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Technological frontiers: addressing renewable energy supply chain and sustainability challenges

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Abstract
This study examines the sustainability and supply chain challenges within Africa's renewable energy sector, proposing solutions grounded in green supply chain management principles and Industry 4.0 technologies. Utilizing an interpretive research strategy, we collected qualitative data from mini-grid companies, regulatory authorities, and a global financial institution that funds renewable energy projects across the continent. Our findings reveal a range of supply chain issues related to importation processes, economic policies, regulatory frameworks, logistics, skills shortage, and corruption. Additionally, we identified sustainability challenges such as a lack of environmental awareness and inadequate end-of-life management practices. To address these issues, we propose green supply chain management practices like recycling, responsible sourcing, and carbon footprint assessment. We also advocate leveraging Industry 4.0 technologies—including the Internet of Things, blockchain, and big data analytics—for smart metering and energy management. This study offers vital insights into the supply chain and sustainability challenges within the renewable energy sector, presenting practical solutions through the integration of green supply chain management and industry 4.0 technologies. Also, by addressing barriers unique to a developing economy, the research provides insights into actionable strategies for policymakers and industry stakeholders to enhance efficiency, reduce environmental impact, and promote sustainable development. The study similarly underscores practical implications, calling for robust strategies to resolve supply chain and sustainability challenges, the enactment of policies favourable to the renewable energy sector, and enhanced collaboration among government departments and law enforcement agencies.

Keywords Industry 4.0 · Green supply chain management · Renewable energy · Sustainability

Abbreviations

AI	Artificial intelligence
BDA	Big data analytics
EIA	Environmental Impact Assessment
ESIA	Environmental and Social Impact Assessment
GSCM	Green supply chain management
IoT	Internet of things
PV	Photovoltaic
RE	Renewable energy
RES	Renewable energy sector
RESC	Renewable energy supply chain

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SIA Social Impact Assessment
SC Supply chain
SCM Supply chain management

1 Introduction

Despite the importance of renewable energy (RE) technologies in the transition towards carbon neutrality, it is argued that ramping up the deployment of RE technologies is problematic [1–3]. As suggested by Ali, Kalantzakos [4] and Watari, Nansai [5], huge amounts of metal feedstock among other minerals will eventually be needed to build green energy infrastructure and the imminent challenge is on how to get the unprecedented quantities of raw materials needed to close this infrastructure gap to decarbonize the global energy systems in a sustainable way. This therefore poses a noticeable challenge in the renewable energy sector (RES).

Numerous scholars [4, 6–9] have highlighted a number of issues within RES that are related to sustainability and supply chain management (SCM). These issues cut across the entire RES SCs from upstream to downstream segments. For instance, Rachidi, Nwaila [10] highlighted labour issues (Child labour) in upstream mining activities arguing that cobalt mining rely greatly on child labour. Furthermore, in the downstream segment of renewable energy supply chain (RESC), Winkler, Kilic [11] highlighted that by 2030, it is estimated that about 1800 off-shore wind turbines (OWTs) will reach their end of life, and that means decommissioning around 225 OWTs from 2020 to 2023 and 1310 OWTs between 2029 to 2030 where the cost of decommissioning amounts to between 1 to 2 million euros which is staggering 60–70% of initial cost of installation.

Moreover, to proffer solutions to the RES issues identified by researchers, scholars have researched on ways to curb these challenges. For instance, Almutairi, Hosseini Dehshiri [12] suggested that Industry 4.0 technologies could tackle a lot of these challenges adding that blockchain technology is beneficial to the RES by providing real-time facilitation of transparency that brings about trust among partners, seamless payment processes, lead time reduction, improvement in demand forecasts, enhancing sustainable practices in business. Industry 4.0 technologies comprise of intelligent, innovative and disruptive technologies [13–16] like the blockchain, Internet of Things (IoT), cloud computing and big data analytics (BDA) among others which collectively enhance seamless connectivity, automation and communication [17]. BDA for instance, was found to help firms make informed decisions on green operations across their SCs [18, 19].

In addition to their general benefits, Industry 4.0 technologies significantly enhance SCM in the RES by addressing its specific complexities and demands [14]. For instance, IoT enables real-time tracking and monitoring of RE assets and components throughout the SC, improving visibility and efficiency in logistics operations [17]. This is particularly critical in the RES, where components like wind turbines and solar panels are large, complex, and require precise handling. By integrating IoT devices, companies can monitor the condition and location of these assets, anticipate maintenance needs, and optimize transportation routes, thereby reducing delays and costs associated with logistics.

Moreover, BDA plays a crucial role in optimizing SC processes by analysing vast amounts of data generated across the SC [18, 19]. In the RES, BDA can be utilized to forecast demand more accurately, manage inventory levels efficiently, and identify potential SC disruptions before they occur [13]. This predictive capability is essential for mitigating risks associated with the supply of critical raw materials and components. Additionally, BDA supports strategic decision-making by providing insights into supplier performance, market trends, and customer preferences, enabling companies to develop more resilient and responsive SCs. By leveraging these Industry 4.0 technologies, the RES can enhance its SCM practices, leading to improved operational efficiency, reduced environmental impact, and a more sustainable energy future [15].

While some researchers [20–22] suggested digital technologies to tackle these issues, others proposed green supply chain management (GSCM) principles like recycling and green product design or eco-design [23–25]. Also, resource loops in the RES could be closed through the enhancement of effective disassembly, material recovery and recycling at the end-of-life stage of RE infrastructure [26, 27]. GSCM is a management paradigm which embeds "green" philosophy in procurement, logistics, distribution and manufacturing [28–30] through which competitive advantage is arguably achieved through its implementation [31]. GSCM buttresses the incorporation of environmental aspects into various facets of SCM [32].

This study aims to fill the existing theoretical gaps by examining SC and sustainability issues within the RES based on interpretive research strategy involving professionals in the African RES. In the same way, the study examines GSCM and Industry 4.0 solutions proffered by researchers and industry players to tackle these issues.

The remainder of the paper is structured as follows: Sect. 2 presents a background to this study, Sect. 3 covers the methodology used, Sect. 4 covers the presentation of results and findings, Sect. 5 covers Discussion and Sect. 6 covers conclusions.

2 Background

By the end of 2050, the International Renewable Energy Agency and the International Energy Agency Photovoltaic Power Systems Programme have projected that the global Photovoltaic (PV) modules waste will reach to about 78 million metric tonnes, with the annual quantities equalling the total quantity of new installations [33]. The RES has a network of complex SCs that involve thousands of suppliers, traceability of minerals therefore poses a great challenge and a complex exercise that limits firms from identifying where unsustainable mining practices are involved [6, 34]. According to Deberdt and Billon [6], analysis of 1300 companies found that 80% of them couldn't determine countries of origin of their minerals, only one percent regard their minerals as conflict free. There are numerous challenges in the RES that are related to SCM and sustainability.

2.1 SCM issues in the RES

According to Mastrocinque, Ramírez [35], some of the RE businesses like PV business are both technology and capital intensive posing high entry barrier where operations and construction are often not feasible without appropriate industrial policies by governments. Xiong, Devlin [36] believes that RES is heavily impacted by these government regulations and policies which could lead to artificially bloated demands and bottlenecks. A study by Mason-Jones, Davies [1] found that manufacturing and engineering companies in the United Kingdom are hesitant to enter the RE market at the rate required, therefore, RE SCs are lacking in the ability to respond to surging demand due to a lack of willingness by businesses to move into the RES because of (among other reasons) the barrier to entrance as opined by Mastrocinque, Ramírez [35].

In the solar RES, the component of solar panels that makes up the majority of PV modules' mass is the PV glass which has a problematic SC due to its characterisation as a high-quality material that is highly sensitive to impurities during manufacturing [37]. Furthermore, in the RE SCs, there are unique issues with regards to raw materials procurement such that SCs are reliant upon globally sourced raw materials from specific concentrated geographical locations, many of which are prone to disruptions and shortages [36, 38]. Some scholars have reported insufficiency of information exchange among actors of the solar industry value chain [39], while Keivanpour, Ramudhin [40] have found the wind turbine subsector of the RES to be capital intensive with limited number of turbine manufacturers and value chain activities often requiring complex installations.

2.2 Sustainability issues in the RES

In the upstream segment of the RES, there are sustainability issues with mining (of conflict minerals: Tantalum, Tin, Tungsten & Gold) whose current conditions are linked to human rights violation [10] and violent conflicts financing [23]. Also, the mining of raw materials needed for Lithium-ion battery manufacturing bring about significant environmental impacts like depletion of local water sources in lithium mining locations [38] and there are concerns about raw materials depletion especially cobalt, lithium and graphite [41, 42]. Also, in the construction of wind turbines, large amounts of cement are required, and large quantities of water and sand are needed in cement production. This represents major greenhouse gas emission [38].

Additionally, there are technical challenges regarding recycling of minerals including low collection rates often due to lack of incentives, lack of infrastructure and inconvenience of systems of collection. In 2018, only about 29% of consumed cobalt was recycled and only 22% (11,000 tonnes) of tin's consumption was recycled from scrap [23]. Furthermore, with regards to components of wind turbines, electrical and electronic materials are recycled at 50% rate, whereas, materials like fibreglass, polyvinyl chloride, lubricants, paints and adhesives commonly find their ways to the landfills [26]. It is pertinent to say that failure to adopt circular economy principles through the consideration of entire life cycle of RE components will result in a darker future for RES [33].

2.3 GSCM solutions to SCM and sustainability issues

To tackle sustainability issues within the RES resource and raw material security, there is need for enhancement of RE component durability and lifetime extension, for example, in the wind energy subsector, better coating of blades and/or producing lighter materials to reduce structural loads could help in reducing material needs for cement [43]. Maquera, da Costa [44] propose GSCM practices to tackle some of the RES sustainability and SCM issues by leveraging design for durability to prolong technologies and infrastructure lifetimes, reuse, refurbishment, retrofitting, remanufacturing and repurposing. They added that, resource loops could also be closed through the enhancement of effective disassembly, material recovery and recycling at the end-of-life stage of RE infrastructure.

Diversification of RE SCs to include recycling in upstream activities like mining alongside midstream processing is very necessary [4, 45]. In the PV SCs, to reduce short- and long-term supply risks, prolongation of PV lifetime from 25 to 30 years could result in 6.7–24% cumulative metal conservation [42]. Duran, Atasu [33] suggested that there is need for a regulatory action with regards to the recycling of projected quantities of PV waste and huge investments in logistics infrastructure and innovation are also needed in the handling and recycling of retired panels. This is particularly important because closed-loop recycling diverts waste from landfills and could reduce virgin materials demand significantly [37].

2.4 Industry 4.0 solutions to SCM and sustainability issues

In RES energy markets, blockchain provides decentralised trading platforms while Artificial Intelligence (AI) helps with the optimal operational control of power systems and the prediction of system uncertainties in smart grids [46]. To tackle upstream irregularities in the RES, Rufino, Sanseverino [41] asserted that through blockchain, lithium-ion batteries' raw materials tracking helps in preventing their respective ores from being harnessed through unsustainable means. In other words, blockchain makes it possible to create immutable contracts that explicitly enumerate business rules to ensure transparency and security throughout the SC. Also, the juxtaposition of blockchain and geolocation technologies potentially brings about significant enhancements to global minerals SCs in terms of transparency and sustainability.

Blockchain technology can be used in the RES in various ways that include smart metering/billing, decentralized energy trading, cryptocurrency powered energy tokens, carbon trading and green certificates, smart grid management, among others [47]. Also, to achieve recyclability of RES components, emerging (Industry 4.0) technologies could be utilized in designing for circularity prior to commercialisation [37]. With the help of Industry 4.0, blockchain enhances data sharing, for example, environmental data like greenhouse gas emission statistics to be more transparent to stakeholders across the value chain [48]. BDA is useful in terms of tackling challenges within the RES like demand-side management, power generation management and smart-grid optimization. BDA tools enhance effective optimisation, traceability, forecasting, classification and clustering [49].

This study therefore aims to investigate the following overarching research question:

> How can GSCM principles and Industry 4.0 technologies be leveraged to address sustainability and SCM challenges within the RES?

To answer the above research questions, semi-structured interviews were conducted with participants being high-ranking officials from different organisations within the African RES. These informants/respondents were from mini-grid development companies, regulatory authorities, solar home installation companies and an international development organisation (global bank). Through these interviews, experts provided insights into a number of sustainability and SCM issues they face in their organisations and discussions around measures and solutions to these issues were raised. The findings of this study provide a novel perspective on sustainability and SCM issues within RES with a plethora of innovative solutions proffered. The findings of the study also help managers and policymakers within RES on divergent innovative ways to tackling their business challenges.

To explore more about various sustainability and SCM challenges within the RES and to examine how can GSCM principles as well as industry 4.0 technologies could be leveraged in terms of addressing those challenges, primary/empirical data was collected. The next section contains in-depth discussion around the method of data collection adopted in this study.

3 Methodology: interpretive research (thematic analysis)

This research aimed to examine the RES in Nigeria primarily to uncover sustainability and SCM challenges within the sector. Additionally, the other objective of this study is to examine GSCM and Industry 4.0 solutions that are in practice or proffered by professionals. Interpretive research strategy proposed by Darby, Fugate [50] was used for data analysis. To sufficiently understand observable relationships between variables, interpretive strategy is adopted to expand understanding of relationships beyond surface level understanding [51]. Through the interpretive research strategy, we aim to construct meaning and raise comprehension. According to Darby, Fugate [50], to investigate unique events in unique settings and to generate in-depth descriptions connected to their contexts, the interpretive research strategy excels. Figure 1 illustrates the iterative process of qualitative content analysis employed in this study, grounded in an interpretive research strategy, adopted form Darby, Fugate [50]. The cycle highlights key steps such as orienting the frame of reference, data examination, and theme identification, showcasing how insights into SCM and sustainability challenges were derived. This approach emphasizes depth in understanding context-specific issues.

The cycle starts with the orienting frame of reference which demonstrates relevance of the context in question [50]. Through this approach, a more in-depth understanding of sustainability and SCM challenges within RES is provided alongside solutions based on GSCM principles and Industry 4.0 technologies. This study found the key elements in the orienting frame of reference in this research to be sustainability related issues in the RES, SCM related issues in the RES and the role of Industry 4.0 and GSCM Practices towards tackling the issues identified.

3.1 Sample selection

According to Darby et al. [50], the ideal number of informants (respondents) selected in the interpretive research approach falls between three and twenty informants, and this is due to the fact that interpretive research method emphasizes the acquisition of a holistic understanding of the environment. Also, context selection in this approach is driven by understanding instead of generalisation [51]. Therefore, the context selected for this study is sustainability and SCM issues within RES alongside solutions proffered to tackle these issues. Since this research approach is grounded upon a judgement sample technique, eight organisations operating within the RES in Nigeria from mini-grid development companies, RES regulatory authorities, solar home systems installation companies and a global banking organisation were selected. These firms were selected after deliberations with a professional with more than a decade long experience in the Nigerian RES so that a true representation of firms operating within the Nigerian RES is achieved. The Informants belonging to senior cadre in their respective organisations with background in SCM, strategic and operations management were notified that utmost anonymity would be maintained of their identities and those of their organisations. Table 1 provides a detailed overview of the study's participants, including their roles, organizational affiliations, and the size of their respective organizations. The diversity of participants, ranging from mini-grid companies to regulatory authorities and a global financial institution, reflects the multifaceted perspectives included in the analysis. This ensures the findings capture a holistic view of the challenges and solutions within the Nigerian RES.

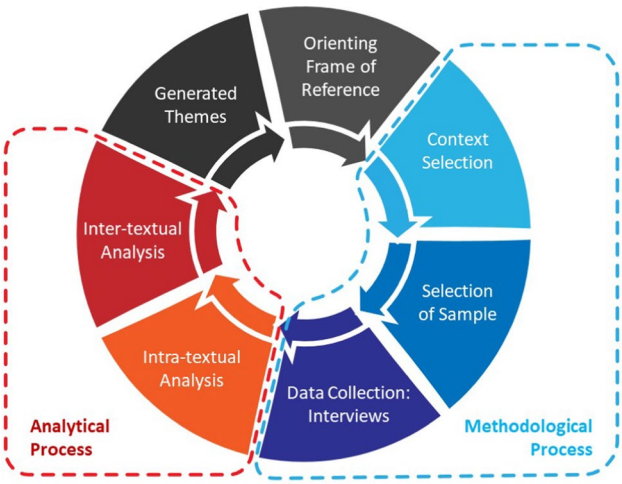

Fig. 1 Process of qualitative content analysis (Hermeneutic circle), adapted from [50]

Table 1 Research participants information

Organisation	Category	Role	Size (People)
1	Mini-grid	Founder/CEO	10–50
2	Mini-grid	Founder/CEO	10–50
3	Solar Home systems provider	Senior Manager	100–200
4	Solar home systems provider	Senior Manager	100–200
5	Global bank	Project/Operations Manager	5000–10,000
6	Regulatory authority 1	Director	400–500
7	Regulatory agency	Manager	1300–1500
8	Regulatory authority 2	Managing Director	300–400

3.2 Data collection

To collect primary data based on the interpretive research method, the eight informants participated in semi-structured interviews with discussions focused on the research questions. Questions weren't strictly structured, rather, a conversational two-way exchange of information to understand the challenges faced within their SCs with regards to sustainability and SCM [52]. To explore how informants connect between their cognitive processes, experiences and lives, questions were made concise and open-ended so that these connections are established [51]. Interview audios were carefully transcribed and secondary data (industry reports and articles) was gathered to strengthen the primary data.

3.3 Data analysis

Transcripts of the interviews were thoroughly examined specifically to extract major themes that centre around sustainability and SCM issues in RES and their corresponding solutions found to be in practice or proffered by informants. This intra-textual exercise involved several reading and re-reading of transcripts to adequately understand the context. Each transcript was thoroughly examined, and summaries of key themes were made to visualise key findings and trends. Intertextual cross-examination was carried out for entire transcripts for the identification of recurring themes. Coding of data was performed manually to determine the emergence of themes and patterns after which the codes were imported into *Atlas.ti* software for qualitative data analysis so that a relationship could be established between themes and codes. Appendix 1 contains codes for sustainability and SCM issues within RES and solutions based on Industry 4.0 and GSCM among others.

Files were uploaded onto *Atlas.ti* software and these were arranged in project folders and memos to keep the data structured to prepare for a seamless conduct of the next step. The data was carefully and thoroughly reviewed for a further understanding of context and content. Themes, patterns and concepts were identified and were manually annotated or highlighted in-text. On *Atlas.ti*, nodes were created corresponding to the manually generated codes where each node represented a theme. Relevant text sections were added under each corresponding node manually on the *Atlas.ti* platform after which the features of the software were leveraged to determine the relationships between codes. This was followed by creating queries, networks and visualisations while the "Code Document Table" was used to visualise how often code re-occurred in different documents.

Codes and code combinations were searched across the dataset using *Atlas.ti*'s query tools, the relationship between codes that appeared together frequently were identified using the "Code Co-occurrence" query. To capture reflections, thoughts and insights, memos were written on the software during this analytical process after which these memos were linked to specific documents and codes to uphold a record of analytical thinking. Conclusions and insights were drawn from identified patterns and relationships which were both synthesized through the continuous interpretation of themes and concepts while reviewing the coded data. Visual representation of findings and reports were generated for effective communication of findings, then these were exported to help in improving research presentation and reports. One of the most important steps in this data analysis was "data conceptualisation" that has to do with turning data groups into abstract concepts. This iterative process of analysing themes continued until the orientation frame of reference was properly defined.

4 Results of thematic analysis

The section presents discussions around SCM and sustainability issue in the RES, and solutions to these issues based on GSCM principles and Industry 4.0 technologies alongside other solutions proffered by experts and scholars. We examined the challenges and issues faced by experts in the RES as well as solutions to these issues. Results and remarks that were obtained from the analysis are focused on in the next stage.

4.1 Supply chain management issues in RES

Informants have mentioned a plethora of SCM related issues in the RES and these generally fall under six categories, namely, importation, knowledge and skill gap, logistics, regulation, economy and corruption related issues. Figure 2 depicts the network perspectives of the SCM issues and their respective categories.

4.1.1 Importation related issues

The entirety of our interviewees mentioned that the Nigerian RES is faced by issues that impact their businesses negatively due to some impediments that are related to importation and border clearance. Respondent 1 said: "most of this hardware equipment, we only have assembly plants here, most of them are imported. And then you have all this hassle of importation, FX, and then down to even when it gets to our Nigerian borders, there are multitudes of bottlenecks." Respondent 4 commented on how lead times are affected negatively due to customs and clearance delays: "…customs, the clearing and all that. So, most times we end up spending even far above the cost of the purchase of those items in trying to clear and it takes a long time there. I think there are situations where it takes between three to six months to clear goods…".

4.1.2 Knowledge and skills gaps related issues

Knowledge and skills gap is another area in which the Nigerian RES is suffering from as alluded by respondents. Respondent 7 stated the lack of manpower capacity and expertise in terms of effective technology deployment: "There is currently no certified training scheme curriculum for building such in our institutions. I think that along the value chain, we need to have institutions that train people… most of the people that are going to deploy are not trained, they are just people

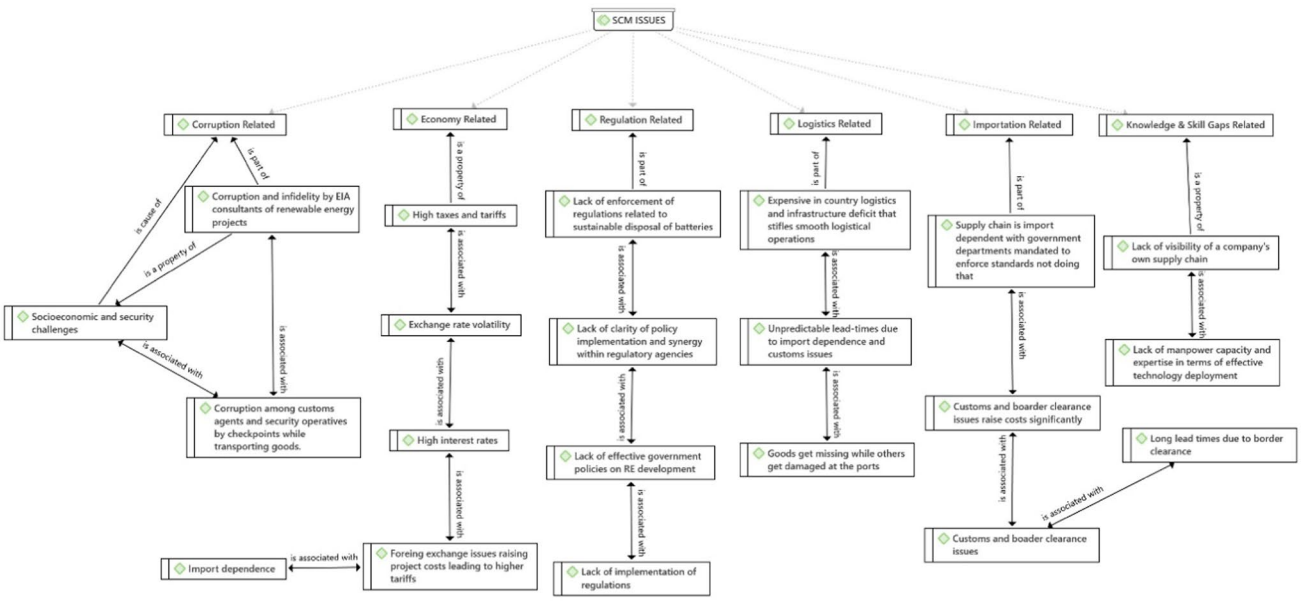

Fig. 2 SCM issues in Nigerian RES based on empirical findings. Dotted lines between the topmost cell and the first row beneath it symbolises a subset relationship while the undotted lines depict other types of relationships that are clearly marked

that get to learn on the job". Respondent 1 raised another organisational knowledge gap which is the issue of the lack of knowledge and capability of tracking the activities of a company's own SC, "I think one of the problems is, as a global institution, we have the ability, we have tracking tools that we can actually track some of this. So, if there are any issues, we can actually tell right…, as part of our responsibility working with the client is to also improve on their systems, right. I am not aware of any tracking tool that speaks to how to even quantify some of these challenges, and then how to actually even address them. I don't think Nigeria is actually at that level, unfortunately." Respondent 6 added: "In terms of sourcing materials from local vendors, we don't really look at their own environmental standards."

4.1.3 Logistics related issues

Some of the SCM issues include expensive in country logistics as well as infrastructure deficit that stifles smooth logistical operations. Respondent 2 touched on that saying: "…in-country logistical requirements that are there, the cost of that… Someone will tell you that the cost of transporting an equipment from Europe to Lagos is cheaper than transporting that same equipment from Lagos to Kano… Then the infrastructure requirements also moving this equipment from one place to another is also something of a concern". Talking about damages that happen to goods on transit, Respondent 4 said: "…when they (goods) finally arrive, you will see a lot of damages, you see sometimes a lot are missing, some will be missing from the ports,"

4.1.4 Regulation related issues

Lack of effective government policies on RE development, lack of regulation/policy implementation, lack of clarity of synergy among regulatory authorities were all mentioned by respondents. Respondent 1 stressed that "…having all these things properly spelled out in our regulations is not the issue, the issue is the inability of the regulatory bodies to implement… We are not in short of all these regulatory bodies." Respondent 2 also stated: "At times, there's lack of clarity also in terms of… okay for this category of equipment, this has this kind of tariff, levy or… this is it! so there's a lot of mismatches… there is lack of clarity in policy implementation". Respondent 6 spoke on the lack of enforcement of regulations related to sustainable disposal of batteries "…the gap is there because also since companies are not held accountable, or forced to do this waste management, they don't see any reason to pay anybody to dispose of this…". Respondent 7 commented on lack of effective RE development policies: "there has not been policies that are in place that push for them to be formed normal, there was a policy of government on RE, but they are not effective".

4.1.5 Economy related issues

High taxes and tariffs were among the issues raised by respondents, Respondent 8 who works for a government department stated that: "the RE has an abridged process because it is an intervention project and is considered environment friendly project. However, the timelines and cost implications sometimes affect the promoters of the projects, and it can also affect the financial angle especially for investors that are not used to the process. The other charges, the tax and the rest of them in the country as well as some socio-cultural issues". Respondent 5 talked about exchange rate volatility affecting businesses negatively in terms of their SCM: "because of the exchange rates, sometimes you cannot predict how much you're going to spend, and in that process, because of that, usually it affects the project implementation because you may have budgeted to spend, let's say, 100 million Naira (£50,000) in the mini-grid project, but due to the volatility in the exchange rates, at the end of the day before you conclude you might see that your cost is running to 120 or 130 million Naira".

4.1.6 Corruption related issues

Corruption is another issue that affects the Nigerian RES, Respondent 7 who works for a regulatory authority in the Nigerian government talked about the issue of corruption and infidelity by Environmental Impact Assessment consultants of RE projects: "…they have some consultants who are accredited as consultants on ESIA [Environmental and Social Impact Assessment] who you must go to, pay them that amount, they write a report for you, sometimes they don't even visit the place. The mini-grid projects are going on around the country, each of them is supposed to get SIA [Social Impact Assessment] report, but you get somebody apply for mini grid project today, by tomorrow he gets an EIA [Environmental Impact Assessment] report, when was the study done!" Respondent 4 who works for a mini-grid company added that

there is corruption among customs and security agents on the roads stating: "but like the security agencies, they stop at every checkpoint… especially those transporting to the southern part of the country, they have lots of checkpoints on the road and most times you need to be settling… In a nutshell, corruption is a big challenge."

Energy theft is one of the issues stated by respondents, Respondent 5 said: "so one of the problems we have in the mini grid space is issues that have to do with energy thefts, energy through bypass and a lot of commercial losses". Respondent 4, a mini grid company representative, added: "we have scenarios where you give a customer your products, and then they destroy, they open up the pack and then throw away the containers". Figure 2 categorizes the SCM challenges identified during the study into six broad areas: importation, logistics, economy, regulation, knowledge and skill gaps, and corruption. The relationships between these categories are depicted, demonstrating how interconnected challenges impact the RES. This visualization aids in understanding the systemic nature of these issues and their implications for stakeholders.

4.2 Sustainability issues in RES

Key sustainability challenges identified include:

1. Lack of Environmental Consciousness: Respondent 4 said: "I think there is a huge gap… I don't think we have this consciousness of the environment."
2. Absence of End-of-Life Management Plans: Respondent 7 noted: "…project involving rural areas, now they are deploying solar panels in villages, but what would happen to them at their end-of-life? So, is there a program to bring them back? Whether for recycling or disposal or remanufacturing, currently there is no plan!". Respondent 4 added: "they dispose those batteries and sometimes our staff they go and say, I saw part of our product in the waste bin…".
3. Unsustainable Disposal Practices: Lack of enforcement leads to improper disposal. Respondent 6 said: "the gap is there because also since companies are not held accountable or forced to do this waste management". Respondent 7 mentioned: "…and it's even only one battery company that has the capability to actually dispose of lead acid batteries properly in Nigeria… lithium-ion batteries to dispose of them properly, they have to fly out to the UK and crush. So, there is a gap in terms of waste management".

To further confirm the SCM and sustainability issues obtained in this study and to ascertain how experts perceive these to be pressing, in other words, how important are individual issues to be tackled. Each respondent was provided with the highlights of categories of SCM and sustainability issues. They were asked to assess each issue on a scale of 1 to 10, 1 being least important and 10 being most important to be addressed. The scores assigned to individual categories of issues were compiled to ascertain the weightage scores of each issue by taking the average of entire scores assigned to each issue category. Assigning these scores to issues helps stakeholders and firms to prioritize their efforts and allocate resources where due at the right time. This approach is adopted from Akram et al. [51]. Table 2 quantifies the relative importance of identified challenges based on participant evaluations. By assigning weightage scores, it prioritizes issues that require immediate attention, such as economic barriers, importation challenges, and logistics inefficiencies. The data serves as a decision-making tool for stakeholders to allocate resources effectively and address the most critical barriers in the sector. Figure 3 categorizes the sustainability challenges faced in the Nigerian RES, such as a lack of environmental consciousness, unsustainable waste management practices, and inadequate regulatory enforcement. The relationships between these issues are depicted, highlighting systemic gaps that hinder the adoption of sustainable practices. The visualization underscores the need for integrated approaches to address these challenges.

4.3 Solutions to SCM and sustainability issues

During this empirical study, we have gathered several solutions proffered by respondents to tackle some of these SCM and sustainability issues in the RES. Experts proposed several solutions to address the identified challenges, categorized into GSCM solutions, Industry 4.0 solutions, and other approaches. Figure 4 depicts the solutions proffered based on GSCM and Industry 4.0 among other solutions. In the following subsections, we discuss GSCM and Industry 4.0 solutions to SCM and sustainability issues in RES.

4.3.1 GSCM solutions

The following GSCM solutions were identified through the empirical study.

Table 2 SCM and sustainability issues weightage scores

SCM issues		Sustainability issues	
Category	Weightage score	Issue	Weightage score
Importation related issues in the sector (customs & border clearance issues, high levies & taxes, substandard goods flooded into RE market)	8.4	Logistics are fossil based and there is absence of any plans to green the logistics	6.8
Economy related issues in the sector (Foreign exchange issues, access to finance, high interest rates)	9	Lack of environmental consciousness among vendors as well as customers within the sector	6.6
Regulatory issues in the sector (Lack of clarity on policy implementation & synergy among regulatory agencies, lack of effective policies, lack of enforcement of policies)	5.2	Unsustainable disposal of solar modules like batteries by customers	6
Corruption related issues in the sector (Goods missing & damaged at port, corruption among customs agents, security operatives at checkpoints & EIA consultants, energy theft)	6.8	Lack of firms that recycle and sustainably dispose of batteries in Nigeria	6.6
Logistics related issues in the sector (Expensive in-country logistics, long lead times due to border clearance & high cost of border clearance)	7.4	Lack of enforcement of regulations related to sustainable disposal of batteries	6.2
Knowledge & skill gap related issues in the sector (Lack of knowledge & capability of tracking SCs, lack of manpower in effective technology deployment)	6.2	There are often no plans for end-of-life management of RE modules	7.4

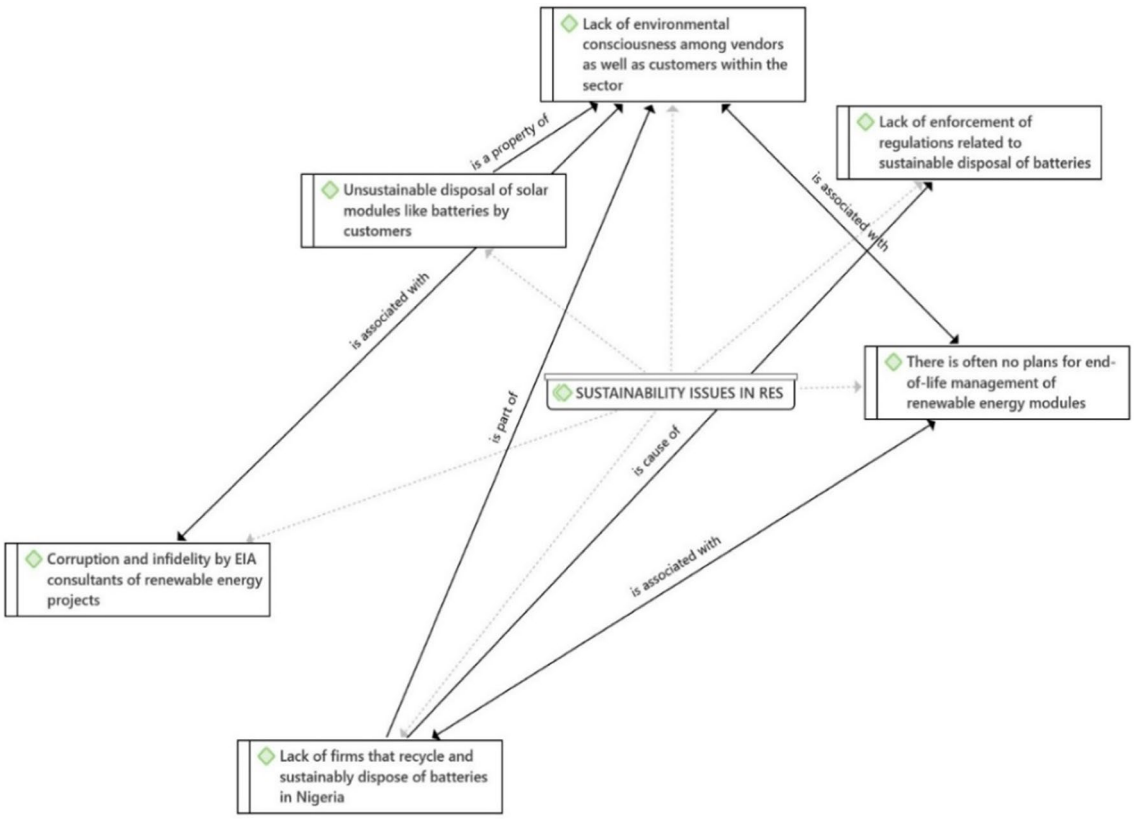

Fig. 3 Sustainability issues in the Nigerian RES based on empirical findings

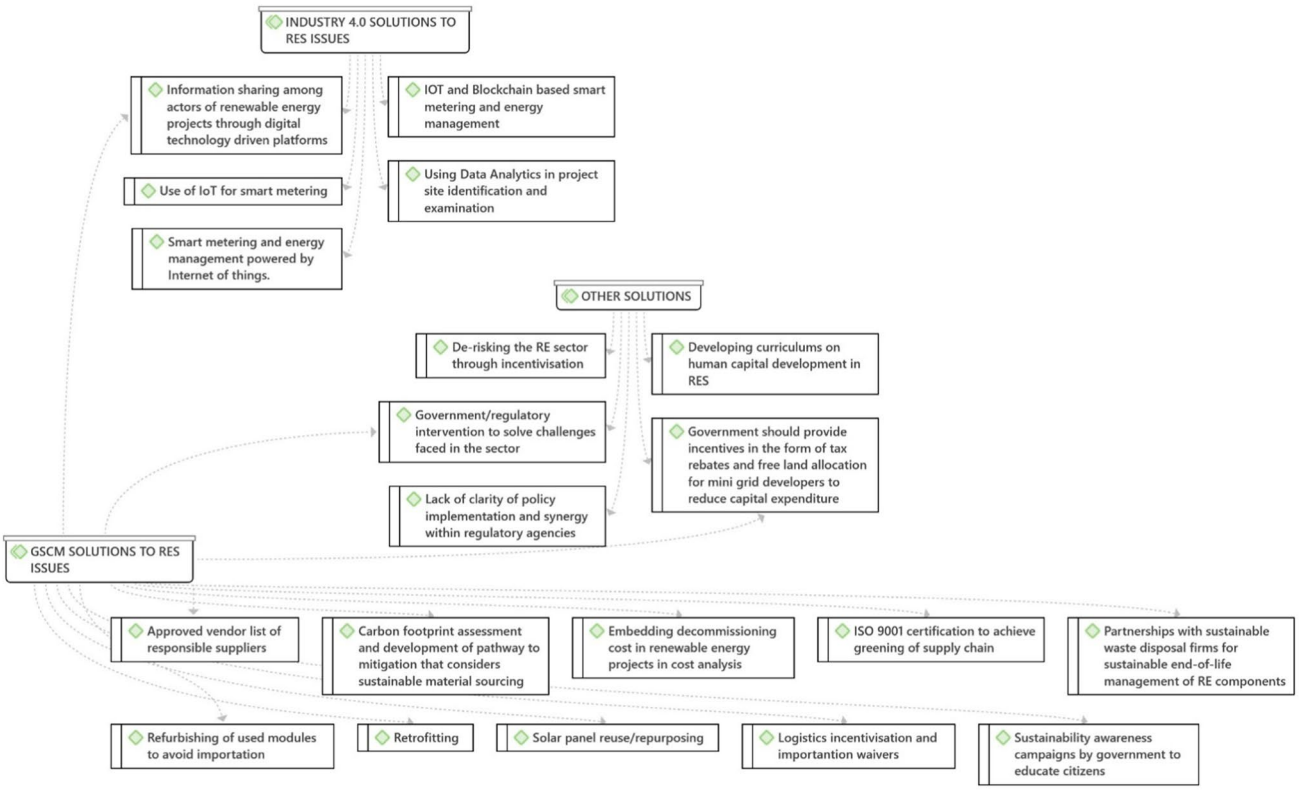

Fig. 4 Solutions to SCM and sustainability issues in RES based on empirical findings

1. Approved Vendor Lists: Maintaining databases of vetted, responsible suppliers. Respondent 1 said: "we have identified companies that are credible, that also through their backend SCs, there is predictability in terms of how they source their raw materials, how they interact with people, and they interact with environments and all that. So, we have a database that speaks to companies that we've vetted".
2. Carbon Footprint Assessment: Conducting assessments to understand emissions. Respondent 3 suggested: "assess where we are and then also have a pathway to reducing our carbon emission and I think that is not just internally as companies, but also you know the components and factors of production that are coming into your business, especially from your vendors."
3. Embedding Decommissioning Costs: Including decommissioning in budgets. Respondent 7 proposed: "We have what we call decommissioning cost, which is built in the budget, so that as you are collecting your money, you can also keep that amount… So, over time that money that has accumulated, and is grown, it can be used to tackle that issue."
4. ISO 9001 Certification: Pursuing environmental management standards. Respondent 3 said: "we are actually trying to get the ISO certification. I believe is ISO 9001, environmental management system… so, we are definitely very curious about making sure that we have the right structures in place to sustain very high environmental standards as well as quality standards."
5. Partnerships with Waste Disposal Firms: Collaborating for proper recycling. Respondent 3 added: "RE wastes in the environment and we have partnerships with some waste disposal firms who are focused in the sector for ensuring that whenever we have batteries that have reached end of life, we can actually hand them over to them for appropriate recycling."
6. Refurbishing and Reusing Modules: Reducing importation through refurbishment. Respondent 4 mentioned: "but in the last six months, I don't think we have imported any items from outside. So, most times what we've been doing for this period, is mostly refurbish."
7. Recycling and Retrofitting Initiatives: Encouraging full recycling. Respondent 1 emphasized: "And that is why I said as part of the ESMP for the projects, there is a need to ensure that there is full recycling or full retrofitting, and most of these assembly plants that we have, we're encouraging them to see how they can also retrofit." Respondent 5 stressed the importance of reusing modules: "I mean this has been one of the challenging aspects that at the end of the lifetime of your equipment what are you going to do with them? So, starting with the solar panels… they are being reused… which also increases the sustainability, that re-usage".
8. Logistics Incentivization and Importation Waivers: Seeking government support. Respondent 1 suggested: "So in terms of logistics challenges, and then importation and then getting them down to individual project sites, you know, I did mention something about waiver, that's our own way of providing a solution to that challenge"
9. Promoting Environmental Education: Enhancing consciousness. Respondent 6 said: "we've tried our best and since we mandate our customers already, staff in the warehouse have been trained. So, in terms of the organization, yes, the mindset of sustainability is there… Government has to force people, and government has to train the population. If you don't do that, it's not going to happen."

4.4 Industry 4.0 solutions

Adoption of Industry 4.0 technologies is currently limited but focused on:

1. IoT for Smart Metering: Implementing smart meters for energy management. Respondent 2 said: "Yeah, so the IoT thing, smart metering is a key thing that we definitely do… because that is what shows that revenue comes from it." Respondent 4 added: "what we use is IoT. So, because it helps you… the remote control of the device itself… to be able to control the unit, switch on switch off, you know, tests to see the power, how well the unit is working."
2. Data Analytics for Site Identification and Planning: Utilizing analytics for planning. Respondent 2 mentioned: "Village Intelligence Data Analytics that we use a lot it helps in identification of sites and creating some socio-economic data of the site, which shows whether that site has the viability for a particular capacity of a mini grid to be developed."

4.4.1 Other solutions

Other solutions obtained in the study that are not directly related to GSCM or Industry 4.0 are discussed below.

1. Human Capital Development: Developing curricula and training programs. Respondent 1 said: "so we're working with NAPTIM, we're also working with NEMSA, the technical regulatory body, we're also working with them coming up with different curriculums to see how to also engage people in installation, certification, operation, O and M."
2. De-risking the Sector through Incentives: Providing financial incentives. Respondent 2 stated: "we de-risk the sector so that we get more private sector to come and participate in the RES and one of it is now provided this um, this Nigeria Electrification Project where we provide um the subsidy grants to private sector just purposely to incentivize them in um harnessing the opportunities in the sector."
3. Supply Chain Financing Initiatives: Establishing procurement processes with reduced upfront costs. Respondent 5 said: "…companies who are enablers of RE, …so what they did recently, they just launched a RESC or procurement kind of enabling process where if you have a project you want to embark on, you can engage them… You can just pay 10% or let's say 10 to 30% of that amount."
4. Information Sharing Platforms: Utilizing digital platforms for collaboration. Respondent 5 added: "all the projects now come in through odyssey platform. So you go on odyssey, create your own account register that project and for what purpose, and with that, you are not only entering, you're also entering all the relevant databases… when you're looking for information on RE projects in Africa, or in Nigeria you can go to odyssey, all the projects that have been completed or under construction, or ongoing or planned projects that are yet to come."

Figure 4 presents a comprehensive framework of solutions categorized into GSCM practices, Industry 4.0 technologies, and other innovative strategies. The figure emphasizes actionable approaches, such as recycling, smart metering, and capacity building, illustrating how these interventions can tackle interconnected challenges in the sector. This provides a roadmap for stakeholders to enhance sustainability and efficiency.

5 Discussion

The primary aim of this study was to investigate how GSCM principles and Industry 4.0 technologies can address the sustainability and SCM challenges within Nigeria's RES. Through an empirical approach, this research identified critical SCM and sustainability challenges and assessed the feasibility of proposed solutions. The findings highlight significant barriers, including import dependency, logistical inefficiencies, economic constraints, regulatory gaps, corruption, and knowledge deficits, all of which contribute to a complex operational landscape.

The Nigerian RES is heavily reliant on imported components, which creates substantial challenges in terms of prolonged lead times, high tariffs, and foreign exchange volatility. This import dependency not only escalates project costs but also leaves the sector vulnerable to external shocks. In addition, logistical challenges, such as poor infrastructure and high transportation costs, exacerbate delays and increase the risk of damages during transit. Economic constraints, including unstable exchange rates and limited access to financing, further hinder the growth of the sector. These issues are compounded by regulatory inefficiencies, characterized by unclear policies, weak enforcement, and a lack of coordination among government bodies, which stifle progress and discourage private sector participation. Corruption across various touchpoints, including customs, security checkpoints, and environmental assessments, undermines trust and increases costs for stakeholders. Finally, a pervasive knowledge and skills gap limits the sector's ability to adopt advanced technologies and implement sustainable practices effectively.

In addressing these challenges, this study identified significant opportunities through GSCM principles and Industry 4.0 technologies. Recycling, reuse, and retrofitting of RE components were highlighted as critical strategies for reducing import dependency and enhancing sustainability. The inclusion of decommissioning costs in project budgets and partnerships with waste management firms emerged as practical approaches to tackling end-of-life management issues. Responsible procurement practices, supported by carbon footprint assessments and environmental certifications, could foster greener SCs and improve resource efficiency.

The integration of Industry 4.0 technologies, such as the IoT, data analytics, and blockchain, presents transformative potential for the Nigerian RES. IoT has shown promise in improving smart metering, energy management, and predictive maintenance, while data analytics can enhance decision-making in site selection, demand forecasting, and SC optimization. Blockchain, although underutilized in Nigeria, offers the potential to improve transparency and accountability across the SC, particularly in the ethical sourcing of raw materials.

However, the implementation of Industry 4.0 technologies in Nigeria faces several barriers. Infrastructure deficits, such as inconsistent internet connectivity and unreliable power supply, pose significant challenges to the deployment

of connected systems like IoT. High costs associated with adopting advanced technologies further limit their feasibility, particularly for smaller firms. Regulatory and policy gaps, including the lack of incentives for digital innovation and unclear frameworks for technology adoption, hinder private sector investment. Moreover, the knowledge and skills gap remain a critical impediment, as there are insufficient training programs to develop the technical expertise required for deploying and managing these technologies.

Insights from participants, who represented a diverse range of stakeholders including government agencies, mini-grid companies, and financial institutions, shed light on systemic inefficiencies within the sector. A recurrent theme was the inadequacy of government operations, particularly in economic policies and interdepartmental coordination. Issues such as multiple taxation, delays in customs clearance, and regulatory inconsistencies were frequently cited as barriers to progress. These findings align with the literature, which emphasizes the importance of addressing both upstream and downstream challenges in the RE value chain. However, in the Nigerian context, downstream challenges such as import dependency and weak policy implementation were particularly pronounced, reflecting the nascent state of the sector compared to more mature markets.

This study underscores the urgent need for a multifaceted approach to overcome these challenges. Regulatory reforms, including the introduction of cohesive policies and robust enforcement mechanisms, are essential to reducing corruption and improving operational efficiency. Capacity-building initiatives, such as the development of certified training programs and partnerships with academic institutions, can bridge the skills gap and equip the workforce for the demands of Industry 4.0 technologies. Furthermore, incentivizing technology adoption through tax rebates, subsidies, and government-backed pilot projects can lower financial barriers and encourage private sector investment. Public–private partnerships are crucial for addressing infrastructure deficits and fostering innovation in the sector.

In summary, while the Nigerian RES faces significant challenges, the integration of GSCM principles and Industry 4.0 technologies offers a pathway toward greater efficiency, sustainability, and resilience. However, addressing the structural barriers to implementation—such as infrastructure deficits, policy gaps, and skills shortages—is paramount. These efforts will be critical to aligning the Nigerian RES with global best practices and unlocking its potential for sustainable development. Figure 5 contrasts insights from the literature review with findings from semi-structured interviews. While the literature emphasizes upstream and downstream segments of the RESC globally, the interviews focus on downstream challenges specific to Nigeria. This comparison highlights gaps in the adoption of best practices and underscores the need for tailored solutions in the Nigerian context.

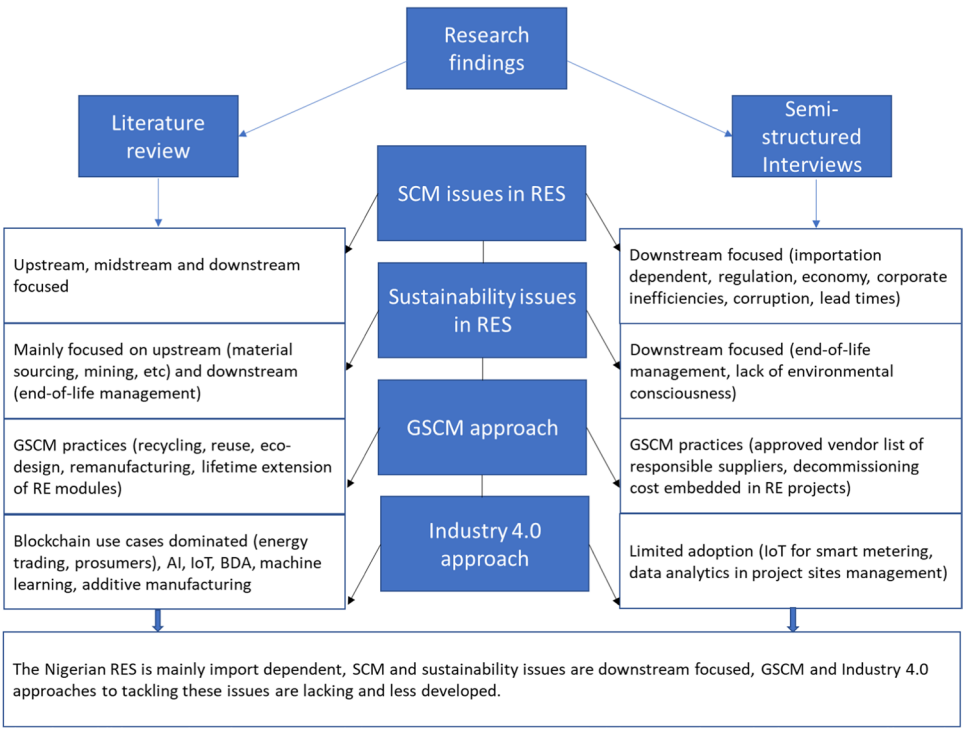

Fig. 5 Comparison between literature and semi-structured interviews findings

5.1 Practical implications

Numerous practical implications can be synthesized from the examination of SCM and sustainability issues as well as solutions to these issues in the RES. Governments, firms and stakeholders in the RES should, as a matter of necessity, embrace robust approach in terms of solving SCM and sustainability issues in the RES. Leveraging on multifaceted approach that involves adopting digital or industry 4.0 technologies and robust management paradigms like the GSCM to tackle these sustainability and SCM issues. This approach includes Information sharing among actors of RE projects through digital technology driven platforms, leveraging IoT and blockchain in smart metering and energy management, carbon footprint assessment and development of pathway to mitigation that considers sustainable material sourcing, keeping approved vendor list of responsible suppliers, adopting recycling techniques of end-of-life management of RE components and modules among others.

The role of government can never be overemphasized in implementing many of the solutions to the SCM and sustainability issues obtained by this study. These include the enactment of policies that are favourable to the RES, providing incentives and tax rebates for RE projects and mini grid developers, bringing synergy among government departments and law enforcement agencies.

5.2 Theoretical implications

The research contributes to the RES, GSCM and Industry 4.0 literature specifically in terms of outlining a set of SCM and sustainability issues in the sector, GSCM practices and industry 4.0 technologies that are instrumental in tackling the challenges uncovered. Additionally, this study offers an understanding of how GSCM practices and industry 4.0 technologies could be used in terms of tackling SCM and sustainability issues in the RES. This contributes to discussions around how SCM and sustainability issues could be tackled through leveraging sustainable management paradigms, digital technologies and the role of regulatory and government intervention in solving some of these issues. This study also depicts the potential of industry 4.0 technologies in the RES SCs.

The multidisciplinary approach presented in this study prompts further theoretical examination of the role and applicability of the combination of industry 4.0 technologies and GSCM practices in different constructs. This research uncovered SCM and sustainability issues in the RES while emphasizing how crucial managing RES SCs with environmental consciousness and the adoption of industry 4.0 technologies is. Studies around RES SCs could benefit from how GSCM and industry 4.0 approach could influence the achievement of sustainable and resilient SCs.

5.3 Limitations and future research direction

This study despite its findings is limited in some ways and that presents gaps that future research works could focus on. This study examines SCM and sustainability issues in the RES and solutions proffered based on GSCM principles and industry 4.0 technologies. This obviously does not include other issues in the RES as well as the same issues in other sectors, so also the solutions. This therefore limits the generalizability of the findings of this study and presents a need for future research in the RES to examine other challenges and their solutions that fall beyond the scope of this study. Since a lot of the issues uncovered have to do with government policies and regulations and such policies and regulations change rapidly when regimes change, it will be pertinent to re-examine the RES in Nigeria when that happens.

Another limitation of this study could be the sample size, the study involved eight firms within the Nigerian RES based on specific selection criteria with the aim of gaining a holistic understanding. The sample size cannot afford generalizability of findings since the eight firms may not be representative of RES companies in Nigeria. This study might be missing on some variables that are peculiar to companies that have not been sampled. We therefore suggest that future researchers sample more RES companies in Nigeria from various market sizes and areas.

The thematic analysis conducted in this study was based on manual coding. Although the analysis was detailed, this presents some subjectivity that may skew the identification of themes and patterns. Other researchers and analysts could interpret the data in a different way there by affecting the findings of this study. It is suggested that future research could leverage machine learning tools and Natural Language Processing to make coding automatic so that interpretation is made more objective in terms of themes and patterns discovery. Finally, these research limitations and future directions

could help in providing a roadmap towards tackling SCM and sustainability issues using GSCM principles and industry 4.0 technologies for a better management of SCs sustainably and efficiently.

6 Conclusions

This study provides an in-depth analysis of the sustainability and SCM challenges within Nigeria's RES, identifying critical barriers such as import dependency, logistical inefficiencies, economic constraints, regulatory gaps, corruption, and knowledge and skills shortages. By focusing on localized challenges in a developing market, the research enhances the understanding of unique obstacles faced by emerging economies in the RES.

Integrating GSCM practices and Industry 4.0 technologies offers a viable pathway toward enhancing both sustainability and operational efficiency in Nigeria's RES. Practices like recycling, reuse, and retrofitting can mitigate import dependency and extend the lifecycle of RE components. Concurrently, technologies such as the IoT and blockchain have the potential to improve transparency, resource optimization, and energy management. A unique aspect of this study is its emphasis on downstream challenges within the RESC, highlighting issues like inefficient logistics, weak end-of-life management, and a lack of environmental consciousness among stakeholders. Addressing these downstream inefficiencies is critical for the overall sustainability of the energy SC.

The research also identifies key barriers to the adoption of Industry 4.0 technologies in emerging markets, including infrastructure deficits, policy gaps, and skills shortages. By highlighting these challenges, the study provides actionable recommendations for overcoming obstacles through targeted policy interventions, capacity-building initiatives, and public–private partnerships. Policy implications of this research emphasize the need for regulatory reforms, streamlined processes, and enforcement mechanisms to address corruption and inefficiencies. The study advocates for capacity-building programs to equip the workforce with the skills necessary to adopt and manage advanced technologies. Additionally, incentivizing technology adoption through tax rebates, subsidies, and pilot projects can encourage investment and innovation in the sector.

In conclusion, this study bridges critical gaps in the literature by offering a localized yet globally relevant analysis of sustainability and SCM challenges in the RES. The integration of GSCM principles and Industry 4.0 technologies provides scalable solutions for enhancing global SCM and sustainability practices alongside operational efficiency. As developing economies like Nigeria continue their energy transitions, these insights will be instrumental in shaping resilient and sustainable SCs, contributing to global efforts toward a greener and more sustainable future.

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Data availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethical approval and informed consent to participate This study was carried out in accordance with the departmental ethics committee guidelines of the University of Strathclyde's Department of Design, Manufacturing and Engineering Management. Each participant gave written consent and was informed that their participation was voluntary, with the option to withdraw at any time. The collected data was anonymous and kept strictly confidential. The study's design prioritised participant safety, which did not use any patient clinical data, and was not carried out as a clinical trial.

Competing interests The authors have no competing interests to declare.

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