



Full Review Article

Electrochemical energy conversion and Storage Systems: A perspective on the challenges and opportunities for sustainable energy in Africa



Idris Temitope Bello^{a,b}, Lateef A. Jolaoso^c, Ridwan Adesoye Ahmed^{d,**},
Abdulkakeem Bello^{d,e,f,*}

^a Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

^b Centre for Advances in Reliability and Safety (CAiRS), Hong Kong Science Park 12/F, Building 19W, Pak Shek Kok, NT, Hong Kong, China

^c School of Aerospace and Mechanical Engineering, University of Oklahoma, Norman, OK, USA

^d Department of Materials Science and Engineering, African University of Science and Technology (AUST), Abuja, Nigeria

^e Department of Theoretical and Applied Physics, African University of Science and Technology (AUST), Abuja, Nigeria

^f Centre for Cyber Physical Food, Energy & Water Systems (CCP-FEWS), University of Johannesburg, South Africa

ARTICLE INFO

Keywords:

Lithium batteries
Ceramic fuel cells
Africa
Clean energy
Technical challenges
Sustainable energy future

ABSTRACT

The increasing demand for energy in Africa poses challenges in terms of sustainability, affordability, and accessibility. Although Africa is rich in renewable resources, their use remains limited. Implementing electrochemical energy conversion and storage (EECS) technologies such as lithium-ion batteries (LIBs) and ceramic fuel cells (CFCs) can facilitate the transition to a clean energy future. EECS offers superior efficiency, cost, safety, and environmental benefits compared to fossil fuels. Their modularity also enables distributed renewable integration and off-grid access. However, Africa lacks production, deployment, and recycling capacities for these technologies. Infrastructure, policy, costs, consumer awareness, and technical expertise are major obstacles. This perspective review provides environmental and technical context for LIBs and CFCs. Adopting a comprehensive framework encompassing manufacturing, deployment, integration, and recycling, we analyze their benefits and adoption barriers in Africa. The review aims to enlighten policies and investments that can promote the scalability of these energy storage and conversion technologies. If strategic efforts are implemented, these technologies could catalyze sustainable electrification and position Africa at the forefront of global energy innovation. Realizing this potential requires holistic value chain solutions.

1. Introduction

The exponential growth in global energy consumption driven by the fast-growing human population, technological advancement, and the pursuit of comfort, prosperity, and urbanization has highlighted the significance of energy for human development and well-being [1]. However, the escalating global energy consumption, motivated by various human requirements and desires, threatens the environment and climate. Hence, the world faces a dual energy dilemma: providing access to clean and affordable energy for all while decarbonizing the energy sector to mitigate the extinction-threatening impacts of global warming.

In Africa, more than 600 million people do not have access to electricity, and more than 900 million rely on biomass (i.e., wood and charcoal) for cooking, exposing them to domestic air pollution and other

health risks [2]. In addition, Africa is particularly susceptible to the impacts of climate change, such as floods, crop failures, droughts, and heat waves, due to poverty, deforestation, the lack of adequate infrastructure, and poor urban planning [3,4]. These highlight the severity of the situation in Africa.

According to the International Energy Agency (IEA) in the World Energy Outlook (WEO) 2021, the global energy demand is projected to increase by 25 % by 2050 if the current trends and policies continue [5, 6]. However, this projected energy demand implies that global CO₂ emissions will increase by ~40 % by 2050, exceeding the levels necessary to limit global warming to below 2 °C as specified in the Paris Agreement [7,8]. The IEA mandates that achieving net-zero emissions by 2050 and addressing the current challenges requires a massive energy sector transformation. This transformation requires a fourfold increase in

* Corresponding author. Department of Materials Science and Engineering, African University of Science and Technology (AUST), Abuja, Nigeria

** Corresponding author.

E-mail address: abello@aust.edu.ng (A. Bello).

<https://doi.org/10.1016/j.enrev.2024.100109>

Received 27 February 2024; Received in revised form 23 May 2024; Accepted 15 July 2024

2772-9702/© 2024 The Authors. Published by Elsevier Ltd on behalf of Shenzhen City Clean Energy Research Institute, Shenzhen University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

renewable energy sources, a 90 % and 75 % reduction in coal and oil consumption, respectively, and tripling annual investments in clean and sustainable energy [5,6].

As Africa continues its pursuit of technological advancement and its mission to provide access to electricity to more than one billion people, the continent must leapfrog the fossil fuel-based development path and embrace a low-carbon energy future [4]. Despite facing challenges such as inadequate funding, insufficient infrastructure, political instability, and unfavorable policies and regulations, Africa's efforts towards sustainable energy are noteworthy. In line with the International Renewable Energy Agency's (IRENA) Renewable Energy Roadmap (REmap 2030), Africa aims to increase the share of renewables in its energy mix to 22 % by 2030, reflecting a significant commitment to the clean energy transition [9,10]. Although Africa contributed only 3.3 % to global energy consumption in 2019 and 3.6 % to global energy-related carbon dioxide emissions in 2020, it possesses an abundance of renewable energy resources such as wind, solar, geothermal, hydro, and biomass, which could potentially meet the continent's electricity demand [3]. However, the intermittent nature of these renewable sources necessitates a focus on integrating energy conversion and storage technologies to achieve a more sustainable future. This integration is crucial for harnessing Africa's full renewable potential and ensuring a reliable and consistent energy supply [11].

Several African countries are making appreciable efforts towards implementing sustainable energy solutions. For example, South Africa developed the Renewable Energy White Paper (REWP 2003) to drive its renewable energy policy. The country's renewable power penetration includes solar, hydropower, wind, and biomass energy generation [12, 13]. Additionally, the Electricity Regulation Act and National Energy Act were introduced in 2006 and 2008, respectively [12]. According to a 2022 International Trade Administration (ITA) report, Egypt aims to boost its electricity generation from renewable sources to 20 % by 2022 and 42 % by 2035. By 2035, the renewable energy mix is projected to include contributions from wind (14 %), hydropower (1.98 %), photovoltaic (PV) solar (21.3 %), and concentrating solar power (CSP) (5.52 %) [14]. The Nigerian government introduced the National Energy Transition Plan in August 2022, aiming to generate 30,000 MW of electricity from renewable sources and achieve carbon neutrality by 2060. This initiative, supported by utility-enabled distributed energy resources, aligns with global climate targets and has the potential to create up to 340,000 jobs by 2030 [15]. Additionally, Nigeria aims to become the Solar Panel and EV Battery Manufacturing Hub of Africa by 2024, which is strategic for driving its renewable energy footprint [16].

Embarking on a sustainable energy pathway in Africa offers numerous benefits at both local and global levels. Contributing to the COP2023 agreement, Africa's renewable energy initiatives will help mitigate its contribution to global climate issues. Enhancing large-scale modular distribution of energy will improve the lives of those in rural areas, thus boosting economic conditions across the continent. Utilizing abundant gas resources will enable Africa to produce energy for itself and promote energy export, generating additional revenue for the continent.

Transitioning from fossil fuels to greener energy sources is pivotal for sustainable development, and electrochemical energy conversion and storage (EECS) technologies play a crucial role in this shift [17–19]. Within the spectrum of EECS technologies—which includes batteries, fuel cells, and electrolyzers [20–22]—Lithium-ion batteries (LIBs) and ceramic fuel cells (CFCs) stand out for their potential to address Africa's energy challenges [23–25]. LIBs are significant in the energy storage industry due to their ability to store chemical energy as lithium ions and efficiently convert it into electrical energy. They are suitable for various applications, from portable electronics to electric vehicles and even grid-scale storage solutions [26,27]. CFCs convert chemical energy directly into electrical energy, primarily for stationary power generation [17,28]. Both LIBs and CFCs surpass conventional fossil fuels in terms of efficiency, cost-effectiveness, safety, environmental impact, energy density, and resource availability [29–31].

Critical technical challenges must be overcome before the LIB and CFC technologies can be widely deployed in Africa. For example, CFCs and LIBs require high-quality materials and complex manufacturing processes, which may make them scarce and expensive in low-income countries [30,32,33]. Additionally, if handled unprofessionally, LIBs pose significant risks, such as explosion, fire, and toxicity [23]. CFCs face technical obstacles, such as degradation and durability issues, which affect their performance and lifespan [34]. These challenges highlight the need for a perspective review that analyzes the potential and feasibility of LIBs and CFCs for Africa's energy transformation.

This review explores in depth how EECS can change the energy landscape of Africa. We first provide a fundamental technical and environmental background for these two advanced technologies, explaining their working principles, types, applications, and reliability as EECS solutions. We then outline the significant environmental advantages LIBs and CFCs have over conventional fossil fuel-based power systems in terms of low emissions, high efficiency, and sustainability. This review also examines the barriers to the widespread adoption and production of EECS technologies in Africa. We use a comprehensive framework that covers infrastructure, policy, consumer awareness, costs, technical expertise, and end-of-life recycling. Based on these barriers, we discuss emerging opportunities and strategic interventions that could create an environment conducive to leapfrogging these innovative technologies. This multi-faceted review aims to provide novel insights into EECS that can inform policies and investments to speed up Africa's transition to a greener, more electrified, and cleaner future. With coordinated efforts, it is envisioned that the widespread deployment of these technologies could electrify millions, create skilled jobs, significantly reduce pollution, and position Africa at the forefront of global clean energy innovation.

2. Electrochemical energy conversion and storage technologies (EECS)

EECS are devices that use electrochemical reactions to convert or store energy in different forms [35]. These technologies include fuel cells, batteries, electrolyzers, supercapacitors, and photoelectrochemical cells [36–39]. They have various applications in renewable energy generation, grid management, transportation, and portable electronics [40–42]. EECS technologies offer several advantages over conventional energy sources, such as high efficiency, low emissions, flexibility, and scalability [43,44].

This perspective primarily focuses on two important EECS: LIBs and CFCs. LIBs are rechargeable batteries that use lithium ions as the charge carrier between the electrodes. They have a high energy density, long lifespans, and low self-discharge rates. They are widely used in electric vehicles, mobile devices, and grid storage [45]. CFCs are fuel cells that use ceramic materials as electrolytes and electrodes. They have high power density, fuel flexibility, and cogeneration potential. They can operate at high temperatures and use various fuels, such as hydrogen, methane, and syngas [29]. They are suitable for stationary power generation and other applications [17].

We will elaborate on the background, types, characteristics, advantages, and challenges of LIBs and CFCs in sections 2.1 and 2.2, respectively. Moreover, we will explore these technologies' current state-of-the-art and prospects in advancing clean energy conversion and storage.

2.1. Lithium-ion batteries (LIBs)

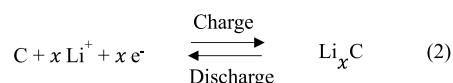
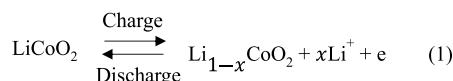
Lithium-ion (Li-ion) batteries are electrochemical energy storage devices that store and release electrical energy using Li-ions [26,46]. Since its commercialization in 1991 by Sony, this technology has witnessed significant advancements, placing it among the most advanced energy storage technologies currently available [27,47]. It is the predominant power source for portable electronics such as mobile phones and laptops and has found extensive application in grid storage and electric vehicles (EVs) [48,49]. Conventional Li-ion batteries' energy

density is higher than other rechargeable batteries, including lead acid and Ni-Cd batteries [26,50]. Nonetheless, the constraint of energy density remains a pertinent challenge, particularly for applications requiring high energy density, such as electric vehicles. For instance, with the current Li-ion battery, it is still challenging to achieve an energy density that enables EVs to travel the same distance as gasoline vehicles [49]. Furthermore, Li-ion battery technology faces obstacles including high cost, resource limitation, and safety [48].

This section highlights the fundamentals of Li-ion batteries, including their various classes and characteristics. In addition, future research trends in developing next-generation (or beyond Li-ion) batteries with the potential to address the current challenges with LIBs are emphasized.

2.1.1. Basic principles of LIBs

A Li-ion battery consists of multiple cells connected in series, parallel, or a combination of both configurations. Each Li-ion cell consists of an anode (e.g., graphitic carbon, silicon, and $\text{Li}_4\text{Ti}_5\text{O}_{12}$) and a cathode (e.g., LiCoO_2 , LiMnO_2 , and $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$) immersed in an organic liquid electrolyte (e.g., LiPF_6 salt dissolved in dimethyl carbonate (DMC), and ethylene carbonate (EC)) [51]. In addition, polymer gel and ceramic electrolytes have been investigated [52–54]. A microporous and polymeric material called the separator is placed between the anode and the cathode to allow ion flow but blocks electron flow and prevents physical contact between the electrodes. An applied current causes the cathode active material to dissociate during the charging process according to equation (1) for the LiCoO_2 cathode. The Li-ions formed during this process flow internally through the electrolyte (Fig. 1) to recombine with the electrons that flow through the external circuit to the anode (negative electrode) in accordance with equation (2).



Li-ions flow from the anode through the electrolyte to the cathode (positive electrode), while the electrons flow through the external circuit, supply electrical energy to the external load, and recombine with Li-ion at the cathode during the discharging process (Fig. 1) [55].

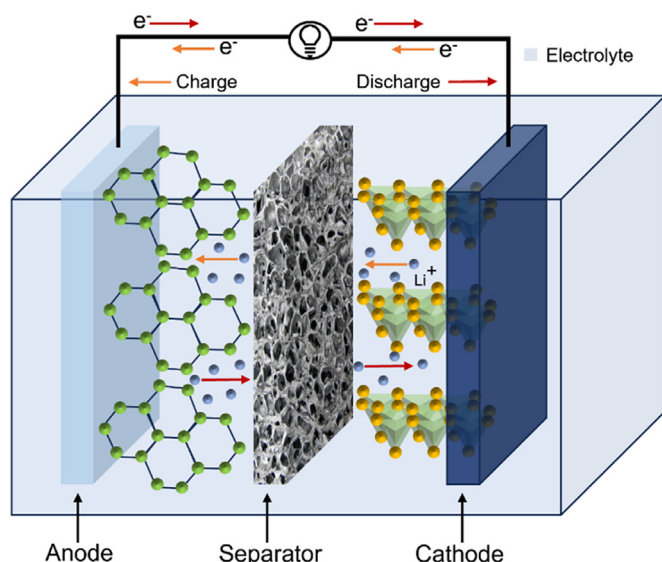


Fig. 1. Schematic of a conventional lithium-ion battery.

2.1.2. Types and characteristics of state-of-the-art LIBs

Typically, LIBs are classified based on their cathode active materials, which fall into one of three main categories: The layered structures (Fig. 2a), such as LiCoO_2 , LiNiO_2 , LiMnO_2 , and $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$, the olivine structures (Fig. 2b) including LiFePO_4 , LiMnPO_4 and the spinel structures (Fig. 2c), such as LiMn_2O_4 , LiCo_2O_4 [56]. Each type of LIB is identified using an acronym indicating the cathode material used. For example, the cathode active material of LCO batteries is LiCoO_2 , while that of LFP batteries is LiFePO_4 .

The LCO LIBs are the first and most commercially successful LIBs due to higher theoretical specific and volumetric capacities, excellent cycling performance, and high average potential [27,57]. However, LCO batteries have a high cost due to the high cost of Co, low thermal stability, and low-capacity retention at high current densities [27]. To address these problems, new cathode chemistries, such as $\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$ (NMC), with comparable or superior characteristics at lower cost compared to LCO, are being developed and actively studied [58–60]. LiMn_2O_4 (LMO) batteries benefit from Mn's abundance and low cost; however, these batteries suffer poor long-term cycling stability, amongst other issues at high current densities due to Mn dissolutions [61]. LiFePO_4 (LFP) batteries have high power density and excellent thermal stability. However, low voltage and poor electrical and ionic conductivities are major limitations of LFP batteries [61]. Table 1 presents the gravimetric capacity, volumetric capacity, and average potential of a selection of commercially available LIBs.

2.1.3. Advancements and challenges in LIB technology

The advent of LIBs can be traced to the development and commercialization of Li-ion primary batteries in the 1960s, manifesting the results of years of extensive research [67,68]. Following this, Whittingham's development of Li/TiS_2 in 1974 and Goodenough et al. discovery of LiCoO_2 (LCO) in 1979 paved the way for the development of the first LIB with an LCO cathode and carbonaceous anode in 1986 by Yoshino et al. [69]. This battery is based on the rocking chair principle derived from the movement of Li-ion during the charge and discharge processes. Since their commercialization, there has been a significant improvement in performance and a decrease in cost. Specifically, the specific energy has increased from 120 Wh/kg in 1991 [70] to more than 270 Wh/kg today [71,72]. In addition, the price per kW/h has reduced significantly from \$5000 in 1991 to \$101 per kW/h in 2021 [73]. The reduced cost and increased energy density revolutionized the market for consumer electronics.

This technology has recently revolutionized the automotive industry and grid storage, causing an unprecedented increase in demand that is expected to reach ~2–3.5 TWh by 2030 [74]. This high demand and the stricter technical requirements presented by these emerging applications pose new challenges for LIBs. For instance, electric vehicles require high-energy-density batteries to cover long-range, low-cost, and safe batteries, while the current state-of-the-art LIBs are characterized by low energy density, safety concerns, and high cost. Consequently, extensive research efforts are focused on developing the next generation of LIBs. All

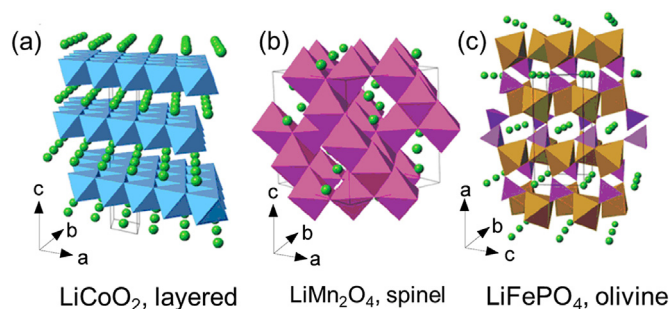


Fig. 2. The crystal structures of (a) layered cathode, (b) spinel cathode, and (c) olivine cathode. Adapted with permission from Ref. [66].

Table 1

Characteristics of some common Li-ion batteries.

Cathode	Specific Capacity (mAhg ⁻¹) (Theoretical/Experimental)	Volumetric capacity (mAh cm ⁻³) (Theoretical/Experimental)	Average Voltage (V)	Ref.
LiCoO ₂	273/145	1363/550	3.8	[27,62]
LiNi _{0.33} Mn _{0.33} Co _{0.33} O ₂	280/160	1333/600	3.7	[27]
LiNi _{0.8} Co _{0.15} Al _{0.05} O ₂	279/199	1284/700	3.7	[27,63]
LiMn ₂ O ₄	148/120	596	4.1	[64]
LiFePO ₄	170/165	589	3.4	[65]

solid-state lithium metal batteries (ASSBs), lithium-sulfur (Li-S), and lithium-air (Li-air) batteries are among the next-generation lithium batteries that are widely studied [75–77].

ASSBs use solid-state electrolytes instead of organic flammable liquid electrolytes used in conventional LIBs. This advancement mitigates safety concerns associated with conventional LIBs, enabling the use of lithium metal anodes with a high theoretical capacity of 3860 mAh/g, thereby facilitating the development of high-energy-density batteries [78]. Li-S batteries leverage the high specific capacity of lithium metal anodes, cost-effective and abundant sulfur cathodes. These characteristics make Li-S batteries highly promising for achieving high energy density and cost-effectiveness. Similarly, Li-air batteries exhibit remarkable improvements in energy density and significant cost reductions. However, these next-generation lithium batteries face challenges such as the high reactivity of lithium anodes, interfacial issues, and the formation of soluble polysulfides in Li-S [79–81].

In response to these challenges, researchers from both industry and academia are making significant efforts to develop solutions. Collectively, these efforts can potentially shape the future of lithium batteries and advance energy storage technology.

2.2. Ceramic fuel cells (CFCs)

CFCs are ceramic electrolytes-based energy conversion technologies that directly convert chemical energy from fuels such as hydrogen, methane, or other hydrocarbons into electrical energy with high efficiency and low emissions [29]. CFCs have witnessed various advancements over time [24,82–85]. The solid oxide fuel cells (SOFCs) of the first generation of CFCs utilize yttria-stabilized zirconia (YSZ) and operate at temperatures between 800 and 1000 °C [86–90]. Nonetheless, the high operating temperature of YSZ-based SOFCs presents significant technical challenges, such as component degradation, thermal cycling due to thermal mismatch, extended start-up and shutdown times, physical and chemical instability, and high maintenance costs [91–95]. In response to these challenges, developing CFCs that could operate at lower temperatures led to the emergence of protonic ceramic fuel cells (PCFCs) [96–100]. This section will discuss the basic principles of SOFCs and PCFCs, focusing on their essential components, functions, and associated challenges.

2.2.1. Basic principles of CFC

A typical CFC consists of three components: the electrolyte, the cathode, and the anode [101]. The ceramic electrolyte facilitates the conduction of either oxide ions (O²⁻) or protons (H⁺) between the anode and cathode, where electrochemical reactions occur [102,103]. The fuel, which may be hydrogen or a suitable hydrocarbon, is oxidized at the anode, releasing electrons that travel to the cathode through an external circuit [104,105]. At the cathode, electrons from the anode combine with oxygen to produce O²⁻ (for SOFCs, Fig. 3a) or H₂O (for PCFCs, Fig. 3b), depending on the type of electrolyte used [34,106–108]. This exothermic reaction produces useable heat for cogeneration [109].

2.2.2. Types and characteristics of state-of-the-art CFCs

The classification of fuel cells is based on the type and composition of their electrolyte material. CFCs can be further categorized into two main

types: oxide ion-conducting ceramic fuel cells (SOFCs) and proton-conducting ceramic fuel cells (PCFCs), as shown in Fig. 3 [111]. SOFCs use O²⁻ conducting electrolytes such as YSZ, which require high temperatures (800–1000 °C) to achieve adequate ionic conductivity and electrode kinetics. SOFCs could directly use various fuels, such as methane, ethanol, and syngas, without requiring external reforming [112–114]. However, high-temperature operation presents challenges such as thermal fatigue, component degradation, and material instability [115–118].

On the other hand, PCFCs use H⁺ conducting electrolytes, such as doped BaCeO₃, BaZrO₃, or BaCe_{1-x}Zr_xO₃ oxides, which enable high ionic conductivity with reasonable stability at lower temperatures (400–600 °C) compared to SOFCs [119–121]. The reduced operating temperature of PCFCs provides benefits such as decreased thermal stress, decreased component degradation, and improved material stability [20]. In addition, PCFCs exhibit low activation energies and avoid fuel dilution issues at the anode caused by water formation and electro-osmotic drag of O²⁻ observed in SOFCs [122–124]. However, PCFCs also encounter challenges, such as diminished cathode performance, due to reduced electrode kinetics at lower temperatures and low ionic transfer in the electrolyte, which may lead to potential power output limitations [43].

2.2.3. Advancements and challenges in CFC technology

CFCs, solid-ceramic electrolyte-based fuel cells, have several advantages over conventional thermal power plants, including efficiency, low emissions, and fuel flexibility [82,125]. However, they continue encountering significant technical and economic challenges that limit their widespread adoption and commercialization [125,126].

The high operation temperatures (typically above 600 °C) of CFCs, which require complex thermal management due to the degradation of the cell components, including the electrolytes and electrodes, are among the primary challenges associated with using CFCs [29]. Various strategies to reduce the operating temperatures of CFCs have been investigated [24,127–129]. These strategies include developing novel electrolyte materials with high ionic conductivity and low activation energy, optimizing the electrode materials and their microstructures, and enhancing all cell components' thermal stability and compatibility [24,127–129].

The cost reduction and scale-up of the technology is another challenge for CFCs [130]. Due to the high cost of ceramic components and system integration, the present cost of CFCs is still too high to compete with conventional power generation technologies [131]. Nevertheless, some strategies have been pursued to increase CFC production, including simplifying the fabrication processes, increasing the power density and output, reducing the complexity and size, and improving the mass manufacturing techniques [131–134].

Despite these challenges, CFCs have made significant progress in performance improvement, durability enhancement, cost reduction, and market penetration in recent years. Some examples of recent advances in CFC technology include.

- The development of the ceramic electrolyte material BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-δ}, which operates at lower temperatures (up to 450 °C) and has higher conductivity and stability than conventional doped Barium Cerate and Barium Zirconate based electrolyte materials [17,135].

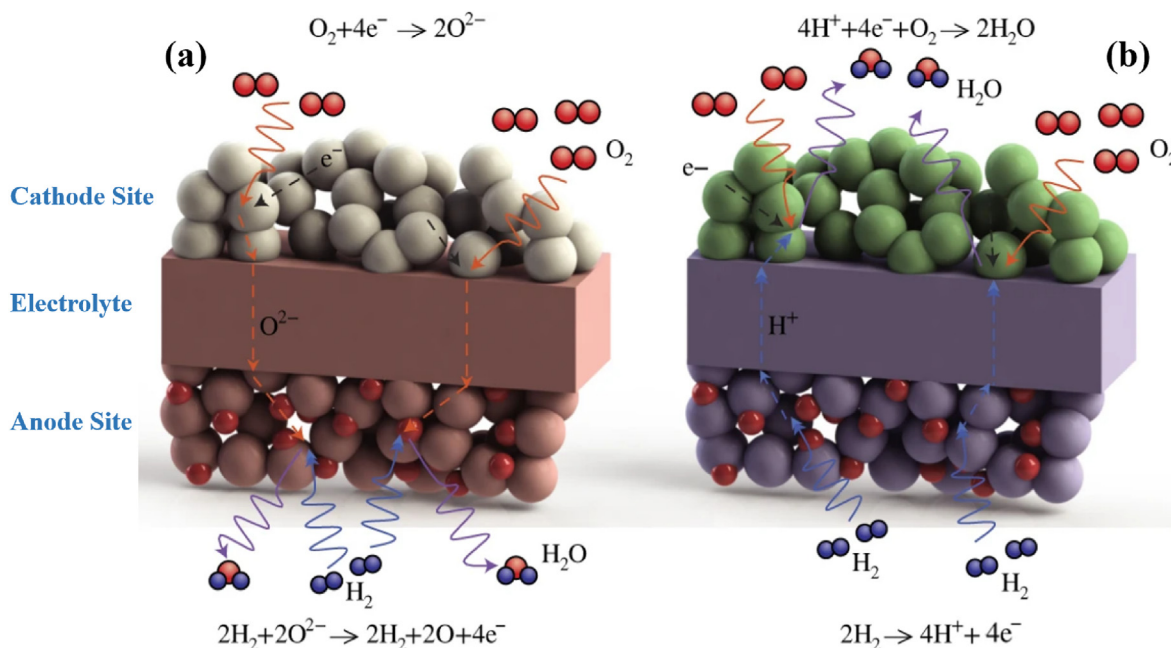


Fig. 3. Schematic illustrating the basic principle of operation of CFCs fed with H_2 fuel (a) SOFCs and (b) PCFCs. Copyright, Elsevier 2021 [25,110].

- (b) The demonstration of a grid-parallel CFC system (BlueGen, Fig. 4) that can generate up to 2 kW of electricity with an efficiency of 60 % and can also be used as a micro-combined heat and power generation system with an efficiency of up to 85 % [136].
- (c) The establishment of production facilities in the US, Australia, and Germany that can manufacture high-quality CFC units and components [136–138].

These developments suggest that CFC technology has great potential to revolutionize the energy industry by providing clean, efficient, and distributed power generation solutions. However, additional research and development must be conducted to address the remaining challenges to achieve wider acceptance and adoption of CFC technology.

3. Environmental benefits of adopting LIBs and CFCs for Africa's energy needs

Africa is the second-largest continent in the world, covering one-fifth of Earth's land area and hosting 54 countries (Fig. 5). The continent is divided by the Equator and surrounded by four oceans, resulting in various climates and environments (Fig. 6a) [139]. Africa is currently faced with the daunting challenge of meeting its growing energy demands while reducing the adverse environmental impacts of conventional fossil-based power sources (Fig. 5b) [140].

The IEA predicts that Africa's energy consumption will increase by 60 % by 2040 due to population growth, urbanization, and economic growth [140]. However, Africa's energy resources are diverse and unevenly distributed Fig. 6c. Oil is the most utilized energy source (~42 % of the total energy consumption), followed by gas (~28 %), coal (~22 %), hydro (~6 %), renewable energy (~1 %), and nuclear (~1 %) [4, 141]. Biomass (wood, charcoal, and dung) is the primary source of energy for cooking and heating for ~85 % of Africans [141,142]. Diesel generators are also widely used to supplement the intermittent grid supply or provide electricity in off-grid areas, accounting for 6 % of the total electricity generation in Africa [41,143]. The regional distribution of Africa's energy mix is summarized in Fig. 6c. Nevertheless, these conventional energy sources have significant environmental and health risks. Some of the negative side effects are described as follows.

- Greenhouse gas emissions (GHGs):** The combustion of fossil fuels and biomass are significant sources of GHG (CO_2 , CH_4 , and N_2O) and other pollutants (black carbon and organic carbon). These gases contribute to global warming, climate change, air pollution, and health problems. In 2019, Africa emitted ~1.3 billion tonnes of CO_2 , accounting for 3.6 % of the global total (Fig. 6b) [140]. Although Africa's emissions per capita are relatively low compared to other regions, they are expected to increase as the energy demand grows and more fossil fuel-based power plants are constructed (Fig. 6) [144].
- Air pollution:** Fossil fuels and biomass combustion produce harmful pollutants such as particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOCs), which degrade air quality and cause respiratory diseases, cardiovascular diseases, and premature deaths. According to the World Health Organization (WHO), ambient air pollution caused ~176,000 fatalities in Sub-Saharan Africa in 2012, while household air pollution from biomass burning caused ~490,000 deaths [145].
- Land degradation:** The extraction and use of fossil fuels and biomass can lead to land degradation through deforestation, soil erosion, water contamination, and biodiversity loss [146–148]. For instance, coal mining in South Africa has resulted in acid mine drainage, threatening human and ecological health by polluting the surface and groundwater resources [146]. Similarly, biomass harvesting in sub-Saharan Africa has led to deforestation, desertification, and a decline in soil fertility [147].
- Health risks:** Using fossil fuels and biomass can expose people to various health risks, such as fire accidents, explosions, poisoning, and electrocution [149,150]. For example, diesel generators can cause fire hazards due to fuel leakage or overheating, as well as noise pollution and vibrations that can affect hearing and mental health. Similarly, biomass use can cause burns, injuries, or carbon monoxide poisoning from smoke inhalation or exposure [149].

Advanced EECS technologies, including LIBs and CFCs, can provide a more eco-friendly and recyclable solution for Africa's future energy needs. The environmental advantages of LIBs and CFCs over conventional energy sources are discussed as follows.

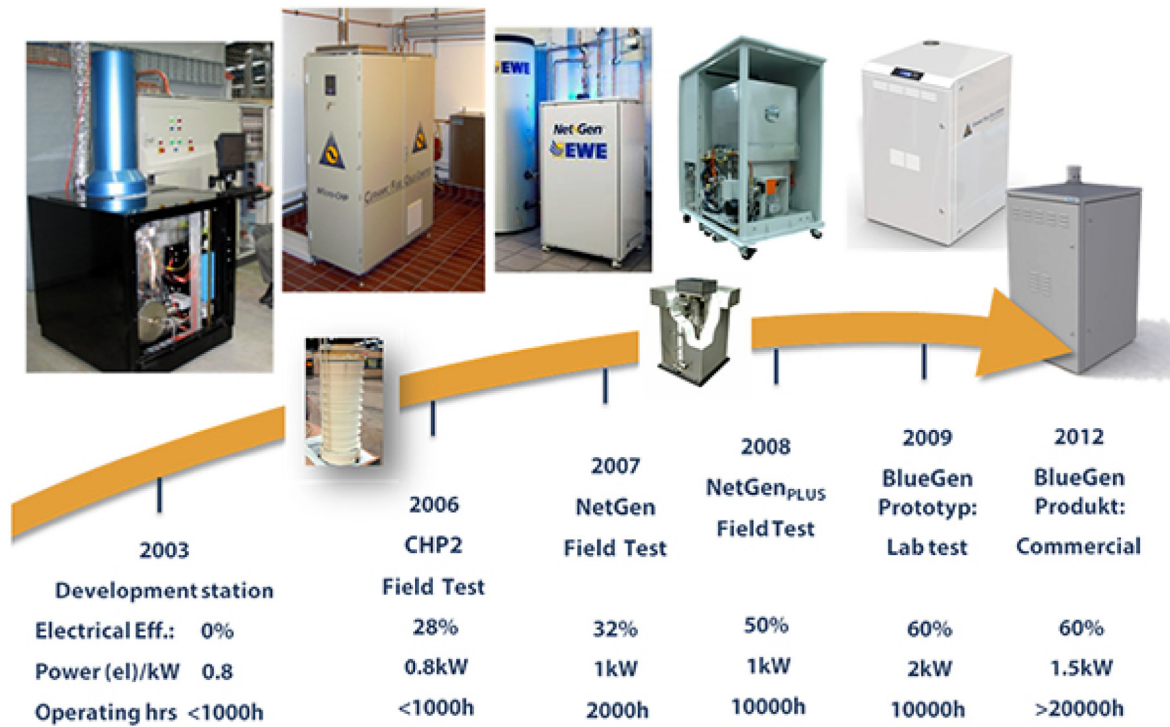


Fig. 4. Historical development trend for BlueGen CFC systems [136].

- Low emissions:** LIBs and CFCs emit negligible to zero GHG and air pollutants during operation. LIBs can store electrical energy from renewable sources, such as solar or wind power, without emitting CO₂ or other harmful byproducts [30]. CFCs convert chemical energy from hydrogen or other fuels into electricity and heat, with only water vapor as a byproduct [43,153]. Therefore, LIBs and CFCs can help reduce the carbon footprint and improve the air quality of Africa's power sector.
- High efficiency:** The energy storage and conversion efficiencies of LIBs and CFCs are superior to those of conventional power sources. The energy efficiency of LIBs is ~90 %, meaning that only 10 % of the stored energy is lost during charging or discharging [154]. The electrical efficiency of CFCs is ~50–60 % but could reach 80–90 % if residual heat is recovered for cogeneration [155]. Therefore, LIBs and CFCs can help save and reduce the energy losses in the power system in Africa.
- Long lifespan:** LIBs and CFCs possess a longer lifespan than conventional energy sources. LIBs can withstand 1000 cycles of charging or discharging before their capacity drops below 80 % [154]. CFCs can operate for up to 10 years before their performance significantly degrades [156,157]. Therefore, LIBs and CFCs can help extend the service life and reduce the cost of maintaining power equipment in Africa.

In addition, LIBs and CFCs have great potential for recycling and waste management, which can create opportunities for resource recovery and a circular economy in Africa. LIBs and CFCs contain valuable materials, such as lithium, cobalt, nickel, iron, cerium, and zirconium, which can be recovered and reused to manufacture new batteries, fuel cells, and other products [154,158–160]. Recycling LIBs and CFCs can also prevent the environmental and health risks associated with their disposal, such as contamination of soil and water, fire risks, and toxic exposure [161–163]. Table 2 summarizes the environmental characteristic features of the energy conversion and storage technologies relative to the conventional energy sources.

4. Adoption of lithium batteries and fuel cells in Africa – challenges and opportunities

In the global pursuit of a sustainable future, transformative technologies like Lithium-ion Batteries (LIBs) and Ceramic Fuel Cells (CFCs) are being rapidly adopted by leading nations such as the US and China. These countries are making significant investments in advancing these technologies, with the US funding research and start-ups [25,164], and China hosts major manufacturing facilities [24,165]. In contrast, Africa's adoption and development of LIBs and CFCs lag due to limited local production, manufacturing, and recycling capabilities [137,164,166].

The continent's reliance on imported energy technologies persists amidst underdeveloped policies, incentives, and infrastructure [164]. Moreover, the absence of formal recycling systems and the knowledge gap in waste management pose additional challenges [165]. However, the projected increase in demand for energy storage solutions in Africa signals a critical opportunity for domestic development [167]. Addressing the challenges of scaling up infrastructure is essential for meeting this demand and fostering economic growth and energy independence. By leveraging Africa's material resources and focusing on local manufacturing, Africa can not only transform its energy landscape but also create jobs and promote a circular economy. Strategic efforts must be made to overcome the initial challenges across the entire lifecycle of these technologies, from production to end-of-life recycling [40,167,168]. This will require collaborative efforts and a comprehensive approach involving investments, institutional backing, and technological innovation to establish an enabling environment for the widespread adoption of EECS technologies in Africa. Some of the scale-up challenges for EECS as addressed by Jolaoso et al. [169] are also applicable to Africa.

4.1. Challenges associated with adopting production and manufacturing

In establishing domestic production and manufacturing capabilities for LIBs and CFCs, Africa faces several hurdles, including a shortage of raw materials processing and refining capabilities. The continent has abundant mineral resources, such as lithium, cobalt, nickel, manganese,

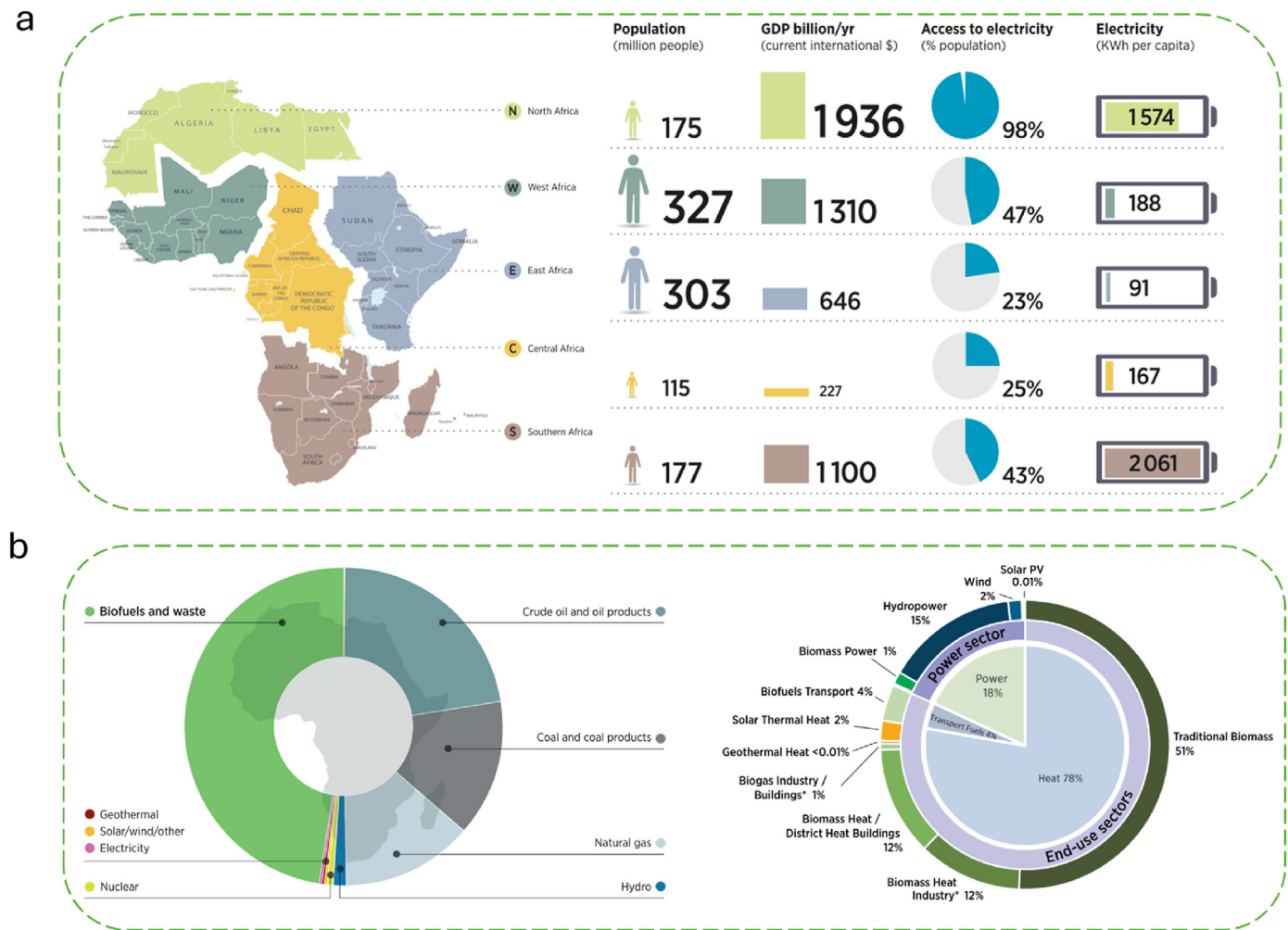


Fig. 5. (a) Africa's access to electricity distribution [10] (b) Primary energy supply and renewable energy use percentages in Africa based on IRENA and REmap 2030 reports [9,10].

and rare earth elements necessary for LIBs and CFCs [31,143,170,171]. However, most of these resources are exported as unprocessed ores or concentrates to other countries, mainly China, where they are refined and processed into battery-grade materials [172]. This means that Africa loses the value-added benefits of these resources and depends on imports of expensive battery materials. Hence, it is essential to establish local refining and chemical processing facilities to supply manufacturers with materials [173].

Another challenge is the high cost of setting up LIBs and CFCs manufacturing plants [174]. These plants require sophisticated equipment, infrastructure, and skilled labor, often scarce or unavailable in many African countries [175]. Moreover, they are expensive and complex, requiring long-term investments that companies may hesitate to commit to the perceived risks in Africa [174]. Importing equipment and machinery can also be prohibitively expensive for investors. Moreover, the technical complexity of CFC production and quality control necessitates substantial upfront investments. Hence, the limited access to capital and low market demand for energy storage and conversion technologies prevent investors from establishing large-scale local manufacturing [176].

Furthermore, Africa lacks sufficient technical knowledge and R&D support for these energy storage and conversion technologies [177]. The complex engineering and stringent quality standards require high technical expertise and innovation capacities. However, to conduct cutting-edge research on energy storage and conversion technologies in

Africa, only a few academic institutions, research centers, or industrial partners have the expertise and resources [4,5,142]. Consequently, most of the innovation and advancement in these technologies come from outside the continent, limiting opportunities for local adaptation and customization.

Finally, policy incentives and government support for domestic manufacturing remain insufficient across Africa [2,143,170,176,178]. Few or no fiscal incentives exist, such as tax holidays and export subsidies. Also uncommon are priority lending rates that facilitate access to affordable financing. Robust industrial policies fostering competitiveness and export-led growth are lagging. Additional precise regulations and standards regarding safety, performance, and environmental impact are required to provide manufacturers with certainty. Addressing these policy and regulatory gaps could stimulate private investment [178,179].

4.1.1. Challenges to deployment and integration

Even if production capacities are established, widespread deployment and integration of energy storage and conversion technologies into Africa's energy mix will face challenges [4,177]. The continent's underdeveloped energy storage and distribution infrastructure is one of these challenges [142]. The grid infrastructure is often unreliable, inefficient, or inadequate to meet the growing energy demand, especially in rural areas. Hence, the required modern electricity infrastructure, charging networks, pipelines, and storage terminals essential for integrating these technologies are lacking across Africa [4]. In addition, the lack of

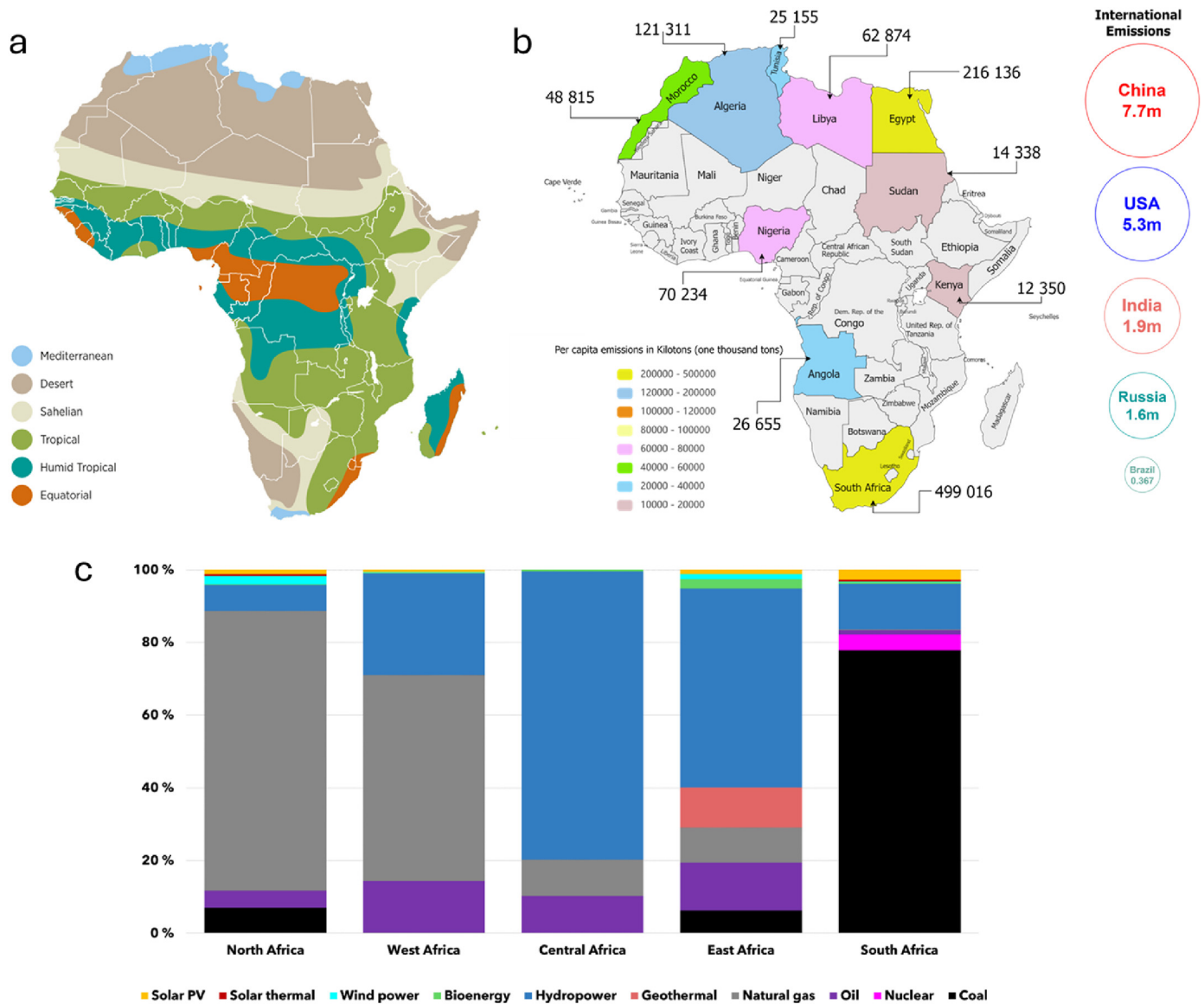


Fig. 6. (a) Map illustrating the distribution of diverse climate zones across Africa [151]. (b) Per capita emissions in selected African countries compared with notable international emissions [151]. (c) Chart showing the regional distribution of energy sources in Africa for the year 2020 [152].

Table 2
Environmental benefits of adopting EECs relative to conventional energy sources.

Energy Source	Emissions (g CO ₂ -eq/kWh)	Efficiency (%)	Lifespan (years)	Recycling Potential (%)	Ref.
Fossil Fuels	820	33	30–50	Low	[138,145,157]
Biomass	230	20–40	20–30	Low	[138,145,157]
LIBs	0 (during operation)	90	5–10	High (up to 95)	[157,158]
CFCs	0 (using hydrogen fuel)	50–60 (electrical), 80–90 (cogeneration)	10	High (up to 90)	[10,159]

interconnection between regions or countries limits the potential for transnational energy trade or sharing. Therefore, transmission and distribution modernization is a capital-intensive endeavor that needs to be undertaken.

In comparison to conventional energy sources such as fossil fuels or biomass, the high costs of these technologies remain relatively high. Even if petroleum savings can be realized, Africa's price-sensitive consumers are deterred by the initial high costs of emerging technologies. Therefore, cost competitiveness relative to existing technologies remains a significant barrier [176,180].

Africa's lack of widespread service and maintenance capabilities for

these technologies is another barrier [181,182]. To ensure optimal performance and safety, these technologies require regular inspection, testing, repair, or replacement. However, only a small number of trained technicians, spare parts suppliers, and service centers can provide these services in many African countries, especially in rural areas [181,182]. Hence, consumers may hesitate to implement these technologies if maintenance support is not guaranteed.

Finally, consumer awareness and understanding of emerging technologies such as LIBs and fuel cells remain low [183,184]. Many consumers or end-users are uninformed or unfamiliar with the benefits, features, and applications of LIBs or CFCs, which are some of the common

concerns about safety, complexity, or reliability [184]. There is a need for public education campaigns to enhance understanding of their economic and environmental benefits. In addition, credible demonstrations and partnerships with local installers can also foster consumer confidence and demand.

Even if Africa expands its manufacturing sector, it must parallelly invest in modernizing its energy infrastructure, regulations, technical training, and public education. To successfully implement transformative technologies such as LIBs and CFCs, a holistic view of production and the end-user experience is imperative. This strategy will create abundant opportunities for affordable, sustainable, and secure energy in Africa.

4.1.2. Challenges to end-of-life recycling

Recycling also presents significant hurdles to maximizing the sustainability benefits of LIBs and CFCs in Africa [170,185–188]. Firstly, many countries lack formal collection and management systems for e-waste [170]. It is common for hazardous battery and fuel cell waste to be dumped or burned without regulation, causing environmental and health risks [189,190]. It is essential to establish licensed waste operators and treatment facilities.

Secondly, the infrastructure and capabilities for the safe disassembly, dismantling, and processing of end-of-life products are limited [185, 191]. To recover the valuable elemental components of these advanced technologies, sophisticated recycling methods are required. However, in Africa, automated lines and integrated shredding, sorting, and refining capacities barely exist.

Significant knowledge gaps exist regarding the appropriate handling, storage, transport, and recovery of battery and fuel cell waste [170,192, 193]. There is a lack of technical skills for recycling, from collection crews to facility operators. Consequently, e-waste recycling research and training programs are imperative.

In Africa, recycling regulations and policies are inadequate or poorly enforced [140,142,176,178]. There are no clear standards for hazardous waste treatment, reporting, and licensing of facilities. Legislators must also define extended producer responsibility and recycling incentives. Robust frameworks that promote circularity are vital.

In summary, while lithium batteries and fuel cells have the potential to transform Africa's energy landscape, addressing end-of-life challenges is critical for sustainability. In tandem with adoption efforts, cultivating the expertise and infrastructure for safe, efficient recycling can unlock their maximum potential and create jobs. More work remains to address these recycling gaps.

4.2. Opportunities for overcoming the challenges

Africa's journey towards sustainable energy is fraught with challenges, yet it also presents numerous opportunities to foster the adoption of energy conversion and storage technologies. Measures are already in place to secure a sustainable future, with a notable commitment to renewable energy adoption. Table 3 summarizes supportive policies for the continent's electrification [10]. However, the path forward requires a nuanced understanding of Africa's diverse regional energy landscapes, as depicted in Fig. 6c.

Recognizing the continent's heterogeneity is crucial; strategies for implementing EECS technologies must be customized to fit the distinct contexts of each region [176]. Factors such as resource availability, existing infrastructure, and cultural nuances must be considered. Significant investment is needed to develop an EECS-friendly environment across various regions in Africa. A generic approach is less likely to succeed due to the substantial variance in challenges and opportunities across different areas.

Thus, fostering collaborative efforts among regional stakeholders, local communities, and experts is vital. Such partnerships are key to developing context-specific solutions that resonate with the unique needs and priorities of each region. Embracing this localized strategy enhances the chances of successful EECS technology adoption and integration,

ensuring that the solutions are not only effective but also culturally resonant and socially acceptable.

Government subsidies for renewable energy technologies are essential to encourage more players and investors. Another critical approach is the privatization of major technologies, with the government retaining a small stake. This strategy can enhance productivity and ensure adequate monitoring of technologies. In many parts of Africa, government businesses and entities often do not receive the attention and care required for optimal productivity. Therefore, the sustainable energy pathway should be led by private sector players and regulated by the government, given that most private companies in Africa tend to perform better than their government counterparts.

4.2.1. Opportunities for adopting production and manufacturing

- i. Localizing production by leveraging Africa's mineral resources can stimulate economic growth and create skilled jobs while reducing imports. Refining lithium, cobalt, nickel, and platinum group metals from African mineral reserves could provide manufacturers with raw materials and reduce costs [147,174,194].
- ii. With supportive policies such as tax breaks and subsidies, companies may invest in giga-factories to serve Africa's massive untapped market. Governments can facilitate joint ventures with foreign tech providers to facilitate the transfer of knowledge [140, 174,178].
- iii. Strengthening the R&D capacity and collaboration for LIBs and CFCs in Africa. To conduct cutting-edge research on LIBs and CFCs in Africa, it may be necessary to establish additional academic institutions, research centers, or industrial partners with the expertise and resources. It could also involve fostering regional or international cooperation and exchanging knowledge and best practices among researchers, innovators, or entrepreneurs in this field [185,187].
- iv. Providing affordable financing through development banks and funds that can absorb some risk can assist manufacturers in covering high initial capital investment for plants and equipment [177,191].

4.2.2. Opportunities for deployment and integration

- i. Improving Africa's energy storage and distribution infrastructure. This could involve expanding or upgrading the grid infrastructure to make it more reliable, efficient, or adequate to meet the growing energy demand. It could also involve increasing the interconnection between regions or countries to facilitate energy trade or sharing across-border [50].
- ii. Reducing the costs of LIBs and CFCs compared to conventional energy sources. This could involve improving the technological performance and efficiency of LIBs and CFCs to reduce operational costs. Standardizing products could also increase scope and reduce costs over time. It could also involve increasing competition and innovation in the energy conversion and storage market to reduce capital costs [176].
- iii. Enhancing the service and maintenance capabilities for LIBs and CFCs in Africa. This could entail training more technicians, spare parts suppliers, or service centers that can provide these services in many African countries. It could also involve developing remote monitoring or diagnostic systems to detect or prevent potential problems with LIBs or CFCs [4,195].
- iv. Increasing consumer awareness and adoption of LIBs and CFCs in Africa. This could involve conducting consumer education, information, or communication campaigns regarding the benefits, features, and applications of LIBs and CFCs [184]. Furthermore, it could address their misconceptions or concerns about safety, reliability, or environmental impacts. In addition, it could entail

Table 3

Policies implemented to promote sustainable energy realization in Africa, based on REN21 2015 [10]. These policies aim to address the continent's energy challenges while promoting renewable and sustainable energy sources. = Implemented.

	Regulatory Policies							Fiscal Incentives and Public Financing				
	Feed-in-tariff (incl. premium payment)	Electric utility quota obligation/RPS	Net metering	Tradable renewable energy certificate	Auctions	Heat Obligation/Mandate	Biofuel Obligation/Mandate	Capital Subsidy, grant, Or rebate	Investment Or production Tax credits	Reductions in Sales, CO ₂ , VAT, or other tax	Production payment	Public Investment Loans, or grants
Algeria	♥				♥				♥			
Angola							♥					♥
Benin										♥		
Botswana								♥		♥		
Burkina Faso					♥				♥	♥	♥	
Cabo Verde			♥		♥					♥	♥	
Cameroon										♥		
Côte d'Ivoire										♥		
Egypt			♥		♥					♥		
Ethiopia							♥	♥		♥		♥
Gambia										♥		
Ghana	♥	♥		♥		♥	♥			♥	♥	♥
Guinea								♥			♥	
Kenya	♥				♥	♥					♥	♥
Lesotho			♥		♥							♥
Libya											♥	
Madagascar											♥	
Malawi											♥	
Mali							♥				♥	
Mauritius	♥							♥				♥
Morocco					♥							♥
Mozambique					♥		♥					
Niger											♥	♥
Rwanda	♥										♥	
Senegal		♥				♥					♥	♥
South Africa		♥	♥		♥		♥	♥			♥	
Sudan							♥					
Tanzania	♥				♥		♥				♥	
Togo											♥	
Tunisia			♥					♥			♥	♥
Uganda	♥							♥			♥	♥
Zambia							♥	♥			♥	
Zimbabwe							♥					

engaging with local communities or stakeholders to foster trust, acceptability, or preference for these technologies.

- v. Offering micro-loans and pay-as-you-go models for consumer financing makes adoption more affordable. Partnerships with mobile money providers facilitate access expansion [4,142].
- vi. Prioritizing equitable access and distribution to ensure that the benefits of these technologies are not concentrated in wealthier urban areas, further exacerbating existing inequalities in energy access. Targeted efforts and policies should be implemented to facilitate the deployment of LIBs and CFCs in rural and underserved areas, where energy poverty is often more prevalent. This could involve exploring decentralized and off-grid solutions, providing subsidies or financing mechanisms for low-income communities, and engaging local stakeholders to ensure that the deployment aligns with their needs and priorities [9,10,152].
- vii. Meaningful involvement of local communities, civil society organizations, and marginalized groups is essential to ensure that energy policies and investments align with the needs and priorities of the people they affect. Engaging with these stakeholders through consultations, workshops, and collaborative platforms can help identify potential barriers, address concerns, and co-create solutions that are culturally appropriate and socially acceptable. This inclusive approach can foster a sense of ownership, increase public acceptance, and ultimately contribute to the successful deployment and integration of EECS technologies in Africa [196,197].

4.2.3. Opportunities for recycling

- i. Establishing appropriate collection and disposal systems for spent LIBs or CFCs in many African countries. This could involve establishing formal mechanisms or incentives to encourage consumers or businesses to return their used batteries or fuel cells to authorized recyclers or collectors. It could also involve raising awareness of the environmental hazards associated with improper disposal of these technologies [185,186].
- ii. Developing adequate LIBs or CFCs recycling facilities or technologies in Africa. This may involve investing in additional facilities or businesses with the capacity or capability to recover valuable materials or components from spent LIBs or CFCs. It could also entail adopting advanced or sustainable methods such as pyrometallurgy, hydrometallurgy, or biometallurgy, which result in higher recovery rates and better quality of recycled materials while minimizing the health and safety risks to workers and the environment [170,192,193].
- iii. Developing regulatory frameworks or standards for regulating LIBs or CFCs recycling in Africa. This could include enacting laws, policies, or guidelines that define the roles and responsibilities of different stakeholders in the recycling process, such as producers, importers, distributors, consumers, collectors, recyclers, or regulators. It could also include establishing quality or safety standards or certifications for recycled materials and products. This could increase recycling chain transparency, accountability, or traceability, preventing fraud, corruption, and illegal activities [170, 192,193].

Finally, while EECS technologies offer numerous benefits, it is crucial to acknowledge and address their potential risks and unintended consequences. The production and disposal of batteries and fuel cells can have significant environmental impacts, such as resource depletion, water and air pollution, and hazardous waste generation. However, previous studies have shown that EECS technologies are more climate-friendly compared to the majority of other energy-generating systems, making them a viable choice for the continent [198,199].

Furthermore, the widespread adoption of these technologies may disrupt traditional energy sectors, leading to potential job losses and

social implications for communities reliant on these industries. A comprehensive transition strategy must consider and mitigate these risks through robust environmental regulations, waste management systems, and social support programs. Addressing these issues is essential to ensure the sustainability and long-term viability of EECS technologies in Africa. Failure to do so could undermine the benefits and progress achieved through the adoption of these advanced energy technologies.

5. Summary and outlook

In conclusion, the imperative for all Africans to have access to clean, affordable, and reliable energy is clear. The continent's increasing energy demands present a pivotal opportunity to move beyond fossil fuel dependency and towards the adoption of sustainable technologies. Lithium-ion batteries (LIBs) and ceramic fuel cells (CFCs) are promising for this transition, offering a host of benefits over traditional power sources, including efficiency, cost-effectiveness, safety, and environmental friendliness. Their modular nature also allows for decentralized and off-grid solutions, essential for rural electrification.

Africa's abundant renewable resources, such as solar and wind power, make it an ideal candidate for large-scale deployment of batteries and fuel cells. The integration of these technologies with renewable energy sources is key to accelerating the electrification process and achieving a sustainable energy future.

However, it is imperative to acknowledge that technology alone cannot solve Africa's complex energy challenges, which are rooted in political, institutional, and economic factors. A holistic approach that prioritizes equity, sustainability, and local empowerment is necessary to address these challenges effectively. This approach informs our strategy to tackle the continent's interconnected challenges in manufacturing, infrastructure, education, and recycling. With supportive policies, strategic investments, and partnerships, Africa can leverage these technologies to transform its energy landscape.

The path to a sustainable energy future in Africa involves collaboration among policymakers, industry, civil society, and researchers. The social and economic benefits for African populations are substantial, making this effort both necessary and urgent. If widely adopted, batteries and fuel cells powered by renewable energy can alleviate energy poverty, stimulate economic growth, reduce pollution, and position Africa as a leader in clean technology. The future holds as many opportunities as challenges, and now is the time for Africa to embrace innovation and collaboration for a cleaner, more electrified, and prosperous future. The prospects for Africa's energy sector are bright if it can capitalize on these advancements and partnerships.

CRediT authorship contribution statement

Idris Bello: Writing – original draft. Lateef Jolaoso: Writing, review, and editing. Ridwan Ahmed: Writing, review and editing. Abdulhakeem Bello: Supervision, review, and editing.

Declaration of competing interest

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

Acknowledgments

We are grateful to the African University of Science and Technology and the Centre for Advances in Reliability and Safety (CAIRS), Hong Kong SAR, China, admitted under AIR@InnoHK Research Cluster, for supporting this work.

References

- [1] M. Ritchie, Roser Hannah, Fossil fuels; our world in data, our world in data. <https://ourworldindata.org/fossil-fuels>, 2018. (Accessed 2 April 2023).
- [2] Africa: Electricity Access by Region, Statista, 2020. <https://www.statista.com/statistics/1278291/share-of-population-with-electricity-access-in-africa-by-region/>. (Accessed 12 June 2023).
- [3] BP, Statistical review of world energy 2021, BP statistical review of world, Energy (2021). <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf>. (Accessed 12 June 2023).
- [4] Key findings – Africa Energy Outlook 2022 – Analysis - IEA, (n.d.). <https://www.iea.org/reports/africa-energy-outlook-2022/key-findings> (accessed June 12, 2023).
- [5] Outlook for energy demand – World Energy Outlook 2022 – Analysis - IEA, (n.d.). <https://www.iea.org/reports/world-energy-outlook-2022/outlook-for-energy-demand> (accessed June 12, 2023).
- [6] Scenario trajectories and temperature outcomes – World Energy Outlook 2021 – Analysis IEA. <https://www.iea.org/reports/world-energy-outlook-2021/scenario-trajectories-and-temperature-outcomes> (accessed June 12, 2023).
- [7] Unfccc, ADOPTION OF THE PARIS AGREEMENT - Paris Agreement Text English, (n.d.).
- [8] I. Sognnaes, A. Gambhir, D.J. van de Ven, A. Nikas, A. Anger-Kraavi, H. Bui, L. Campagnolo, E. Delpiazzo, H. Doukas, S. Giarola, N. Grant, A. Hawkes, A.C. Köberle, A. Kolpakov, S. Mittal, J. Moreno, S. Perdana, J. Rogelj, M. Vielle, G.P. Peters, A multi-model analysis of long-term emissions and warming implications of current mitigation efforts, *Nat. Clim. Change* 11 (2021) 1055–1062, <https://doi.org/10.1038/s41558-021-01206-3>.
- [9] International Renewable Energy Agency (IRENA), Remap 2030: Summary of Findings, January 2014 (n.d.), www.irena.org/remap.
- [10] IRENA, A renewable energy Roadmap report, irena, 173, www.irena.org/remap, 2014.
- [11] G. Notton, M.-L. Nivet, C. Voyant, C. Paoli, C. Darras, F. Motte, A. Fouilloy, Intermittent and stochastic character of renewable energy sources: consequences, cost of intermittence and benefit of forecasting, *Renew. Sustain. Energy Rev.* 87 (2018) 96–105, <https://doi.org/10.1016/j.rser.2018.02.007>.
- [12] A.K. Aliyu, B. Modu, C.W. Tan, A review of renewable energy development in Africa: a focus in South Africa, Egypt and Nigeria, *Renew. Sustain. Energy Rev.* 81 (2018), <https://doi.org/10.1016/j.rser.2017.06.055>.
- [13] D. Banks, J. Schäffler, The potential contribution of renewable energy in South Africa, *Sustainable Energy & Climate Change Project (SECCP) Johannesburg* (2005), South Africa.
- [14] The International Trade Administration, Electricity and Renewable Energy, 2022.
- [15] R.A.-P., S.B. Maxine Chikumbo, Closing Nigeria's Power and Green Skills Gaps: A Pathway to Increased Energy Access, RMI.ORG, 2023.
- [16] Ajuri Ngelale, My Government Is Set to Make Nigeria the Solar Panel and EV Battery Manufacturing Hub of Africa – President Tinubu, 2024.
- [17] I.T. Bello, S. Zhai, Q. He, C. Cheng, Y. Dai, B. Chen, Y. Zhang, M. Ni, Materials development and prospective for protonic ceramic fuel cells, *Int. J. Energy Res.* 46 (2022) 2212–2240, <https://doi.org/10.1002/er.7371>.
- [18] I.T. Bello, R. Taiwo, O.C. Esan, A. Habeeb Adegoke, A. Olanrewaju Ijaola, Z. Li, S. Zhao, C. Wang, Z. Shao, M. Ni, AI-enabled materials discovery for advanced ceramic electrochemical cells, *Energy and AI* 15 (2024) 100317, <https://doi.org/10.1016/j.egyai.2023.100317>.
- [19] Q. Liu, Z. Pan, E. Wang, L. An, G. Sun, Aqueous metal-air batteries: fundamentals and applications, *Energy Storage Mater.* 27 (2020) 478–505, <https://doi.org/10.1016/j.ensm.2019.12.011>.
- [20] I.T. Bello, D. Guan, N. Yu, Z. Li, Y. Song, X. Chen, S. Zhao, Q. He, Z. Shao, M. Ni, Revolutionizing material design for protonic ceramic fuel cells: bridging the limitations of conventional experimental screening and machine learning methods, *Chem. Eng. J.* 477 (2023), <https://doi.org/10.1016/j.cej.2023.147098>.
- [21] S. Zhao, Y. Zuo, T. Liu, S. Zhai, Y. Dai, Z. Guo, Y. Wang, Q. He, L. Xia, C. Zhi, J. Bae, K. Wang, M. Ni, Multi-Functional hydrogels for flexible zinc-based batteries working under extreme conditions, *Adv. Energy Mater.* 11 (2021) 1–29, <https://doi.org/10.1002/aenm.202101749>.
- [22] L.A. Jolaoso, I.T. Bello, O.A. Ojelade, A. Yousuf, C. Duan, P. Kazempoor, Operational and scaling-up barriers of SOEC and mitigation strategies to boost H₂ production- a comprehensive review, *Int. J. Hydrogen Energy* 48 (2023) 33017–33041, <https://doi.org/10.1016/J.IJHYDENE.2023.05.077>.
- [23] C.P. Grey, D.S. Hall, Prospects for lithium-ion batteries and beyond—a 2030 vision, *Nat. Commun.* 11 (1 11) (2020) 1–4, <https://doi.org/10.1038/s41467-020-19991-4>, 2020.
- [24] I.T. Bello, S. Zhai, Q. He, Q. Xu, M. Ni, Scientometric review of advancements in the development of high-performance cathode for low and intermediate temperature solid oxide fuel cells: three decades in retrospect, *Int. J. Hydrogen Energy* 46 (2021) 26518–26536, <https://doi.org/10.1016/j.ijhydene.2021.05.134>.
- [25] I.T. Bello, S. Zhai, S. Zhao, Z. Li, N. Yu, M. Ni, Scientometric review of proton-conducting solid oxide fuel cells, *Int. J. Hydrogen Energy* 46 (2021) 37406–37428, <https://doi.org/10.1016/j.ijhydene.2021.09.061>.
- [26] D. Deng, Li-ion batteries: basics, progress, and challenges, *Energy Sci. Eng.* 3 (2015) 385–418, <https://doi.org/10.1002/ese3.95>.
- [27] N. Nitta, F. Wu, J.T. Lee, G. Yushin, Li-ion battery materials: present and future, *Mater. Today* 18 (2015) 252–264, <https://doi.org/10.1016/j.mattod.2014.10.040>.
- [28] J. Suntivich, H.A. Gasteiger, N. Yabuuchi, H. Nakanishi, J.B. Goodenough, Y. Shao-Horn, Design principles for oxygen-reduction activity on perovskite oxide catalysts for fuel cells and metal–air batteries, *Nat. Chem.* 3 (2011) 546–550, <https://doi.org/10.1038/nchem.1069>.
- [29] Q. Xu, Z. Guo, L. Xia, Q. He, Z. Li, I. Temitope, K. Zheng, M. Ni, I. Temitope Bello, K. Zheng, M. Ni, A comprehensive review of solid oxide fuel cells operating on various promising alternative fuels, *Energy Convers. Manag.* 253 (2022) 115175, <https://doi.org/10.1016/j.enconman.2021.115175>.
- [30] A greener future: Lithium-ion batteries and Hydrogen fuel cells | CAS, (n.d.). <https://www.cas.org/resources/cas-insights/sustainability/lithium-batteries-hydrogen-fuel-cells> (accessed June 12, 2023).
- [31] The Lithium Landscape in Africa: Promising Developments and Future Outlook, (n.d.). <https://www.energycapitalpower.com/lithium-africa-developments-future-outlook/> (accessed June 12, 2023).
- [32] Y. Lyu, X. Wu, K. Wang, Z. Feng, T. Cheng, Y. Liu, M. Wang, R. Chen, L. Xu, J. Zhou, Y. Lu, B. Guo, An overview on the advances of LiCoO₂ cathodes for lithium-ion batteries, *Adv. Energy Mater.* 11 (2021) 2000982, <https://doi.org/10.1002/aenm.202000982>.
- [33] A.J. Jacobson, Materials for solid oxide fuel cells, *Chem. Mater.* 22 (2010) 660–674, <https://doi.org/10.1021/cm902640j>.
- [34] I.T. Bello, N. Yu, S. Zhai, Y. Song, S. Zhao, C. Cheng, Z. Zhang, M. Ni, Effect of engineered lattice contraction and expansion on the performance and CO₂ tolerance of Ba_{0.5}Sr_{0.5}Co_{0.7}Fe_{0.3}O_{3-δ} functional material for intermediate temperature solid oxide fuel cells, *Ceram. Int.* 48 (2022) 21457–21468, <https://doi.org/10.1016/j.ceramint.2022.04.110>.
- [35] D. Noel Buckley, C. O'Dwyer, N. Quill, R.P. Lynch, Electrochemical Energy Storage, The Royal Society of Chemistry, 2018, <https://doi.org/10.1039/9781788015530-00115>.
- [36] F. Xie, J. Xu, Q. Liao, Q. Zhang, B. Liu, L. Shao, J. Cai, X. Shi, Z. Sun, C.-P. Wong, Progress in niobium-based oxides as anode for fast-charging Li-ion batteries, *Energy Rev.* 2 (2023) 100027, <https://doi.org/10.1016/J.ENREV.2023.100027>.
- [37] Y. Yang, Z. Wu, J. Yao, T. Guo, F. Yang, Z. Zhang, J. Ren, L. Jiang, B. Li, An overview of application-oriented multifunctional large-scale stationary battery and hydrogen hybrid energy storage system, *Energy Rev.* (2024) 100068, <https://doi.org/10.1016/J.ENREV.2024.100068>.
- [38] X. Liu, Y. Zeng, W. Yuan, G. Zhang, H. Zheng, Z. Chen, Advances in multi-scale design and fabrication processes for thick electrodes in lithium-ion batteries, *Energy Rev.* 3 (2024) 100066, <https://doi.org/10.1016/J.ENREV.2023.100066>.
- [39] L. Yan, L. Jiang, C. Qian, S. Zhou, Electrocatalytic conversion of methane: recent progress and future prospects, *Energy Rev.* 3 (2024) 100065, <https://doi.org/10.1016/J.ENREV.2023.100065>.
- [40] B. Diouf, R. Pöde, Potential of lithium-ion batteries in renewable energy, *Renew. Energy* 76 (2015) 375–380, <https://doi.org/10.1016/j.renene.2014.11.058>.
- [41] I. Renewable Energy Agency, K. Development Bank, D. Gesellschaft für Internationale Zusammenarbeit, The Renewable Energy Transition in Africa Powering Access, Resilience and Prosperity on Behalf of the, (n.d.).
- [42] J. Kim, S. Sengodan, S. Kim, O. Kwon, Y. Bu, G. Kim, Proton conducting oxides: a review of materials and applications for renewable energy conversion and storage, *Renew. Sustain. Energy Rev.* 109 (2019) 606–618, <https://doi.org/10.1016/j.rser.2019.04.042>.
- [43] M. Ni, Z. Shao, Fuel cells that operate at 300° to 500°C, *Science* (1979) 369 (2020) 138 LP – 139, <https://doi.org/10.1126/science.abc9136>.
- [44] M. Zhao, B.Q. Li, X.Q. Zhang, J.Q. Huang, Q. Zhang, A perspective toward practical lithium-sulfur batteries, *ACS Cent. Sci.* 6 (2020) 1095–1104, <https://doi.org/10.1021/acscentsci.0c00449>.
- [45] A. Manthiram, A reflection on lithium-ion battery cathode chemistry, *Nat. Commun.* 11 (2020) 1–9, <https://doi.org/10.1038/s41467-020-15355-0>.
- [46] C. Liao, Fundamentals of rechargeable lithium ion and beyond lithium ion batteries, *Batteries* (2021), <https://doi.org/10.1088/978-0-7503-2682-7ch1>.
- [47] T. Kim, W. Song, D.Y. Son, L.K. Ono, Y. Qi, Lithium-ion batteries: outlook on present, future, and hybridized technologies, *J Mater Chem A Mater* 7 (2019) 2942–2964, <https://doi.org/10.1039/C8TA10513H>.
- [48] Y. Chen, Y. Kang, Y. Zhao, L. Wang, J. Liu, Y. Li, Z. Liang, X. He, X. Li, N. Tavajohi, B. Li, A Review of Lithium-Ion Battery Safety Concerns : the Issues , Strategies , and Testing Standards, vol. 59, 2021, pp. 83–99.
- [49] A. Masias, J. Marcicki, W.A. Paxton, Opportunities and challenges of lithium ion batteries in automotive applications, *ACS Energy Lett.* 6 (2021) 621–630, <https://doi.org/10.1021/acsenrgylett.0c02584>.
- [50] Y. Huang, J. Li, Key challenges for grid-scale lithium-ion battery energy storage, *Adv. Energy Mater.* 12 (2022) 2202197, <https://doi.org/10.1002/aenm.202202197>.
- [51] A. Manthiram, An outlook on lithium ion battery technology, *ACS Cent. Sci.* 3 (2017) 1063–1069, <https://doi.org/10.1021/acscentsci.7b00288>.
- [52] P.A.R.D. Jayatilaka, M.A.K.L. Dissanayake, I. Albinsson, B.E. Mellander, Effect of nano-porous Al₂O₃ on thermal, dielectric and transport properties of the (PEO)₉LiTFSI polymer electrolyte system, *Electrochim. Acta* 47 (2002) 3257–3268, [https://doi.org/10.1016/S0013-4686\(02\)00243-8](https://doi.org/10.1016/S0013-4686(02)00243-8).
- [53] G. Homann, L. Stolz, J. Nair, I.C. Laskovic, M. Winter, J. Kasnatscheew, Poly(Ethylene oxide)-based electrolyte for solid-state-lithium-batteries with high voltage positive electrodes: evaluating the role of electrolyte oxidation in rapid cell failure, *Sci. Rep.* 10 (2020) 2–10, <https://doi.org/10.1038/s41598-020-61373-9>.
- [54] R.A. Ahmed, N. Ebechidi, I. Reisa, K. Orisekeh, A. Huda, A. Bello, O.K. Oyewole, W.O. Soboyejo, Pressure-induced interfacial contacts and the deformation in all solid-state Li-ion batteries, *J. Power Sources* 521 (2022) 230939, <https://doi.org/10.1016/J.JPOWSOUR.2021.230939>.
- [55] C. Liao, Fundamentals of rechargeable lithium ion and beyond lithium ion batteries, *Batteries* (2021), <https://doi.org/10.1088/978-0-7503-2682-7ch1>.

- [56] A. Manthiram, A reflection on lithium-ion battery cathode chemistry, *Nat. Commun.* 11 (2020) 1–9, <https://doi.org/10.1038/s41467-020-15355-0>.
- [57] A. Du Pasquier, I. Plitz, S. Menocal, G. Amatucci, A comparative study of Li-ion battery, supercapacitor and nonaqueous asymmetric hybrid devices for automotive applications, *J. Power Sources* 115 (2003) 171–178, [https://doi.org/10.1016/S0378-7753\(02\)00718-8](https://doi.org/10.1016/S0378-7753(02)00718-8).
- [58] L. Azhari, B. Sousa, R. Ahmed, R. Wang, Z. Yang, G. Gao, Y. Han, Y. Wang, Stability enhancement and microstructural modification of Ni-rich cathodes via halide doping, *ACS Appl. Mater. Interfaces* 14 (2022) 46523–46536, https://doi.org/10.1021/ACSAMI.2C11773/ASSET/IMAGES/LARGE/AM2C11773_0011.JPEG.
- [59] J.U. Choi, N. Voronina, Y.K. Sun, S.T. Myung, Recent progress and perspective of advanced high-energy Co-less Ni-rich cathodes for Li-ion batteries: yesterday, today, and tomorrow, *Adv. Energy Mater.* 10 (2020), <https://doi.org/10.1002/AENM.202002027>.
- [60] K.M. Shaju, P.G. Bruce, Macroporous $\text{Li}(\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3})\text{O}_2$: a high-power and high-energy cathode for rechargeable lithium batteries, *Adv. Mater.* 18 (2006) 2330–2334, <https://doi.org/10.1002/ADMA.200600958>.
- [61] P. Selinis, Review-A review on the anode and cathode materials for lithium-ion batteries with improved subzero temperature performance, <https://doi.org/10.1149/1945-7111/ac49cc>, 2022.
- [62] J. Cho, Y.W. Kim, B. Kim, J.G. Lee, B. Park, A breakthrough in the safety of lithium secondary batteries by coating the cathode material with AlPO_4 nanoparticles, *Angew. Chem., Int. Ed.* 42 (2003) 1618–1621, <https://doi.org/10.1002/anie.200250452>.
- [63] S.K. Martha, O. Haik, E. Zinigrad, I. Exnar, T. Drezen, J.H. Miners, D. Aurbach, On the thermal stability of olivine cathode materials for lithium-ion batteries, *J. Electrochem. Soc.* 158 (2011) A1115, <https://doi.org/10.1149/1.3622849/XML>.
- [64] M.J. Lee, S. Lee, P. Oh, Y. Kim, J. Cho, High performance LiMn_2O_4 cathode materials grown with epitaxial layered nanostructure for Li-ion batteries, *Nano Lett.* 14 (2014) 993–999, <https://doi.org/10.1021/nl404430e>.
- [65] A. Yamada, S.C. Chung, K. Hinokuma, Optimized LiFePO_4 for lithium battery cathodes, *J. Electrochem. Soc.* 148 (2001) A224, <https://doi.org/10.1149/1.1348257>.
- [66] C.M. Julien, A. Mauger, K. Zaghib, H. Groult, Comparative issues of cathode materials for Li-ion batteries, *INORGA* 2 (2014) 132–154, <https://doi.org/10.3390/INORGANICS2010132>.
- [67] G.E. Blomgren, The development and future of lithium ion batteries, *J. Electrochem. Soc.* 164 (2017) A5019, <https://doi.org/10.1149/2.0251701jes>.
- [68] J.M. Tarascon, M. Armand, Issues and challenges facing rechargeable lithium batteries, *Nature* 414 (2001) 359–367, <https://doi.org/10.1038/35104644>, 2001.
- [69] A. Yoshino, The birth of the lithium-ion battery, *Angew. Chem.* 51 (2012) 5798–5800, <https://doi.org/10.1002/anie.201105006>.
- [70] S.T. Mayer, J.H. Feikert, J.L. Kaschmitter, Testing and Evaluation of Lithium-Ion, Lawrence Livermore National Laboratory under Contract, 1992. No. W-7405-ENG-48.
- [71] J.T. Frith, M.J. Lacey, U. Ulissi, A non-academic perspective on the future of lithium-based batteries, *Nat. Commun.* 14 (2023), <https://doi.org/10.1038/s41467-023-35933-2>.
- [72] T. Waldmann, R.G. Scurtu, K. Richter, M. Wohlfahrt-Mehrens, 18650 vs. 21700 Li-ion cells – a direct comparison of electrochemical, thermal, and geometrical properties, *J. Power Sources* 472 (2020) 228614, <https://doi.org/10.1016/j.jpowsour.2020.228614>.
- [73] M.S. Ziegler, J.E. Trancik, Re-examining rates of lithium-ion battery technology improvement and cost decline, *Energy Environ. Sci.* 14 (2021) 1635–1651, <https://doi.org/10.1039/d0ee02681f>.
- [74] Global EV Outlook 2022 – Analysis - IEA, (n.d.). <https://www.iea.org/reports/global-ev-outlook-2022> (accessed July 16, 2023).
- [75] R. Zettl, L. De Kort, M. Gombotz, H.M.R. Wilkening, P.E. De Jongh, P. Ngene, Combined effects of anion substitution and nanoconfinement on the ionic conductivity of Li-based complex hydrides, *J. Phys. Chem. C* 124 (2020) 2806–2816, <https://doi.org/10.1021/acs.jpcc.9b10607>.
- [76] M. Zhao, B.Q. Li, X.Q. Zhang, J.Q. Huang, Q. Zhang, A perspective toward practical lithium-sulfur batteries, *ACS Cent. Sci.* 6 (2020) 1095–1104, <https://doi.org/10.1021/acscentsci.0c00449>.
- [77] N. Ebechidi, R. Ahmed, O. Oyewole, A. Bello, P. Ngene, W. Soboyejo, Charge-discharge-induced local strain distributions in a lithium amide-borohydride-iodide $[\text{LiBH}_4\text{-LiNH}_2\text{-LiI}]$ solid electrolyte, *J. Energy Storage* 47 (2022) 103600, <https://doi.org/10.1016/J.EST.2021.103600>.
- [78] T. Yu, X. Yang, R. Yang, X. Bai, G. Xu, S. Zhao, Y. Duan, Y. Wu, J. Wang, Progress and perspectives on typical inorganic solid-state electrolytes, *J. Alloys Compd.* 885 (2021) 161013, <https://doi.org/10.1016/J.JALLCOM.2021.161013>.
- [79] Y. Rao, J. Yang, S. Chu, S. Guo, Solid - State Li - Air Batteries : Fundamentals , Challenges , and Strategies, *SmartMat*, 2023, p. e1205, <https://doi.org/10.1002/smm2.1205>.
- [80] M. Zhao, B.Q. Li, X.Q. Zhang, J.Q. Huang, Q. Zhang, A perspective toward practical lithium-sulfur batteries, *ACS Cent. Sci.* 6 (2020) 1095–1104, <https://doi.org/10.1021/acscentsci.0c00449>.
- [81] R.A. Ahmed, N. Ebechidi, I. Reisiya, K. Orisekeh, A. Huda, A. Bello, O.K. Oyewole, W.O. Soboyejo, Pressure-induced interfacial contacts and the deformation in all solid-state Li-ion batteries, *J. Power Sources* 521 (2022) 230939, <https://doi.org/10.1016/J.JPOWSOUR.2021.230939>.
- [82] M. Rafique, H. Nawaz, M. Shahid Rafique, M. Bilal Tahir, G. Nabi, N.R. Khalid, Material and method selection for efficient solid oxide fuel cell anode: recent advancements and reviews, *Int. J. Energy Res.* 43 (2019) 2423–2446, <https://doi.org/10.1002/er.4210>.
- [83] I.Y. Wuni, G.Q.P. Shen, R. Osei-Kyei, Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018, *Energy Build.* 190 (2019) 69–85, <https://doi.org/10.1016/j.enbuild.2019.02.010>.
- [84] K. Chen, S.P. Jiang, Review—materials degradation of solid oxide electrolysis cells, *J. Electrochem. Soc.* 163 (2016) F3070–F3083, <https://doi.org/10.1149/2.0101611jes>.
- [85] E.V. Tsipis, V.V. Kharton, Electrode materials and reaction mechanisms in solid oxide fuel cells: a brief review. III. Recent trends and selected methodological aspects, *J. Solid State Electrochem.* 15 (2011) 1007–1040, <https://doi.org/10.1007/s10008-011-1341-8>.
- [86] R. Campana, A. Larrea, J.A. Kilner, V.M. Orera, Performance and aging of microtubular YSZ-based solid oxide regenerative fuel cells, *Fuel Cell.* 11 (2011) 116–123, <https://doi.org/10.1002/fuce.201000069>.
- [87] Z.L. Moreno Botello, A. Montenegro, N. Grimaldos Osorio, M. Huvé, C. Pirovano, D.R. Småbråten, S.M. Selbach, A. Caneiro, P. Roussel, G.H. Gauthier, Pure and Zr-doped YmO_{3-x} as a YSZ-compatible SOFC cathode: a combined computational and experimental approach, *J. Mater. Chem. A Mater* 7 (2019) 18589–18602, <https://doi.org/10.1039/c9ta04912f>.
- [88] M. Jafari, H. Salamati, M. Zhiani, E. Shahsavari, Enhancement of an IT-SOFC cathode by introducing YSZ: electrical and electrochemical properties of $\text{La}_{0.6}\text{Ca}_{0.4}\text{Fe}_{0.8}\text{Ni}_{0.2}\text{O}_{3-\delta}$ -YSZ composites, *Int. J. Hydrogen Energy* 44 (2019) 1953–1966, <https://doi.org/10.1016/j.ijhydene.2018.10.151>.
- [89] A. Hauch, S.H. Jensen, J.B. Bilde-Sørensen, M. Mogensen, Silica segregation in the Ni/YSZ electrode, *J. Electrochem. Soc.* 154 (2007) A619, <https://doi.org/10.1149/1.2733861>.
- [90] T. Norby, M. Hartmanová, Electrical conductivity and ionic transport number of YSZ and Cr-doped YSZ single crystals at 200–1000°C, *Solid State Ionics* 67 (1993) 57–64, [https://doi.org/10.1016/0167-2738\(93\)90309-Q](https://doi.org/10.1016/0167-2738(93)90309-Q).
- [91] T. Matsui, J.E. Soc, T. Matsui, R. Kishida, J. Kim, H. Muroyama, K. Eguchi, Performance deterioration of Ni – YSZ anode induced by electrochemically generated steam in solid oxide fuel cells performance deterioration of Ni – YSZ anode induced by electrochemically generated steam in solid oxide fuel cells, *J. Electrochem. Soc.* 157 (2010), <https://doi.org/10.1149/1.3336830>.
- [92] B. Song, E. Ruiz-Trejo, A. Bertei, N.P. Brandon, Quantification of the degradation of Ni-YSZ anodes upon redox cycling, *J. Power Sources* 374 (2018) 61–68, <https://doi.org/10.1016/j.jpowsour.2017.11.024>.
- [93] M. Mori, Mechanisms of thermal expansion and shrinkage of $\text{La}_{0.8}\text{Sr}_{0.2}\text{MnO}_{3+\delta}$ perovskites with different densities during thermal cycling in air, *J. Electrochem. Soc.* 152 (2005) A732, <https://doi.org/10.1149/1.1864312>.
- [94] H. Hayashi, T. Saitou, N. Maruyama, H. Inaba, K. Kawamura, M. Mori, Thermal expansion coefficient of yttria stabilized zirconia for various yttria contents, *Solid State Ionics* 176 (2005) 613–619, <https://doi.org/10.1016/j.ssi.2004.08.021>.
- [95] S. Vaidya, J.H. Kim, Finite element thermal stress analysis of solid oxide fuel cell cathode microstructures, *J. Power Sources* 225 (2013) 269–276, <https://doi.org/10.1016/j.jpowsour.2012.10.054>.
- [96] K. Thabet, A. Le Gal La Salle, E. Quarez, O. Joubert, Protonic-based Ceramics for Fuel Cells and Electrolyzers, *INC*, 2020, <https://doi.org/10.1016/b978-0-12-818285-7.00004-6>.
- [97] E.C.S. Transactions, *Electrodes for Protonic Ceramic Electrolysis Cells*, 2021, pp. 2–16.
- [98] T. Yajima, H. Suzuki, T. Yogo, H. Iwahara, Protonic conduction in SrZrO_3 -based oxides, *Solid State Ionics* 51 (1992) 101–107, [https://doi.org/10.1016/0167-2738\(92\)90351-O](https://doi.org/10.1016/0167-2738(92)90351-O).
- [99] J. Cao, Y. Ji, Z. Shao, Perovskites for protonic ceramic fuel cells: a review, *Energy Environ. Sci.* 15 (2022) 2200–2232, <https://doi.org/10.1039/D2EE00132B>.
- [100] E.K. Shin, M. Shin, H. Lee, J.S. Park, Catalysts for composite cathodes of protonic ceramic fuel cells, *Ceram. Int.* 44 (2018) 8423–8426, <https://doi.org/10.1016/j.ceramint.2018.02.036>.
- [101] S. Revankar, P. Majumdar, *FUEL CELLS: Principles, Design and Analysis*, first ed., CRC Press, 2014.
- [102] A. Dubois, *Protonic Ceramic Fuel Cells: Design Analysis from Cells to Systems*, PhD, Colorado School of Mines, 2019.
- [103] N. Wang, C. Tang, L. Du, R. Zhu, L. Xing, Z. Song, B. Yuan, L. Zhao, Y. Aoki, S. Ye, Advanced cathode materials for protonic ceramic fuel cells: recent progress and future perspectives, *Adv. Energy Mater.* 12 (2022) 2201882 1–220188229, <https://doi.org/10.1002/aenm.202201882>.
- [104] W. Wang, J. Qu, P.S.B. Juliao, Z. Shao, Recent advances in the development of anode materials for solid oxide fuel cells utilizing liquid oxygenated hydrocarbon fuels: a mini review, *Energy Technol.* 7 (2019) 33–44, <https://doi.org/10.1002/ente.201700738>.
- [105] R.J. Kee, H. Zhu, D.G. Goodwin, Solid-oxide fuel cells with hydrocarbon fuels, *Proc. Combust. Inst.* 30 II (2005) 2379–2404, <https://doi.org/10.1016/j.proci.2004.08.277>.
- [106] J. Richter, P. Holtappels, T. Graule, T. Nakamura, L.J. Gauckler, Materials design for perovskite SOFC cathodes, *Monatsh. Chem.* 140 (2009) 985–999, <https://doi.org/10.1007/s00706-009-0153-3>.
- [107] E. Fabbri, S. Licoccia, E. Traversa, E.D. Wachsman, Composite cathodes for proton conducting electrolytes, *Fuel Cell.* 9 (2009) 128–138, <https://doi.org/10.1002/fuce.200800126>.
- [108] J.M. Vohs, R.J. Gorte, High-performance SOFC cathodes prepared by infiltration, *Adv. Mater.* 21 (2009) 943–956, <https://doi.org/10.1002/adma.200802428>.
- [109] S. Biswas, A.P. Kulkarni, S. Giddey, S. Bhattacharya, A review on synthesis of methane as a pathway for renewable energy storage with a focus on solid oxide

- electrolytic cell-based processes, *Front. Energy Res.* 8 (2020), <https://doi.org/10.3389/fenrg.2020.570112>.
- [110] J.H. Shim, Ceramics breakthrough, *Nat. Energy* 3 (2018) 168–169, <https://doi.org/10.1038/s41560-018-0110-7>.
- [111] I.T. Bello, Y. Song, N. Yu, Z. Li, S. Zhao, A. Maradesa, T. Liu, Z. Shao, M. Ni, Evaluation of the electrocatalytic performance of a novel nanocomposite cathode material for ceramic fuel cells, *J. Power Sources* 560 (2023) 232722, <https://doi.org/10.1016/j.jpowsour.2023.232722>.
- [112] N. Bausá, S. Escolástico, J.M. Serra, Direct CO₂ conversion to syngas in a BaCe_{0.2}Zr_{0.7}Y_{0.1}O_{3-δ}-based proton-conducting electrolysis cell, *J. CO₂ Util.* 34 (2019) 231–238, <https://doi.org/10.1016/j.jcou.2019.05.037>.
- [113] M.C. Steil, S.D. Nobrega, S. Georges, P. Gelin, S. Uhlenbruck, F.C. Fonseca, Durable direct ethanol anode-supported solid oxide fuel cell, *Appl. Energy* 199 (2017) 180–186, <https://doi.org/10.1016/j.apenergy.2017.04.086>.
- [114] M.D. Mat, X. Liu, Z. Zhu, B. Zhu, Development of cathodes for methanol and ethanol fuelled low temperature (300–600 °C) solid oxide fuel cells, *Int. J. Hydrogen Energy* 32 (2007) 796–801, <https://doi.org/10.1016/j.ijhydene.2006.12.012>.
- [115] J. Laurencin, G. Delette, F. Lefebvre-Joud, M. Dupeux, A numerical tool to estimate SOFC mechanical degradation: case of the planar cell configuration, *J. Eur. Ceram. Soc.* 28 (2008) 1857–1869, <https://doi.org/10.1016/j.jeurceramsoc.2007.12.025>.
- [116] P. Sr, C. Fe, M. Choi, S.J. Kim, W. Lee, Effects of water atmosphere on chemical degradation of, *Ceram. Int.* 47 (2021) 7790–7797, <https://doi.org/10.1016/j.ceramint.2020.11.124>.
- [117] M. Choi, S.J. Kim, W. Lee, Effects of water atmosphere on chemical degradation of PrBa_{0.5}Sr_{0.5}Co_{1.5}Fe_{0.5}O_{5+δ} electrodes, *Ceram. Int.* 47 (2021) 7790–7797, <https://doi.org/10.1016/j.ceramint.2020.11.124>.
- [118] M.S. Khan, X. Xu, R. Knibbe, Z. Zhu, Air electrodes and related degradation mechanisms in solid oxide electrolysis and reversible solid oxide cells, *Renewable and Sustainable Ener. Rev.* E. 143 (2021) 110918, <https://doi.org/10.1016/j.rser.2021.110918>.
- [119] Yu.G. Lyagaeva, D.A. Medvedev, A.K. Demin, P. Tsiakaras, O.G. Reznitskikh, Thermal expansion of materials in the barium cerate-zirconate system, *Phys. Solid State* 57 (2015) 285–289, <https://doi.org/10.1134/S1063783415020250>.
- [120] X. Yang, L. Jia, B. Pan, B. Chi, J. Pu, J. Li, Mechanism of proton conduction in doped barium cerates: a first-principles study, *J. Phys. Chem. C* 124 (2020) 8024–8033, <https://doi.org/10.1021/acs.jpcc.0c01284>.
- [121] R.C.T. Slade, N. Singh, Systematic examination of hydrogen ion conduction in rare-earth doped barium cerate ceramics, *Solid State Ionics* 46 (1991) 111–115, [https://doi.org/10.1016/0167-2738\(91\)90137-Z](https://doi.org/10.1016/0167-2738(91)90137-Z).
- [122] Q. Li, J.O. Jensen, R.F. Savinell, N.J. Bjerrum, High temperature proton exchange membranes based on polybenzimidazoles for fuel cells, *Prog. Polym. Sci.* 34 (2009) 449–477, <https://doi.org/10.1016/j.progpolymsci.2008.12.003>.
- [123] I.T. Bello, N. Yu, Y. Song, J. Wang, T. Chan, S. Zhao, Z. Li, Y. Dai, J. Yu, M. Ni, Electrokinetic insights into the triple ionic and electronic conductivity of a novel nanocomposite functional material for protonic ceramic fuel cells, *Small* 18 (2022) 2203207, <https://doi.org/10.1002/sml.202203207>.
- [124] A. Seong, J. Kim, D. Jeong, S. Sengodan, M. Liu, S. Choi, G. Kim, Electrokinetic Proton Transport in Triple (H⁺/O²⁻/e⁻) Conducting Oxides as a Key Descriptor for Highly Efficient Protonic Ceramic Fuel Cells, *Adv. Sci.* 8 (2021) 1–6, <https://doi.org/10.1002/adv.202004099>.
- [125] E. Fabbri, D. Pergolesi, E. Traversa, Materials challenges toward proton-conducting oxide fuel cells: a critical review, *Chem. Soc. Rev.* 39 (2010) 4355–4369, <https://doi.org/10.1039/b902343g>.
- [126] C. Duan, J. Huang, N. Sullivan, R. O'Hayre, Proton-conducting oxides for energy conversion and storage, *Appl. Phys. Rev.* 7 (2020) 011314, <https://doi.org/10.1063/1.5135319>.
- [127] P. Boldrin, E. Ruiz-Tejro, J. Mermelstein, J.M. Bermúdez Menéndez, T. Ramírez Reina, N.P. Brandon, Strategies for carbon and sulfur tolerant solid oxide fuel cell materials, incorporating lessons from heterogeneous catalysis, *Chem. Rev.* 116 (2016) 13633–13684, <https://doi.org/10.1021/acs.chemrev.6b00284>.
- [128] D.A. Medvedev, J.G. Lyagaeva, E.V. Gorbova, A.K. Demin, P. Tsiakaras, Advanced materials for SOFC application: strategies for the development of highly conductive and stable solid oxide proton electrolytes, *Prog. Mater. Sci.* 75 (2016) 38–79, <https://doi.org/10.1016/j.pmatsci.2015.08.001>.
- [129] M. Bilal Hanif, M. Motola, S. qayyum, S. Rauf, A. khalid, C.J. Li, C.X. Li, Recent advancements, doping strategies and the future perspective of perovskite-based solid oxide fuel cells for energy conversion, *Chem. Eng. J.* 428 (2022) 132603, <https://doi.org/10.1016/j.cej.2021.132603>.
- [130] L.Q. Le, C.H. Hernandez, M.H. Rodriguez, L. Zhu, C. Duan, H. Ding, R.P. O'Hayre, N.P. Sullivan, Proton-conducting ceramic fuel cells: scale up and stack integration, *J. Power Sources* 482 (2021) 228868, <https://doi.org/10.1016/j.jpowsour.2020.228868>.
- [131] J. Tong, D. Clark, M. Hoban, R. O'Hayre, Cost-effective solid-state reactive sintering method for high conductivity proton conducting yttrium-doped barium zirconium ceramics, *Solid State Ionics* 181 (2010) 496–503, <https://doi.org/10.1016/j.ssi.2010.02.008>.
- [132] D. Chen, C. Chen, Z.M. Baiyee, Z. Shao, F. Ciucci, Nonstoichiometric oxides as low-cost and highly-efficient oxygen reduction/evolution catalysts for low-temperature electrochemical devices, *Chem. Rev.* 115 (2015) 9869–9921, <https://doi.org/10.1021/acs.chemrev.5b00073>.
- [133] A. Dubois, S. Ricote, R.J. Braun, Benchmarking the expected stack manufacturing cost of next generation, intermediate-temperature protonic ceramic fuel cells with solid oxide fuel cell technology, *J. Power Sources* 369 (2017) 65–77, <https://doi.org/10.1016/j.jpowsour.2017.09.024>.
- [134] A. Dubois, S. Ricote, R.J. Braun, Comparing the expected stack cost of next generation intermediate temperature protonic ceramic fuel cells with solid oxide fuel cell technology, *ECS Trans.* 78 (2017) 1963–1972, <https://doi.org/10.1149/07801.1963ecst>.
- [135] L. Yang, S. Wang, K. Blinn, M. Liu, Z. Liu, Z. Cheng, M. Liu, Enhanced sulfur and coking tolerance of a mixed ion conductor for SOFCs: BaZr_{0.1}Ce_{0.7}Y_{0.2-δ}Yb_δO_{3-δ}, *Science* 326 (2009) 126–129, <https://doi.org/10.1126/science.1174811>, 1979.
- [136] Solid Oxide Fuel Cell Technology – CSIROpedia, (n.d.). <https://csiropedia.csiro.au/Ceramic-Fuel-Cells/> (accessed June 20, 2023).
- [137] Global Solid Oxide Fuel Cells (SOFCs) Markets, 2021–2027 -, (n.d.). <https://www.globenewswire.com/en/news-release/2021/08/16/2281028/28124/en/Global-Solid-Oxide-Fuel-Cells-SOFCs-Markets-2021-2027-Planar-SOFC-Remains-the-Dominant-SOFC-Technology-in-the-Market.html> (accessed June 20, 2023).
- [138] Cummins takes leadership role in promising fuel cell technology | Cummins Inc., (n.d.). <https://www.cummins.com/news/2020/11/01/cummins-takes-leadership-role-promising-fuel-cell-technology> (accessed June 20, 2023).
- [139] Africa | History, People, Countries, Regions, Map, & Facts | Britannica, (n.d.). <https://www.britannica.com/place/Africa> (accessed July 3, 2023).
- [140] F.V. Bekun, A.A. Alola, B.A. Gyamfi, A.B. Ampomah, The environmental aspects of conventional and clean energy policy in sub-Saharan Africa: is N-shaped hypothesis valid? *Environ. Sci. Pollut. Control Ser.* 28 (2021) 66695–66708, <https://doi.org/10.1007/S11356-021-14758-W/TABLES/8>.
- [141] UNEP, Atlas of Africa Energy Resources, United Nations Environment Programme 36 (2017) 399, <https://doi.org/10.2307/2610110>, 399.
- [142] Africa Energy Outlook 2022 – Analysis - IEA, (n.d.). <https://www.iea.org/reports/africa-energy-outlook-2022> (accessed July 3, 2023).
- [143] The Renewable Energy Transition in Africa, (n.d.). <https://www.irena.org/publications/2021/March/The-Renewable-Energy-Transition-in-Africa> (accessed July 3, 2023).
- [144] J.K. Balch, R.C. Nagy, S. Archibald, D.M.J.S. Bowman, M.A. Moritz, C.I. Roos, A.C. Scott, G.J. Williamson, Global combustion: the connection between fossil fuel and biomass burning emissions (1997–2010), *Phil. Trans. Biol. Sci.* 371 (2016), <https://doi.org/10.1098/RSTB.2015.0177>.
- [145] A.K. Amegah, S. Agyei-Mensah, Urban air pollution in sub-saharan Africa: time for action, *Environ. Pollut.* 220 (2017) 738–743, <https://doi.org/10.1016/j.envpol.2016.09.042>.
- [146] S. Mxinwa, E.D. Deenanath, S.W. Robertson, S. Ndlovu, P. Basson, The application of coal discards for acid mine drainage neutralization, *J. South Afr. Inst. Min. Metall.* 120 (2020) 531–540, <https://doi.org/10.17159/2411-9717/527/2020>.
- [147] J. Fairhead, I. Scoones, Local knowledge and the social shaping of soil investments: critical perspectives on the assessment of soil degradation in Africa, *Land Use Pol.* 22 (2005) 33–41, <https://doi.org/10.1016/J.LANDUSEPOL.2003.08.004>.
- [148] H.K. Jeswani, A. Chilvers, A. Azapagic, Environmental sustainability of biofuels: a review, *Proceedings of the Royal Society A* (2020) 476, <https://doi.org/10.1098/RSPA.2020.0351>.
- [149] J.J. Buonocore, P. Salimifard, D.R. Michanowicz, J.G. Allen, A decade of the U.S. energy mix transitioning away from coal: historical reconstruction of the reductions in the public health burden of energy, *Environ. Res. Lett.* 16 (2021), <https://doi.org/10.1088/1748-9326/ABE74C>.
- [150] K. Vohra, A. Vodonos, J. Schwartz, E.A. Marais, M.P. Sulprizio, L.J. Mickley, Global mortality from outdoor fine particulate pollution generated by fossil fuel combustion: results from GEOS-Chem, *Environ. Res.* 195 (2021), <https://doi.org/10.1016/j.envres.2021.110754>.
- [151] Sub-Saharan Africa | Total including LUCF | Greenhouse Gas (GHG) Emissions | Climate Watch, (n.d.). https://www.climatewatchdata.org/ghg-emissions?en_d_year=2020®ions=SSA&start_year=1990 (accessed July 3, 2023).
- [152] A.S. Oyewo, S. Sterl, S. Khalili, C. Breyer, Highly renewable energy systems in Africa: rationale, research, and recommendations, *Joule* 7 (2023) 1437–1470, <https://doi.org/10.1016/j.joule.2023.06.004>.
- [153] M. Li, M. Ni, F. Su, C. Xia, Proton conducting intermediate-temperature solid oxide fuel cells using new perovskite type cathodes, *J. Power Sources* 260 (2014) 197–204, <https://doi.org/10.1016/j.jpowsour.2014.03.013>.
- [154] C.P. Grey, D.S. Hall, Prospects for lithium-ion batteries and beyond—a 2030 vision, *Nat. Commun.* 11 (2020) 1–4, <https://doi.org/10.1038/s41467-020-19991-4>.
- [155] I.T. Bello, S. Zhai, Q. He, C. Cheng, Y. Dai, B. Chen, Y. Zhang, M. Ni, Materials development and prospective for protonic ceramic fuel cells, *Int. J. Energy Res.* (2021) 1–29, <https://doi.org/10.1002/er.7371>.
- [156] Bloom Energy Server unveiled, Bloom Box not for the home just yet, *Mobile Magazine* (2010). <http://www.mobilemag.com/2010/02/25/bloom-energy-server-unveiled-bloom-box-not-for-the-home-just-yet>. (Accessed 3 July 2023).
- [157] Bloom Box, What is it and how does it work? *Christ Sci. Mon.* (2010). <http://www.csmonitor.com/USA/Society/2010/0222/Bloom-Box-What-is-it-and-how-does-it-work>. (Accessed 3 July 2023).
- [158] L.-N. Xia, J. You, Z.-P. He, X.-W. Huang, Y. Yu, Performances of nickel-doped SmBa_{0.2}Co_{0.8}Sm_{0.2}O_{3-δ} composite cathodes for IT-SOFC, *Int. J. Hydrogen Energy* 41 (2016) 1176–1186, <https://doi.org/10.1016/j.ijhydene.2015.10.027>.
- [159] Z. Li, M. Peng, Y. Zhao, J. Li, Y. Sun, cobalt-based perovskite air electrodes for, 20299–20308, <https://doi.org/10.1039/d1nr06845h>, 2021.
- [160] F. Zhou, Y. Liu, X. Zhao, W. Tang, S. Yang, S. Zhong, M. Wei, Effects of cerium doping on the performance of LSCF cathodes for intermediate temperature solid oxide fuel cells, *Int. J. Hydrogen Energy* 43 (2018) 18946–18954, <https://doi.org/10.1016/J.IJHYDENE.2018.08.041>.

- [161] H. Pinegar, Y.R. Smith, Recycling of end-of-life lithium ion batteries, Part I: commercial processes, *Journal of Sustainable Metallurgy* 5 (2019) 402–416, <https://doi.org/10.1007/S40831-019-00235-9/FIGURES/8>.
- [162] W. Mroziak, M.A. Rajaeifar, O. Heidrich, P. Christensen, Environmental impacts, pollution sources and pathways of spent lithium-ion batteries, *Energy Environ. Sci.* 14 (2021) 6099–6121, <https://doi.org/10.1039/D1EE00691F>.
- [163] P. Boldrin, N.P. Brandon, Progress and outlook for solid oxide fuel cells for transportation applications, *Nat. Catal.* 2 (2019) 571–577, <https://doi.org/10.1038/s41929-019-0310-y>.
- [164] US DOE, Advanced Battery R&D Consortium, 2023. <https://www.energy.gov/articles/biden-harris-administration-announces-192-million-advance-battery-recycling-technology>.
- [165] Global market share of lithium ion battery makers as of Q1 2022. <https://www.statista.com/statistics/235323/lithium-batteries-top-manufacturers/>, 2023. (Accessed 16 July 2023).
- [166] B. Jan, Achieving clean energy access in sub-Saharan Africa A case study for the OECD, UN Environment, World Bank project: “Financing Climate Futures: Rethinking Infrastructure,” (n.d.). <https://impactalpha.com/solar-mini-grid-project-pipeline-comes-into-focus-in-africa-asia-and-latin-america/> (accessed July 22, 2023).
- [167] F. Moreno-Brieva, C. Merino, African international trade in the global value chain of lithium batteries, *Mitig. Adapt. Strategies Glob. Change* 25 (2020) 1031–1052, <https://doi.org/10.1007/S11027-020-09911-8/TABLES/5>.
- [168] W. Mroziak, M.A. Rajaeifar, O. Heidrich, P. Christensen, Environmental impacts, pollution sources and pathways of spent lithium-ion batteries, *Energy Environ. Sci.* 14 (2021) 6099–6121, <https://doi.org/10.1039/D1EE00691F>.
- [169] L.A. Jolaoso, I.T. Bello, O.A. Ojelade, A. Yousuf, C. Duan, P. Kazempoor, Operational and scaling-up barriers of SOEC and mitigation strategies to boost H₂ production: a comprehensive review, *Int. J. Hydrogen Energy* 48 (2023), <https://doi.org/10.1016/j.ijhydene.2023.05.077>.
- [170] K.A. Asante, Y. Amoyaw-Osei, T. Agusa, E-waste recycling in Africa: risks and opportunities, *Curr. Opin. Green Sustainable Chem.* 18 (2019) 109–117, <https://doi.org/10.1016/j.cogsc.2019.04.001>.
- [171] Executive summary – The Role of Critical Minerals in Clean Energy Transitions – Analysis - IEA, (n.d.). <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary> (accessed July 22, 2023).
- [172] China-US battle for African influence shifts to green critical minerals | South China Morning Post., (n.d.). <https://www.scmp.com/news/china/diplomacy/article/3216457/china-us-battle-african-influence-shifts-green-critical-minerals> (accessed July 22, 2023).
- [173] K. Goodenough, E. Dedy, R. Shaw, Lithium resources, and their potential to support battery supply chains, in Africa, (n.d.). British Geological Survey, 21pp. <https://nora.nerc.ac.uk/id/eprint/530698>.
- [174] A. Gelb, V. Ramachandran, C.J. Meyer, D. Wadhwa, K. Navis, Can sub-saharan Africa Be a manufacturing destination? Labor costs, price levels, and the role of industrial policy, *J. Ind. Compet. Trade* 20 (2020) 335–357, <https://doi.org/10.1007/S10842-019-00331-2/TABLES/6>.
- [175] D. Chung, E. Elqvist, S. Santhanagopalan, Automotive lithium-ion cell manufacturing: regional cost structures and supply chain considerations. www.nrel.gov/publications, 2016. (Accessed 22 July 2023).
- [176] Financing Options Key to Africa's Transition to Sustainable Energy > Press releases | World Economic Forum, (n.d.). <https://www.weforum.org/press/2021/09/financing-options-key-to-africa-s-transition-to-sustainable-energy> (accessed July 22, 2023).
- [177] World Bank Group Provides \$465 Million to Expand Energy Access and Renewable Energy Integration in West Africa, (n.d.). <https://www.worldbank.org/en/news/press-release/2021/06/10/world-bank-group-provides-465-million-to-expand-energy-access-and-renewable-energy-integration-in-west-africa> (accessed July 22, 2023).
- [178] L. Rushby, LibGuides: South African Government Policy: Library Guide: Waste management, (n.d.). <https://libguides.lib.uct.ac.za/c.php?g=194637&p=1395733> (accessed July 3, 2023).
- [179] Africa Waste Management Outlook International Environmental Technology Centre, (n.d.). <https://www.unep.org/ietc/resources/publication/africa-waste-management-outlook> (accessed July 3, 2023).
- [180] Africa: Refiners call for investment in storage, distribution infrastructure, (n.d.). <https://www.vanguardngr.com/2021/05/africa-refiners-call-for-investment-in-storage-distribution-infrastructure/> (accessed July 22, 2023).
- [181] Service providers appointed for Eskom battery energy storage initiative | SAnews, (n.d.). <https://www.sanews.gov.za/south-africa/service-providers-appointed-eskom-battery-energy-storage-initiative> (accessed July 22, 2023).
- [182] Eskom appoints service providers for its battery energy storage project - Eskom, (n.d.). <https://www.eskom.co.za/eskom-appoints-service-providers-for-its-battery-energy-storage-project/> (accessed July 22, 2023).
- [183] The world's biggest hydrogen fuel cell EV has started work in South Africa | Ars Technica, (n.d.). <https://arstechnica.com/cars/2022/05/the-worlds-biggest-hydrogen-fuel-cell-ev-started-work-in-south-africa/> (accessed July 22, 2023).
- [184] T. Carmichael, Potential consumer perceptions of hydrogen fuel cell vehicles in South Africa Consumer perceptions of hydrogen fuel cell vehicles in SA View project, (n.d.). <https://doi.org/10.13140/RG.2.2.12269.03049>.
- [185] Z.J. Baum, R.E. Bird, X. Yu, J. Ma, Lithium-ion battery Recycling—Overview of techniques and trends, *ACS Energy Lett.* 7 (2022) 712–719, https://doi.org/10.1021/ACSENERGYLETT.1C02602/ASSET/IMAGES/LARGE/NZ1C02602_0005.JPEG.
- [186] B. Swain, Recovery and recycling of lithium: a review, *Sep. Purif. Technol.* 172 (2017) 388–403, <https://doi.org/10.1016/j.seppur.2016.08.031>.
- [187] R. Bird, Z.J. Baum, X. Yu, J. Ma, The regulatory environment for lithium-ion battery recycling, *ACS Energy Lett.* 7 (2022) 736–740, <https://doi.org/10.1021/ACSENERGYLETT.1C02724>.
- [188] V. Eveloy, Anode fuel and steam recycling for internal methane reforming SOFCs: analysis of carbon deposition, *J. Fuel Cell Sci. Technol.* 8 (2011) 1–8, <https://doi.org/10.1115/1.4002230>.
- [189] A. Mayyas, D. Steward, M. Mann, The case for recycling: overview and challenges in the material supply chain for automotive li-ion batteries, *Sustainable Materials and Technologies* 19 (2019), <https://doi.org/10.1016/J.SUSMAT.2018.E00087>.
- [190] L. Gaines, Lithium-ion battery recycling processes: research towards a sustainable course, *Sustain Mater Technol* 17 (2018) e00068, <https://doi.org/10.1016/j.susmat.2018.e00068>.
- [191] A.V. Naumov, M.A. Naumova, Modern state of the world lithium market, *RUSS J NON-FERR MET* 51 (2010) 324–330, <https://doi.org/10.3103/S1067821210040127>.
- [192] T. Maes, F. Preston-Whyte, E-waste it wisely: lessons from Africa, *SN Appl. Sci.* 4 (2022) 1–12, <https://doi.org/10.1007/S42452-022-04962-9/FIGURES/2>.
- [193] V. Maphosa, M. Maphosa, A.W. K Tan, E-Waste management in sub-saharan Africa: a systematic literature review vusumuzi maphosa & mfowabo maphosa, *Cogent Business & Management* 7 (2020), <https://doi.org/10.1080/23311975.2020.1814503>.
- [194] M. Schönmann, Multiscale simulation approach for battery production systems (sustainable production, life cycle engineering and management). <http://www.amazon.ca/exec/obidos/redirect?tag=citeulike09-20&path=ASIN/3319493663>, 2017.
- [195] A.M. Mineev, I.A. Zvonareva, D.A. Medvedev, Z. Shao, Maintaining pronounced proton transportation of solid oxides prepared with a sintering additive, *J Mater Chem A Mater* 9 (2021) 14553–14565, <https://doi.org/10.1039/d1ta03399a>.
- [196] M.A. Rosen, Energy sustainability with a focus on environmental perspectives, *Earth Systems and Environment* 5 (2021) 217–230, <https://doi.org/10.1007/S41748-021-00217-6/TABLES/7>.
- [197] K.O. Adu-Kankam, L.M. Camarinha-Matos, Renewable energy communities or ecosystems: an analysis of selected cases, *Heliyon* 8 (2022) e12617, <https://doi.org/10.1016/J.HELIYON.2022.E12617>.
- [198] L.A. Jolaoso, Integrated Protonic Ceramic Electrochemical Cell for Sustainable Energy Economy Using Water-Energy Nexus Framework, 2023.
- [199] L.A. Jolaoso, C. Duan, P. Kazempoor, Life cycle analysis of a hydrogen production system based on solid oxide electrolysis cells integrated with different energy and wastewater sources, *Int. J. Hydrogen Energy* 52 (2024) 485–501, <https://doi.org/10.1016/j.ijhydene.2023.07.129>.