

# From Load shedding to opportunity: distributed solar and storage usage in South African SMEs

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## Keywords

Load shedding, storage usage, South Africa, SMES

## Abstract

South Africa's electricity shortfalls have imposed significant productivity and revenue losses on small and medium-sized enterprises, catalyzing the rapid adoption of distributed solar and storage solutions. This literature and grey evidence review synthesizes peer-reviewed studies alongside regulatory filings, utility plans, market intelligence, and program documentation to answer three questions: (1) what is the magnitude and heterogeneity of SME impacts from outages, (ii) which distributed solutions and financing instruments are most prevalent, and (iii) what supply chain and policy frictions constrain diffusion? Following a systematic review plan and quality checks, this paper screens more than 400 records from 2013 to 2025 across various databases, including Scopus, Web of Science, Eskom TDPs, IPP office, Nersa, CSIR, GreenCape, and bank/fintech reports. Key findings indicate that SMEs face energy challenges due to outages, which cause business disruptions. In urban areas, formal SMEs are increasingly installing rooftop solar panels and hybrid systems. The primary bottlenecks encountered include financial (high upfront costs, difficulty accessing financing) and installation-related challenges. Another important discovery indicates that the efficiency of solar and hybrid appliances, as well as their maintenance, has a significant effect on the actual savings businesses achieve. We propose a practical guide on providing working capital to solar installers, enabling businesses to scale up. This includes creating quality assurance programs to ensure systems perform reliably and sharing data openly, so businesses and policymakers can see what works well in terms of performance. Finally, this paper contributes to achieving several targets under United Nations Sustainable Development Goal 7 (Affordable and Clean Energy), particularly those related to universal energy access, clean energy, energy efficiency, and industry partnerships.

## Introduction

South Africa's decade-long electricity crisis has significantly impacted the operating environment for small and medium-sized enterprises (SMEs), which form the backbone of the country's economic vitality by contributing over 60% of employment and 34% of GDP (Mokati and Steyn, 2023; Nedungwana, 2023). After the record-breaking blackouts in 2023, where approximately 6950 hours of interruptions were recorded nationally, driven by Eskom's systematic generation shortfalls (CSIR, 2024). However, the electricity supply improved significantly in 2024. This is evidenced in the Council for Scientific and Industrial Research (CSIR) reporting an increase in Eskom's average energy availability factor to about 60%, up from an average 55% in 2023 (CSIR, 2024). Public disclosures corroborate this trajectory, registering 2024 load shedding at roughly 1650 hours, a reduction of over 75% from 2023, while diesel open-cycle gas-turbine (OCGT) dispatched by a significant 50% (Eskom, 2024). Despite these significant improvements in electricity, outages resurfaced in early 2025, highlighting the fragility of these gains for businesses (Eskom, 2025). These outages were caused by unit failures and depleted emergency reserves (Eskom, 2024, 2025; CSIR, 2025).

These disruptions not only erode productivity but also exacerbate financial vulnerabilities, as businesses struggle to maintain continuity amid escalating electricity tariffs and regulatory complexities. In response, many SMEs resort to using diesel generators and installing their own solar panels and batteries, which helps ease the strain on the national grid (CSIR, 2024). For SMEs often operating on tight budgets,

excessive electricity use and limited loan availability can result in lost sales, wasted stock, damaged tools, and high costs for backup generators. This is due to diesel backup incurring prohibitive fuel costs, often exceeding ZAR 20 per kWh during peak shortages (Mokati and Steyn, 2023; Energy, 2024).

Research on businesses and small power networks shows that distributed energy resources (DERs) as evidenced in solar panels, known as photovoltaic (PV), combined with batteries, can reduce these risks, lower bills, and keep operations running smoothly, even on weak or disconnected grids (Ahmad et al., 2022; Kofi, Afonope and Asare, 2022; Babayomi et al., 2023; Mourtada, 2023; Nyarko, Urmee and Ofei-Mensah, 2023; Town Carabajal, Stearns Selby and Ouedraogo, 2024). In South Africa, techno-economic structures affirm the PV battery viability in combating load shedding, as evidenced by its possibility of reducing costs of ZAR 1.2-1.5 per kWh and payback periods under 5 years (Ozoegwu, Mgbemene and Ozor, 2022).

Comparable insights from other countries' SME settings have shown that the long-term financial effect of investing in solar panels has minimised energy costs while offering strong resilience against power outages (Kofi, Afonope and Asare, 2022). This perception has been supported by other studies, which viewed the effect of using solar panels from other economic perspectives. For instance, in Pakistan and Kenyan industries, studies have shown that solar panels improve energy access in areas facing unreliable energy access (Ahmad et al., 2022; Kasau, Munji and Onyango, 2022). Other studies have shown that investing in solar panels and batteries cuts fuel needs and improves energy services (Babayomi et al., 2023; Mourtada, 2023; Nyarko, Urmee and Ofei-Mensah, 2023; Town Carabajal, Stearns Selby and Ouedraogo, 2024). For South Africa, the baseline is not a reliable hydroelectric supply but is overdependent on its coal plants and costly diesel during peak hours. The vulnerabilities that can be replaced by DERs, where behind-the-meter PV and storage systems can mitigate the effects of load shedding (CSIR, 2024; Eskom, 2024).

From an economic perspective, the rationale for SMEs adopting DERs stems from the need to manage reliability in uncertain environments. Interruptions introduce random disruptions to productivity, prompting firms to invest up to the point where the cost of added resilience balances expected losses, often quantified as the value of lost load (VOLL) (Kofi, Afonope and Asare, 2022; Ozoegwu, Mgbemene and Ozor, 2022; Nedungwana, 2023). Batteries offer immediate support during blackouts (Makhubele, Thango and Ogudo, 2025). PV reduces daytime reliance on the grid and outage risk, and their integration enables peak demand reduction, diesel substitution, and benefits from time-of-use pricing. Collectively, DERs expand the range of feasible production during supply risks, stabilising resource use and costs (Ahmad et al., 2022; Kofi, Afonope and Asare, 2022; Ozoegwu, Mgbemene and Ozor, 2022).

From a strategic perspective, DER adoption strengthens a firm's capacity to adapt to disruptions, while frameworks on technology diffusion and behavioural adoption reveal variation in uptake. Factors such as perceived affordability, technical familiarity, maintenance concerns and environmental considerations influence decisions as observed in Tanzanian manufacturing SMEs (Lyakurwa, 2023, 2024).

### **Problem statement**

The load shedding issue is multifaceted, rooted in both infrastructural deficiencies, as evidenced by gaps in mitigation strategies. This includes the limited focus on energy reliability assessment. Many techno-economic analyses for SMEs overlook site-specific outage frequency and duration, expected unserved energy (EUE), loss of load probability (LOLP), or sector-adjusted VOLL. All these measures are critical for designing PV battery systems that prioritise stability over mere cost savings (Bello, Adebayo and Ogunmodede, 2023; Nedungwana, 2023; Christopher, Kusakana and Numbi, 2025).

Equally critical issue is the insufficient attention to tariff and connection realities. Studies on grid-connected SMEs frequently disregard country-specific tariff elements, such as demand charges, ratchets, time of use or critical peak pricing, export limits, and non-bypassable fees, which can diminish projected savings by 20-30% with targeting adjustments (Opstal and Smeets, 2022; Ozoegwu, Mgbemene and Ozor, 2022; Bello, Adebayo and Ogunmodede, 2023; Mokati and Steyn, 2023).

Additionally, there is the issue of incomplete mapping of financing and the adoption of solar PV plants. While East African research discusses zero upfront arrangements (for example, is evidenced in Kenya's financial support system (Kasau, Munji and Onyango, 2022), and mini grid overviews address blended financing and tariff structures (Babayomi et al., 2023; Nyarko, Urmee and Ofei-Mensah, 2023). Whereas South African SMEs' financial structure is different, as evidenced in borrowing rates, terms, and risk

protection, which is different from its East African counterpart (Mokati and Steyn, 2023; Nedungwana, 2023).

There is also an under-explored supply and capacity challenge. Broader African reviews identify issues like complex licensing, standard gaps, operational and maintenance shortfalls and grid integration risks for mini grids (Babayomi et al., 2023; Nyarko, Urmee and Ofei-Mensah, 2023). For South Africa, quantitative insights on SME PV-battery projects, including installer availability, permitting delays, import during and post-installation support, remain sparse (Ozoegwu, Mgbemene and Ozor, 2022; Mokati and Steyn, 2023).

Based on these problems, this study is driven by three key gaps: the scale and variation in outage effects on SMEs, the prevalence and effectiveness of DER solutions and financing for SMEs, and barriers to DER diffusion in supply chains and policy. By addressing these gaps, this study examines how South African SMEs incorporate rooftop PV and battery storage to mitigate reliability risks, manage energy costs, and foster sustained growth. In particular, it assesses the scale and variation of outage impacts on SMEs through reliable metrics (EUE, LOLP, VOLL) and sector-specific process analysis, anchored in post-2023 system trends and business reliability. This paper also catalogues the DER solutions and financing mechanisms employed by SMEs, e.g. direct ownership, leases, hybrid configuration and evaluates their performance under local tariff and interconnection conditions, informed by recent techno-economic analysis and advances in energy management systems (Bello, Adebayo and Ogunmodede, 2023; Nedungwana, 2023; Christopher, Kusakana and Numbi, 2025). Furthermore, this study pinpoints supply chain and policy barriers to adoption, drawing from regional reviews and weak grid cases to inform South Africa's regulatory and market environment (Babayomi et al., 2023; Bello, Adebayo and Ogunmodede, 2023; Mokati and Steyn, 2023; Nedungwana, 2023; Christopher, Kusakana and Numbi, 2025).

By combining reliability evaluation with practical tariff modelling and drawing on insights, this paper provides a targeted evidence base for SME leaders, investors, and policymakers to enhance energy security in South Africa. This paper examines how SMEs are integrating distributed energy resources (DERs), specifically rooftop solar photovoltaic (PV) and battery storage, in their energy structures to mitigate energy reliability risks, reduce energy costs, and sustain SMEs' growth. This paper also addresses the strengths and weaknesses of the evidence base that informs policy and entrepreneurial decision-making in their energy structures.

Based on the research objectives, the paper addresses three research questions:

- (1) What is the magnitude and heterogeneity of SME impacts from outages?
- (2) Which distributed solutions and financing instruments are most prevalent, and
- (3) What supply chain and policy friction constrain diffusion?

Theoretical underpinnings

To interpret SMEs' experiences with outages and challenges related to DER adoption and diffusion, this study draws on a suite of complementary frameworks from economics, management, and innovation literature. These lenses provide a structured basis for analysing how firms navigate uncertainty, allocate resources, and respond to institutional constraints. Below, we outline each theory, its core principles, and their relevance to research questions 1-3, as well as the linkages in the empirical papers of the included study.

### **Reliability economics (VOLL, EUE, LOLP)**

Core principles: Outage costs arise from the value of lost load (VOLL), the economic cost of an underved kilowatt-hour, and expected unserved energy (EUE), which aggregates outage frequency, duration, and timing. Loss of load probability (LOLP) quantifies the risks associated with supply shortfalls. Firms invest in resilience until marginal benefits equal costs, balancing reliability against operational trade-offs (Ahmad et al., 2022; Kofi, Afonope and Asare, 2022).

Reliability of this for RQ1 is that it frames outages' magnitude and variation by sector and process. For RQ2, it guides solution selection (e.g. storage for high EUE scenarios. For RQ3, it explains the need for data on VOLL/EUE to overcome the measurement gap in policy design.

Mini grid studies reveal high implemented VOLL through post-connection income gains (Babalola, Daramola and Iwarere, 2022; Town Carabajal, Stearns Selby and Ouedraogo, 2024), whole South African

techno-economic analysis (TEAs) claims resilience benefits without explicit VOLL quantifications (Kofi, Afonope and Asare, 2022).

### **Production theory under uncertainty**

Core principles: Supply shocks, such as outages, shift the production possibility frontier inward, reducing capacity utilisation and raising unit costs through idle labour, spoilage, or rework. DERs expand and stabilise this frontier by smoothing input variability, enabling better resource allocation (Ahmad et al., 2022; Kofi, Afonope and Asare, 2022).

The relevance of this theory to RQ1 is that it highlights the sectoral differences in shock sensitivity. RQ2 explains why hybrids or storage thicken the frontier for reliability-dependent SMEs. For RQ3, it identifies capability gaps, such as maintenance, as barriers to realising these gains. These are linked to evidence, such as regional reviews that emphasise productive use-load vulnerability (Babayomi et al., 2023; Nyarko, Urme and Ofei-Mensah, 2023) and hindrance cases show cost reduction through stabilised operation (Mourtada, 2023).

These frameworks integrate to explain empirical patterns, high but varied outage costs (RQ1), drive solution choices (RQ2), constrained by institutional frictions (RQ3). They also guide measurement, such as VOLL/EUE data, and design, including standardised contracts, to reduce transaction costs.

#### **Methodology**

This paper is based on a systematic literature review methodology. The scholarly databases employed include Google Scholar, Scopus, and Web of Science, among others. To improve the robustness of the literature, assistive tools such as Undermind were employed. These papers were downloaded and collated as one. Covidence was used to combine the papers. This is done as a form of data screening and cleaning method to remove redundant papers, especially studies that appeared in more than one source. The duplicate papers were deleted. Additionally, the remaining papers were evaluated for their relevance to the topic area. Based on the author's discretion, papers were assessed manually. Those that were found to be irrelevant to the study were also deleted. The remaining relevant papers were included in the review.

## **Discussion**

### **Overview of the challenges faced by SMEs in South Africa**

Small and medium enterprises play a crucial role in the development of South Africa's economy, accounting for about 91% of formal businesses (Mokati and Steyn, 2023; Nedungwana, 2023). Despite this, SMEs face numerous challenges that hinder their growth and sustainability. This section discusses the challenges and opportunities faced by SMEs in South Africa, drawing from relevant bodies of literature. Managerial skills and planning are among the major challenges facing SMEs in South Africa, as evidenced by research carried out on SMEs in Mpumalanga Province, South Africa (Smith & Chimucheka, 2014). Furthermore, Fatoki (2014) also reveals the importance of managerial skills and development in fostering an enabling environment for SME development. Complimenting these findings, Molefe et al. (2018) explains that infrastructural impediments, including the lack of skilled labour, insufficient business training and poor local economic conditions, collectively constrain SME viability and longevity.

While sustained energy further compounds these issues, the challenges surrounding distributed solar and storage further increase the challenges faced by SMEs. This is evidenced in the deployment and maintenance of these systems, which require specialised technical knowledge and skills (Sodomaco et al., 2025). Training and capacity building are vital to address this challenge and ensure that local communities have the necessary skills to deploy and maintain these systems. Maintenance and operation issues can also pose as challenges to the adoption and usage of the distributed solar and storage systems. Thus, ensuring their long-term reliability and efficiency requires regular maintenance and upkeep (Sodomaco et al., 2025).

The financial support system is another salient challenge faced by SMEs. Studies have also revealed that the inaccessibility of finance is a major challenge faced by South African SMEs, as reflected in its impact on hindering business performance and growth. For instance, (Msomi & Olarewaju, 2021) highlighted that funding remains one of the major problems faced by small businesses in South Africa. This results in a low rate of business establishments and a high rate of discontinuance. This limits the ability of SMEs to assist in economic development.

While these financial constraints are a global challenge which is not limited to South Africa, studies on South Africa have shown that factors such as lack of demand and their inability to penetrate the markets, as well as high transportation costs, are specific challenges faced by South African (Molefe, Ayo and Lubbe, 2018). Despite SMEs being recognised as a major determinant of local growth, equitable income distribution, economic development, employment creation, and poverty alleviation within the African environment, the challenges faced by SMEs have led to low rates of entrepreneurial activities in South Africa (Nieuwenhuizen, 2019; Mokati and Steyn, 2023).

Given that SMEs have the potential to drive innovation, create employment opportunities, and make significant contributions to the Gross Domestic Product (GDP), it is imperative to address the constraints that hinder their growth. To address the challenges faced by SMEs in South Africa, there is a need to restructure policy measures that improve their energy accessibility. Moreover, there is a need to invest more in the upscaling of managerial capabilities and invest in staff training regarding energy management. This will equip workers with the necessary skills and knowledge needed to take on real-life responsibilities.

### **Distributed solar & storage in SMEs**

Distributed solar and storage have numerous benefits for SMEs, including cost savings, revenue generation, energy independence, resilience, environmental sustainability, and employment creation. Regarding cost savings and revenue generation, SMEs can significantly reduce their energy bills through the installation of solar panels and energy storage systems. According to the study by (Zakeri et al., 2021) pairing solar PV with a home battery in California and Hawaii can provide a payback period of less than 10 years for different building types. Moreover, SMEs can generate revenue by selling excess energy back to the grid through net metering or feed-in tariffs. For example, a study in the UK found that combining solar PV and storage without the policy intervention is not economically profitable under current market conditions. But, with the right incentives, such as dynamic retail pricing mechanisms and storage policies, SMEs can break even and even generate profits (Zakeri et al., 2021).

**Energy independence and resilience:** Distributed solar and storage enable SMEs to become less reliant on the grid, thereby reducing their vulnerability to power outages and price volatility. By storing excess energy generated during the day, to be used at the peak hours or at nights, SMEs can ensure a stable and reliable energy supply. This is particularly important for SMEs in regions with frequent power outages or those operating in industries that require a continuous energy supply, such as data centres or manufacturing facilities.

**Environmental sustainability and employment creation:** Solar energy is a clean and renewable source of energy, reducing the carbon footprint of SMEs and contributing to a more sustainable future. Additionally, the transition to a decarbonised energy future presents key opportunities to grow regional gross value added (GVA) through the creation of joint business ventures and trading models, thereby increasing local earning potential (Bray et al., 2022).

The solar energy section has created lots of employment opportunities globally, ranging from research and development to manufacturing, installation and maintenance. This job creation contributed to local and national economies by enhancing overall energy security and reducing reliance on fossil fuel imports. Bray et al. (2022) found that a smarter and more flexible energy system could result in financial benefits of between £17bn and £40bn generation to the United Kingdom by 2050. Many of these benefits are forecasted to be realised at the local distribution level. Therefore, if South Africa adopts these distributed solar and storage technologies, SMEs can reduce their energy bills, create more jobs, and stimulate economic growth.

### Discussion of RQ1: Magnitude and heterogeneity of SME impacts from outages

This question probes the scale of outage damages for SMEs and the factors driving variations across firms, sectors, and contexts. Then explored heterogeneity through sectoral, temporal, and firm-level lenses. Global patterns from weak and off-grid settings provide a benchmark, which we adapt to South Africa's scheduled load shedding. Interpretations draw on reliability economics (VOLL \* EUE), production theory under uncertainty, and dynamic capabilities to argue that outages impose substantial, unequal burdens, often exceeding simple energy cost estimates.

Global evidences consistently reveal outages as a major drag on SME performance, with damages inferred from post-migration or avoidance behaviours. In reliability economics, the expected outage equals VOLL, which is the cost of an unserved kilowatt-hour (kWh) multiplied by EUE, summing outages by frequency, duration, and load during events (Ahmad et al., 2022; Kofi, Afonope and Asare, 2022). SMEs seldom measure VOLL directly, but revealed values emerge from choices like diesel spending or electrification outcomes. Cohort studies in Kenya and Nigeria, for instance, demonstrate that PV-battery mini-grids increase operating hours by 2-4 hours daily and enhance incomes by 20-50% within the year, suggesting that pre-connection outages result in SMEs losing 15-30% of their potential revenues (Babalola, Daramola and Iwarere, 2022; Town Carabajal, Stearns Selby and Ouedraogo, 2024).

A Nigerian case study of 83 micro and small enterprises further demonstrates that generated replacement and activity increases, suggesting that outages previously halve generated replacement and activity increases. Suggestions outages previously halve production time (Babalola, Daramola and Iwarere, 2022). These gains represent lower bounds on damages, as production theory under uncertainty posits outages as shocks that contract the output frontier, idling labour and capital, while raising unit costs through rework or spoilage ((Ahmad et al., 2022)). In a weak grid context, avoided diesel costs reinforce this magnitude. Lebanon's intermittent grid hybrid shows PV-battery integration cutting fuel use by 40-60%, with total expenses dropping 25-35%. This indicates outages amplified grid unreliability, or levels where diesels' high price (often \$0.3–0.50/kWh) made it to default, yet still uneconomic (Mourtada, 2023). Ghana's warehouse analysis echoes this, modelling PV diesel hybrids yielding 15%-25% savings and emission cuts, revealing outages' roles in inflating baseline costs (Kofi, Afonope and Asare, 2022). Across sub-Saharan Africa, the review synthesises that production SMEs, e.g milling or welding, face EUE levels of 10-20% annually, translating to a VOLL equivalent of \$0.50-2.00/kWh when factoring lost sales (Babayomi et al., 2023; Nyarko, Urmee and Ofei-Mensah, 2023). Dynamics capabilities explain why some firms absorb these better. Those reconfiguring processes. E.g. batching tasks incur lower losses than rigid operations.

Moreover, the impact of an outage on SMEs is amplified by heterogeneity. This includes sector, timing, duration, power quality, and firm training. Regarding sectoral heterogeneity, SMES do not suffer similar impacts from outages; rather, sectors that depend more heavily on energy usage are more strongly affected during power failures than other sectors that do not directly depend on energy usage. For instance, high VOLL processes, such as cold-chain storage (which poses spoilage risks) or motor-driven manufacturing (which incurs restart penalties), suffer more than low-sensitivity tasks, such as energy for lightning purposes. Timing factors also matter. For instance, outages during the daytime may have different effects than those at nighttime. The impact of outages can be minimised during the daytime by companies that benefit from solar PV-aligned structures. Whereas evening outages hit sectors like hospitality the hardest, due to the concentration of their activities at nighttime. According to cohort data, there is a 30% income sensitivity to after-dark reliability in the hospitality sector.

Duration and predictability also affect the heterogeneity impact of outages on SMES. Short, frequent outages may have lesser impacts than a long outage, while long ones require a hybrid approach, frequent outages images poor scheduling, which raises coordination costs (Mourtada, 2023). Power quality issues (voltage sags) also compound blackouts. For instance, poor-quality electricity, as evidenced by small voltages, is found to trip equipment in 20-30% of events for sensitive SMEs. Despite this tripping of electrical equipment, reviews have shown that these effects are still hidden issues that are merely metered (Nyarko, Urmee and Ofei-Mensah, 2023). Moreover, regarding training, firm capabilities demonstrate that flexible operator shift loads can reduce effective VOLL by 20-40% compared to constrained peers (Lyakurwa, 2023).

Globally, three patterns emerge. Damages justify capital-intensive fixes, with storage key for reliability (Storage often 40% of costs, per reviews) (Babayomi et al., 2023). PV-only suits daytime loads under uncertainty (real opt-in stations (Kasau, Munji and Onyango, 2022) and hybrid hedge diesel baseline (Mourtada, 2023). Production theory ties this to frontier stabilisation, where DERs cut variance in input, boosting utilisation 15-25% (Kofi, Afonope and Asare, 2022).

Streamlining to South Africa, load shedding's semi-scheduled nature (4-6 hours daily in each) results in an annual increase of 5-10% in EUE for urban SMEs, with a VOLL of \$0.40-1.5/kWh, based on analogues (Eskom, 2024, 2025). The Johannesburg TEA implies substantial avoided losses for commercial scales, where storage mitigates evening peak heterogeneity. Cold chain and manufacturing face higher VOLL from quality needs, while daytime firms benefit from PV, and capabilities enable rescheduling (CSIR, 2024). Yet, methodological gaps persist. Few studies measure site EUE/LOLP in relation to sector VOLL, which biases the approach toward energy-focused sizing. Tariff omission (domain charges) further understates during peaks (Nyarko, Whale and Urmee, 2023; Borrego-Orpinell et al., 2025).

The theory-backed implication of this shows that reliability economies urge VOLL/EUE collection for sizing. Production theory recommends process mapping to target high-vulnerability sectors. Dynamic capability suggests training to amplify gains (Lyakurwa, 2023). For South African SMEs, this means outages cost 10-25% of revenue in affected segments, large enough for DERs to shift frontiers, but uneven enough for tailored interventions. In summary, outages impose economically significant damages on SMEs, which vary widely by context, with global evidence indicating a potential uplift of 15-50% from mitigation. South Africa's schedules cut heightened predictability but not magnitude, demanding localised measurement to avoid underinvestment. This gap, sparse site data and VOLL estimates remain the primary hurdle for effective planning.

**Table 1: Summary for RQ 1 - Magnitude and heterogeneity of SME impacts from outages**

Component	Description & Key Points (Verified Data)	Moderators (Theories/Funding)	Outcome (Reliability/Costs/Feasibility)
<b>Context (Evidence)</b>	<ol style="list-style-type: none"> <li><b>Global:</b> Unreliable grids drive hybrid adoption (e.g., Lebanon/Ghana: 40-60% cost cuts; Kenya/Nigeria mini-grids: 20-50% income boost).</li> <li><b>South Africa:</b> Load shedding causes 5-10% EUE increase; 10% PV import duties raise costs (Makhubele et al., 2025; CSIR, 2024; SARS, 2024).</li> </ol>	Transaction-cost theory (negotiation delays); Real options (uncertainty hedging).	Widens gap for SMEs; hybrids enhance reliability (70-90% diesel reduction; Kofi et al., 2022).
<b>Barriers (Mediators)</b>	<ol style="list-style-type: none"> <li><b>Regulatory:</b> Licensing/tariff delays, standard voids (Babayomi et al., 2023; Nyarko et al., 2023).</li> <li><b>Financial:</b> High CAPEX (40% for storage), credit rationing, 10% import duties (Opstal &amp; Smeets, 2022; FinMark, 2025).</li> <li><b>Operational:</b> Expertise gaps, maintenance, import dependence (Nedungwana, 2023; Halsey et al., 2024; NenPower, 2024).</li> </ol>	SME finance principles (green bonds/low-interest loans); Diffusion theory (awareness campaigns).	Increases costs (LCOS \$0.10-0.15/kWh; Zakeri et al., 2021); reduces feasibility (10-31% sales loss; World Bank, 2024).

Component	Description & Key Points (Verified Data)	Moderators (Theories/Funding)	Outcome (Reliability/Costs/Feasibility)
<b>Adoption Gap (Outcome)</b>	<ol style="list-style-type: none"> <li>Low DER uptake (e.g., 15% IRR for PV-only;</li> <li>hybrids yield 20–40% savings but limited by barriers; Ahmad et al., 2022; BNEF, 2024).</li> </ol>	Standardized regulations, O&M capacity building (Partnership, 2021; Esau et al., 2024).	Balances via hybrids: 9–30% savings in Kenya analogs; targeted surveys for VOLL/EUE (Nyarko et al., 2023; IEA, 2024).

### Discussion of RQ2: distributed solutions and financing instruments- prevalence and effectiveness

RQ2 examines which DER configurations and funding mechanisms best suit SME, balancing reliability, costs and feasibility. This study synthesises data from global evidence, assessing performance under varying outage and tariff conditions, then adapts to the South African context. Justifications is based on reliability economies for sizing, real options for staging, transaction-cost theory for contracts, and SMEs finance principles for accessibility. These revealing PV storage hybrids offer high value for reliability needs, with financing innovations key to overcoming capital barriers .

Solution archetypes target distinct goals. PV only emphasises energy savings for daytime loads. PV batteries add outage protections and peak management. Hybrid systems integrate diesel for extended events. Mini-grids serve clusters of SMEs. EMS/second-life batteries optimise across these systems. Reliability economies posit effectiveness as avoided EUE \* VOLL plus savings exceeding costs.

Global evidence shows that PV-battery systems yield 20-40% bill cuts in cumulative TEAs, with < 2-year paybacks where tariffs favour self-supply (Kofi, Afonope and Asare, 2022). The Pakistan SME cluster report indicates a 15% IRR and 7-8 year paybacks for PV-only systems, effective for daylight-based operations but limited by earnings (Ahmad et al., 2022). Kenya’s medium industry sees 9-30% savings via PV, boosted by zero-upfront leases for capital-poor firms (Kasau, Munji and Onyango, 2022).

Moreover, hybrids excel in unreliable grids. This is evidenced in Lebanon’s PV-diesel-battery case which cuts 40-60% and reduces costs by 25-35%, displacing peakers during intermittency (Mourtada, 2023). Ghana's warehouse hybrid yields fiscal and emission benefits, with storage enabling a 70-90% reduction in diesel use (Kofi, Afonope and Asare, 2022). Sub-Saharan reviews affirm their dominance for predictive uses, through storing 40% CAPEX shares, raising LCOS concerns (Babayomi et al., 2023). Minio grids from SMEs extend hours 2-4 daily and increase incomes 20-50%, per Kenya and Nigeria cohorts, implying high pre-connection VOLL. EMS and second-life batteries enhance all. Digital twins optimise dispatch for 10-20% extra savings, lower LCOS via repurposed cells if warranted (Borrego-Orpinell et al., 2025).

Furthermore, real options explain staging. PV is only considered a low-risk entry, with storage added when outages are clarified (Kasau, Munji and Onyango, 2022). Transaction cost theory can be used to explain how hybrid structure hedges diesel (Mourtada, 2023). SME finance theory highlights credit rationing, establishing the upfront cost of storage as a barrier. The hybrid structure mitigates this by leveraging existing diesel (Kofi, Afonope and Asare, 2022).

For South Africa, the Johannesburg PV battery case demonstrates the significant effectiveness of upper SME scales, resulting in substantial savings during load shedding (Makhubele, Thango and Ogudo, 2025). Daytime loads suit PV only (inferred from Pakistan/Kenya); evening/high VOLL sectors need storage/hybrid, given the predictability of scheduled citizens (CSIR, 2024). Financing prevalence is sparse. Capex dominates documented cases. But Kenyan leases suggest potential for South African SME. Diffusion theory notes warranties reduce perceived risk.

Implication: Prioritising PV storage hybrid proves most effective for outage-prone SMEs, with financing options such as leases enabling scale. South Africa’s tariffs amplify arbitrage, but evidence on prevalence remains inferential, warranting a targeted survey (Nyarko, Urmee and Ofei-Mensah, 2023; Borrego-Orpinell et al., 2025).

**Table 2: Summary of RQ 2 - distributed solutions and financing instruments**

Component	Description & Key Points	Outcome for SME (Reliability/Costs/Feasibility)
<b>Inputs: Theories &amp; Funding</b>	- Theories: <ol style="list-style-type: none"> <li>1. Reliability economies (sizing),</li> <li>2. real options (staging),</li> <li>3. transaction-cost (contracts),</li> <li>4. SME finance (accessibility).</li> </ol> - Funding: Capex, zero-upfront leases, warranties/incentives.	Enables low-risk entry; reduces credit barriers; 20–40% bill cuts.
<b>Processes: DER Configurations</b>	<ol style="list-style-type: none"> <li>1. - PV-only: Daytime savings.</li> <li>2. - PV-battery: Outage/peak protection.</li> <li>3. - Hybrids: Diesel integration for extended events.</li> <li>4. - Mini-grids: Cluster serving.</li> <li>5. - EMS/second-life: System optimization.</li> </ol>	Balances reliability (70–90% diesel reduction) with costs (<2-year payback); feasible for capital-poor SMEs via staging.
<b>Outputs: Balanced Suitability</b>	<ol style="list-style-type: none"> <li>1. - Reliability: Avoided EUE * VOLL.</li> <li>2. - Costs: 9–60% savings.</li> <li>3. - Feasibility: 15% IRR, 20–50% income boost.</li> </ol>	Prioritizes hybrids for South African outages; surveys needed for prevalence.
<b>Contextual Moderators</b>	- Global: Unreliable grids favor hybrids (Lebanon/Ghana). - South Africa: Load shedding amplifies PV-battery value; tariffs enable arbitrage.	Adapts to local tariffs/outages; overcomes barriers via leases.

**Discussion on RQ3: supply chain and policy friction constraining diffusion**

RQ3 identifies barriers to DER adoption among SMEs. This includes regulatory, financial and operational hurdles. This paper synthesises African evidence on mini-grids and weak grids, and draws parallels with South African experiences for the behind-the-meter PV battery. Transaction-cost and regulatory economics explain rule-induced delays, and real options highlight the chilling effect of uncertainty. SMEs' finance theory addresses capital mismatches, and diffusion theory reveals awareness gaps, collectively arguing that frictions widen the gap between potential and adoption.

Literature has established the complexity of licensing and tariffs as primary challenges to the adoption of distributed solar and storage. Evidence from West/Sub-Saharan reviews details bureaucratic approvals of these licenses, a slow tariff process, standard voids, and grid arrival risks that can strand assets (Babayomi et al., 2023; Nyarko, Urmee and Ofei-Mensah, 2023). In Lebanon's hybrid case, these standards bottlenecks were confirmed, despite diesel savings (Mourtada, 2023).

Storage costs (40% capex) elevate LCOS, deterring uptake, and absent subsidies/and monitoring shortfalls cause reliability lapses, per reviews (Babayomi et al., 2023). The SMEs survey identifies upfront/repair costs, as well as risks, as barriers, with availability driving adoption. Market risks like tariff volatility undermine bankability (Lyakurwa, 2023; Nyarko, Urmee and Ofei-Mensah, 2023). Transaction cost economies attribute delay to negotiation/enforcement burdens; real options to waiting under discretion, and credit rationing explain strong aversion. Diffusion theory links standards gaps to low observability (Lyakurwa, 2023; Nyarko, Urmee and Ofei-Mensah, 2023).

Other challenges to distributed and storage systems adoption include high upfront cost, financing investment issues, technical expertise and skills gaps, regulatory hurdles and maintenance and operational issues (Opstal and Smeets, 2022; Mokati and Steyn, 2023; Nedungwana, 2023). Regarding the high upfront

costs, studies have shown that it is a major barrier to the adoption of distributed solar and storage systems. High cost persists, despite tax credits (Opstal and Smeets, 2022; Mokati and Steyn, 2023). The cost of solar panels and energy storage systems, including batteries, can be excessively expensive for many households and SMEs. While governance and organisations offer various incentives and subsidies, such as tax credits and grants, to help reduce the upfront costs and to improve the adoption of sustainable energy, the high upfront costs still remain a significant challenge (Zakeri et al., 2021).

Moreover, financing and investment issues are similar challenges for the adoption of distributed solar and storage systems. Securing funding for these projects can be difficult, particularly for smaller communities or those with limited financial resources. Dedicated financing programs, such as green bonds or low-interest loans, can help address this challenge and provide more accessible funding options for smaller communities and projects.

Regulatory hurdles can also hinder the development and deployment of distributed solar and storage systems. Adjusting regulatory processes to accommodate these systems can make it easier for communities to follow regulations and deploy these systems. Public awareness and educational campaigns have also been found to increase understanding of the associated benefits of distributed solar and storage systems.

For South Africa, as of June 2024, a 10% import duty was imposed on PV solar panels (SARS, 2024). This raises the cost of solar panels for installers who must include the 10% tariff in their costs (IBC Solar, 2025). While this aims to bolster local manufacturing, it could increase project costs, delay procurement of solar panels, and limit competitiveness (Cliffe Dekker Hofmeyr, 2024). Imported lithium-ion batteries currently dominate the solar PV market, despite increased import duties and associated import-related risks. The country's dependence on foreign manufacturing also exposes it to component quality issues. All these are because the domestic value chain for battery cells is not yet well established within the country (Halsey et al., 2024) (WATTS Report, 2024; DTIC, 2025). Aside from the increased upfront cost associated, unclear regulations and weak local manufacturing capacity constrain storage investment in South Africa (NenPower, 2024). The regulatory uncertainty in licensing, interconnection, and market design is another major barrier (Partnership, 2021; NenPower, 2024).

While the challenges may be easily overcome by the larger firms due to their ability to absorb higher risks and capital costs, the small firm may be unable to overcome these hurdles, leading to their inability to install the DERs even during load shedding. To address these challenges, there is a need for standardised regulations, dedicated financing for solar PV and storage deployment that mirrors Kenya's structure. There is also a need for a stronger operations and maintenance capacity (Partnership, 2021; Esau, Ryoichi and Hiroyuki, 2024).

All this evidence shows that the barriers to DERs deployments in South Africa go beyond technical limitations, but also include regulatory fragmentation, high capital costs, import dependence, and insufficient local capacity. While South Africa benefits from growth opportunities through IPP tenders and storage procurement (IEA, 2024), there exists sparse empirical research on how SMEs are impacted by load shedding and the effect on distributed solar and storage systems.

**Table 3: Summary of RQ 3 - supply chain and policy friction constraining diffusion**

<i>Component</i>	<i>Description &amp; Key Points</i>	<i>Moderators (Theories/Funding)</i>	<i>Outcome (Reliability/Costs/Feasibility)</i>
<b>Context (Evidence)</b>	Global: Unreliable grids favor hybrids (Lebanon/Ghana/Kenya; 40-60% savings). South Africa: Load shedding, 10% import duties, regulatory voids (Makhubele et al., 2025; CSIR, 2024).	Transaction-cost (negotiation burdens); Real options (uncertainty waiting).	Widens adoption gap for SMEs; hybrids optimal for reliability.
<b>Barriers (as presented in Table 1)</b>	Regulatory: Licensing/tariff delays (Babayomi et al., 2023).	SME finance (leases/green bonds); Diffusion theory	Increases costs (e.g., stranded assets); reduces feasibility (e.g., 20-50% income boost untapped).

	Financial: Upfront costs, credit rationing (Opstal & Smeets, 2022). Operational: expertise/maintenance gaps (Nedungwana, 2023).	(awareness campaigns).	
<b>Adoption Gap (Outcome)</b>	Low DER uptake among SMEs; hybrids yield 20-40% bill cuts but limited by barriers (Ahmad et al., 2022).	Standardized regulations, O&M capacity (Esau et al., 2024).	Balances via strategies: 50% rural coverage by 2030; targeted surveys needed (Nyarko et al., 2023).

**Conclusion**

This review examined how South African SME can transform load shedding from a persistent constraint into a strategic opportunity through distributed solar PV and battery storage, identifying effective solutions and financing instruments while explaining diffusion frictions. Anchored in reliability economics, production theory under uncertainty, real options transaction costs and regulatory economies, SME financial principles, diffusion and adoption framework, dynamics capabilities, and lifecycle cost of storage reasoning, their core insights emerge from the synthesis of evidence across grid-connected, weak grid, and off-grid contexts.

First, the impacts of outages on SME are substantial and systematically heterogeneous, far exceeding incidental disruptions. African mini-grid household studies in Kenya and Nigeria revealed gains in operating hours (2-4 additional hours) and income increases of 20-50%. This implies that pre-electrification outages imposed high revealed VOLL through productivity and generator costs (Babalola, Daramola and Iwarere, 2022; Town Carabajal, Stearns Selby and Ouedraogo, 2024). A South African technological economic analysis at the commercial SME scale: corroborating this, projecting OPV plus outage configurations yields large bill savings alongside resilience benefits under load shedding, consistent with meaningful avoided EUE \* VOLL (Makhubele, Thango and Ogudo, 2025). Heterogeneity arises across sectors, with cold-chain, hospitality/ICT, and motor-intensive light manufacturing incurring elevated losses due to perishability, customer churn, and restart penalties, which are driven by temporal patterns and firm capabilities. Reliability economics demonstrates that the VOLL process is process-specific, while production under certainty explains how outages contract the output frontier, idle resources, and amplify unit costs. This necessitates resilience valuation beyond energy savings in SME planning.

The solution section should be context-conditioned and phased, with storage being essential where reliability predominates. PV only excel for daytime-based loads with moderate outage exposure. MES and second-life batteries further enhance efficacy, optimised dispatch, shift upfront and performance risks. All these are vital under capital rationing. Although the prevalence in South Africa remains undocumented. Transaction cost theory justifies bundled O&M in the whole diffusion of leases. Third, diffusion lags technical progress due to entrenched rules and risk frictions rather than inherent flaws. Regulatory economic attributes delay incomplete contracts and discretion, and real options to elevate deferred value and ambiguity. For South Africa, inferences suggest interconnection time and zero export rules on weak feeders, compromising costs, while export duties increase LCOS. This mirrors the regional patterns but is tailored to tariff intricacies.

Collectively, these insights call for a viable trajectory from load scheduling to opportunity: for SMEs, initiate with outage logging and process. VOLL mapping for targeted sizing. Favour PV only for diurnal flexibility, escalating to PV battery/hybrids as reliability warranta, leveraging leases for risk transfer (Ahmad et al., 2022; Babalola, Daramola and Iwarere, 2022; Kasau, Munji and Onyango, 2022; Babayomi et al., 2023; Mourtada, 2023; Makhubele, Thango and Ogudo, 2025).

For financiers and developers, standardised PPAs/leases with M&V and modular storage. Their offerings, by archetype (e.g., diesel hybrids for legacy users), integrate EMS for dispatch optimization (Kasau, Munji and Onyango, 2022; Babayomi et al., 2023; Nyarko, Urmee and Ofei-Mensah, 2023; Borrego-Orpinell et al., 2025). For policymakers and regulators, expedite interconnections with clear export.net billing, enforce battery/EMS standards and warranties; subsidise storage through guaranteed rates to curb

LCOS, mandate realistic tariff TEAs and capacity building for installers (Lyakurwa, 2023; Borrego-Orpinell et al., 2025).

This review's contributions lie in consolidating fragmented SME-centric evidence into a unified framework that foregrounds reliability alongside savings, matches archetypes with financing, and prioritises actionable frictions. Mitigation persists, with South Africa and Pericas confined to select TEA. Broader insights are inferred from African analogues. PPA/lease prevalence/terms, sector-VOLL, site EUE/LOLP, and storage under local tariffs warrant direct measurement (Makhubele, Thango and Ogudo, 2025).

A future research suggestion includes examining SME outages/PQ datasets with VOLL elicitation, standardising tariff-inclusive TEAs incorporating EUE\*VOLL, surveying PPA/lease uptake and structure, and assessing storage finance impacts via outcome tracking. This synthesis confirms that PV and storage, when sized and financed in response to quantified risks, offer scalable resilience for South African SEMs, converting systemic fragility into enduring competitiveness and equitable growth.

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