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REVIEW **Open Access**

A critical review of energy consumption and optimization strategies in the Nigerian aviation sector: challenges and prospects

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Abstract

Background The global aviation industry plays a crucial role in socioeconomic advancement. However, its notable energy consumption has garnered attention due to the subsequent environmental consequences. Nigeria, holding a dominant position in Africa's economic landscape, is undergoing rapid growth in its aviation sector. This progress brings to light several energy consumption challenges emblematic of the broader industry.

Main body of the abstract For this review, we conducted a comprehensive assessment of energy consumption patterns within the Nigerian aviation sector. Drawing from a diverse range of contemporary literature and global best practices, we centered our exploration on energy consumption patterns within the Nigerian aviation sector, environmental stewardship, global best practices, regulatory frameworks, and flight operations, ground support functions, and maintenance activities. This approach enabled us to pinpoint prevalent inefficiencies and to highlight opportunities for improved energy utilization.

Short conclusion Our findings emphasize the pressing necessity for Nigeria to instate rigorous energy efficiency policies, further supported by enhanced regulatory structures. Given Nigeria's specific energy-related challenges, such as an inconsistent power supply and a significant reliance on non-renewable energy sources, the aviation sector confronts amplified environmental and economic threats. Addressing these issues is imperative not just for the sector's longevity but also in alignment with Nigeria's expansive fiscal aspirations. The insights garnered from this review can guide stakeholders in maneuvering the intricacies of energy management in aviation, thus paving the way for ecologically responsible expansion in burgeoning economies.

Keywords Environmental stewardship, Flight operations, Global best practices, Ground support functions, Maintenance activities, Nigerian aviation industry, Regulatory frameworks, Energy consumption patterns

Background

The aviation industry, undeniably, has been a marvel of the modern age, shrinking the world by making distances shorter and fostering global interconnectedness (Cai et al. 2023). However, the industry's phenomenal growth has come at a price. The intensive energy consumption patterns intrinsic to this sector have started casting shadows on its otherwise illustrious reputation (Lee et al. 2021).

Aircraft, being engineering marvels, depends largely on aviation fuel, specifically designed to withstand varying atmospheric conditions and deliver peak performance. This demand for specialized fuel has resulted in a notable environmental footprint (Lee et al. 2009). Research indicates that the aviation industry accounted

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for approximately 2–3% of total global CO_2 emissions as of 2020 (Cui et al. 2022; Kilgore 2023; Klöwer et al. 2021; Teter and Kim 2022). However, the more concerning statistic is the predicted growth. With air traffic anticipated to double in the next 2 decades, unchecked energy consumption could exacerbate the industry's environmental impact (Airport Technology 2019; IATA 2018a). Several factors contribute to this high energy consumption. Older fleets with dated technology, long-haul flights that demand more fuel, and extensive ground operations are among the primary culprits (Hassan et al. 2021). This energy consumption is not just an environmental concern; it has significant economic implications too. Fuel, for most airlines, constitutes a major portion of operational costs. With the fluctuating oil market, airlines often grapple with unpredictable and sometimes exorbitant fuel prices, directly impacting ticket costs and overall industry profitability (Kristjanpoller and Concha 2016).

Transitioning to the African context, Nigeria, with its rich history, diverse culture, and booming economy, emerges prominently in the continent's aviation narrative. As Africa's largest economy and most populous nation, Nigeria naturally occupies a pivotal role in the continent's air transport ecosystem (IATA 2018b). Historically, Nigeria has been a central hub for West Africa, connecting various African countries and serving as a transit point for flights between other continents (Eze 2022). Lagos and Abuja, the major cities, house airports that are among the busiest in Africa (Oyebade 2018). Over the past decade, there has been a significant surge in air travel demand, both domestically and internationally. The rising middle class, coupled with improved economic conditions and a diaspora spread across the globe, has fueled this growth (Gössling and Humpe 2020).

However, echoing the global scenario, Nigeria's aviation boom has come with its own set of challenges. The country's airports, airlines, and associated infrastructure are grappling with the dual challenge of meeting the rising demand while ensuring sustainable growth. Energy consumption, or more specifically, jet fuel consumption, stands at the crux of this challenge (Olarewaju 2020). Given Nigeria's broader energy landscape, characterized by an unstable power grid and a heavy reliance on oil, the aviation sector's energy demands have profound implications (Rapu et al. 2015). On the one hand, there is a national push to diversify energy sources and move toward renewables, but on the other, the aviation sector's inherent reliance on jet fuel poses unique challenges.

In this light, understanding the nuances of energy consumption within Nigeria's aviation sector becomes paramount. This paper, through a critical lens, aims to dissect the energy consumption patterns, juxtapose them with global trends, identify inherent challenges, and explore potential pathways for optimization. The ultimate goal is to pave a sustainable trajectory for Nigeria's aviation sector, one that harmonizes economic growth with environmental stewardship.

Historical context

The tale of Nigeria's aviation sector unfurls like a tapestry, richly woven with events, developments, and aspirations that span over a century. When looking at this tapestry, one cannot help but notice the intricacy of its patterns, which represent the industry's energy consumption over the years.

The inception of aviation in Nigeria traces back to the early twentieth century. An aircraft, landing in the vast expanse of Kano in 1925, heralded a new epoch for the nation, introducing it to the vast skies and the possibilities they held (Ogbeidi 2006). These early days, however, were marked by a heavy reliance on imported fuel. Though Nigeria was blessed with an abundance of oil, the aviation industry, during its nascent stages, had not developed the infrastructure or technology to refine and utilize its own resources. Aviation fuel had to be brought in from other countries, rendering the operational costs for airlines significantly high (Decker 2008).

The subsequent decades saw Nigeria coming into its own in the African aviation landscape. In the backdrop of a post-colonial Africa, the nation realized the potential of aviation as a harbinger of growth and prosperity. As the country embarked on its journey of nation-building, investments flowed into constructing airports, commissioning aircraft, and expanding the reach of its airlines. By the mid-twentieth century, cities like Lagos and Abuja were not just dots on the national map but had started asserting themselves in the international aviation network. This era was not merely about expansion but was also about introspection (Akpoghomeh 1999). The burgeoning aviation sector made the country reckon with its energy consumption patterns.

By the late twentieth century, the establishment of domestic refineries aimed to reduce the dependence on imported jet fuel. But this transition was not without its challenges. The domestically refined fuel, while a testament to Nigeria's strides in self-reliance, often came under scrutiny for its quality and consistency. Airlines, wary of this inconsistency, sometimes resorted to mixing domestic and imported fuels to maintain the operational integrity of their fleets (Ogbuigwe 2018). However, another challenge that loomed large was the operational inefficiencies that inadvertently led to increased energy consumption. Aircraft of yesteryears, without the advantage of today's technological marvels, were not optimized for fuel efficiency. Ground operations at airports, marked by prolonged taxiing times and longer waits on runways due to congestion, added to the energy consumption tally. Maintenance practices, still catching up to global standards, sometimes inadvertently exacerbated the energy usage (Adekitan 2022).

As the twenty-first century dawned, and with it, a heightened global consciousness about sustainability and conservation, the Nigerian aviation sector found itself at crossroads. On the one hand, there was the imperative to grow, to serve a burgeoning population with aspirations of global mobility. On the other, was the realization that this growth could not be pursued at the expense of environmental sustainability (Mojeed 2023). The early 2000s became a period of reckoning. Stakeholders in the Nigerian aviation industry began to understand the depth and breadth of the energy challenge. Initial attempts to address these were, admittedly, sporadic and lacked a cohesive, strategic vision. Yet, they marked the beginning of a journey—a journey toward making Nigeria's aviation sector more energy-efficient, more attuned to global best practices, and more sustainable (Okorafor 2022).

To encapsulate the key points discussed, the historical trajectory of Nigeria's aviation sector is not just a tale of aircraft, airports, or airlines. It is a reflection of a nation's aspirations, its challenges, its victories, and its lessons. The energy story, intertwined with this larger narrative, offers valuable insights for the present and future, reminding us of the delicate balance between growth and sustainability.

Present state of energy consumption

The aviation industry's mammoth rise in Nigeria, mirrored in its infrastructural growth, increasing number of airlines, and burgeoning passenger numbers, comes with an equally large energy footprint. The nexus between growth and energy consumption presents a compelling tableau of challenges and opportunities. As we dissect the present state of energy consumption, it is pertinent to understand the three major components—flight operations, ground support activities, and maintenance processes. A summary of the energy consumption in the Nigerian Aviation Sector in 2022 is given in Table 1.

Methodology of the energy consumption table

The energy consumption table presented for the Nigerian aviation sector in 2022 was constructed based on a multistep methodology:

1. *Literature review*: An initial literature review was conducted to gather information on energy consumption patterns in similar global aviation sectors. This served as a preliminary guideline for identifying key components that typically consume energy within such sectors.
2. *Hypothetical data modeling*: Due to the lack of specific data, we employed a hypothetical data modeling approach. Estimates were generated based on the proportional consumption seen in other aviation sectors, adjusting for the specific conditions and size of the Nigerian Aviation Sector.
3. *Assumptions*: Several assumptions were made to facilitate this modeling:
    - The average cost of energy was estimated at $100 per MWh, drawing from global averages and adjusted for Nigerian market conditions.
    - Energy consumption and costs were considered to be generalized and consistent, though in actual scenarios, they would fluctuate based on multiple factors such as weather, operational changes, and passenger traffic.
    - Proportional consumption was inferred from available literature, with specific components like aircraft operations typically consuming more energy than others, like administrative operations.

Table 1 Energy consumption in the Nigerian aviation sector (2022)

Item/component	Monthly consumption (MWh)	Annual consumption (MWh)	Associated costs (USD)	% of total energy consumption
Airport operations (e.g., lighting, HVAC)	8000	96,000	$9,600,000	38
Aircraft operations (fuel)	9500	114,000	$11,400,000	45
Ground support equipment	1200	14,400	$1,440,000	6
Air traffic control systems	1000	12,000	$1,200,000	5
Maintenance and repair operations	900	10,800	$1,080,000	4
On-site transportation (e.g., shuttle buses)	400	4800	$480,000	2
Security systems (e.g., scanners, cameras)	500	6000	$600,000	2
Administrative operations (offices, etc.)	500	6000	$600,000	2
Totals	22,000	264,000	$26,400,000	100

4. *Validation with experts*: While our table is based on generalized estimates, in a real-world application, it would be essential to validate these figures with industry experts, energy auditors, and through consultation with stakeholders in the Nigerian aviation sector.
5. *Feedback loop*: We recommend that this table serves as an initial representation and should be revised as actual energy consumption data becomes available. This iterative process will refine the accuracy of the table over time.

Flight operations

The story of aviation in Nigeria is a tapestry of progress, connectivity, and a testament to human ingenuity. It is also, inevitably, a narrative of vast energy consumption, primarily due to flight operations. From the roar of engines at takeoff to the final taxi after landing, each aircraft's journey is a series of meticulously coordinated actions that together create a significant energy profile.

Flight operations essentially encompass the complete journey of an aircraft—starting with its taxi onto the runway, followed by takeoff, cruising through the skies, and concluding with the descent, landing, and the final taxi to its resting spot (Leoni et al. 2022). Each phase is intrinsically linked to specific energy demands. Jet fuel, specifically designed and refined for aviation, powers these operations (Adekitan et al. 2018). The sheer significance of jet fuel goes beyond merely being the fuel for propulsion; in several modern aircraft designs, it serves multiple auxiliary functions, such as acting as a coolant for various onboard systems or even as a hydraulic fluid (Kim et al. 2023). While the engines' initial roar during the takeoff phase requires them to work near their peak capacity, leading to maximum fuel consumption, cruising at altitude showcases a more efficient burn rate. Yet, given that cruising can last several hours for long-haul flights, this phase still constitutes a lion's share of the energy consumed in a flight's duration. Descent, landing, and taxiing, though shorter in duration compared to cruising, have their specific energy needs (Hassan et al. 2021).

Modern aircraft, while marvels of efficiency compared to their historical counterparts, still have significant energy requirements. Several factors, such as the aircraft's design, weight, flight duration, and even external conditions like weather, play a role in determining the exact energy footprint of a flight (Lyu and Liem 2020). For instance, aircraft designed with better aerodynamics, utilizing lighter materials, can offer improved fuel efficiencies (Marino and Sabatini 2014; Poll 2014). Similarly, prevailing wind conditions can influence the plane's fuel burn rate. Tailwinds can aid an aircraft, allowing it to achieve its destination with reduced energy expenditure, while headwinds can have the opposite effect (University of Reading 2021; Vazquez et al. 2017; Wells et al. 2023; Zhang et al. 2019a).

Nigeria, given its geographic expanse and role as a key connectivity hub in Africa, witnesses a myriad of flight operations daily. The diverse nature of these operations, from short domestic hops between cities to long-haul international voyages, creates a complex energy consumption tableau. Domestic flights, due to their shorter duration, often have a higher fuel burn rate per mile, primarily because takeoffs and landings, both energy-intensive actions, are closer together in time. On the other hand, international flights, while efficient in terms of fuel burn per mile due to prolonged cruising phases, consume vast amounts of fuel due to their extended duration (Grubesic et al. 2017). To further complexify the energy landscape, the Nigerian aviation sector, like many others globally, has a mix of older and newer aircraft. Older planes, relics of an earlier era of aviation, while often robust and reliable, are not as fuel-efficient as their modern counterparts. This inefficiency is not just in terms of their design but also extends to the need for more frequent maintenance—actions that, indirectly, contribute to the sector's overall energy footprint. Conversely, newer aircraft models, fruits of decades of research and engineering advancements, promise and often deliver better operational efficiencies. They benefit from cutting-edge technologies, from improved aerodynamics to engine designs that maximize every drop of fuel (Csereklyei and Stern 2020). Yet, these modern marvels are investments—often significant ones. For Nigerian airlines, balancing the books while ensuring fleet modernization remains an ongoing challenge.

Furthermore, beyond the aircraft and their operations, several extrinsic factors play into the energy scenario. For instance, air traffic conditions, especially in bustling hubs, can lead to extended waiting times on runways or holding patterns in the skies—both scenarios that can inflate fuel consumption (Atasoy 2023; Hamdan et al. 2022). Similarly, weather patterns, from storm systems that necessitate flight reroutes to temperature fluctuations that might require different flight profiles, play a significant role (Singh and Sharma 2015). For Nigeria, with its diverse climatic zones, weather can often be a wildcard in the energy consumption narrative. Operational variables, such as optimal flight routing, efficient air traffic control, and even on-ground logistics, further add layers to this intricate energy puzzle. An efficient air traffic control system can reduce unnecessary airtime, leading to energy savings (Han 2023; Kwasiborska and Skorupski 2021; Wen et al. 2022). Similarly, efficient ground operations, ensuring rapid turnarounds and minimizing taxiing times, can also chip away at the overall energy bill (Jeon et al. 2022; Kim and Baik 2020; Zhang et al. 2019b).

Yet, at the core of the Nigerian aviation sector's energy story is a broader global narrative—one of sustainability, environmental responsibility, and the looming shadow of climate change. As the world grapples with the urgent need for sustainability, aviation, given its energy demands, is squarely in the spotlight. Nigerian airlines, cognizant of both the environmental and economic imperatives, are at a crossroads. While the economic pressures, exacerbated by volatile global oil prices and local economic dynamics, push for maximum operational efficiency, the environmental mandate demands sustainability. These twin pressures, though seemingly at odds, can also be complementary. After all, improved fuel efficiency translates to both cost savings and reduced carbon footprints.

Ground support activities

The pulsating rhythm of an airport is emblematic of more than just the airplanes that grace its runways. Equally, if not more integral, are the numerous ground support activities that ensure each flight's smooth operation. These activities, often overshadowed by the larger-than-life nature of flight operations, present their own unique set of challenges and energy demands.

Ground support, in essence, facilitates the dance between land and sky (Saha et al. 2021). It encompasses a vast array of functions, from marshaling an incoming aircraft to its allotted gate, to ensuring every piece of luggage reaches its rightful owner (de Oliveira et al. 2021). Each activity, whether it is the ground power units (GPUs) providing auxiliary power to an aircraft during its layover or the de-icing trucks ensuring safe winter departures, has a significant energy footprint (Machon 1985). Picture, for a moment, the sheer number of vehicles and equipment needed to support just one aircraft. Luggage trolleys zig-zagging, catering vehicles lifting meals onboard, refueling trucks pumping thousands of liters of jet fuel, and maintenance vehicles attending to any repair needs. These myriad activities, happening simultaneously, require an orchestrated approach to ensure efficiency and safety (Szabo et al. 2021).

One of the primary energy culprits in ground operations is the refueling process. Given the considerable volumes of jet fuel needed, especially for long-haul flights, the vehicles responsible are, by necessity, large and heavy-duty. These trucks, often powered by diesel engines, present a dual challenge. Firstly, the sheer act of transporting vast quantities of fuel across the airport uses substantial energy. Secondly, given the emissions associated with diesel combustion, they contribute significantly to the airport's overall carbon footprint (Li and Zhang 2023; Mangold et al. 2022; Parry and Hubbard 2023). Furthermore, consider the auxiliary power needs of an aircraft during its layover. While main engines are off, onboard systems—from lights to air conditioning—need power. Historically, this has been provided by onboard auxiliary power units (APUs) which burn jet fuel. However, many modern airports, in a bid to reduce emissions, are transitioning to ground power units (GPUs) which provide electricity to aircraft from the airport's main power grid (Altuntas et al. 2014; Baxter 2021, 2022; Padhra 2018). Yet, in Nigeria, with its irregular power grid situation, this transition is not straightforward. The reliability on diesel-powered generators due to grid intermittency translates to higher energy consumption and emissions.

Beyond fuel and power, there are several other ground operations that contribute to an airport's energy profile. The conveyor belts transporting luggage, the hydraulic systems elevating catering trucks, and the vast array of lighting and signaling equipment all draw power. Given the 24/7 nature of major airports, ensuring uninterrupted power supply to these systems is paramount (Bahman 2023). For Nigeria, with its power grid challenges, this often means backup generators are continually on standby, further adding to the energy equation. One cannot also overlook the environmental control systems within an aircraft during layovers. Be it the blistering heat or the chilly winter nights, ensuring a comfortable environment inside the plane for both passengers and crew is non-negotiable. The energy required for this, especially in regions with extreme weather, can be significant (Qiu et al. 2021). Additionally, the surge in air travel and cargo volumes has naturally led to a proportional increase in ground support demands. More flights mean more luggage to handle, more fuel to pump, and more mouths to feed onboard. The scalability challenge is further compounded by the growth trajectories projected for the Nigerian aviation sector. As more people fly and as businesses increasingly leverage air cargo, the demands on ground support operations will only intensify. However, every challenge presents an opportunity. The world over, there is a growing cognizance about the environmental and economic benefits of greening ground operations. Electrification of ground vehicles, deployment of solar arrays to power airport ancillary functions, and investments in energy-efficient equipment are but some of the steps being considered or implemented.

Nigeria, too, with its abundant sunlight, could consider solar power as a viable supplement, if not a replacement, for certain ground functions. Solar-powered pathway lights or even solar-assisted GPUs might sound futuristic, but they are well within the realm of feasibility. Similarly, transitioning to electric or hybrid ground vehicles, while a significant upfront investment, promises both reduced emissions and operational cost savings in the long run. Moreover, efficient management and planning can significantly curtail energy wastage. Simple actions, like ensuring rapid aircraft turnarounds or optimally routing refueling trucks to minimize travel distances, can cumulatively lead to significant energy savings. Additionally, training and awareness campaigns for ground staff about the importance and methods of energy conservation can have a ripple effect, leading to an ingrained culture of efficiency.

Maintenance processes

In the high-stakes world of aviation, the importance of maintenance cannot be overstated. Often functioning behind the scenes, this sector ensures that aircraft—these marvels of engineering—remain in pristine condition, ensuring the safety and efficiency of every flight. Yet, this very importance translates to a significant energy demand, with implications for the environment and economics of aviation.

The scope of aircraft maintenance is vast, spanning from routine daily checks to the more comprehensive heavy maintenance visits (HMs) which might occur every few years. These processes require a complex mix of manpower, machinery, and materials, each contributing to the energy consumption of the process (Santos and Melício 2019). Routine checks, for instance, encompass a range of activities from visual inspections of the aircraft's exterior to more detailed inspections of essential systems. While some of these checks rely primarily on the keen eye and experience of an engineer, others may need sophisticated diagnostic equipment. These tools, such as X-ray machines to detect internal structural flaws, borescopes or electronic diagnostic kits for aircraft systems, consume electricity, sometimes in significant amounts. Their continuous and frequent use means that their energy consumption, while individually small, can cumulatively become significant (Doğru et al. 2020). Furthermore, as aircraft age and accumulate flight hours, they require more intensive maintenance procedures. Overhauls involve stripping the aircraft down, often to its skeletal structure, and then meticulously inspecting, repairing, or replacing components. Such activities require large, often specialized equipment. For instance, the process of removing and then reinstalling an aircraft engine requires not just a team of skilled technicians but also machinery like hoists and cranes. These heavy-duty machines, powered either by electricity or diesel, have a substantial energy footprint (Korba et al. 2023).

Similarly, aircraft painting, a process that might seem superficial, is far from it. Beyond aesthetics, the paint on an aircraft serves protective functions, shielding the aircraft's metal body from the elements. Repainting an aircraft, typically done during a comprehensive overhaul, is energy-intensive. The old paint needs to be stripped off, often using high-pressure water jets or chemical solvents. Then, temperature-controlled paint booths ensure that the new paint adheres properly and dries efficiently. Both processes require substantial amounts of energy (Prapan et al. 2020). Now, let us consider the facilities housing these maintenance activities: the hangars. These colossal structures, designed to accommodate aircraft of all sizes, have their unique energy needs. Maintaining optimal conditions inside the hangar, whether it is the lighting ensuring technicians can work with precision or the heating and cooling systems maintaining comfortable temperatures, adds to the energy tally (Gaptek 2021). Especially in Nigeria, where temperatures can soar, ensuring that hangars remain cool is paramount for both human and machine efficiency. This often means large air conditioning systems working overtime.

The issue of spare parts further complicates Nigeria's maintenance energy narrative. Given the nation's limited capacity for manufacturing aviation-grade components, a bulk of the spare parts used are imported. This import process, from manufacturing facilities often continents away to the Nigerian maintenance hangars, involves a chain of transport—ships, trucks, and sometimes even flights. Each mode of transport, with its associated energy use and emissions, indirectly but significantly adds to the energy consumption of the maintenance process. Additionally, the processes that go into producing these spare parts should not be overlooked. The production of aviation-grade materials—whether it is the aluminum for the aircraft's body, the rubber for its tires, or the myriad electronics guiding its systems—is energy-intensive. The factories producing these components consume vast amounts of electricity, water, and other resources. And while this energy consumption might occur outside Nigeria's borders, it is inextricably linked to the nation's aviation maintenance activities. Moreover, as Nigerian airlines modernize their fleets, embracing newer aircraft models with more sophisticated systems, the maintenance landscape evolves. Newer aircraft, while often more fuel-efficient in the air, can sometimes have more complex systems, requiring specialized maintenance procedures and equipment. These new systems and procedures, while often designed with efficiency in mind, can present new energy demands.

Yet, just as with other facets of aviation, innovation offers promise. Around the world, research is underway to make maintenance processes more energy-efficient. Whether it is the development of more efficient diagnostic tools, techniques that reduce the need for energy-intensive procedures, or even the push toward greener, less energy-intensive materials for aircraft components, the future holds potential. For Nigeria, embracing these innovations could be transformative. Investing in energy-efficient infrastructure for maintenance, from LED lighting in hangars to more efficient machinery, can lead to substantial energy savings. Similarly, by strengthening domestic capacities, whether through partnerships or home-grown initiatives, to produce more maintenance components locally, the nation can reduce the energy-intensive import chain.

Challenges in energy optimization

The transition toward an energy-optimized aviation industry is not without its fair share of challenges. Despite the global push toward more sustainable operations, several barriers hinder progress, especially in regions like Nigeria. The country's unique socioeconomic and political climate brings its own set of complexities to the table. Here, we dissect the most pressing challenges the Nigerian aviation sector faces in its quest for energy optimization.

Reliance on fossil fuels

For decades, the backbone of the aviation industry, not just in Nigeria but globally, has been fossil fuels. Jet fuel, derived from crude oil, powers the vast majority of aircraft engines. This dependency stems from the high energy density of fossil fuels, which is unmatched by current sustainable alternatives. Given the need for aircraft to carry their fuel, weight becomes a critical factor, and fossil fuels have, historically, provided the most energy per unit of weight. For example, the energy content of aviation fuel, also known as Jet A or Avgas, is approximately 33.5 kilowatt-hours per gallon (Male et al. 2021).

In Nigeria, the reliance on fossil fuels is even more pronounced due to the country's vast oil reserves. With the oil sector being a dominant player in the national economy, there is a natural inclination toward maintaining the status quo. This abundant availability of oil might seem like an advantage, but it has inadvertently deterred investment and research into alternative fuels within the region.

Unstable power grid

The intricacies of aviation are not limited to what happens in the sky. On the ground, from airport terminals to maintenance hangars, electricity plays a pivotal role. However, Nigeria's power grid is notoriously inconsistent. Power outages are common, and while major airports have backup generators, these are often diesel-powered, contributing further to the industry's carbon footprint (Ohajianya et al. 2014).

This instability means operations can be disrupted. Critical systems, from air traffic control to baggage handling, need consistent power. Every outage, even if only for a few minutes, can lead to delays, increasing fuel burn as aircraft wait on the ground. Furthermore, the irregular power situation pushes costs up, as airports and airlines invest in backup systems and pay premium prices for diesel.

Financial constraints in adopting new technologies

The aviation sector is capital intensive. Aircraft, their maintenance, and the infrastructure supporting them require significant investments. While there is a global push toward greener technologies, from more fuel-efficient aircraft engines to ground equipment powered by renewable energy, these innovations come with hefty price tags.

For Nigerian airlines, many of which operate on thin profit margins, making the switch to these newer, more expensive technologies is a daunting prospect. The immediate financial implications often overshadow the long-term benefits, both economic and environmental. Additionally, securing capital for such investments can be challenging, given the risk-averse nature of many financial institutions when considering the volatile aviation sector (Okeke 2017).

Regulatory and policy limitations

Government regulations and policies play a significant role in shaping industry practices. In the realm of energy optimization, the right policies can incentivize sustainable practices, from tax breaks for airlines adopting greener technologies to grants for research into sustainable aviation fuels. However, in Nigeria, the regulatory landscape has often lagged behind global standards. While there are regulations governing aviation safety and operations, those targeting environmental sustainability and energy optimization are either nonexistent or not enforced rigorously (Oyedepo 2012). Furthermore, policy inconsistencies and frequent changes can deter investment. If an airline, for instance, is not sure whether a tax break supporting the adoption of a new technology will remain in place long enough for them to recoup their investment, they might be less likely to invest at all.

In essence, while the path to energy optimization in Nigeria's aviation sector is clear, the journey is fraught with challenges. Each of these barriers, from infrastructural to financial and regulatory, intertwines, creating a complex web that requires a multi-faceted approach to navigate. However, acknowledging these challenges is the first step toward crafting solutions. With collaborative efforts between the government, industry stakeholders, and the broader global community, the Nigerian aviation sector can indeed soar toward a sustainable future.

Comparative analysis

To assess the progress and challenges within Nigeria's aviation sector, it is enlightening to juxtapose its energy consumption and optimization efforts against other emerging markets. Additionally, understanding global best practices provides a road map for what is achievable and offers insights into the strategies that have proven most effective.

Energy consumption and optimization practices in similar emerging markets

Emerging markets, while diverse in their cultural and socioeconomic contexts, often grapple with similar challenges in their quest for industrial modernization and sustainability. Here, we will delve into a few comparable scenarios:

Brazil: As one of the BRICS nations, Brazil has seen rapid growth in its aviation sector. While it has a vast territory like Nigeria, it differs in its utilization of bio-jet fuel. Derived mainly from sugarcane, Brazilian airlines have started mixing this with conventional jet fuel. This initiative not only reduces carbon emissions but also supports local agricultural sectors (Cortez et al. 2015).

India: With a burgeoning middle class and a rush toward urbanization, India's aviation sector mirrors Nigeria's growth trajectory in many ways. The primary energy challenges for India's aviation sector revolve around infrastructure. Modern airports in cities like Mumbai and Delhi are adopting solar power for their operations. Furthermore, India's push toward manufacturing aircraft parts locally reduces the energy costs linked to importing them (Ravishankar and Christopher 2022; Thummala and Hiremath 2022).

South Africa: Africa's second-largest economy offers another illustrative comparison. The nation has made significant strides in integrating renewable energy sources into its grid, and this extends to its airports. Johannesburg's O.R. Tambo International Airport, for instance, is pioneering energy-saving measures like rainwater harvesting and natural lighting (Rhoades 2004).

Lessons from global best practices

Examining the pinnacle of energy optimization in the aviation industry provides not just inspiration, but tangible strategies that can be adapted to the Nigerian context.

Flight optimization: European airlines have made significant strides in optimizing flight paths. Advanced air traffic management systems, in conjunction with real-time weather data, allow aircraft to take the most efficient route, saving fuel (Rosenow et al. 2021).

Infrastructure upgrades: In places like Singapore's Changi Airport or Denmark's Copenhagen Airport, technological advancements like smart LED lighting, energy-efficient air conditioning systems, and the adoption of electric ground vehicles have set new standards in energy optimization (Kumar and Cao 2021).

Alternative fuels: While Brazil champions sugarcane biofuel, nations like the USA are researching algae-derived fuels. The pursuit of sustainable aviation fuel (SAF) is becoming a focal point in reducing the carbon footprint of flights (Balogu et al. 2022; Dodd and Yengin 2021; Zhang et al. 2016).

Training and awareness: Canadian and Australian airlines prioritize training their pilots in fuel-efficient flying practices. Simple strategies, such as optimal aircraft taxiing and efficient ascent and descent profiles, make a considerable difference (Casner et al. 2013).

Regulatory incentives: Many European nations provide tax incentives for airlines and airports to adopt green technologies. These financial stimuli often make the difference, bridging the gap between higher initial investments and long-term gains (Abate et al. 2020).

Prospects for energy optimization in the Nigerian aviation sector

The urgency of optimizing energy in the aviation sector cannot be overstated, especially in an era marked by rapid climatic changes and global efforts to curtail greenhouse gas emissions. Nigeria, with its expanding aviation industry and ambitious growth trajectory, stands at a crossroads where the decisions taken today will mold the sector's future sustainability. There are abundant prospects for energy optimization in Nigerian aviation, some of which we will delve into in this section.

Innovative energy-saving technologies suitable for Nigeria

The rapidly advancing technological landscape presents Nigeria with an opportunity to leapfrog some of the older energy-consuming technologies, directly transitioning to greener, more efficient solutions.

Electrification of ground vehicles: Electric vehicles are gaining traction worldwide. In an airport setting, tugs, baggage carts, and maintenance vehicles can be electrically powered, eliminating diesel consumption and reducing local emissions (Air Transport Action Group 2023).

Advanced aircraft materials: Aircraft manufacturers are increasingly looking into lighter and more durable materials. Carbon-fiber composites, for example, can reduce an aircraft's weight, leading to lower fuel consumption (Parveez et al. 2022; Zhu et al. 2018).

Data analytics and AI: By employing artificial intelligence and machine learning algorithms, airports can better manage energy consumption, analyzing patterns to determine optimal times for energy-intensive activities, and predicting system maintenance to reduce downtimes (Ahmad et al. 2022; Kierzkowski and Kisiel 2021).

Potential policy shifts and regulatory reforms

For a sector as vast and complex as aviation, regulatory frameworks play a crucial role in guiding and nudging it toward sustainable practices.

Carbon credits: One initiative could be the introduction of an aviation-specific carbon credit system. Airlines achieving below a set emissions level could earn credits, which they can trade with other airlines.

Incentivizing green technology adoption: Airports and airlines that invest in green technologies could be provided with tax breaks, reduced landing fees, or other financial incentives.

Stricter emission standards: By setting progressive emission reduction targets, the Nigerian aviation regulator can encourage the industry to adopt cleaner technologies.

Role of renewable energy in aviation

While aircraft might still be some years away from running purely on renewable energy, other aspects of the aviation value chain can benefit immediately from green power sources.

Solar airports: Large expanses of land around airports, particularly their rooftops, can be used to install solar panels. These can power a significant part of an airport's operations, from terminal lighting to conveyor systems (Baxter 2023; Emeara et al. 2021).

Biofuels: Biofuels, derived from organic sources like plants, have the potential to reduce the carbon footprint of aviation fuel significantly (Yang et al. 2019). Research into tropical crops, abundant in Nigeria, could yield viable sources of biofuel.

Wind energy: Larger airports with vast adjoining areas could consider harnessing wind energy. Turbines, strategically placed without interfering with flight paths, could supplement the energy mix (Cuadra et al. 2019).

Collaboration with International Organizations for Sustainable Aviation

The challenges of sustainable aviation are global, and so should be the solutions. Collaborating with international bodies provides Nigeria with a pathway to share knowledge, gain insights, and access funding for green projects.

International Civil Aviation Organization (ICAO): ICAO has been at the forefront of advocating for sustainable aviation. Its "No Country Left Behind" initiative could be a valuable platform for Nigeria to align its aviation growth with global best practices.

Clean Sky Joint Undertaking: A European initiative, Clean Sky, aims to develop cleaner air transport technologies. While primarily European, collaboration or partnership can provide Nigeria with insights into the latest research and developments.

The Air Transport Action Group (ATAG): This global coalition works toward sustainable aviation. Engaging with ATAG can provide Nigerian stakeholders with valuable networking opportunities, knowledge resources, and potential partnerships.

Recapping the main themes of this section, Nigeria's aviation sector, with its rich history and potential for growth, stands at a pivotal moment. The prospects for energy optimization are vast and multi-faceted. By intertwining innovative technologies, regulatory foresight, renewable energy solutions, and global collaborations, Nigeria can sculpt a future where its skies are not only busier but greener. This vision, while challenging, is achievable, laying the foundation for a sustainable, efficient, and prosperous aviation industry.

Implications for sustainable development in the Nigerian aviation sector

Sustainable development, at its core, intertwines the principles of economic growth, social inclusion, and environmental sustainability. The aviation sector, with its enormous reach and impact, is intrinsically tied to each of these dimensions. As Nigeria intensifies its efforts to optimize energy in aviation, it is imperative to examine the broader implications of these endeavors on the nation's path to sustainable development.

Economic implications

Cost savings: Energy optimization, by its very definition, involves deriving more value from less energy (Sieniutycz and Jezowski 2018). For the Nigerian aviation industry, this could translate to significant cost savings. Whether it is through efficient flight operations reducing fuel bills, or solar-powered airport terminals cutting down on electricity costs, the economic benefits are tangible. Over time, these savings can accumulate, providing airlines and airports with greater financial leeway to invest in service upgrades, staff welfare, or expansion projects.

Profitability: The aviation business is notorious for its razor-thin profit margins. Any initiative that can enhance efficiency can thus significantly impact the bottom line.

An airline saving on fuel or an airport reducing its power bills can bolster profitability. This not only ensures the longevity and health of the sector but also attracts more investments, both domestic and international.

Competitiveness: As global travelers become increasingly eco-conscious, airlines and airports that can boast of sustainable practices gain a competitive edge. It is not just about cost savings but about branding, customer loyalty, and market positioning. An airport powered by renewable energy or an airline with a young, fuel-efficient fleet can be powerful marketing tools in attracting both passengers and partners.

Environmental implications

Emissions reduction: The aviation sector is a significant contributor to global carbon emissions. Nigeria, with its expanding air traffic, bears a responsibility to mitigate its share. Energy optimization can play a crucial role here. From biofuels reducing the carbon footprint of flights to electrified ground vehicles eliminating local emissions, the opportunities for making Nigerian aviation greener are numerous. Each ton of carbon saved is a step closer to global climate targets and a testament to Nigeria's commitment to planetary stewardship.

Environmental stewardship: Beyond just carbon, the aviation industry interacts with the environment in multiple ways. Noise pollution, water runoff from airports, land use—all these have environmental implications. An energy-optimized, sustainability-conscious aviation industry can address these challenges head-on. For instance, green airport designs can manage water better, reduce land wastage, and even create habitats for local flora and fauna.

Social implications

Job creation: Sustainable industries are often innovation-driven. As Nigeria's aviation sector leans into energy optimization, it will invariably necessitate new skills, technologies, and services. This can spur job creation. Solar panel installers for airports, biofuel researchers, energy efficiency auditors—these are jobs that can emerge from a greener aviation industry. Moreover, as the sector becomes more profitable and expands, it can further boost employment in various ancillary services, from catering to logistics.

Health benefits: Aircraft, especially when taking off or landing, emit not just carbon but also other pollutants. By optimizing energy and reducing fuel consumption, these emissions can be curtailed. For communities living around airports, this can have direct health benefits, reducing respiratory ailments and improving the overall quality of life.

Community engagement: A sustainable aviation sector cannot operate in isolation. It needs the understanding, support, and even participation of the communities it serves. Whether it is through awareness campaigns on green flying or involving local communities in airport greening projects, there is a symbiotic relationship to be nurtured. An energy-optimized, community-engaged aviation industry can serve as a beacon of development, echoing the principles of inclusivity, participation, and shared growth.

In wrapping up this section, the path to sustainable development in Nigeria's aviation industry is laden with opportunities and challenges. Each stride taken toward energy optimization has ripple effects, touching the economy, the environment, and society in profound ways. As stakeholders—from policymakers to airlines, from passengers to communities—come together in this journey, they are not just shaping the future of Nigerian aviation but also contributing to a more sustainable, inclusive, and prosperous nation.

Recommendations for energy optimization in the Nigerian aviation sector

The Nigerian aviation sector, while brimming with potential and growth opportunities, is at a crossroads. The choices made today, especially in the realm of energy optimization, can significantly influence its trajectory in the decades to come. Drawing from the insights shared in the preceding sections, this segment provides targeted recommendations to different stakeholders.

Policy recommendations for government and regulatory bodies

1. *R&D investment*: The government should prioritize and boost funding in research and development (R&D) aimed at aviation energy efficiency. Emphasizing areas like biofuels, electric propulsion, and efficient airport infrastructure can put Nigeria at the forefront of aviation sustainability in Africa.
2. *Tax incentives*: To promote energy-efficient practices and the adoption of green technologies, the government could offer tax breaks or rebates to airlines and airports making tangible strides in this direction.
3. *Robust regulatory framework*: Regulatory bodies should work toward creating a comprehensive framework that mandates energy audits, establishes clear benchmarks, and integrates global best practices. This framework should be flexible enough to adapt to technological advancements and changing global standards.
4. *Training and capacity building*: Authorities should collaborate with educational institutions to develop

training programs tailored for the aviation industry, focusing on sustainability, energy efficiency, and new technological applications.
5. *Infrastructure development*: Ensuring a stable power supply, investing in green airports, and improving air traffic management systems can significantly cut down the energy footprint of the sector.

Operational recommendations for airlines and airports

1. *Fleet modernization*: Airlines should prioritize acquiring newer, more fuel-efficient aircraft. While this requires substantial investment, the long-term savings in fuel costs and the reduced environmental impact make it a worthy endeavor.
2. *Data-driven decisions*: Both airlines and airports should invest in data analytics tools that can provide insights into energy consumption patterns, operational inefficiencies, and areas of potential improvement.
3. *Green infrastructure*: Airports can explore green building principles for terminals, install solar panels, optimize water usage, and deploy electric ground support equipment.
4. *Operational best practices*: Airlines can adopt best practices like single-engine taxiing, continuous descent approach, and optimal flight planning to save fuel.
5. *Employee training*: Energy optimization is not just about technology but also about human behavior. Training programs aimed at pilots, ground staff, and maintenance crews can instill best practices and heighten awareness about energy conservation.

Collaborative efforts between stakeholders

1. *Public–private partnerships (PPP)*: The government and private enterprises can enter PPPs to undertake ambitious projects like the development of green airports, establishment of biofuel production facilities, or electrification of ground operations.
2. *Stakeholder dialogues*: Regular dialogues between airlines, airport operators, regulators, and even passengers can ensure a shared understanding of challenges and collaborative strategizing of solutions.
3. *International collaboration*: Engaging with global aviation bodies, international regulatory agencies, and airlines from other countries can provide Nigerian stakeholders with insights, technologies, and practices that have proven successful elsewhere.
4. R&D collaborations: Universities, research institutions, airlines, and airport operators can work together on targeted research projects, drawing from both academic insights and on-ground practicalities.
5. *Community engagement*: The success of many energy optimization initiatives often depends on the local communities. Whether it is sourcing biofuels from community-managed farms or ensuring noise and pollution control in airports near populated areas, the active engagement of communities is crucial.

In the grand tapestry of the Nigerian aviation sector's sustainable future, each recommendation represents a stitch, a step, a choice that can shape its narrative. Some of these recommendations call for bold investments, some for policy shifts, and some for a change in mindset. However, the cumulative effect of these actions can propel the industry into an era marked by efficiency, sustainability, and shared prosperity. As Nigeria aspires to become an aviation hub in Africa, its energy optimization endeavors will not only determine its success in this ambition but also its legacy in the annals of sustainable aviation.

Conclusions

The evolving landscape of the Nigerian aviation sector provides a compelling lens through which the challenges and opportunities of energy optimization can be examined. The journey taken within this discourse illuminates the multi-faceted nature of energy consumption, with historical trends blending with current practices and the possibilities of what lies ahead.

The Nigerian aviation sector, with its unique challenges, is a reflection of larger global concerns. The sector's dependence on fossil fuels, the intermittent power grid, financial limitations, and regulatory constraints provide a somber backdrop. Yet, the transformative power of technology, the potency of informed policy, and the promise of international collaboration paint a more optimistic future. The case studies and comparative analyses offer a nuanced understanding, drawing lessons from both similar emerging markets and global best practices.

However, the road ahead is not without its hurdles. While the prospects are promising, they necessitate a confluence of innovative technologies, strategic policy shifts, rigorous regulatory reforms, and a genuine commitment to sustainable practices. The intersection of economic viability, environmental sustainability, and social equity remains the fulcrum on which the sector's future rests.

In terms of future research directions, there is vast potential. The application and impact of renewable energy sources in aviation, detailed life-cycle analyses of various energy-saving technologies, the socioeconomic implications of transitioning to green aviation, and the exploration of public perceptions and their influence on policy are just a few areas warranting deeper exploration. Furthermore, studies focused on the interplay between global aviation trends and localized Nigerian contexts can offer insights beneficial not just for Nigeria but for other emerging markets with similar challenges and aspirations.

As the narrative of the Nigerian aviation sector continues to unfold, it stands at an exciting crossroads. The choices made today can echo into the annals of history, heralding an era where the Nigerian skies are not just pathways for aircraft but also beacons of sustainable progress and innovation. It is a journey that demands collective will, persistent effort, and visionary leadership. And, as with any journey, while the destination is essential, the voyage itself, marked by learning, adapting, and growing, holds intrinsic value. The Nigerian aviation sector's quest for energy optimization is more than just a technical endeavor; it is a testament to the resilience, ambition, and potential of a nation on the rise.

Abbreviations

APU	Auxiliary power unit
ATAG	Air Transport Action Group
AI	Artificial intelligence
EVs	Electric vehicles
GPUs	Ground power units
HMs	Heavy maintenance visits
HVAC	Heating, ventilation, and air conditioning
ICAO	International Civil Aviation Organization
kWh	Kilowatt-hour
LED	Light emitting diode
MWh	Megawatt-hour
ML	Machine learning
PPP	Public–private partnerships
R&D	Research and development
SAF	Sustainable aviation fuel
USD	US Dollars

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OFO: contributed to study conceptualization and design, led literature review and analysis on specific aspects of the aviation sector, and participated in manuscript writing and revision. NMG drafted sections related to his domain expertise, reviewed, and edited specific portions of the manuscript. EE collaborated in manuscript drafting and contributed to literature cross-referencing and validation. DREE offered overarching guidance on the synthesis of literature, supervised the review process, and coordinated manuscript revisions and acted as the primary liaison for editorial communications. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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