an environmentally friendly manner and the airport aims to minimize the impact of its activities on both the environment and the community. As part of this policy, environmental management is an integral part of the airport's business strategy that is designed to ensure that the airport achieves credibility and business sustainability. Delhi International Airport Private Ltd (DIAL) is committed to the protection of the environment, and the mitigation of climate change. The airport also ensures the sustainable usage of resources at Indira Gandhi Airport (Delhi International Airport Limited, 2020).

Delhi International Airport Private Ltd (DIAL) being a responsible organization strives to fulfill its environmental obligations and commitments by:

- Fulfilling all applicable environmental compliance obligations.
- Establishing and maintaining a management system to fulfil its commitments as well as safeguarding the interests of all interested parties.
- The airport comprehensively assesses and manages all environmental risks and opportunities associated with its development and operational activities.
- The airport sets, monitors, and reviews its environmental objectives and targets to ensure continual improvement of its Environmental Management System to enhance its environmental performance.
- The airport develops and reviews environmental objectives and targets so it can ensure continual improvement of its Environmental Management System, and thereby, enhance its environmental performance.
- The airport develops adequate competency in its employees and other relevant stakeholders to manage environmental risks and opportunities associated with their activities.
- The airport establishes an integrated approach toward its long-term absolute greenhouse gas (GHG) emission reduction targets and the sustainable management of natural resources.
- The airport promotes the “green” supply chain to the maximum degree and considers all stakeholder expectations.
- The airport promotes the use of the “green building” concepts in all of Indira Gandhi International Airport infrastructure (Delhi International Airport Limited, 2020).

Indira Gandhi International Airport has an ISO 14001: 2015 certified Environmental Management System and an ISO 50001: 2018 certified Energy Management System (GMR Infra, 2021).

4.2.3. Indira Gandhi Airport Energy Sources

Indira Gandhi Airport direct energy sources are diesel, and petrol. Grid electricity is Indira Gandhi Airport’s primary indirect energy source. The airport has an onsite solar energy plant, and the airport also uses open access renewable energy. In India, the open access is a mechanism under which consumers can purchase electricity directly from power producers, rather than through electricity distribution companies (Gupta, 2022). In India, commercial and industrial consumers can procure Open Access power from three kinds of renewable energy plants – third-party owned, wholly owned (captive) or owned by a group of consumers (group captive) (Garg et al., 2022). More than 90% of the gross electricity consumed by Delhi Airport was sourced from renewable energy sources in the 2020-21 financial year (GMR Infra, 2021).

4.2.4. Indira Gandhi Airport Hydro and Solar Energy System

In 2022, Delhi’s Indira Gandhi Airport became the first airport in India to be powered entirely by hydro and solar energy sources. This energy-related measure is one of the airport’s key actions that it has taken to move closer to realising its 2030 objective of being a Net Zero Carbon Emission Airport (Airports Council International, 2022a; Delhi Airport, 2022).

At the time of the present study, the airport was sourcing around 6% of its electricity requirement from onsite solar power plants and the remaining 94% from hydropower plants (Delhi Airport, 2022; Joshi, 2022). For its hydropower, the airport has signed a long-term power purchase agreement (PPA) with Himachal Pradesh-based hydropower producing company to supply hydroelectricity for the airport until 2036 (Joshi, 2022).

Delhi’s Indira Gandhi Airport has used solar power for quite some time and following the introduction of the new system it is now fulfilling its major electricity requirements from a hydropower plant (Gandhiok, 2022).

The airport has also installed a 7.84 MW solar power plant on the airside, and, as part of stakeholder collaboration, operators of the air cargo terminals at the airport have added a further 5.3 MW rooftop solar power plant (Airports Council International, 2022a; Joshi, 2022).

4.2.5. The Environmental Benefits of Indira Gandhi Airport Hydro and Solar Energy System

As previously noted, Indira Gandhi Airport has moved to green energy, and since June 1, 2022, now only uses only hydro and solar power for all its energy requirements. This initiative is a key part of the airport’s goal of becoming a Net Zero Carbon Emission Airport by 2030 (Airports Council International, 2022a). The airport’s operator, Delhi International Airport Limited (DIAL), has estimated that by moving to renewable sources for its energy requirements the airport is expected to indirectly reduce 200,000 tons of carbon dioxide (CO_2) emissions every year

(Delhi Airport, 2022; Gandhiok, 2022; Joshi, 2022). Consequently, the airport has been able to reduce its carbon footprint from the use of its new renewable green energy system. In addition, the airport has also been able to increase its energy efficiency, which is a very favorable outcome. A further important environmental-related benefit is that the airport has been able to reduce its use of energy that may have been produced from fossil-based fuels. This alleviates harmful emissions produced from the consumption of fossil fuels that may have been used in the generation of electricity previously used by the airport cause environmental damage (Hao & Van Brown, 2019; Nicoletti et al., 2015).

V. CONCLUSION

Using an in-depth instrumental case study research approach this study has examined the role played by renewable green energy technologies and systems at Mumbai's Chhatrapati Shivaji Maharaj International Airport, and Delhi's Indira Gandhi International Airport. The qualitative data used in the study was examined by document analysis. The case study was underpinned by the case study research framework as recommended by Yin (2018).

The case study revealed that Chhatrapati Shivaji Maharaj International Airport has entirely switched to green sources for its energy consumption needs, thereby making it one of India's 100 per cent sustainable airports. Mumbai International Airport achieved 100% use of green energy sources in August 2022. The airport is committed to continuous reduction in energy consumption, and hence, a reduction in its carbon footprint. In April 2022, Mumbai Airport enhanced its usage of green energy when it deployed a 10Kwp Hybrid SolarMill consisting of 2Kwp TurboMill (three Savonious vertical axis type wind turbine (VAWT) and 8Kwp Solar PV modules, with an estimated minimum energy generation of 36 kWh/day. This first-of-its-kind, fully integrated, hybrid renewable energy product, harnesses both solar and wind energy that are combined to generate electricity at the airport. The new green energy powered system will enable Chhatrapati Shivaji Maharaj International Airport to reduce its carbon footprint as the new system will reduce its annual carbon dioxide (CO_2) emissions by 120,000 tonnes (The Economic Times, 2022). The reduction in carbon dioxide emissions (CO2) is contributing to the airport's goal of Net Zero emissions by 2029. Another important environmental-related benefit of the new system is that it is assisting the airport to enhance its energy efficiency.

Like Mumbai's Chhatrapati Shivaji Maharaj International Airport, Delhi's Indira Gandhi Airport has also taken a range of steps to "green" its operations and to make the airport more sustainable. In 2022, Delhi's Indira Gandhi Airport became the first airport in India to be powered entirely by hydro and solar energy sources. This energy-related measure is one of the airport's key actions that it has taken to move closer to realizing its 2030 objective of being a Net Zero Carbon Emission Airport. The airport's operator, Delhi International Airport Limited (DIAL), has estimated that by moving to renewable sources for its energy requirements the airport is expected to indirectly reduce 200,000 tons of carbon dioxide (CO_2) emissions every year. Consequently, the airport has been able to reduce its carbon footprint from the use of its new renewable green energy system. In addition, the airport has also been able to increase its energy efficiency, which is a very favorable outcome for the airport. At the time of the present case study, the airport was sourcing around 6% of its electricity requirement from onsite solar power plants and the remaining 94% from hydropower plants.

By embracing the use of renewable and green energy sources, both airports have been able to reduce the use of fossil fuels and, as a result, they have been able to reduce their carbon dioxide (CO_2) emissions, and hence, their carbon footprint. This is very important for airports because the global aviation industry generates a substantial carbon footprint. In addition, by using renewable and green energy sources the two airports have been able reduce their dependency on fossil fuels, and consequently, they have reduced pollutants being released into the atmosphere. The use of clean green energy sources has helped the two airports to mitigate the environmental damage associated with fossil fuel usage.

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