OPERATIONAL PAPER

WHY GRID CODES MATTER FOR EMBEDDED GENERATORS – COMPARING UTILITY VS FACTORY PERSPECTIVES

Ahlschlager R[1], Seebran P[1] and Gent R[1]

[1]*Zutari (Pty) Ltd, La Lucia, South Africa*

richard.ahlschlager@zutari.com, prasun.seebran@zutari.com, roy.gent@zutari.com

Abstract

Sugar companies, their factories and their estates are under significant pressure, in terms of their financial sustainability; this has been caused by many factors such as international competition, local taxes, escalating utility costs and land-use competition.

Cogeneration in sugar mills, especially those using bagasse as fuel, offers a compelling synergy between sugar production and electricity generation. However, balancing these dual outputs introduces several technical, operational and economic challenges, some of which can be highlighted as follows:

- Fuel supply variability - bagasse availability is tied directly to the sugarcane crushing schedules. Seasonal fluctuations and an inconsistent cane supply can lead to an unreliable fuel input, which affects the continuity of power generation.
- Steam demand – there is typically a conflict between consistent steam requirements for sugar processing and the steam requirements of turbines for exporting power.
- Technology issues – the older mills use inefficient boilers and back-pressure turbines. Upgrading them to condensing extraction turbines and high-pressure boilers is capital-intensive.
- Grid integration issues – many mills lack a robust interconnection infrastructure and are impacted by voltage fluctuations and synchronisation problems that impact a stable grid export.

A challenge (and frustration) to many in the sugar industry is the grid code. It stands as a barrier to the net power export and the associated income from power sales.

This paper attempts to demystify the grid code, to explain its purpose and to offer guidance on key considerations before exporting power. It outlines the importance of grid stability and the role of the grid code in achieving it. Protection requirements and network studies are examined, with the focus on their impact on sugar factories. Two scenarios are presented, based on examples from the southern African sugar industry.

Keywords: Grid code, generation, power, export, stability

Introduction

The past 10 years has seen increasing pressure being placed on the sugar industry in southern Africa. Prior to the introduction of the sugar tax, the South African industry was selling around 1.55 million tons of sugar, but since then, the consumption of sugary drinks has decreased by 30% (Minnaar, 2024). Coupled with this, there has been significant volatility in the reliability of the local utility electrical supply (loadshedding and shortage of capacity in

RSA, Malawi and Zambia, to name a few), which has had a particular impact on the demand costs and production in the agri-zone (Cronje, 2020; MOE, 2024; Nyasa Times, 2024).

With the availability of factory-based embedded generation, several large sugar corporations have grasped the opportunity afforded by the supply shortages and have seriously considered, or embarked on, the expansion of their facilities to become exporters of electrical power. Electricity is a commodity, as the Mauritian sugar industry has demonstrated by contributing 10% to the country's energy mix (EDBmauritius, 2023).

From the authors' experience, several barriers are faced by the sugar industry when developing or converting their facilities for power export, namely:

- the existing facilities have been developed for self-generation, behind-the-meter and islanding configurations, but not for power export; and
- there is a general lack of experience and knowledge relating to utility operations, transactions and technical design requirements.

A recurring theme in industry discussions is a persistent 'fear' of the grid code, which has been driven mainly by concerns over the compliance costs and the potential loss of their licenses. Ironically, due to the evolving standards and policies, many existing facilities are already non-compliant. Each country interprets and enforces their grid code differently, based on its regulatory maturity.

The current approach adopted by many companies that have historical co-generation facilities seems to be the 'don't poke a sleeping lion' approach. Based on the experience in South Africa, in particular, there may be serious merit in this. Any attempt to change the current operational model usually results in the following two drastic outcomes:

- a triggering of the renegotiation of the Distribution Use of System Agreement (DUOSA), with major implications relating to tariffs and possible technical requirements; and
- an in-depth evaluation of areas of the code non-compliance (based on plants installed over 30 years ago, with little supporting documentation).

In the RSA context, the local distributors for the DUOSA (Eskom and Municipalities) tend to be significantly more pragmatic on compliance than the national GCC Technical Evaluation Committees. A key constraint is that the GCC struggles to appropriately differentiate between a 765 MW utility scale base generation unit at a coal-fired power station and an embedded 5 MW cogeneration steam Turbo-Alternator (TA) at a sugar factory. This has not been appropriately resolved over the past two decades.

Furthermore, there is a requirement that any licensed generator must re-evaluate its GCC compliance every 6 years, but this generally does not trigger an 'event', unless there has been a change to the facility generation, which is a fortunate loophole for the industry.

Regardless, whether it is for power export or a compliance triggering event, this paper aims to demystify the grid code and provide some practical rationale and guidance for navigating compliance. The paper aims to minimise the technical jargon and explain why this often-feared regulation ultimately benefits all stakeholders.

Methodology/Approach

Dynamic (unstable) network theory

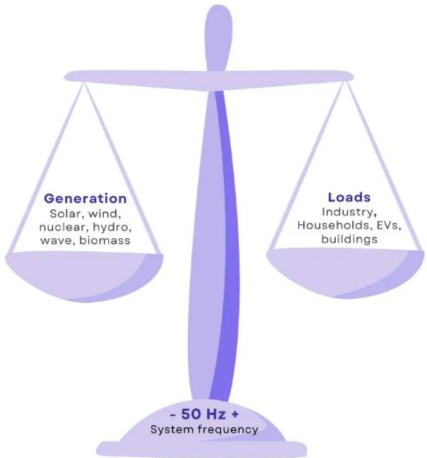

Figure 1. Power system frequency balance (Source: Vargas, 2023)

An electrical network is inherently unstable! What this means is that there is a fine balance that needs to be maintained between the supply and demand (Vargas, 2023). This is measured by monitoring the system frequency. Historically, power is largely generated by rotating machines. As they become overloaded, they slow down, and hence, there is a change in the grid frequency. If a machine rotates too slowly, it generates stress on the mechanical parts; and if it is too fast, heating and over-loading occur (Ibe & Oguejiofor, 2024). Should this happen, units will start to trip and isolate themselves from the electrical grid. This results in less generating capacity being available, with the remaining units becoming more overloaded, and thus tripping out. This is termed as a cascading event. The grid must either shed its load (within 2-3 seconds) to balance the remaining generation, or there is a national black-out. Restoration, after a national black-out, can take up to two weeks, based on the generation mix (BusinessTech, 2023). The economic losses to a nation are catastrophic (Cronje, 2020). The extended black-outs in the Iberian Peninsula in April 2025 are a very recent illustration of this – a cascading event caused 60% of Spain's generating capacity to be lost within 5 seconds (Carbonbrief, 2025)

Why Frequency Hertz? – the purpose of a grid code

A grid code has a very necessary purpose and aims to achieve many different things (Next, 2025). From a system perspective, embedded generation within a sugar factory impacts everyone on a national grid (via the concept of the butterfly effect). However, the impact is related to its scale:

- Safety – protection for all parties, for people and plants (as well as third parties – utility customers);
- Reliability – minimise the impact of internal and external network events on all parties on the network;
- Planning – the utility needs to understand what is happening on the networks as it is serving multiple customers, some locally affected by the embedded plant; and
- Fairness – it creates a standardised framework for all assets that wish to connect to the grid, setting a level playing field for all participants.

Layperson's overview of the grid code

The grid code, irrespective of country, will generally covers the following key aspects (next, 2025):

- the connection requirements regarding the voltage quality and the delivery of active and reactive power;

- the behaviour of the system in the event of failures in the power grid, also with regard to its islanding and black start capability;
- protection of the power grid in case of technical defects on the part of the connected generator;
- the technical requirements on the part of the generator, which allow the grid operator to remotely control (and curtail) power generation in case of turbulences in the power grid or for safety reasons;
- the specifications for the provision of system services (ancillary services) by the connected power generator;
- the tasks of the network operator in relation to the grid capacity and grid architecture; and
- organizational matters of daily operations e.g. the nomination of forecasted power generation, the metering and billing of generated electricity, the scheduling of maintenance works and the resulting down-time, etc.

Theoretically, the requirements for compliance will vary, based on the size and scale of the facility in relation to the general stability of the grid. However, many small rooftop PV units that are summed up can create a massive impact, an issue experienced in Australia (ABC News, 2025).

PPP – Protection for People, Plant and Performance

Protection 101 is firstly about protecting people. Human tissues, especially blood, muscles and nerves, contain a lot of water and ions, which make us susceptible to electricity flow. The consequences are numerous, such as cardiac arrest, thermal damage, involuntary muscle contraction and organ failure. The skin's resistance is only around 100 ohms, with an approximate 80V insulation threshold. Furthermore, it only takes 8 mA to cause the heart to fibrillate (IEEE, 2015). The largest challenge with protection is that electricity (and hence the threat) is unseen, and professional engineers are trained on the concept of earthing, insulation, touch-potential and step-potential.

Secondly, the sustainability of the facility (and shareholder interest) is built on the availability of the plant. Suffice it to say that an electrical plant failure can be catastrophic, depending on the criticality. The repair/replace lead times of a few key items, such as large transformers (8 months), primary HV/MV boards (4 months) and TAs (6 months), excluding transport, installation and commissioning, are measured in months.

What is often not adequately considered in protection, is the impact of performance and reliability. Protection is like a form of 'band-aid' that can be used to stop the bleeding. This is illustrated below, using a KPI called SLI:

Supply Loss Index (SLI):

$$\text{SLI} = \sum(\text{MVA Interrupted} \times \text{Interruption Duration})$$

Consider a simple network in Figure 2 with four loads of 1 MVA each. A fault occurs on L3 for 10 hours. If the L3 breaker operates, we have a SLI of 10 MVA hrs. However, if L3 does not operate and S1 operates instead, the SLI becomes 40 MVA hrs (400% greater impact). This becomes even more important if L2 was a critical service to, say, a boiler. Let us apply a system perspective and say that L3 is the cogenerating facility, and L1, L2 and L4 are grid customers; however, up to L20 customers exist on the node, instead of four customers. Suddenly the perspective changes and the reliability of the L3 breaker (termed the Point of Utility Connection PUC breaker) becomes a very important issue, from a utility perspective.

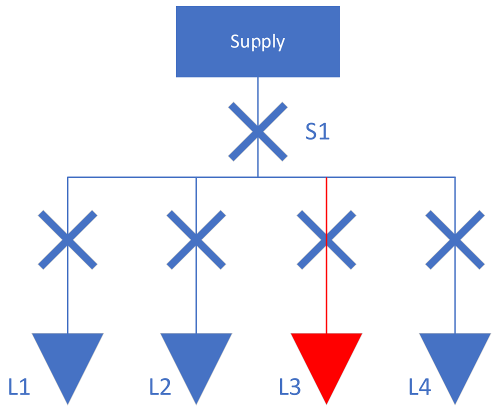

Figure 2. Simple Network to Illustrate Reliability

Protection is both a science and an art, with the key criteria being selectivity, discrimination, sensitivity and speed. It is a central part of a grid code that is aimed at protecting all the affected parties.

Stability – plant and grid

A key aspect of the grid code is to maintain the network stability. A power grid is a complex real network and it obeys certain complex laws (Holland, 2014). Although a network obeys physical laws (primarily Maxwell's equations, Ohm's law, Kirchoff's current law, etc.), the electrical flow is dynamic. Furthermore, networks are subject to both external environmental and internal factors that range from extreme weather, an inadequate design, lightning, a sudden load loss, human error, etc. The aim of the grid code is to maintain the stability of the network, whilst keeping certain operating criteria (the voltage, current and frequency limits) within the design and regulatory requirements. When the operating criteria threaten to step outside of these requirements, protection, and possible cascading, steps in. The national black-outs in Spain in April implies that their grid code application or philosophy had failed (assuming that, at the time of writing, it was not a cyberattack).

What studies inform projects (grid stability, fault, load, etc)

My colleagues and I have been fortunate in being able to assess multiple scenarios across many different countries in Africa (South Africa, Zambia, Nigeria, Eswatini, Malawi, Mozambique and Botswana, to name a few). A key danger for both agents and engineers is to think simplistically, which can manifest itself in several ways i.e.

- by assuming that a facility (factory or agricultural estate) is a closed system, and ignoring that it is embedded in part of a larger system (the national grid), which is embedded in part of a larger system (the Southern African Power Pool); and
- by assuming that the system is complicated and not complex. What is meant by complex is that changes or incidents in one part of a system can result in unforeseen consequences elsewhere. Behaviour can be hard to predict, due to the number of components and interactions, and these systems are not always adaptive (Kunjir, 2024).

This simplistic thinking is often driven by several factors, such as a lack of knowledge or competency, expediency and time constraints, as well as the difficulties involved in engaging with other stakeholders.

Studies are generally separated into static modelling and dynamic modelling. Static models are good for simulating and determining the status of system variables at a point in time. Generally, the network is simulated as a system of interconnected nodes that are linked by networks. Plant and system parameters are assigned to simulate scenarios (what is and what could be), in order to compare various parameters against the plant ratings. These parameters include power and thermal loading, load current and fault current, as well as over- and under-voltages. Static models are good, cheap and give quicker risk assessments to determine whether a project is viable. For instance, they can be used if a sugar factory wants to install a new 20 MW TA and needs to determine whether the internal and external system can accommodate the change (thermal loading, current, fault current and voltage step change for the sudden loss of supply or load).

Dynamic modelling is generally a requirement for most grid codes in larger plants (>10 MW). It looks at the real-time behaviour of the system to changes in the micro-second, milli-second and second range. The level of detail for building a realistic model can be onerous, as the expected accuracy of the model is extremely high by some bodies (i.e. in South Africa). The dynamic studies look at how the various control equipment will perform under various conditions. The equipment control could be the dynamic response of governors, excitation control, voltage regulation and inverter behaviour. The key question to answer is whether they can react appropriately and fast enough to dampen the consequences of an event, in order to prevent it from escalating or cascading.

These issues will be illustrated by considering some scenarios below:

Scenario 1 – Small export vs large export

Facility A has an embedded generation capacity of 20 MW. The capacity is the determining factor, in terms of contributing to the overall system impact. The system does not consider that the facility may already be using all, or 90%, of the power for self-generation and that it may only be exporting a maximum of 2 MW. This is because the embedded generation will still have an impact on both the facility system and the broader grid system. The critical system considerations are as follows:

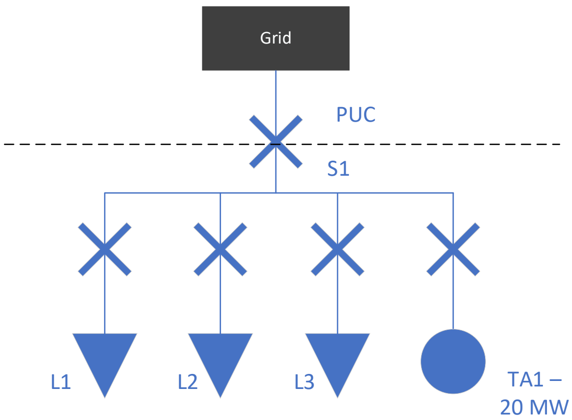

Figure 3. Facility with embedded generator

- The embedded generation contributes to the fault current, which has an impact on the fault current ratings of the existing equipment. The authors have encountered numerous industrial facilities that have 'evolved' over time. System considerations are aften omitted within the scope of work, and it may emerge over time that the equipment is underrated, that the facility does not comply with safety considerations, and that the cost of rectification is significant. The fault current contribution feeds back to the utility equipment ratings. It may transpire that the utility switchgear is now under-rated for its fault capacity, which poses a risk for the utility operators, such as exploding MV panels.

- Embedded generation changes the thermal loadings of the plant, primarily the networks (cables and lines) and transformers. Under different operating configurations (generally contingencies), it is not unknown for a plant to become thermally overloaded, which leads to it either becoming damaged (if protection is inadequate), or it may result in thermal tripping, which creates a cascading loss of production.

Scenario 2 – Weak vs strong networks

- While still considering the same Facility A of 20 MW embedded generation, there are some considerations regarding the strength of the network. What does that mean exactly? Strength can be a very technical term that incorporates system impedance, installed capacity, robust design and the inertia of an 'infinite' grid. Typically, it refers to the ability of the local grid to remain stable during system events, such as faults (voltage or current). Some of the factors affecting the connection to a network are explained below: Dynamic stability – A key constraint with a 'weak' network is that it cannot hold its frequency or voltage during a system event. There is a fundamental difference between the 4 GW of installed high-speed (3000 rpm) steam turbines and the 4 GW of a mixed hydropower (1000 rpm) and coal generation plant. High speed turbines have serious inertia, and when they are stacked together, it allows for a very stable network in terms of maintaining the frequency and voltage. Small TAs and hydropower units are generally much slower and have lower inertia, which means that they will change speed easily and cannot hold up the voltage during faults. So why is this important? Imagine a scenario where the facility is exporting or generating 30 MW in a country where the installed capacity is only 300 MW, and suddenly the facility's TA trips. The grid needs to respond to the sudden supply loss of 10% of available capacity within 2 seconds or risk a black-out. It must either dispatch power (via battery energy storage systems BESS or hydro) or shed the load quickly. Compare this with the 30 MW loss against that of 3 GW or 30 GW (for South Africa), and the issue of network stability for weak networks becomes apparent.
- Location, location, location – Even for South African facilities that are deeply embedded in a 'strong' network, such as the Eskom grid, this does not guarantee a solution. If the facility is assessing the viability of large power export, there are practical power transfer limits to the current infrastructure on the grid system that can set upper limits to project development. There is a major difference in the network capacity and considerations between trying to export 20 MW adjacent a 132/22 kV high-voltage substation, compared to being fed from a 22 kV or 11 kV medium voltage line 20 km away substation. Lower voltages in the MV range constrain the power export thermally and drive the power losses up significantly. For instance, it would be a poor investment if 5% of a new TA's power is lost to heat losses.

Key challenges with GCC planning and approval

From the authors' experience across the sub-continent, the following observations have been made. Each country manages GCC differently, in terms of rigour and expectations (realistic or otherwise). The following are a list of the considerations, without naming and shaming the utilities:

1. Some countries apply an unrealistic, legalistic approach to the GCC. The reality is that many facilities and co-generation TAs are +30 years old. The required plant

characteristics are not available, and the facilities were never designed with GCC in mind (as it did not exist at that time). There may be an exemption process; however, it can be inconsistently applied, and unfortunately, utility thinking is often applied to industrial facilities. The irony is that many of these facilities have been happily grid-tied with large-scale embedded generation for +30 years, without any major issues. If a facility wishes to move from net zero to a positive export of say 500 kW with 20 MW of TA installed based on existing plant, the facility is expected to fully comply, over time, to the utility level requirements, with the associated costs (refer also to Table 1 for the key technical issues).

2. A minor change in operations and infrastructure that is triggered within a project, can have significant unforeseen regulatory and economic ramifications. When applying for a change in the operating regime, opportunistic utilities may use the opportunity to trigger a change to the status quo, i.e. the technical requirements for Distribution System Use, tariff restructuring, etc. This can have major unforeseen consequences on the viability of current operations or on the project, in terms of cost and/or timelines. Although it may come across as cynical, some cash-strapped utilities use (or abuse) non-technical or unsuspecting developers to pay for deferred plant upgrades within their own systems, which have already been charged as embedded allocations within the current tariff.
3. Some utilities have made strategically inappropriate decisions regarding new energy mix and the dispatchability of power, which place the grid at risk. This presents both a constraint and an opportunity. For example, a significantly high level of solar PV, although comparatively economical to develop, is non-dispatchable and creates a network stability risk. The utility cannot call up a solar farm and demand a further 20 MW of power to address supply constraints. These networks are potentially weak and vulnerable to system disturbances (i.e. a cloud coming over a large PV facility, which triggers a rapid supply loss). It is unlikely that utilities will allow sugar factories to develop further PV facilities to support their energy mix; however, there could be a significant appetite to leverage the cogenerating facility upgrades with preferential tariffs, for both the base supply power export and dispatchability (based on facility constraints).
4. There are utilities with institutional challenges; for example, the utility may not have the capability or capacity to model and adequately simulate the planned facility for grid code compliance. As illustrated earlier, it can be tempting to 'chance' it and assume that the facility will behave as planned within the grid. However, an unstable generation node impacts all the stakeholders. The costs are reasonably small and, therefore, the developer should find the appropriate partners to determine the reasonable technical compliance, in order to identify and mitigate the risk to all parties.

Technical considerations and issues for the sugar plant

Based on several years of experience, we have identified the following list of the more common shortcomings, with respect to brownfield installations and the grid code.

Table 1. Typical issues between cogeneration within sugar facilities and the grid code

Grid code Item	Challenge
Power system stabilisers	The code requires that all Co-generators have PSS installed. This should not apply to existing generators, especially those with smaller generation plants. This should be dependent on the Co-generator size and position relative to the transmission system.
Short circuit test	Short circuit testing poses many risks; care needs to be taken when performing the tests, to ensure that no damage is done to the machines. Ideally, these tests should be carried out by the OEM to ensure that they are done within the machine limits. The OEM also then carries all the risks and not the Co-generator. However, many of the cogeneration machines are old, and the OEMs, when in existence, will not carry out the tests and carry all risks, transferring the risk to the Co-generator.
Excitation tests	The required excitation testing comes at a high cost, due to the technical expertise and external measuring equipment. Modern AVRs offer built-in testing tools, which should be allowed to demonstrate compliance; this reduces the cost and saves time. In addition, some excitation tests pose a risk to the units themselves, with one example being the ceiling limit test, which requires the excitation system to have a minimum excitation limit of 1.6pu rotor current. Testing this capability within the cogeneration environment, especially with ageing machines and limited OEM data, is a risk.
Remote control of reactive capabilities	The code calls for the remote control of the cogeneration units. This is not aligned with the SA OHS Act. The SO/NSP is not an authorised person to operate equipment in a cogeneration facility. Further to this, adjustments to the reactive power output of the machines affect the voltage control in the cogeneration plant. In general, this should be an ancillary service.
High & low frequency response	The required frequency range, and the associated time to be able to withstand these changes, are a risk to cogeneration units. Cogeneration plants prioritise both the electrical and steam stability and island themselves under abnormal external grid conditions to prevent a plant black-out. In general, the frequency withstand requirements should be revised, taking into account the machine's capability and plant process steam requirements.
Information exchange	OEM data for most existing cogeneration facilities is not available or limited. Further to this, information requirements are aligned to what is typically provided for modern Gx units, which would not have been available for older units. Proving this OEM data is a serious challenge for most existing plants and should be limited to minimum testing, where they are not available. To provide all the required data would require intrusive testing with the associated risks in an environment that is not conducive for what would typically be type tests.

Considerations at project inception

Should a sugar factory wish to explore a transition to power export, the following can be useful considerations:

- Assemble the appropriate team – It will require a mix of facility and utility competency and experience. Country specific knowledge is preferable. Why? Not all the information is readily available, and experienced practitioners can make informed assumptions, which will reduce the risk.
- Phase the assessment – Power export conversion and feasibility assessments can be phased appropriately. Static studies are faster and cheaper than dynamic studies and can point to system constraints that will affect the decision making. At current prices, a feasibility assessment can cost in the range of R300-500k, whereas a detailed pre-COD (Commercial Operations Date) dynamic modelling is in the range of R1-1.5 million.
- Fail quickly – Determine the economic parameters up-front. The margins in this type of project are narrow, and sometimes a donkey cannot be transformed into a racehorse with a coat of paint. Upgraded grid connections can be expensive (at scale, consider R40 million for a new substation and R3 million per km for network). However, if it is time to upgrade the boilers, or plant efficiencies have created excess steam, then opportunity knocks.

There are no quick and easy solutions. Each facility has evolved and is unique and should be evaluated within its unique context. Do not fall for simplistic thinking but consider the broader context and the impact on others, outside the facility perimeter fence.

Conclusion

The primary objective of this paper is to sensitise practitioners in the sugar industry to grid code compliance. The paper has illustrated how the grid code exists to regulate generation expansion, to level the playing field for those wanting to expand, and to address various technical and safety considerations. The code is applied inconsistently, which can be challenging, and projects that are aligned to a change between parties could trigger unforeseen consequences. Energy is a commodity and opportunities do exist to take advantage of this. However, engineering around large embedded generation is a complex undertaking, and developers should equip themselves with an appropriate team, they should phase their approach and be agile in their decision-making.

Acknowledgments

The authors wish to acknowledge Associated British Foods plc (ABF), Illovo Sugar Africa and Illovo Sugar South Africa for providing the opportunities over many years to partner, practise, explore and innovate around transforming traditional sugar operations in the area of energy production and power export.

References

ABC News (2025). ‘Overabundance of rooftop solar threatens to overload energy grid’, *ABC News*, 18 February. Available at: https://www.abc.net.au/news/2025-02-18/overabundance-of-rooftop-solar-threatens-to/104951632 (Accessed: 26 March 2025).

BusinessTech (2023). *Eskom has 6 ‘barriers’ to prevent a total black-out in South Africa*, *BUSINESSTECH*. Available at: https://businesstech.co.za/news/energy/705371/eskom-has-6-barriers-to-prevent-a-total-black-out-in-south-africa/ (Accessed: 26 March 2025).

Cronje J (2020). *Load-shedding cost SA economy at least R59bn in 2019 - CSIR*, *Fin24*. Available at: https://www.news24.com/fin24/Economy/Eskom/load-shedding-cost-sa-economy-at-least-r59bn-in-2019-csir-20200122 (Accessed: 12 August 2020).

Carbonbrief (2025). 'Q&A: What we do – and do not – know about the black-out in Spain and Portugal'. Available at: https://www.carbonbrief.org/qa-what-we-do-and-do-not-know-about-the-black-out-in-spain-and-portugal/ (Accessed: 30 April 2025).

EDBmauritius (2023). 'Energy Sector in Mauritius'. *Sustainability – the emerging business model – opportunities and challenges*, May. Available at: https://ibcmauritius.org/wp-content/uploads/Renewable-Energy-PRESENTATION.pdf (Accessed: 26 March 2025).

Holland JH (2014). *Complexity: A Very Short Introduction*. OUP Oxford.

Ibe UJ and Oguejiofor VC (2024). 'Under frequency in generating units, effects and mitigations'. *International Journal of Research and Publication* 3(5): 130-140.

IEEE (2015). 'IEEE Guide for Safety in AC Substation Grounding'. IEEE. Available at: https://doi.org/10.1109/IEEESTD.2015.7109078.

Kunjir A (2024). 'Exploring the applications of complex adaptive systems in the real world: A review', in *Artificial Intelligence, Machine Learning and User Interface Design*. Bentham Science Publishers, pp. 136-160. Available at: https://www.benthamdirect.com/content/books/9789815179606.chapter-7 (Accessed: 21 April 2025).

Minnaar K (2024). 'Trouble for sugar in South Africa', October. Available at: https://businesstech.co.za/news/finance/792944/trouble-for-sugar-in-south-africa/ (Accessed: 26 March 2025).

MOE (2024). 'Press statement on the electricity situation in Zambia'. Zambian Ministry of Energy. Available at: https://www.moe.gov.zm/wp-content/uploads/2024/06/PRESS-STATEMENT-ON-THE-ELECTRICITY-SITUATION-IN-ZAMBIA-AT-GOVERNMENT-COMPLEX-12.06.2024.pdf (Accessed: 26 March 2025).

Next (2025). 'What is the Grid code?', *The Power of Many*. Available at: https://www.next-kraftwerke.com/knowledge/what-is-the-grid-code (Accessed: 26 March 2025).

Nyasa Times (2024). 'Malawi: Prolonged black-outs return as Escom is overwhelmed by surge in stormy weather electricity faults', *Nyasa Times*, 28 November. Available at: https://allafrica.com/stories/202411280259.html (Accessed: 26 March 2025).

Sky News (2025). *Spain and Portugal black-outs latest: Power cuts not caused by cyber attack, Spanish grid says - but investigation launched*, *Sky News*. Available at: https://news.sky.com/story/spain-portugal-power-outage-latest-large-parts-of-countries-affected-with-traffic-lights-not-working-and-phone-lines-down-13357538 (Accessed: 30 April 2025).

Vargas B (2023). 'Power grid stability issues. Power grids are critical infrastructure', *Medium*, November. Available at: https://medium.com/@brandonvar/power-grid-stability-issues-aaeb41865718 (Accessed: 26 March 2025).