The impact of grid reliability and power quality on appliances and communities in the Global South, with recommendations for technical and policy actions

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Produced with support from the Efficiency for Access coalition[1], and many friends and colleagues (see acknowledgements).

Abstract

This paper provides a summary of the extent of power reliability and quality problems in the Global South (meaning developing countries) and the impact they have on appliances, people and communities. It sets out why this should be a policy priority as well as options to make progress, some of which are at least partially underway. The paper quantifies the scale and nature of the problems that unreliable and poor-quality grid power causes for appliances in the Global South and explores mitigation options from technological measures, international standards and appliance policy. Opportunities through including power quality in grid codes and energy regulation are identified. It also describes ways that appliance designers, developers of appliance standards, quality frameworks and policy makers can each help to ensure that appliances operate satisfactorily on poor quality electricity supplies. Actions to improve both grid reliability & power quality, and to improve appliance immunity to power problems are necessary to address the chronic problems evident in the Global South, and so ensure that promised benefits of access to energy are secured for communities and businesses in affected regions.

1 Power quality and reliability supports socio-economic development

Grid power that is unreliable and does not meet recommended levels for voltage quality hobbles economic development and degrades the resilience of around one billion people, most of whom live in the Global South[2], particularly affecting those in rural areas. These are the communities most impacted by rising temperatures and loss of climate stability. Whilst progress is being made on increasing the number of people and communities with an electricity connection, the *quality* of AC voltage supplied electrical power - meaning its combined reliability, voltage level, frequency, flicker, total harmonic disturbance (THD) and transient event occurrence - is failing in areas considered by policy makers as ‘connected’ and therefore not in need of further assistance. Power quality is a critical and often overlooked component of the wider challenge of fulfilling UN Sustainable Development Goal 7 - access to energy. Because power interruptions prevent the use of appliances and equipment, and poor power quality damages and destroys them, power reliability and quality are just as crucial to securing benefits as the connection itself. Connection, reliability and quality together help set the trajectory for economic and social development. Poor power quality and reliability impairs social and economic development and undermines healthcare and general wellness. The causes of power quality problems are sufficiently intractable and endemic that approaches are required from multiple directions to mitigate the impacts. Utilities should provide high quality and reliable electricity and/or appliances and equipment should be shielded from disturbances using surge plugs and voltage stabilisers, and/or appliances developed which are immune to these disturbances. These measures are crucial to global development, growth, and equitable energy transitions.

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[1] See https://efficiencyforaccess.org.

[2] The term ‘Global South’ is used in this paper in the spirit embodied in the UN Office for South-South cooperation (see https://unsouthsouth.org). Geographical areas of the Global South would be referred to as ‘developing countries’ or ‘developing regions’ in some contexts (including in the foundational documents of this UN Office), based on levels of welfare, economic development, life expectancy, fundamental rights and more. The term ‘developing’ has subtly varying definitions and is problematic; it was dropped by UNCTAD in 2021, although it still appears in UNOSSC explanatory texts and in some SDGs. See https://unstats.un.org/unsd/methodology/m49/ for the legacy UN listing that identifies 181 countries as ‘developing’, including countries of the Caribbean, Africa, South America, Central, South and Southeast Asia, the Middle East and elsewhere.

The layout of the paper is as follows: the current situation on power quality is described in section 2. This is followed by a description of the effect of poor power quality on equipment and appliances in section 3. Section 4 outlines ways to get a better understanding of the problem; sections 5 and 6 suggest possible solutions from the perspective of the appliances and the grid respectively. Finally, section 7 presents the conclusions and recommendations.

2 The scale and nature of unreliable grid and power that does not meet recommended quality levels

2.1 What do we mean by ‘power quality’ and ‘power reliability’?

‘Power quality’ is defined in standards IEC 61000-4-30 [1] and EN 50160 [2] as:

> *“Characteristics of the electric current, voltage and frequency at a given point in an electric power system, evaluated against a set of reference technical parameters.”*

However, the mindset needed to address equitable access to power of adequate quality and reliability, i.e., the mindset needed for public policy, is that power quality must be defined from the user’s perspective. This is the key to achieving the social and economic benefits of electricity access and was expressed at the initiation of the IEC power quality standards by an IEC advisory group in 1996 [3], which defined power quality as:

> *“An expression of the user’s satisfaction with the supply of electricity power quality. It could be considered ‘good’ if the electricity supply is within statutory and contractual limits and there are no complaints from users. Conversely, power quality is ‘bad’ if the power supply is outside of limits and there are complaints from users.”*

The technical assessment of power quality is complex due to the many factors that contribute to it. Utilities focus on the ‘quality of supply’, as made available by the utility according to factors under its control. This is considered separately to electro-magnetic compatibility (EMC) effects which concern actions by users and emissions from equipment used on the local network. For example, operation of welding equipment, starting of large motors, running power electronics and more can cause or inject distortions of voltage and frequency into the network. The user’s experience of power quality therefore depends not only on the supply but also equipment connected to it and installation practices.

Many of the most common types of AC voltage disturbances are illustrated in Figure 1. In approximate descending order of prevalence and impact, the main power quality issues are:

1. Voltage dip or sag, a voltage drop lasting fractions of a second to a few seconds.
2. Brown-out (longer-term voltage dip) more than 10% below nominal and lasting hours (not shown in Figure 1).
3. Voltage swell or overvoltage, over 10% above nominal for fractions of a second to seconds.
4. Harmonics, the distortion of the sine wave pattern on an AC supply.

’Power reliability’ is an expression of the degree of availability of useful power supply measured over days, weeks or longer. It is expressed in terms of the number and duration of interruptions to power supply provision.

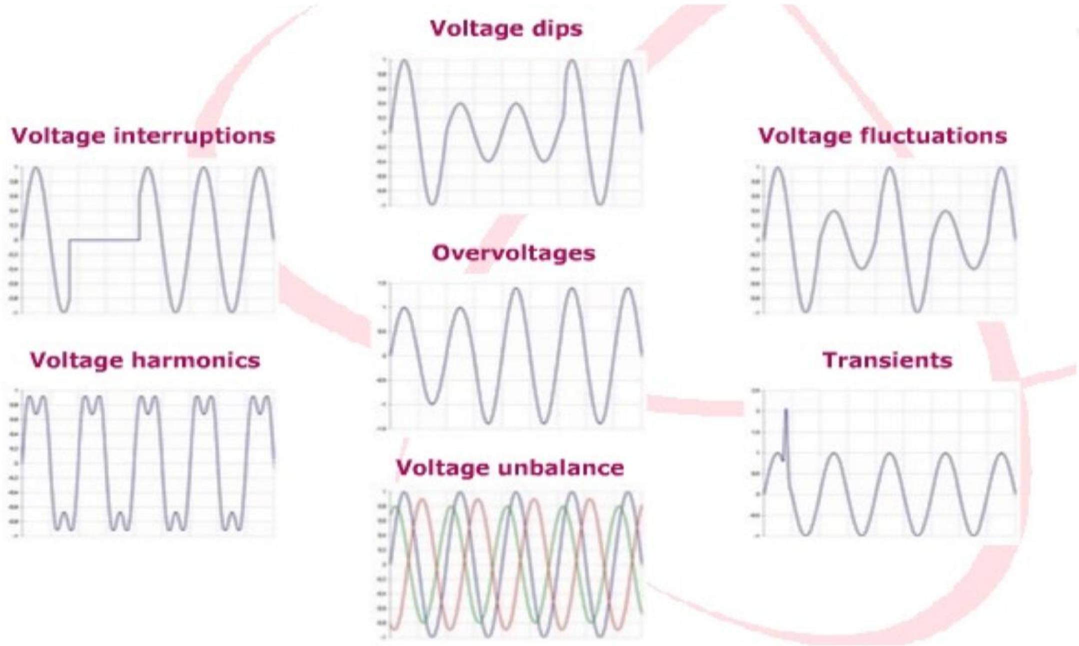

Figure 1. Illustrations of many of the types of voltage disturbances that affect public grid (source: Leonardo Energy).

2.2 How is power quality and reliability measured?

Rigorous quantification of the problem is an essential first step. There are standards defining instrumentation (voltage sensors) as well as formal metrics (see 2.3 below), statistical methods and guidance books by industry organisations and regulators. Unfortunately, the data and metrics are challenging for non-experts and policy makers to understand and are rarely correlated with the economic and practical impacts they have. On the other hand, several NGOs and consumer rights initiatives have developed their own ways to present information more simply, but these metrics lack rigour (they do not comply with IEC measurement requirements) and are too easily dismissed by utilities and policy makers. The large number and complexity of metrics in use and their non-comparability creates a problem for analysts, investors and policy makers. A case in point is that having a public network grid connection is not a simple yes or no: the enormous variations in reliability and quality of power connections mean that they can be almost useless for some or even much of the time (see Figure 2 and 2.3).

2.3 How bad does power reliability and power quality get?

Firstly: how *good* does it get? The ‘gold standard’ quality benchmarks to which all public grids aspire are set out in the ‘recommended power quality’ in standards IEC TS 62749 [30], EN 50160 [2] and similar. The main quality parameters are:

- <+-10% voltage magnitude variations for 95% of the week.
- Supply voltage dips with majority <1sec and depth <60% of Voltage.
- Short (<3 min) interruptions, a few tens-hundreds per year with 70% of them <1s.
- Long (>3 min) interruptions <10-50 per year.
- Interruptions of voltage are often expressed statistically using System average interruption frequency index (SAIFI), typically 1.5 power interruptions per year and System average interruption duration index (SAIDI, indicating average duration of interruptions), <2 hours.

These requirements are addressed in most Global North economies through Grid Codes imposed by energy regulators. Surveys and regulator reports suggest that grids in the Global North have generally met these expectations in recent decades (though power quality challenges are increasing due to distributed renewables, power electronics and other reasons).

The picture for most Global South public grids is very different: Face-to-face interviews with 48,000 citizens across 34 African countries by Afrobarometer in 2022 [15] showed that fewer than half (43%) of Africans received a supply of electricity that worked “most” or “all” of the time. One third of citizens in

Nigeria, Ethiopia and Guinea rated reliable electricity as a “critical problem for government to address” [4]. In 2019 the average household in India received 20.6 hours of power supply per day; most households in India (76%) faced unanticipated supply interruptions; and two-thirds of rural and two-fifths of urban households in India faced outages at least once a day [5].

Figure 2 shows how misleading the simple counting of connections for policy purposes can be. Left shows the proportion of people interviewed that had a connection; right shows the proportion who say their connection works ‘all of the time or most of the time’. In Lagos in Nigeria, close to 100% of its 15 million or more inhabitants had an electrical connection but only 10% of those surveyed said they had a connection that works ‘all of the time or most of the time’; the situation for Accra’s 2.3 million inhabitants is similar with only one third having a ‘reliable’ connection. Businesses in these major modern cities generally have a generator as backup with all its associated costs (and pollution consequences if diesel) to sustain operations.

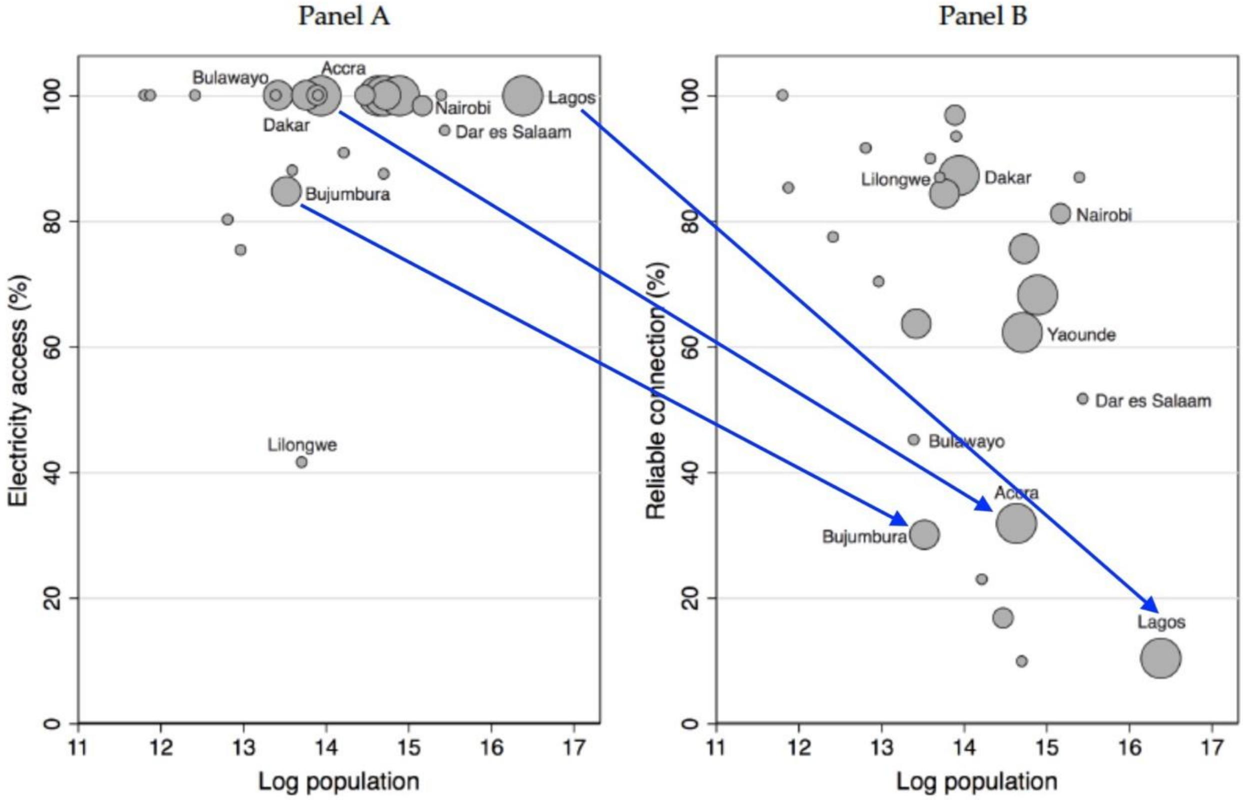

Figure 2. Survey data from cities of sub-Saharan Africa showing electricity access rates (left chart) and reliability of their connection (right chart) defined as ‘works all of the time or most of the time’. (Source: Wolfram 2017 [6]). Circle size is proportional to city’s population density.

Further examples include:

- The Kenya Power and Lighting Company (KPLC) report a SAIFI of 16.5 interruptions per year in Nairobi city (IEC recommended value is 1.5)
- KPLC report a SAIDI of 162 hours per year for Nairobi (recommended 2). World Bank data from businesses [24] suggests a SAIDI for Kenya of 410, for Togo of 495 and for Uganda of 760
- Surveys of nearly 350 health centres across 36 counties of Kenya and 8 states in Nigeria [7] for the World Health Organisation (WHO) 2018-2021 showed that the average number of interruptions at each site per year lasting longer than 48 hours was 2.5 in Kenya and 15 in Nigeria.

The supply voltage quality is also often poor. For example:

- The most common household power conditioners in West Africa are designed to deal with a voltage range of 140V to 260 V rms[3].

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[3] Extending this range requires heavier and more expensive transformers that consumers are reluctant to pay for, even if they are needed. Also, few consumers are aware of what voltage range they receive.

- Refrigerators in Pakistan are prominently advertised (Figure 3) to cope with common voltage excursions.
- The voltage stabilizers specified by WHO [8] to protect vaccine refrigerators are required to deliver stabilized output from input Voltage as low as 173V (standard type) and 110V (extended type), and with input up to 278V. Outside of this range they must withstand and safely isolate the unit from its power source (for up to 415V input).
- From the survey data at 350 health centres in Kenya and Nigeria (quoted above), 18% of locations experienced a voltage level of at least 350V in 3511 separate events; 8% had at least 415V. Sixty events exceeding 350 V were longer than 2 hours, and the longest lasted 15 hours. Any one such event is sufficient to destroy sensitive and life-saving equipment if unprotected, which is why voltage stabilizers are often used combined with WHO certified equipment.

Figure 3. Example advertisement seen in an electrical department store in Lahore, Pakistan promoting a refrigerator that can operate on a voltage between 120 V and 280 V and remain cold for more than five days in the case of power failure (October 2022).

2.4 How many people are affected?

Whilst numbers are hard to determine with accuracy, several authoritative sources such as the World Bank [9], Afrobarometer [4] and GOGLA [11] concur that unreliable and poor-quality grid power impacts around one billion people. Afrobarometer provides a primary survey-based source for the African component of this from its continent-wide survey about electricity provision of 48,000 citizens across 34 African countries.

2.5 Causes of power quality problems

Power quality and reliability problems in the Global South arise from many causes, including overloaded distribution lines and transformers; lack of voltage controls in the network; under-investment in grid protection equipment such as surge arrestors, poor control of EMC[4] in connected equipment and lack of maintenance. Power quality problems can arise and propagate through unprotected grids due to power electronics such as vehicle chargers and poor quality inverters on distributed renewable energy sources. Good engineering practice for utilities to address power quality and reliability is clear and well understood by engineers in Africa and most Global South utilities. The underlying barriers are instead lack of financial investment in the grid infrastructure at distribution level, and resource constraints such as severe shortage of technical staff in electrical power distribution. Evidence from many sources suggests that local distribution system operators in both rural and urban areas of Africa struggle to fulfil

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[4] EMC is electro-magnetic compatibility and relates to Voltage quality disturbances created by emissions from equipment in use on the local network. Useful context can be found in EN 50160 Annex D ‘Relationship between Power Quality and EMC’.

obligations due to highly constrained budgets. As an indication of the challenges to raise power quality in Africa, audits of 18 distribution licensees in South Africa in 2019 [21] concluded that the most common challenge faced by all licensees was budget constraints, with licensees spending less for repairs and maintenance over the years; the most common non-compliances were on repairs and maintenance budgets below target. Audits revealed chronic staff shortages with vacancy rates between 4% and over 70% and an average at 30%. In such circumstances, regulatory pressure is not (and cannot be) effective without increased investment, which is often correlated with other political priorities.

2.6 Power quality and power reliability are both improving and getting worse

Afrobarometer surveys have shown that the overall average proportion of users across 31 African countries receiving a reliable grid connection (that works ‘all of the time or most of the time’) increased by 3 percentage points from 2015 to 2021 [15]. Afrobarometer identified this ‘very modest improvement’ as benefitting economically well-off households most. But this masks national variation of trends with a best improvement of plus 14 points and worst deterioration of minus 38 points. Without doubt, power quality is not getting the focus needed to secure the benefits of energy access for all (as set out in UN Sustainable Development Goal 7 on access to affordable, reliable, sustainable and modern energy[5]) and around one billion are being left behind. Grid reliability at the Low Voltage (LV, local distribution) level remains a major challenge in sub-Saharan Africa where economic conditions and the weak financial condition of most utilities suggest that this will not improve quickly, if at all in many places. There is widespread lack of investment, lack of scope for investment through constrained budgets, and difficulty in recruiting and retain skilled staff to help tackle these challenges in power distribution [12].

3 Consequences of unreliable grid and inadequate power quality on appliances and communities

Power blackouts stop equipment running if there is no backup power, and this makes running a business much harder and more costly. The effects of *power quality* events, on the other hand, are many, varied and far less visible. The fundamental problem is that appliances from virtually all manufacturers around the world, and the testing included in all international appliance standards (individual exceptions noted in this paper), are designed to run on ‘good quality and reliable’ power supplies, whereas appliances are susceptible to different types of power disturbance, depending on their components and functions. For example [18[6] and other sources]:

- Motors: high voltage can cause over-heating and shorter lifetime; reduced torque; reduction in load-carrying ability; higher starting (inrush) current which increases the stress on already stressed grids.
- Computers: Voltage outages of 0.2 – 2secs are particularly harmful to computers and liable to cause hard disk crashes and loss of data; machines can also be destroyed by voltage spikes.
- Controllers that use the AC waveform for timing can be misled by harmonic distortion[7] disrupting manufacturing processes and automated equipment.
- Variable Speed Drives: can be tripped by voltage sags down to 80% of nominal voltage or lower.
- Rectifiers: can be triggered to shut down by voltage sags.
- Lamps: ballasts prevent CFLs lighting under low voltage; incandescent lamps give low light (under sag) or burn out faster (swell).
- Relays: voltage sags approaching 50% for more than a few cycles can cause relays to chatter (open-close-open cycle rapidly) or disconnect.

Any of these effects and more can cause appliances and equipment to under-perform, get damaged or destroyed since most appliances lack immunity from one or more power quality disturbances. When appliances and equipment are damaged or destroyed citizens lose the benefits of energy access and suffer financially, businesses lose money and can fail, appliance manufacturers get more warranty claims and reputation damage, local investment is put off and businesses are harder to start up and

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[5] See https://www.un.org/sustainabledevelopment/energy/.

[6] Note that this reference, IEC TR 63222-100, considers mainly relatively small deviations of power quality, only slightly outside of recommended levels of EN 50160 for example. It does not address the severe power quality issues seen in many Global South public grids.

[7] Harmonics can alter the interval between zero pass points, being points when the voltage passes through zero and the basis of timing for many PLC and other computer controlled systems.

run. Power quality events result in earlier occurring and additional e-waste when equipment is permanently damaged or destroyed, in particular by voltage spikes well above the nominal voltage (see 2.3 with monitoring showing thousands of 350V and higher spikes on 220V nominal in Kenya and Nigeria).

4 Ways to map out the problem

4.1 Quantifying the problem: monitoring the reliability and quality of grid power

Inadequate voltage quality monitoring was clearly identified by ESMAP in its 2015 analysis that underpinned the multi-tier framework for energy access [13]. It was - and is - also true for Europe: The Council of European Energy Regulators confirmed in 2007 that the availability of reliable measurements is 'a very critical issue' for voltage quality [14]. As the adage goes, 'if you can't measure it, you can't manage it'. Unfortunately, monitoring and analysis tools for assessing power quality are often financially and practically out of reach for many utilities in the Global South.

Large scale surveys for World Bank[8,9], Afrobarometer [15] and others focus on reliability (not voltage quality) and have established longitudinal data in many regions of the world. Monitoring of voltage quality, on the other hand, is more technically demanding on monitoring sensors and data analysis, Excellent examples include the Electricity Supply Monitoring Initiative (ESMI) in India by the Prayas Group [16] which ran from 2014 to 2019, measuring minute by minute voltage measurements at over 160 locations across 55 districts of India in households, commercial and agricultural businesses. nLine[10] has deployed two thousand of their PowerWatch sensors[11] to monitor voltage quality in Ghana including for utilities (more in other countries).

Unfortunately, these NGO and consumer-focused initiatives generally lack the technical rigour to be usable by power sector professionals and regulators. A key proposal for change is that more longitudinal measurement campaigns are undertaken in Global South regions with sensors and statistical approaches that comply with IEC and similar standards. A priority need is for more affordable and easier to use power quality monitoring sensors that can automatically upload data to a cloud-based server for analysis. The main author is already working with the leadership of ESMI (Prayas Group), nLine and others in pursuit of this. This enables persuasive data on wider geographical areas to influence policy and priority setting. The Prayas Group has succeeded in using ESMI data to influence investment in and regulation of grid power in India[12] and this must be more widely replicated.

4.2 Building understanding of the socio-economic impacts of unreliable grid

The rationale of several SDGs and in particular SDG7 on energy access make clear the transformative socio-economic benefits of energy access for communities. But more research is needed to quantify those benefits and specifically how reliability and power quality of connections impact outcomes when power does not meet voltage reliability and quality recommendations (one example synthesis study is [17]). The link between reliability, power quality and socio-economic benefits must be made explicit and quantified to achieve a higher policy priority and funding.

4.3 Understanding the impacts power quality on components and appliances

Vulnerabilities of components used in appliances and equipment are well understood and described in technical literature, including an IEC standard on this topic [18]. This information can be promoted more clearly to appliance designers via international standards and, when appropriate, ensured via regulatory requirements. The vulnerability of a component is characterised by voltage tolerance envelopes or 'ITIC

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[8] See www.enterprisesurveys.org/. Enterprise Surveys are conducted with hundreds of business owners in each of 139 countries every three to five years and include one question on the number of hours of outages experienced over the previous month.

[9] See www.doingbusiness.org. Doing Business Surveys annually collect an array of metrics of policy and process relevant to starting and operating small and medium enterprises in 190 countries. Now called B-READY.

[10] See https://nline.io/about.

[11] PowerWatch technical specification available here: https://nline.io/docs/powerwatch_spec_sheet.pdf.

[12] See https://energy.prayaspune.org/our-work.

charts'[13]. A generic example is shown in Figure 4 in which events (black diamonds) above or to the left of the lines are 'tolerated' by the component. Engineers can use these to evaluate the impact that disturbances will have on equipment and to select components that will operate in the expected conditions.

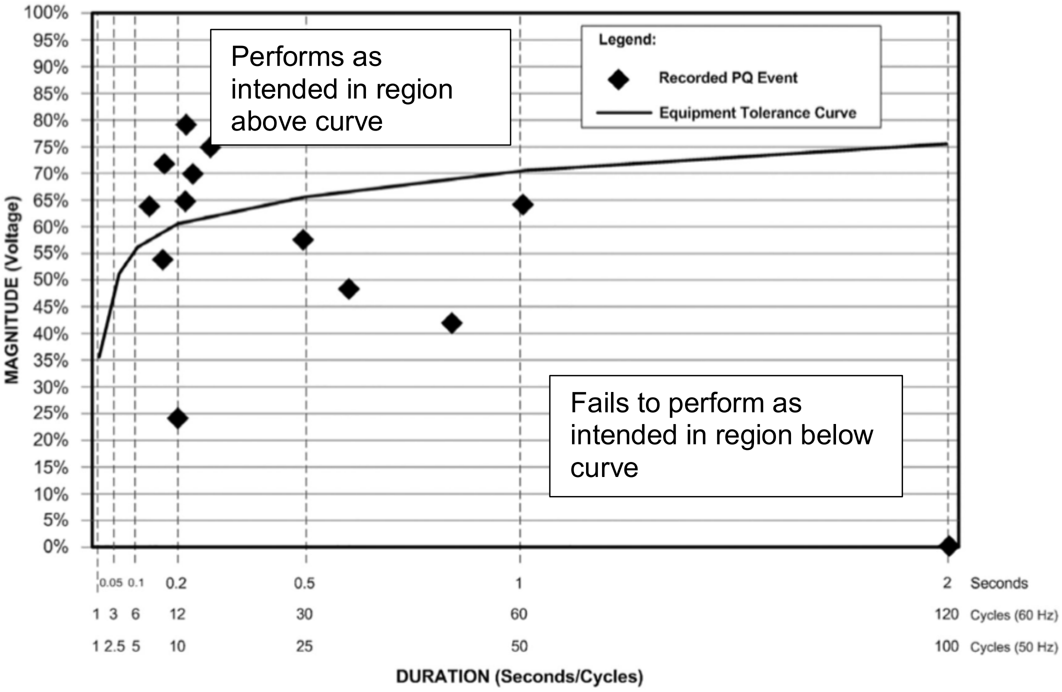

Figure 4. Example test result voltage-sag tolerance curve with power quality (PQ) event data overlaid.

5 Options to mitigate risks to appliances

Power quality problems undoubtedly damage appliances and equipment in Global South regions but this can be reduced by shielding appliances (5.1), by providing appliances that are inherently more immune to the problems (5.2) and to make appropriate immunity more likely by use of standards (5.3) and policy (5.4). Appliances can also be designed to ride through - or at least more effectively recover from - power interruptions and a new IEC standard is designed to assess this functionality and power quality immunity for refrigerators (**Error! Reference source not found.**5.5).

5.1 Shield appliances from harm: use of voltage stabilisers and surge protectors

Consumer level equipment is available to protect appliances from poor quality electricity supply, but at a cost. Home use voltage stabilisers are common in households and businesses in regions with poor power quality. Refrigerators are usually sold in Nairobi (for example) along with an external voltage protector plug for users who can afford them. To protect vaccine refrigerators and other electrical equipment used in health centres, WHO specifies that they should be deployed with voltage stabilisers [20] when in many regions of the Global South. Stabilisers enable attached appliances to continue to function over a defined input voltage range that is far outside of the power quality recommended by IEC and EN standards and once that range is exceeded, power to the appliance is safely cut. If the power supply problems are better understood and characterized in a region, then the design of protection devices can be tailored to avoid over-specification and make them more affordable. Power supply conditioners commonly seen in West Africa[14] are unable to deal with more than 260Vrms, since higher voltages require larger and more expensive transformers that consumers don't want to pay for. The

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[13] The Information Technology Industry Council (ITIC) was formerly known as Computer & Business Equipment Manufacturer's Association (CBEMA) which gave its name to earlier forms of a chart from the late 1970s onwards that defines the voltage tolerance envelope for computer equipment.

[14] Personal correspondence in 2022 with Chris Moller, based on experience running repair cafés for electrical equipment in West Africa.

lower voltage limit is usually around 140Vrms on a 220V nominal. Power supply conditioners able to deal with wider ranges are available at higher prices.

5.2 Improve the immunity of appliances to voltage disturbances

It is possible to make appliances more immune to voltage disturbances. There is little interest in this from appliance manufacturers in the Global North as power quality problems are relatively rare and (other than rare power cuts) unnoticed by consumers. But in the Global South interest is growing, for example:

a) Manufacturers in Pakistan promote voltage immunity of appliances and how long food can stay cool in refrigerators during power interruptions (Figure 3).
b) A multinational appliance manufacturer is improving power quality immunity of its appliances in Pakistan to reduce warranty claims and protect their reputation[15].
c) nLine is helping an electric cookstove manufacturer which sells their product in several countries of Africa to understand how local grid quality issues impact usability of their appliances[16].
d) A2EI is monitoring grid quality in Nigeria to improve immunity of its grid-coupled inverter systems, sharing knowledge gained with other suppliers[17].

Countermeasures can be taken at low or reasonable cost by appliance designers if they are aware of the need for them (as described in 4.3), and make use of the IEC standard about this [18]. The WHO has developed specifications and test methods to ensure immunity of vaccine & healthcare equipment[18] which provide a rich source of transferrable knowledge. Specific steps designers can take to improve immunity and so protect appliances include (various sources):

a) Using a built-in voltage stabiliser and/or safety switch to cut off power when it goes outside of pre-set limits (high or low), ensuring sufficiently fast response times.

b) Use electronically commutated motors (ECM) which can intrinsically operate over a wider input voltage range. Whilst more expensive, they are energy efficient and last longer than conventional motors.

c) Use variable speed refrigeration compressors which tolerate wider voltage variation and generally do not require voltage stability protection. They also have high energy efficiency.

d) Use a resilient LED light driver.

5.3 Develop international appliance standards that address reliability and power quality

Standards provide a consensus-based foundation to enable engineers and policy makers to address challenges. Standardisation offers at least four routes that could be extended or developed to address challenges of power quality and reliability:

1. Characterise the extent and severity of reliability and power quality issues seen in grids that do not meet the IEC recommended levels so that policy makers, appliance designers and others have an authoritative reference source on the issue. The international standards setting out power quality and reliability recommendations for public grids [2, 30 and others] do not yet acknowledge that such poor power quality and reliability exist for public grids. The authors are working with IEC TC8 WG11 to initiate a new IEC technical report (TR) to address this need.

2. Further develop and promote international standards for ride-through testing of appliances so that immunity levels can be objectively verified. Existing standards to provide inspiration include:

    a. IEEE has a generic 'ride-through' test method [21] to establish immunity levels of appliances to voltage sags.

    b. IEC has a standard for certain immunity tests under EMC [22].

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[15] Personal involvement in a meeting with head of R&D Pakistan, October 2022.
[16] Personal correspondence of authors with nLine staff, 2023.
[17] Personal correspondence of authors with A2EI staff, 2023.
[18] See https://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/index.aspx.

    c. An ISO standard describes tests for immunity against transients seen in road vehicle systems [23].

3. Set out how power quality immunity should be presented in technical specifications for appliances in fair and comparable ways, define metrics and how claims should be verified. This starts with the operating voltage range but could extend to a voltage tolerance envelope and how the appliance reacts to and recovers from power quality disturbances, with or without user intervention. IEC TC59/SM59M/WG6 is working on a system to do this for refrigerators in a new standard (see 5.5).
4. Extend and promote guidance to appliance and equipment designers on options to improve immunity, making this available to working groups under IEC SC59M for household appliances.

5.4 Develop appliance policy responses to address power quality and reliability

Appliance policy and regulation in Global North economies has not (yet) had to address the consequences of power that does not meet IEC or CEN/CENELEC recommended quality levels, because those economies have grids which meet those levels. As set out in this paper, however, appliance policy and regulation could and indeed should now address power quality to protect the safety, economic and social development interests of citizens, wherever reliability and power quality fall far short of those recommended levels. Experience shows that despite excellent work to transfer appliance policies into global South economies for example via UNEP United for Efficiency[19] and similar programmes, learning from Global North experience, these almost entirely fail to take the quality of local grid power into account.

To address this, policy makers could work with appliance manufacturers and the local standards community to:

a. Provide benchmark power quality data on what appliance suppliers can expect from the local grid, where it does not meet IEC recommended values.
b. Influence and encourage designers to improve the immunity of appliances to suit local grid supplies.
c. Help buyers to select appliances suitable for the local supply by labelling or rating appliances with immunity information and publishing correlated information about the quality of local grid supplies.
d. Promote and subsidise power quality protection at the building level where appropriate (voltage regulators, surge plugs, power conditioners).

5.5 A new IEC test standard on performance of refrigerators designed to operate on an unreliable and poor quality grid, and off-grid

In 2022 IEC founded a standardization group (TC59/SC59M/WG6[20]) with the objective of developing a standard (IEC 63437 [31]) which defines specifications and the procedures for AC voltage refrigerators used in regions with an unreliable electricity supply[21]. The standard focuses on power interruptions and voltage fluctuations, which are the two disturbances with the largest impact on the performance of refrigerators and most prevalent causes of damage. The IEC 63437 standard uses an approach similar in principle to the IP rating of electrical enclosures (e.g., 'IP65') and defines the Unreliable Grid Protection 'XYZ' Code (UGP-XYZ) consisting of three digits:

1. X represents the AC voltage intermittent supply class, specifying a length of a power outage per day for which the appliance is designed to operate normally.
2. Y represents the AC voltage distorted supply class, specifying a voltage range for which the appliance operates normally, maintaining its compartment temperatures.
3. Z represents the AC voltage withstand supply class, specifying the voltage range within which the appliance will not be damaged.

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[19] See https://united4efficiency.org/resources/model-regulation-guidelines/.

[20] See https://www.iec.ch/dyn/www/f?p=103:14:611659283502951::::FSP_ORG_ID:28668.

[21] IEC 63437 also addresses DC off-grid appliances, but DC appliances are not addressed in this paper.

The objective of the introduction of the UGP-Code is to match a refrigerator with the power quality of the local grid to avoid appliance damage and sustain normal operation. To manage this the following aspects are key:

- Definition of the UGP-Code of the supply of a specific region
- Marking the UGP-Code of a refrigerator on the rating plate.

The IEC 63437 standard is specifically designed for domestic and light commercial refrigerators. However, the supply signals and the UGP-Code are generic and can also be applied to other types of appliances.

6 Options to raise the priority of grid power quality and reliability

As already noted in 2.5, the technical solutions for improving grid power quality and reliability are well documented and generally well understood by electrical engineering specialists, distribution franchisees etc. The priority lies instead in raising awareness amongst investors and policy makers of the scale of power quality problems and their impacts and so encourage them to make available the necessary funding to deploy the technical solutions. This section presents innovative options to address this.

6.1 Make it easier to understand and compare power quality and reliability for benchmarking and prioritising responses

Power quality and reliability data is hard for non-experts to comprehend and compare, including for policy makers, investors, aid bodies and consumers. One notable approach to simplify presentation but remain true to engineering principles has been developed by Professor Sjef Cobben of TU/e Eindhoven[22] [32], dividing electricity supply quality and reliability into ‘A to G’ grades, as used in the EU energy label. An example classification system for reliability is shown in Figure 5. The generic principles of the classification approach are shown in Figure 6. This methodology has been successfully implemented at a Dutch utility and could be applied to any of the key power quality parameters with thresholds tailored to the anticipated range of values (quality) to track problems and progress. This approach could provide an accessible quality framework for use in Grid Codes and for end users.

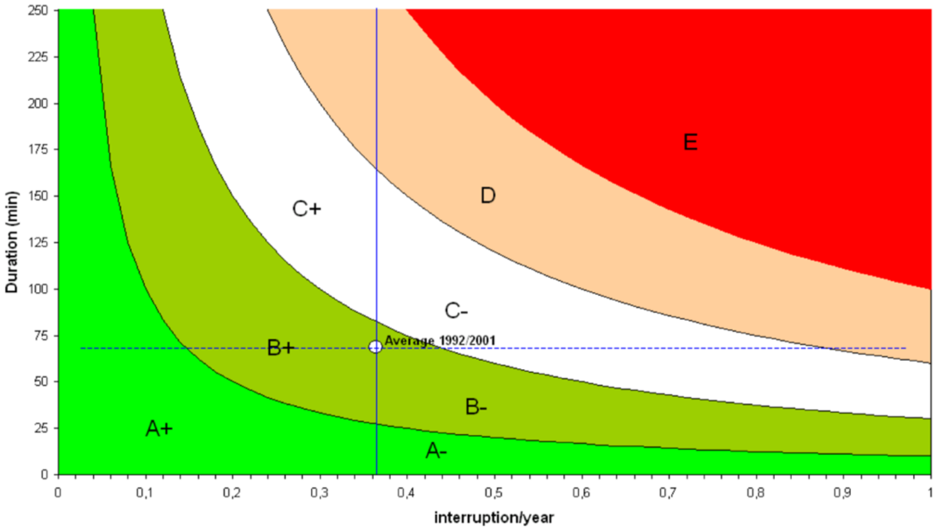

Figure 5. Indicative classification system for reliability of power, combining the frequency of interruptions (number per year) and average duration of interruption (minutes). (Source: Prof. J F G Cobben, presentation to the Power EQuality Initiative, 13 May 2024).

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[22] See https://www.tue.nl/en/research/researchers/sjef-cobben.

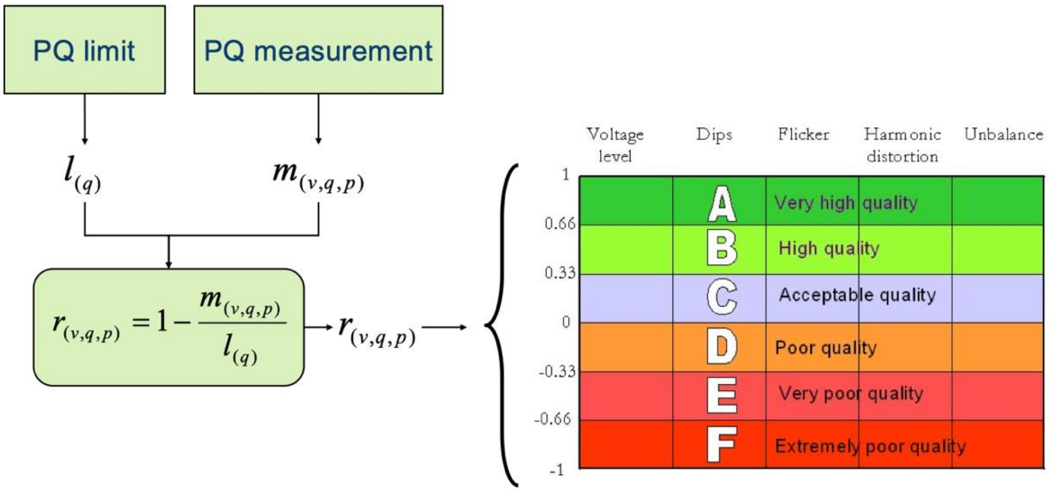

Figure 6. Generic principles of the A to F classification system for power quality event types. (Source: Prof. J F G Cobben, presentation to the Power EQuality Initiative, 13 May 2024).

6.2 Increase monitoring and transparency of power quality and reliability by utilities and regulators in the Global South and ensure it is end user-focused

Power quality must be formally monitored and reported since it cannot be seen or measured by most users. Even monitoring of interruptions, which are more obvious to users, is mis-reported, misunderstood and disputed: World Bank survey data suggests that, on average for many low- and middle-income countries, customers report having more than six times the outage durations reported by their utilities [24], and so official reporting may be nothing like what consumers are experiencing. A blackout is not, in practice, a simple binary state: millions of users with a grid connection may suffer extremely low voltage for a significant proportion of the time. Comparability of statistics on this is poor because the voltage threshold below which a connection is no longer considered of practical use varies. The IEC 61000-4-30 standard defines the concept of the voltage interruption threshold, set as a percentage of the nominal voltage below which a voltage dip (or sag) is defined as an interruption. No specific thresholds are given in the standard, but it suggests that they can, for example, be 5% or 10%[23] of nominal (i.e., 95% or 90% *below* nominal) which corresponds to 11.5V (5%) or 23V (10%). This is below what is of any practical use to end users and means that IEC-based statistics on interruptions as adopted by utilities and regulators around the world do not reflect the user experience. In contrast to this, the ESMI programme monitoring voltage quality across India considers any voltage below 131 V as 'no supply'[24] (blackout condition), which corresponds to -43% for a 230 V supply. The interruption threshold is one example of the need for more user-relevant reporting. Another is lack of transparency in use of SAIFI and SAIDI under which system-wide averages can mask extremely poor performance in certain geographical areas. Access to more affordable and accessible power quality monitoring is needed to quantify these challenges and prioritise investment. Good practice approaches to voltage quality monitoring have been extensively studied by the Council of European Energy Regulators (CEER) since 2005, as reported in their annual benchmarking report and supplementary reports[25]. The CEER handbook on Service Quality Regulation in Electricity Distribution and Retail in 2007 [25] confirms that the availability of reliable measurements is 'a very critical issue' for voltage quality. This good practice is applicable to Global South economies.

6.3 Government regulation of power quality

Power quality must be regulated because end users have little or no scope to change the way they access grid power or supplier, with most operating under de-facto monopolies. The only alternative for businesses (and a minority of homeowners) who can afford it is distributed generation[26], with its associated costs and pollution impacts of diesel generators (extremely common as a backup), or roof-

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[23] Note 1 of paragraph 5.5.2 in IEC 61000-4-30. The corresponding Indian standard IS 18475: 2023 also adopts this 5% voltage threshold.

[24] See FAQ on Voltage classification at http://watchyourpower.org/faqs.php#.

[25] See https://www.ceer.eu/list-of-publications.

[26] Distributed renewables are already seen as a threat to utility revenues in parts of Kenya and elsewhere including - if not especially – in urban locations, driven by poor reliability and quality of grid power.

top solar photovoltaics. In the absence of transparency and competition, regulation is an essential component to achieving improvement in power quality and its aspects include [26]:

- Setting quality standards with minimum requirements (such as EN 50160)
- Implementing monetary penalties or sanctions including customer rebates (or conversely rewards for good performance)
- Publishing data (benchmarking)
- Setting obligations for the management of voltage quality by utilities (VQM).

Regulation of power quality remains patchy in Europe according to the status review in the 2022 CEER 7th Benchmarking report [26]. Section 3 of the report is devoted to voltage quality. (It also confirms that 'a good knowledge of actual [voltage quality] levels is a first step towards any kind of regulatory intervention').

6.4 End user rebates when power quality fails

To ensure proper focus on quality and to drive up standards, some regulators have implemented rebates for consumers based on power quality and reliability. This has happened in only six European countries, all in eastern Europe[27]. Peru has implemented a regulation ensuring end user compensation for poor power quality according to statutory formulae [27] their Decree states that:

> *"5.1.3. Compensation for poor voltage quality - Suppliers must compensate their Customers for those supplies in which it has been proven that the quality of the product does not meet the standards set in section 5.1.2 of the Standard. Compensations are calculated, for the Measurement Period, based on the energy delivered in poor quality conditions in that Period, through the formulae below".*

The level of rebates was negotiated with utilities in the context of investment to enable delivery and sets a valuable precedent from which Global South electricity regulators could learn. Discussion with local experts suggests that the approach is leading to improvement in the experiences of end users. No existing rebate schemes have been identified in Africa, though proposals have been under discussion in Kenya for several years [28][28].

7 Conclusions and recommendations

Behind headlines of good progress on improved energy access and higher connection rates lies a reality that around one billion people across the global South are receiving power from public grids with reliability and voltage quality that often fall far short of IEC and CEN/CENELEC recommended levels. Inadequate power quality damages or destroys appliances and equipment and combined with low reliability, holds back well-being, social development, and healthcare of communities. The people and communities of Africa and all Global South economies deserve better than this.

Engineers and utilities have a high awareness and a good understanding of power quality conditions and impacts. However, this is not sufficiently shared by policy makers and development investors, which means that engineers and utilities are not given the resources to address the problems and the problems persist. A key challenge is raising awareness of the scale of the problem due to lack of data on power quality and reliability. Even when utilities find the resources to monitor quality, the data is often incomprehensible to non-experts. Policy focus thus remains on simplistic metrics such as number of energy connections, paying inadequate attention to associated reliability and almost oblivious to voltage quality. The evidence linking power quality, reliability and economic and social impacts must be much better articulated to attract the necessary investment.

Appliances need an electricity supply of adequate quality - meaning power that is reliable, stable and free of significant voltage and other disturbances. This is critical to global development, growth, and equitable energy transitions. Recommendations to help achieve this are made in this paper, for the standards community, for appliance manufacturers, researchers, utilities and policy makers as summarised in Table 1.

The pathway to improved reliability and power quality could be navigated using four waypoints or enabling activities that have been indicated in this paper:

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[27] Hungary, Moldova, Romania, Slovenia, Latvia and Poland. See CEER 7th Benchmarking Report 2022, section 3.5.1 *Monetary penalty and sanctions when the legislation, the regulations or the standards on voltage quality are not met*.

[28] The government of Kenya rejected a previous rebate proposal in 2015 if businesses were cut off for more than three hours in a day.

1. **Measurement technologies:** Affordable power quality sensors with onboard statistical analysis to capture power quality and reliability data that meets IEC and similar requirements, with automated transmission for centralised analysis.
2. **Data gathering and sharing:** Widespread projects and programmes to deploy the power quality sensors in sufficient numbers to characterise local and regional supply quality and reliability - sharing and publishing data.
3. **Data analysis for insight:** analysis of the data using comparable approaches to derive actionable insights from the power quality and reliability measurements. Agree ways to present data that are end-user focused and accessible, to enable robust decisions on investment and priorities and fair competition.
4. **Policymaking and implementation:** build the analysis results into better regulation, investment decisions and policy. Address the power supply side through Grid Codes and energy regulators and also the demand side through standards and labelling for more suitable protection and intrinsic immunity of appliances and equipment.

All these actions and more should be considered by collaborative working groups that fully engage experts and practitioners from the Global South.

Table 1. Summary of the actions by different stakeholders to mitigate the impact of unreliable electricity supply on appliances.

Type of stakeholders	**Recommendations**
Standards working groups	Take unreliable grid power quality into account when appliance and equipment standards are developed, including testing for immunity to voltage disturbances (primarily sag and surge) and guidance for appliance designers.
Equipment and appliance manufacturers	Understand the reliability and power quality of electricity supply in target markets and how to improve of appliances to match that; include immunity ratings in appliance specifications.
Energy access and development programmes	Move beyond counting connections. Deploy appliances and equipment known to be appropriate and resilient to suit local power quality; invest in power quality protection for appliances and equipment. Monitor power quality and reliability, publish results and quantify the socio-economic consequences.
Buyers of appliances and equipment	Choose appliances and protection equipment suitable for the local power quality.
Utilities	Measure, collect and publish power quality data at regions with poor grid quality in formats that users and policy makers can understand and use to prioritise investment and ensure suitable protection or immunity for appliances.
Electricity regulators	Set standards for power quality and reliability; seek ways for users to be compensated when they fall below agreed thresholds.

Acknowledgements

This analysis was only possible through the support of many stakeholders who gave generously of their time and expertise during nearly two years of research and investigation into these topics (ongoing). The authors thank all who have helped. Input from these people and others has been invaluable:

- Ann Wacera Wambugu, Strathmore University, Nairobi
- Chris Moller, Evonet
- Elisa Lai, CLASP / Efficiency for Access
- Fiona Brocklehurst (for improving clarity of the whole paper)
- Frieder Rabl, A2EI
- Genevieve Flaspohler, Mohini Bariya & Josh Adkins, Rhiza Research
- Jungcheng Liu, IEC TC8 WG11
- Marie-Josée Fortier, IEC TC8 WG11
- Markus Meinke, IEC TC8 WG11 and Meinke Energy

- Martin Kitetu, EED Advisory
- Rod Hinman, New Horizons for Global Health
- Sean Elphick, University of Wollongong
- Shweta Kulkarni, Prayas Group
- Professor Sjef Cobben, TU/e Eindhoven

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