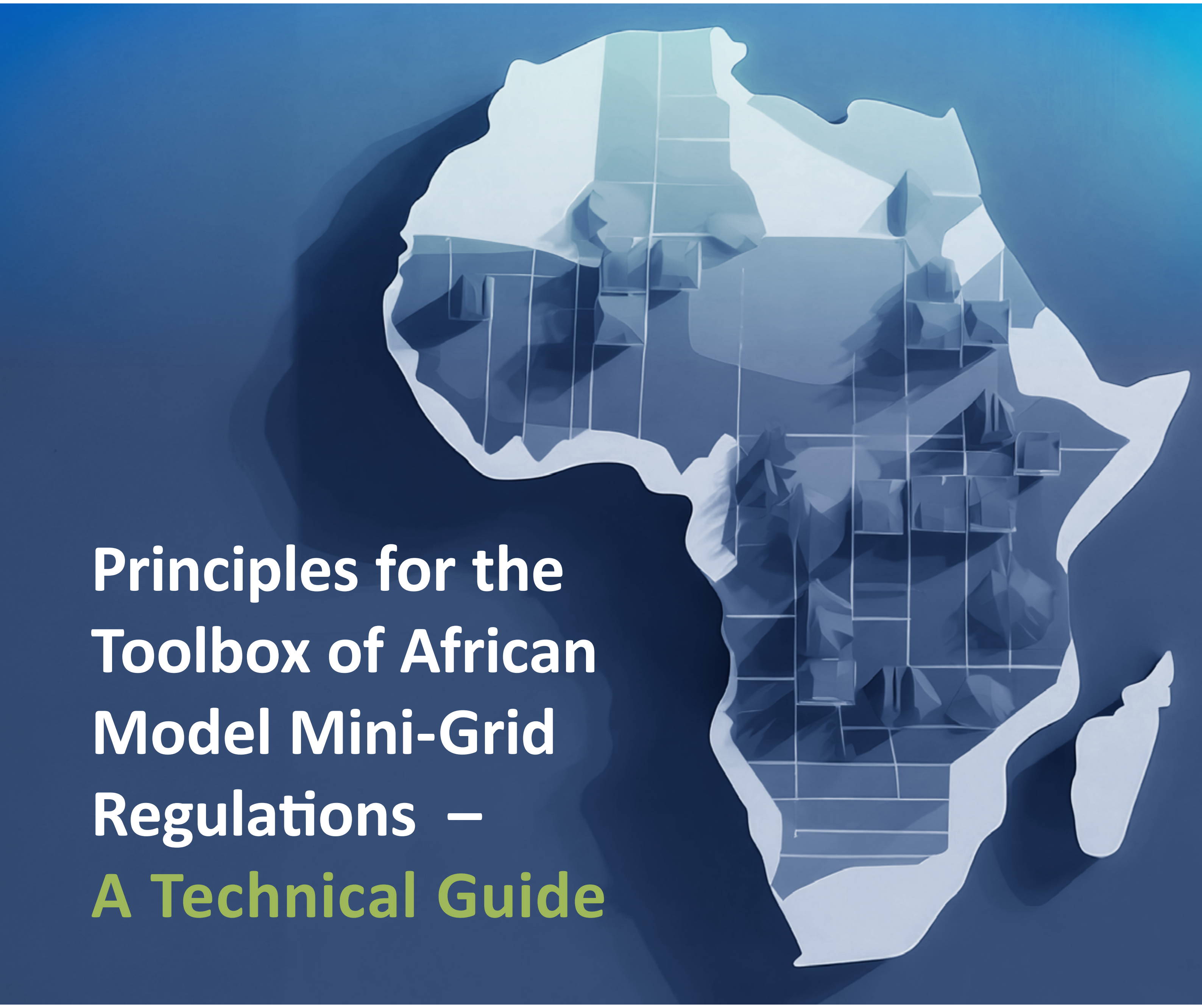
Forum africain pour la régulateurs des services publics
African Forum for Utility Regulators



Principles for the Toolbox of African Model Mini-Grid Regulations – A Technical Guide

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Transforming Energy
Sectors Globally

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Executive Summary

The African Forum of Utility Regulators (AFUR) presents this **Technical Guide** as part of its work on the ***African Model Mini-Grid Regulations*** which AFUR is developing in partnership with GET.transform. AFUR aims to develop a **toolbox**, based on regulator experience, documenting latest developments and continental best practice in mini-grid regulations. With support from GET.transform, the resulting tools under the ***African Model Mini-Grid Regulations*** will provide regulators with best practices to overcome recurring regulatory challenges. At the same time, the tools can be applicable across various jurisdictions and will contribute to the convergence of mini-grid regulations across the African continent and beyond.

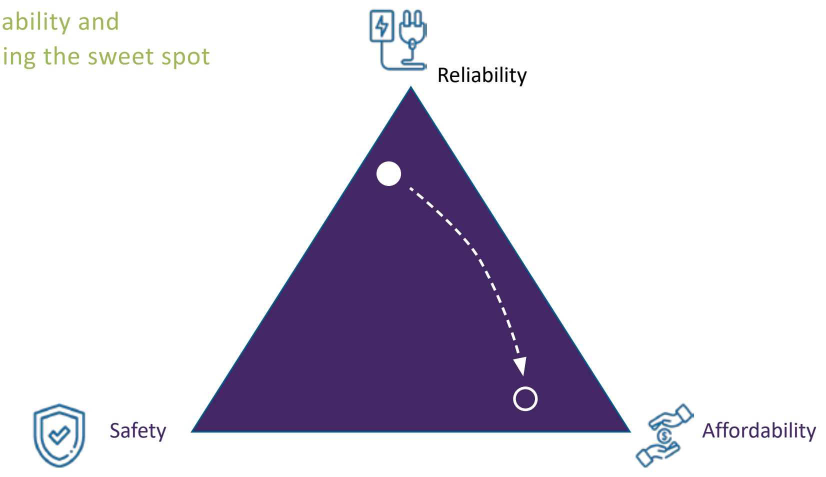
GET.transform supports workshops on technical, financial, legal, and commercial approaches for mini-grids in collaboration with AFUR and its member regulators, to drive the participatory process in the development of publishable tools that make up the ***African Model Mini-Grid Regulations***. This technical guideline is the first of these materials, highlighting innovative technical aspects which could be considered in mini-grid regulation. The principles discussed in this technical guideline will be incorporated in the mini-grid regulation templates, which are currently under development as part of the ***African Model Mini-Grid Regulations***. The mini-grid regulation **templates** are expected to be published in 2024.

AFUR also acknowledges the support of the UKaid through the Transforming Energy Access (TEA) Platform for its support in the Mainstreaming Mini-grid Tariff Settlement Tools across African Regulators project, which has enabled the development of these templates as part of the project.

Mini-grid regulations set **a range of technical, financial and legal requirements** which the mini-grid developers must uphold within a country. Such requirements are not isolated from one another, but have **a complex nature of interdependency** among them. Requirements which are too rigid do not contribute to the growth of the mini-grid sector. On the other hand, too loose requirements may result in subpar systems and poor service levels. The regulators must always find a **sweet spot** for the interdependent requirements. This concept is demonstrated in this report through a triangle of safety, reliability and affordability.

The triangular interrelation of safety, reliability and affordability remains **a zero-sum game** until technological innovation changes the dynamics. The regulator may set the technical requirements in a way that the mini-grids are very safe and reliable. However, the cost of complying with such requirements can drive the tariff up to an unaffordable level; this means that a regulator cannot aim to improve one of the aspects without impacting upon the others.

Figure 1
Triangle of safety, reliability and affordability, and finding the sweet spot



In general, mini-grids face specific challenges compared to much larger main-grid systems. The nature of rural electrification is to bring modern electricity supply services into isolated, underdeveloped, and economically weak communities. High quality provision of unlimited power is not feasible in small systems, which have a similar complexity and cost structure as the main-grid, but not the scale. A trade-off can only work if both the operator and clients are aware of the limited availability of the power generation and distribution capacity of a low-voltage mini-grid infrastructure. Regulations must support the finding of a workable balance of reliability, affordability and safety.

This concept is further validated in this report using a data-driven approach. Several simulations conducted by GET.transform experts reveal further insights into the triangle and beyond with ways of finding a sweet spot.

A mini-grid's availability, quantified through the number of service hours per day, is the pillar of its **reliability**. Availability could be limited due to system failures and capacity constraints (e.g. limited storage capacity). Availability improves with the skill levels of local staff, the efficiency of call centres and warehouse capacity. Simulations suggest that, for a requirement of 99.9% availability, the tariff for a ~75% CAPEX-subsidised mini-grid could be as high as 1.4 US$/kWh, whereas 90% availability will result in **a more affordable tariff** of 0.3 US$/kWh.

Allowable voltage drop is another technical aspect which is closely connected with reliability and quality of supply. All the electrical appliances available on the local market, which meet the local standards, should work within their voltage specification when connected by the clients. Due to the limited size of a mini-grid, the operator must restrict the use of an appliance of inappropriate quality and cautiously select high-power appliances, to ensure voltage remains stable within the required limits. If the allowed voltage drop is too small, larger cable cross-sectional areas will be needed, which are comparatively expensive due to the cost of materials and installation efforts. As an example, with the similar cost considerations (~75% subsidy with 90% availability), if the voltage drop requirement shifts from 5% to 15%, the tariff could reduce from 0.33 US$/kWh to 0.29 US$/kWh. However, allowable voltage drop can differ in various customer groups based on the appliances they use.

Power quality requirement also varies based on the appliances being used. Mini-grid operators must therefore sensitise the consumers and assist them in selecting the appropriate appliances. Poor power quality may lead to equipment failure and overheating of distribution systems which can compromise the **safety of the system**. An inverter is taken as a component to demonstrate how it can impact upon the power quality. Power quality requirements become stricter from household-level appliances, up to more commercial and productive appliances. If low-quality inverters are used, they may fail to handle mini-grids with a high productive usage, resulting in appliance damage. Higher-end inverters are capable of better handling such situations, but are also comparatively costly and will therefore impact upon the tariff.

Safety also depends on the **standards of the components** in use. Different types of energy meters and installation boards with safety measures were considered as examples. Simulations suggest that the combination of a smart meter and rural installation ready-board, or the prepaid meter and rural ready-board, can keep the tariff lower compared to other available options, e.g. post-paid meters and urban area-suited installation boards. The mini-grid regulations must allow the use of appropriate miniature circuit-breakers with a much lower current rating compared to main-grids, in combination with adequate earthing and recommended individual earth-leakage protection. This will allow the reducing of the CAPEX and tariff, whilst not compromising the safety aspect.

Beyond the triangle, other technical considerations also influence the tariff levels. **Interconnection readiness** from the beginning may mean that mini-grid distribution networks are designed as per utility standards. Due to this, distribution CAPEX may increase up to 38%. This may result in a higher tariff, from a 0.27 US$/kWh level, to 0.37 US$/kWh.

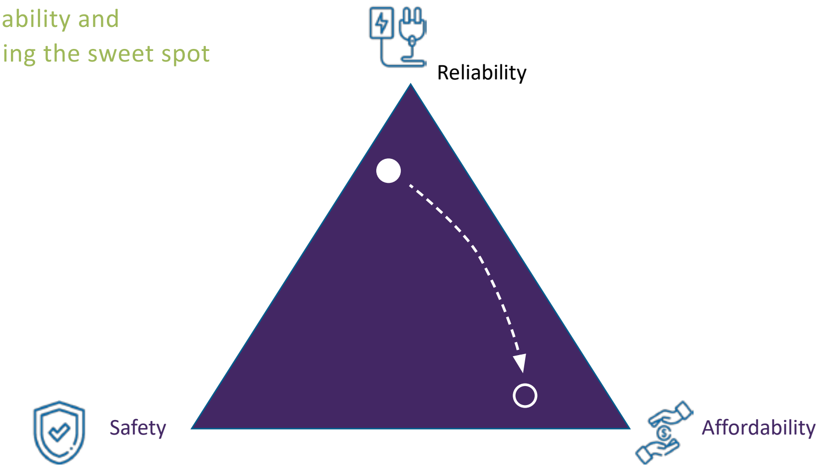
Apart from providing such examples, this knowledge product by AFUR and GET.transform also puts forward a decision-making process for each case which can be used while drafting (or adjusting) the mini-grid regulations.

This novel way of looking into the mini-grid regulations will allow the regulators to take a refined approach to setting appropriate technical regulations. This will also ensure that the mini-grid regulators in Africa take a standardised approach in setting the requirements for the development and operation of mini-grids considering their respective local context.

1 Introduction

Mini-grid regulations cover various technical, financial and legal topics which, in the end, contribute to how the mini-grids will be operated within a country. **Regulatory instruments that are too rigid** do not facilitate the growth of mini-grids in a country; in the worst-case scenario, rigid regulations may have the same effect as a lack of regulations. Rigid requirements are not only about the individual topics that are covered within the regulations, but also the **complex nature of interdependency between different aspects of mini-grid operations**. At the other end of the spectrum, every loose regulation opens a floodgate of subpar systems and service levels. The onus is on the regulators to find the middle ground **(sweet spot)**.

Figure 2
Triangle of safety, reliability and affordability, and finding the sweet spot



This argument can be illustrated with a triangle of safety, reliability and affordability. The regulator may set the technical requirements in such a way that the mini-grids are very safe and reliable. However, the cost of complying with such technical requirements can drive the tariff up to an unaffordable level. Therefore, at a certain point in time, a regulator cannot aim to improve one of the aspects without having an impact on the others. This perspective of looking at the regulations gives rise to the following questions:

- Which of these three aspects is the most important for achieving the country's mini-grid sector?
- How can the regulators ensure that the technical requirements do not end up resulting in socially and politically unacceptable tariffs?
- What considerations must be made in this decision-making process?

This knowledge product focuses on identifying and uncovering some of the linkages between these technical aspects and the affordability of mini-grid electricity, and recommends data-driven decision-making approaches for regulators to find the **sweet spot** between affordable tariffs and technical requirements.

This novel way of looking into the mini-grid regulations will allow the regulators to answer the above-mentioned questions and to take a refined approach to setting appropriate technical regulations.

Before delving deeper into the topics in this subject matter, the relevant technical aspects are briefly discussed in the next sections of this knowledge product.

2 Technical Aspects in Mini-Grid Regulations

Mini-grid regulations not only set the financial, legal and commercial requirements for mini-grid developers to follow, but also set some critical technical requirements in respect of the service quality, safety, allowable measurement devices, options to interconnect with the main-grid, etc. The regulator defines the terms, conditions and procedures for obtaining different types of mini-grid licences, as well as the corresponding consumer services and grid-interconnection possibilities. The mini-grid regulations also provide the guidelines and requirements for components during different development stages of a mini-grid project.

Figure 3
Technical aspects in mini-grid regulations

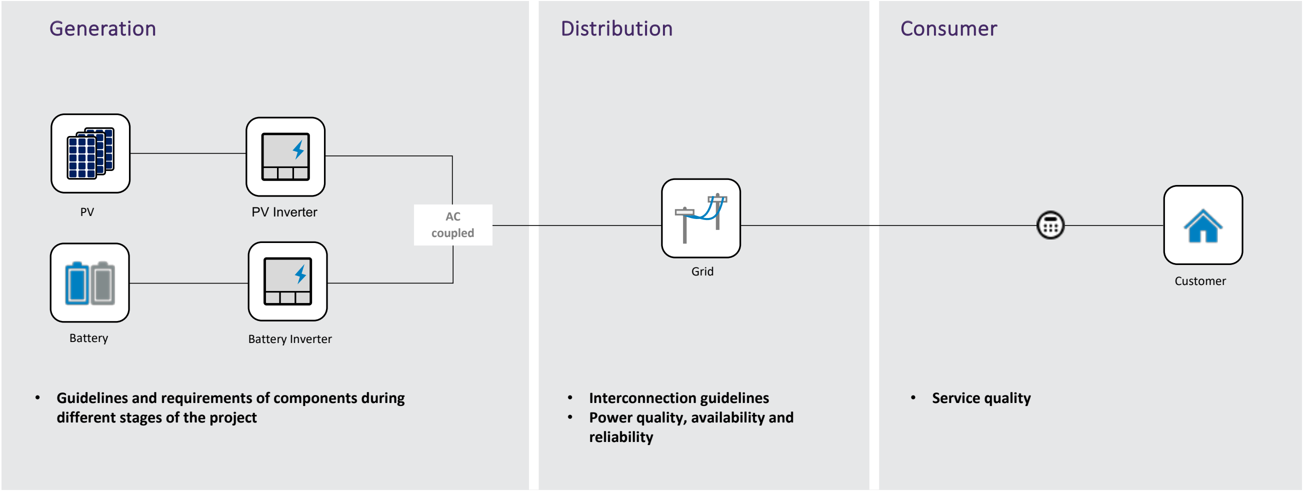


Figure 3 represents the various technical aspects covered in mini-grid regulations which are briefly discussed in the following table.

Table 1
Overview of the technical aspects of mini-grid regulations

ASPECTS	WHAT IS COVERED
GENERATION	Guidelines and requirements are provided for the generation assets. The regulations may refer to the applicable national and/or international standards to be followed. Health and safety guidelines are covered in the regulations across different project development stages and later operation.
DISTRIBUTION	
POWER QUALITY	From the perspective of the client in a mini-grid system, good power-quality relates to a high degree of availability and reliability of supply at stable voltage only. More technically, electrical power-quality is the result of the impact of the appliances connected and interfering with the limitations of power generation and distribution assets. Particularly for mini-grids with limited capacity, a high number of low-power appliances (e.g. LED lamps and many phone chargers) results in a very low power-factor at high harmonic distortion of the voltage and current. Single mono-phase appliances can easily consume a significant portion of the total installed capacity, which results in phase imbalance and critical load fluctuations. Start-up currents of high-power appliances (e.g. water pumps) may bring the inverters to their current limit. In the first place, mini-grid operators must carefully monitor violation of grid voltage limits and overload, especially in the neutral conductor, because of the harmonics. If the operation of appliances adversely affects the specifications required for the safe and reliable operation of the system, restrictions or limitations on the use of high-power appliances must be enforced to re-establish safe and acceptable operating conditions. The operator not only bears full responsibility for defining the maximum acceptable total harmonic distortion, but also for compensating the power factor and phase imbalance, should this be necessary. Considering the nature of the small size of the mini-grid, the IEC 62257 standards offer guidelines for measuring and evaluating the quality of the electrical power supply in stand-alone mini-grids. Once connected to the main-grid, the regulation of the main-grid will be applicable related to the specification of appliances.

AVAILABILITY AND RELIABILITY	The service quality of mini-grids is described quantitatively by means of the following parameters: • Technical availability of the power generation and distribution assets – if they are operational and not disturbed, under repair or maintenance (hours-per-day/month/year). • Reliability (interruption of supply in terms of numbers and duration, both planned and unplanned). The above parameters depend on the balance between generation and demand which can be understood from two perspectives. • Availability of the power generation vs. the demand: Closely related to the available inverter capacity and back-up generator power capacity. It could lead to shut down because of power shortages. • Availability of the energy vs. the demand: Requires storage capacity to cover temporarily low availability of renewable resources, or limited installed PV capacity. Lack of storage capacity could also result in the shutting down of the system because of energy shortage.
INTERCONNECTION REQUIREMENTS	If the mini-grids are to be interconnected with the main-grid at some point, the mini-grideither needs to be designed with the required compatibility from the beginning, or upgraded later. Grid standards are mostly national standards supplemented by international technical standards available from the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE). For an interconnection, the distribution network of the mini-grid also needs to be of the same quality as the main-grid. This is applicable if the mini-grid operator will continue to function as a Single Power Distributor (SPD), or as a combination of SPD and Single Power Producer (SPP). Clear guidelines must be provided in the regulations as pathways for the mini-grid companies regarding what will happen after the main-grid arrives.
TECHNICAL REPORTING	Regulators require the mini-grid licensee to report frequently on the technical and financial performance of their systems. If the reporting is too frequent, it becomes a burden for the mini-grid company, as the reporting requirements will drive their overhead costs up further. Digital tools are available to automate the reporting processes without much effort. There are suitable tools for the mini-grid operators to generate such reports; at the same time, some digital tools are also available to the regulators to quickly review mini-grid performance reports.

2.1
Status-Quo: Key Observations

This section highlights the key observations on the status-quo of mini-grid regulations from the AFUR and GET.transform team. Technical aspects in mini-grid regulations are often set according to the highest available standards which are developed for utility-connected urban areas. Putting in place such high standards for mini-grid regulations is done with the good intention of delivering the highest service quality to the rural populace.

However, these requirements are deeply interconnected with the achievable tariff levels. Stringent requirements compel the mini-grid developers to invest more capital at the beginning, and sometimes to then increase their operating expenditure to comply with the regulatory requirements. This ultimately results in a higher tariff which triggers dissatisfaction among rural customers; it becomes a complex situation to reduce the tariff in hindsight without bringing additional subsidies into play.

Mini-grid developers are also asked to design systems which are main-grid-interconnectable from the onset. Some regulations do not even treat mini-grids separately, but rather like any other independent electrification projects. This approach increases capital expenditures (CAPEX), sometimes also the operating expenditures (OPEX) and, in return, the tariff.

This knowledge product invites the regulators to take a more mini-grid-focused approach, whereby the standards are set considering the local context and capacity. This does not mean foregoing the highest standard, but taking a step-wise **bottom-up approach** to implementing the highest standards more effectively.

The next chapter delves deeper into understanding the linkages between the technical aspects, finding a **sweet spot** which meets a minimum quality, and keeping the financial implications within an acceptable limit.

3 Triangle of Technical Regulation between Safety, Reliability and Affordability

The triangular interrelation between safety, reliability and affordability becomes a zero-sum game at a certain point in time. Pushing the boundary for one of the aspects will adversely affect the others, although this relationship may change in future due to innovative and affordable solutions. Considering this, the regulator's goal therefore should be to find the **sweet spot** within the triangle. The following cases emphasise this argument further:

- Adding the highest safety features means added costs for the developer which ultimately makes the electricity less affordable. Special safety equipment may not be easily available. It may even require a special competency level to fix which, in turn, increases the downtime. **A very safe system may therefore not be particularly reliable and/or affordable.**

- **A highly reliable mini-grid system operation** requires skilled electricians, efficient and around-the-clock customer service centres, and local warehouse(s). These increase the capital and operating costs, thereby raising the tariff.

- **A highly affordable electricity service** (without considering the impact of subsidy) means that the developer will have to cut costs in procuring the assets and operational services. This can impact upon the safety of the system (if subpar products are procured to reduce CAPEX), and reliability (poor customer service and long downtimes if operational expenses are cut down to reduce overall expenses).

A satisfactorily reliable and affordable system should not sacrifice the minimum safety requirements. The complex interactions between these three aspects can be intuitive; however, the challenge for a regulator is to find the right balance between them. There are other technical aspects which are outside the triangle, but still impact upon affordability. These are discussed at the end of the chapter.

To ensure safe and reliable systems, international technical standards and recommendations for renewable energy and hybrid systems for rural electrification are available for individual components, as well as for the whole system. For example, IEC 62257 (overall system), IEC 61215 (PV modules), and IEC 61427-1 (batteries).

3.1
Reliability and Affordability

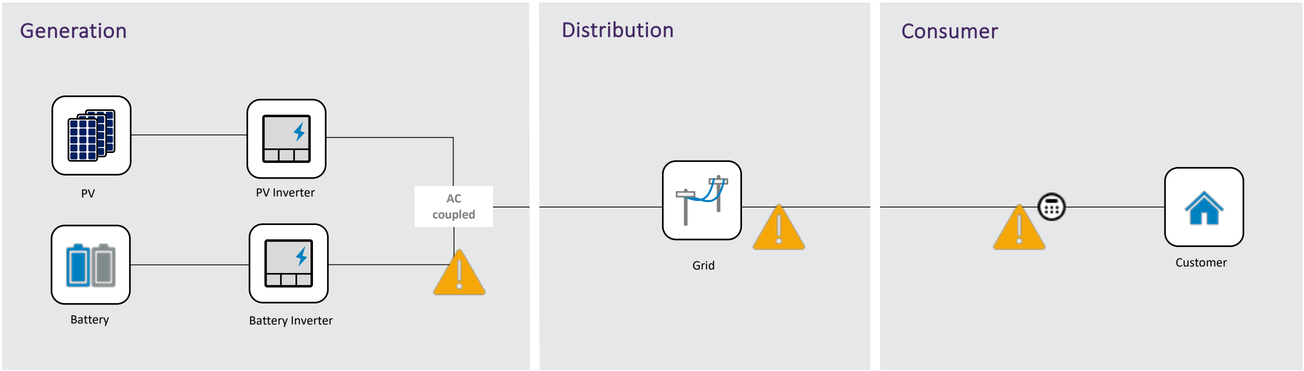
Mini-grid reliability is quantified through the number of agreed service hours per day and the number of planned and unplanned outages in comparison to the agreed daily availability. Finding the appropriate balance between reliability and affordability is discussed using two aspects under the umbrella of 'reliability':

a) Availability
b) Allowable voltage drop which is linked to the mini-grid reliability.

3.1.1
Availability and Affordability

The availability of a mini-grid is defined by the number of outages and their total duration within a period. It must be mentioned that outages may occur at different levels in the mini-grid (Figure 4). Various components may need to be replaced in case of failures. The components must be available on site, or at least as close as possible to the site, so that the reaction time can be kept short.

Figure 4
Failures of components at different parts may impact upon mini-grid reliability

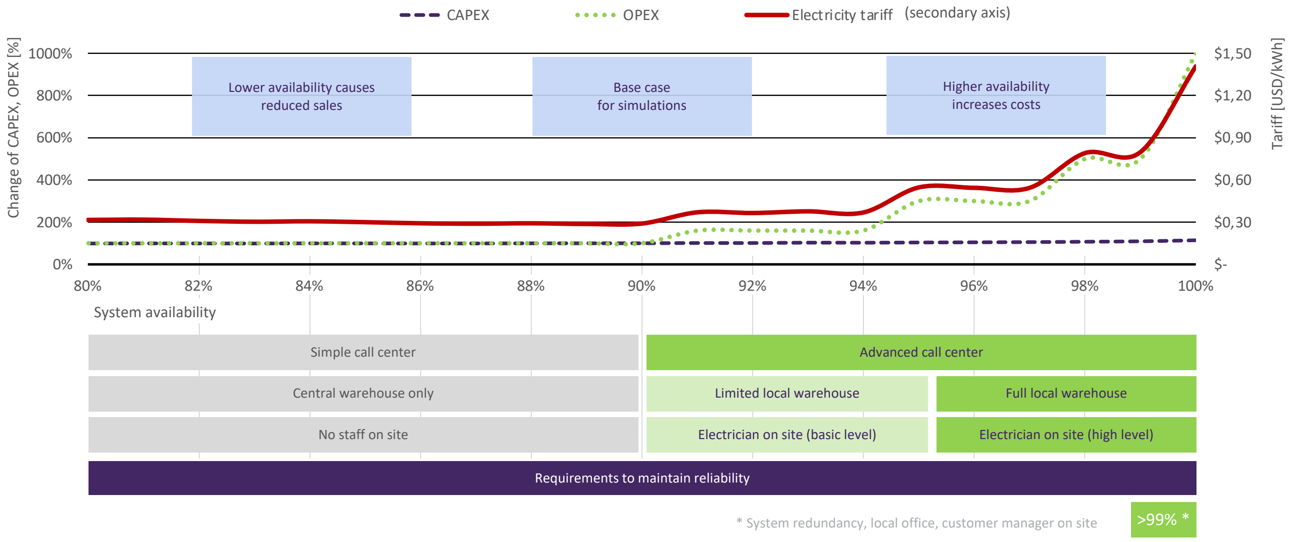


To put this into numbers, 99.9% and 99% availability translates to outages of 8.76 hours and 87.6 hours (3.65 days) per year. Both availability levels correspond to the Tier 5 service level as per the ESMAP's Multi-tier framework. A 90% availability, which is equivalent to 36.5 days per year of unavailability, is in Tier 4.

To reduce the number of outages, various replacement components must be available in stock and as close as possible to the site to shorten the reaction times. Putting a higher requirement of availability into the regulations means that the mini-grid developer will need to have a local warehouse, a skilled electrician on-site, and an advanced call centre.

Simulations of several scenarios were conducted to visualise the impact of the high system availability requirements on CAPEX, OPEX, and the mini-grid tariff. The baseline scenario is simulated considering 75 % of the subsidy level of required CAPEX. The underlying assumptions of the simulations are provided in Annex 1. The different simulated scenarios are as follows:

Figure 5
Impact of higher reliability on CAPEX, OPEX and tariff levels of mini-grids

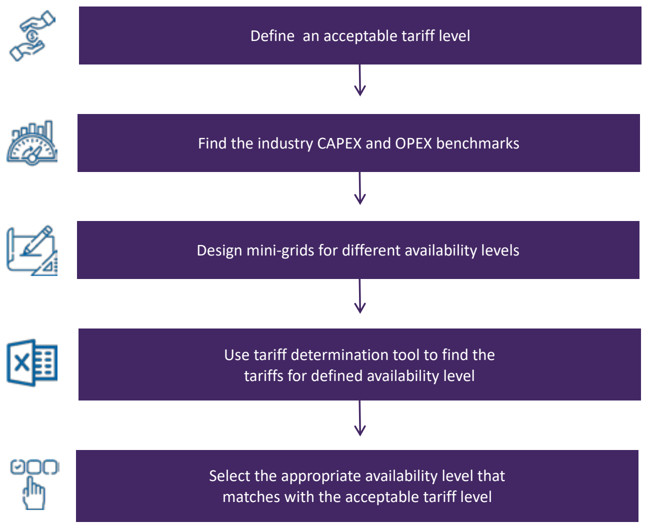


- **Lower availability (<90%):** This level is characterised by a central warehouse only with no staff on-site and a simple call centre. For this reason, in such a scenario, a mini-grid company may take longer to respond to technical issues and customer complaints, mirroring lower availability and reduced electricity sales.

- **Higher availability:** This level is simulated in two steps: a) for up to 95% availability, the mini-grid company sets up an advanced call centre, and has a limited local warehouse (keeping spares of small items like fuses), and b) for >95% availability level, alongside an advanced call centre, the mini-grid operator has a full local warehouse, (e.g. it has spare inverters on-site) and high level electricians to address any technical issues immediately. While such practices improve performance, it also increases the CAPEX, OPEX and tariff levels.

Usually, regulations define the planned and unplanned outage time per connection per year. **As an example, the regulator may set the requirement of 99.9% availability, i.e. 8.76 hours of outage time per year. The simulation reveals that, for such a requirement, the tariff could be as high as 1.4 US$/kWh.** However, if an acceptable tariff level is **0.3 US$/kWh**, it will translate to 876 hours of planned and unplanned outage time per connection per year **(90% availability)**. Therefore, the regulators should consider the affordable and achievable target level for the local context. Based on this understanding, a decision-making approach for setting up the availability in numbers could be the following:

Figure 6
Decision-making approach for selecting the appropriate mini-grid availability requirements


Define an acceptable tariff level

Find the industry CAPEX and OPEX benchmarks

Design mini-grids for different availability levels

Use tariff determination tool to find the tariffs for defined availability level

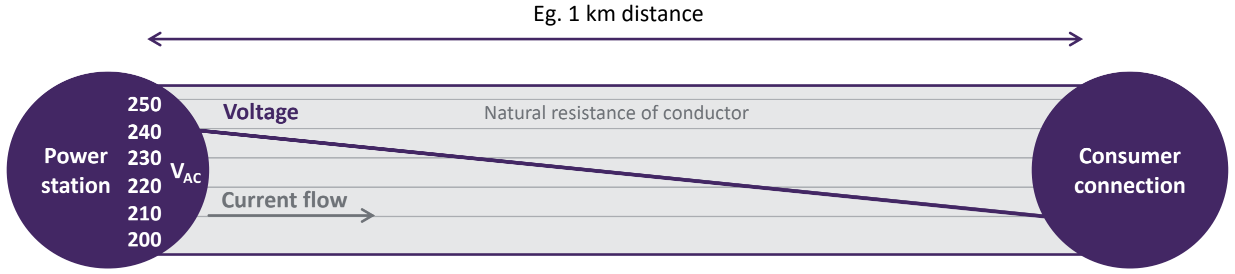
Select the appropriate availability level that matches with the acceptable tariff level

3.1.2
Allowable Voltage Drop and Affordability

Under the ‘reliability’ aspect, another relevant topic is the allowable voltage drop. The appliances at the consumer end may underperform or become non-functional if the voltage is below a certain level. The voltage drops throughout the distribution network due to the resistance of the conductors. The further the distance covered, the higher the voltage drop. The mini-grid generation assets should therefore be as close as possible to the loads, and high-power loads must only be used at a closer distance to the generation assets.

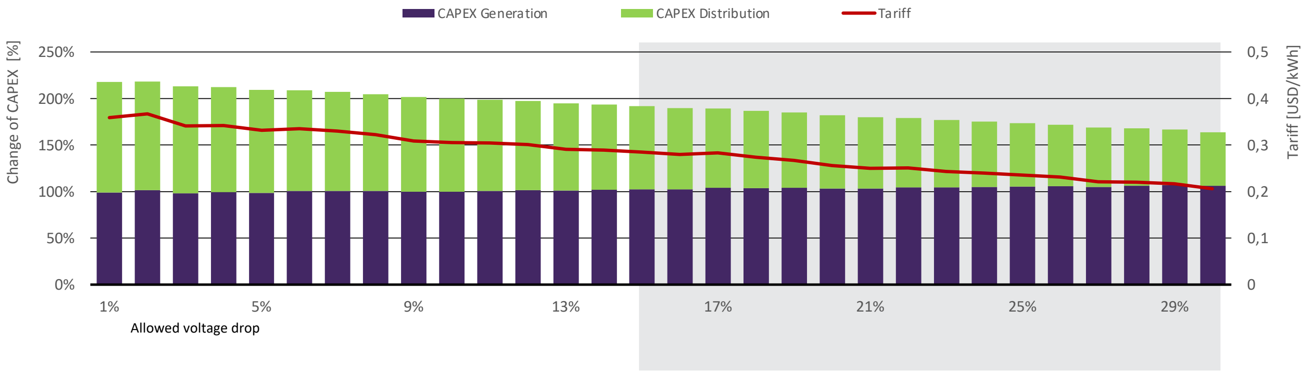
Among other factors, the voltage drop level depends mostly on the cable cross-section and distribution line length, in combination with the constant and transient load current. The line losses and cable cross-sections have an inverse linear relationship, whereas the cable cross-section and costs have almost a linear relationship between them considering the installation and supplementary materials. The bigger the cross-section, the lower the losses. However, bigger cross-section cables are comparatively expensive as regards material cost and installation efforts. Consumers at the end of a long-distance power line are generally more affected by the voltage drop.

Figure 7
Conceptual demonstration of the voltage drop across distance



IEC 60038 ‘standard voltages’ defines the safe operating limits for appliances relative to the nominal voltage. Under normal operating conditions, the supply voltage should not differ from the nominal voltage of the system by more than ±10 % at the client connection or metering point. In addition to the voltage variations at the supply terminal, voltage drops may occur within the consumer’s installations until the point of utilisation by another -5%, which is acceptable. Some modern electrical appliances may have a wide-range power supply and can function within a certain voltage range which is much higher than -10% of nominal voltage (on the lower end).

Figure 8
Impact of allowable voltage drops on CAPEX and tariff level of mini-grids



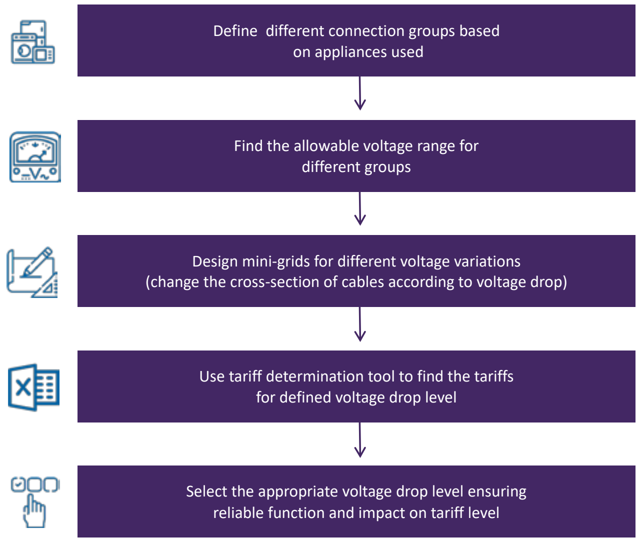
System simulations with 90% targeted reliability reveal that the overall CAPEX and tariff level will go down, if a higher voltage drop is allowed, until the point when electrical appliances start underperforming. The generation CAPEX will go slightly higher to cover up the losses; however, the CAPEX reduction in distribution assets will have a bigger impact. Overall, the CAPEX level will reduce if a higher voltage drop is allowed. As an example, with similar cost considerations, if the voltage drop requirement shifts from 5% to 15%, the tariff could reduce from 0.33 US$/kWh to 0.29 US$/kWh.

Voltage drops along the distance of the power line, with no drop at the source, and the lowest voltage being at the end of the line. Voltage drop is accompanied by unpaid distribution losses and should therefore be limited. For a more thorough examination, the mini-grid should be divided into two areas: the one closest to the power generation source, encompassing an approximately 1 km radius, and the more distant extensions covering larger distances. For the best supply quality, the core zone must fully comply with the IEC 60038, i.e. ±10% voltage limits, but this does not necessarily mean that, outside this zone, no clients can connect – this should, however, be restricted to small appliances only. Careful investigation is needed to ensure that the appliances available in the remotest extension do comply with lower voltage and do not pose any safety concern for the clients.

For this very basic access to rural electricity, regulators may allow a higher voltage drop for the remotest extensions of mini-grids, but only after ensuring that clients are trained and provided with appliances and protection devices fully compatible with the lower voltage. A template for a regulation could read: **‘Operators of mini-grids are allowed to connect clients in the most remote line extensions with the purpose of providing basic access only, even if the supply voltage may constantly be lower than 10% of the nominal voltage. The operator has full responsibility to accept only up to 100W per client, and must ensure that the appliances in use are not only fully compatible with the lower voltage as per the nameplate rating, but also that appropriate protection is installed related to overcurrent and over voltage.’** The text here should only be considered as an example.

The overall decision-making process in this regard could be the following.

Figure 9
Recommended decision-making approach for setting the appropriate voltage level



3.2
Safety and Affordability

Health and safety guidelines are usually discussed in the mini-grid regulations which cover recommendations during transport, installation and operation. Apart from that, the concept of 'safety' is also linked to the technical requirements, e.g. the components' standards and power quality. The concept of power quality was introduced in ***Section 2.*** **Poor power quality may lead to equipment failure and overheating of the distribution systems which can compromise the safety of the system.** In this document, an inverter is taken as an example to show the impact of power quality on affordability. Later, the impact of components' standards is also discussed.

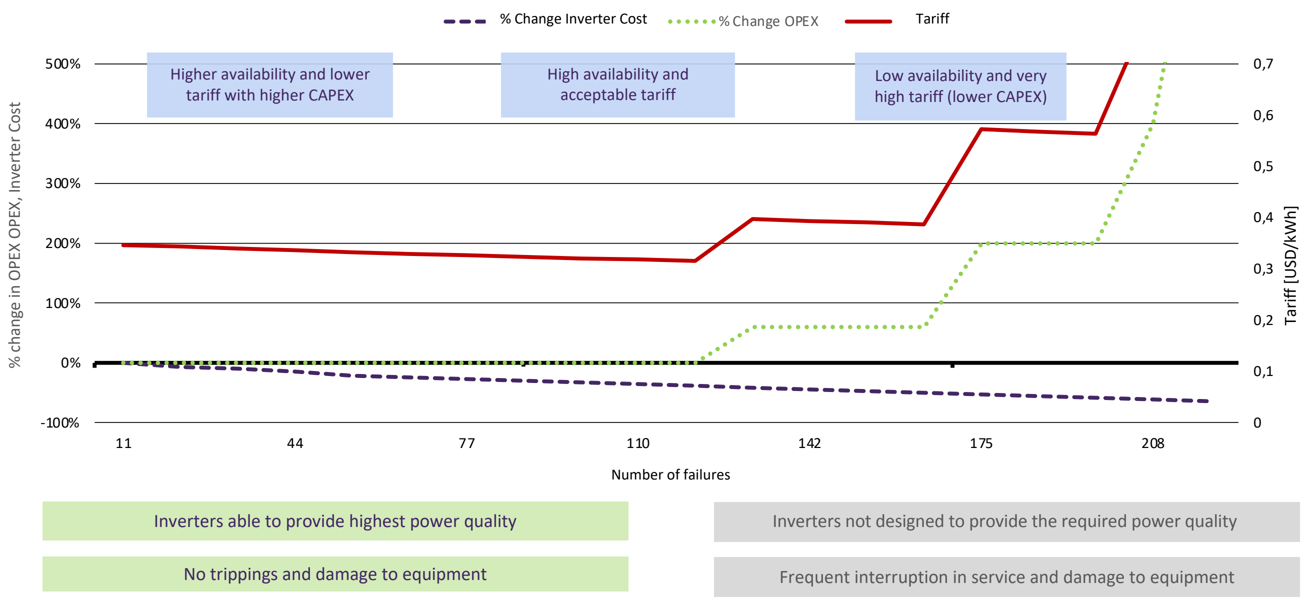
3.2.1
Impact of Power Quality

The inverter works as the 'brain' of the mini-grid system; it sets the voltage and frequency of the system, balances the demand and supply by providing reactive power, or by providing higher power for a short amount of time. Harmonic distortion results from non-sinusoidal current consumed by the appliances, the grid impedance and inverter limitations.

Power quality requirement differs based on the appliances being used. For example, the requirements become stricter from household-level appliances, up to more commercial and productive appliances. Some appliances are sensitive to transients, short-duration voltage variations, etc.

If low-quality inverters are used, they may fail to handle mini-grids with a high productive usage, resulting in appliance damage. Higher end inverters are capable of handling such situations better, but are also comparatively costly. This does not mean that all the 'cheap' inverters are bad per se, but if their technical performance is not aligned with the targeted use, **it could end up in unintended failure.** Such issues may include unwanted tripping due to high loads, communications system failures in the inverters, poor performance due to dust accumulation, and poor ventilation, etc., as well as **components failure (capacitors, DC breakers)**, among others.

Figure 10
Conceptual demonstration of inverter failures on CAPEX, OPEX and tariff



A conceptual figure is shown here to demonstrate the impact of not selecting the proper inverters. If the selected inverter is not able to keep the required power quality, it will result in several failures. Even though the CAPEX will be lower, the OPEX will increase to fix the issues and so will the tariff. In contrast to this scenario, the proper inverters will keep the availability high, ensuring safe operation and achieving a sustainable tariff.

In terms of appropriately setting the requirements, voltage imbalance, transients, short and long voltage duration variation, and frequency variation must all be set up. To ensure that there is a safe operation, it is important to take the following steps:

- **Step 1.** Categorisation of appropriate power quality levels: The regulators must define at least two to three categories, e.g. basic (rural households), intermediate (commercial) and advanced level (productive loads, critical loads).

- **Step 2.** Define voltage variation for each category: Most household appliances can work with a range of voltages. For advanced categories (commercial, productive and even households with high loads), the allowable variation needs to be defined. This has been discussed in section 3.1.2.

- **Step 3.** Define voltage imbalance for each category: This property is of particular importance for three-phase consumers (advanced categories). A typical example of advanced categories is to be <5%; however, considering the type of productive loads, it may be even lower (<3%).

- **Step 4.** Frequency regulation: Setting the allowable frequency variation in a rural set-up is challenging. Most inverters use a frequency-based active power control strategy. For sensitive appliances, the variation should be low, typically within ±1 Hz of the nominal frequency.

- **Step 5.** Transients: Advanced categories with sensitive appliances might be damaged by transients. Surge protective devices must therefore be made available.

- **Step 6.** Short and long duration voltage variations: Short duration (>half cycle, but less than a wminute), and long duration (>1 minute), could both adversely affect sensitive appliances. Typical values for advanced categories are <1 per day, and <5 per day for short and long-term voltage variations.

Figure 11
High loads are more sensitive to power quality than typical household appliances

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Power quality relies on the effectiveness of the inverter system and its compatibility with the distribution network's capacity to handle individual load currents. Additionally, it considers the influence of other clients on the network's overall load. Both the inverter capacity and the distribution grid have their limits, which may necessitate restrictions on the use of high-power appliances. This restriction can be either a complete ban on usage, or a restriction based on geographical location within a mini-grid, or limited usage during specific times, depending on the availability of power.

3.2.2
Impact of Component Standards

All the components, and their standards, also have a direct impact on safety and affordability. However, this report will keep the discussion limited to the components which connect the consumers from poles to appliances, i.e. a dropline, meter, installation board with breakers and switches, and indoor wiring.

For metering, the mini-grid developers have three options, i.e. smart meters, prepaid meters and post-paid meters. In the case of indoor installation, the mini-grid developers can go for a:

a. Ready board with fixed bulbs and load points suitable for rural set-up, or

b. Ready board for urban set-up with higher capacity breakers.

With the second aspect, **the operator may install 5A breakers, instead of 16A or 25A which already provide sufficient safety and, at the same time, come at a lower cost.** Combining these options, different scenarios can be developed.

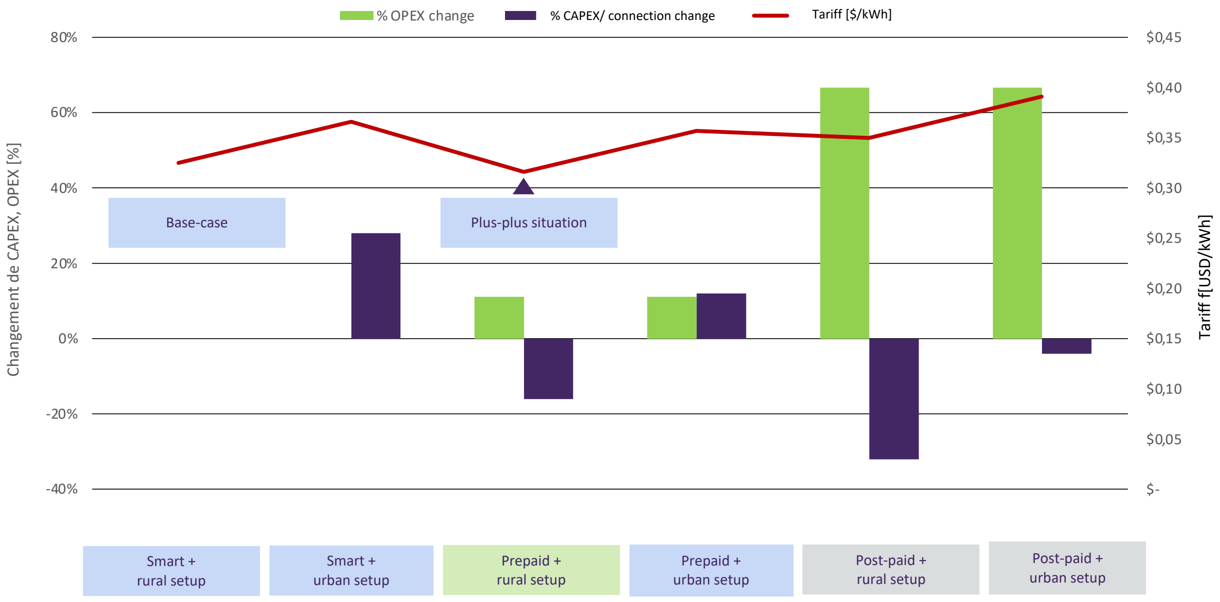
Table 2
Different meter categories and their impacts

METER TYPE	IMPACT
Smart Meters (Automatic recharge, granular data, more functionalities) Examples: SparkMeter, SteamaCo, Inhemeter, etc., used in Nigeria, and Sierra Leone, among other countries[1]	+ Reduced OPEX - Increased CAPEX + Data protection and transparency How much data is sufficient (cost-benefit analysis)?
Prepaid meters (STS Token based with SMS) Examples: Inhemeter, Calin meter, etc., used in Tanzania, Nigeria, and Myanmar, among other countries.	+ Reduced OPEX and - Increased CAPEX + Frequent meter 'recharge' data already indicates the consumption pattern well
Post-paid meters (Manual reading, invoicing, collection) Examples: Not used commonly in mini-grids. Even in grid-connected areas, countries like Kenya, Nigeria, and Ghana, among others, are shifting from post-paid to prepaid solutions.	- Increased OPEX (theft, human resources needed) + Lower CAPEX

1) Names of meter solutions mentioned in Table 2 are examples only. AFUR, GET.transform and associated partners do not endorse any brand of solutions over others.

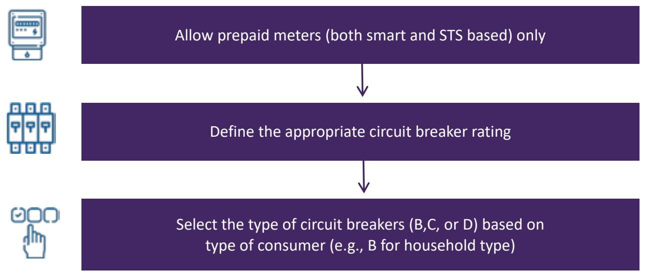
The impact on tariffs from the situations explained above are demonstrated in Figure 12. Simulation of the mentioned scenario suggests that the **combination of smart meters and rural installation-ready boards are as good as prepaid meters and rural ready boards, when considering their impact on tariff**. However, the prepaid meter and rural ready board combination will need lower CAPEX compared to the smart meter and rural board combination. For the remaining combinations, the tariff is higher.

Figure 12
Impact on tariff for selected meter and installation-board



The key takeaway is that a combination of prepaid meter technologies, along with suitable installation boards, will ensure the safety and reliability of the mini-grid service, while coming in at an affordable tariff. A decision-making process is recommended for the regulators.

Figure 13
Recommended decision making approach for component standard



BOX 1.
Consider the local context: The balance of the three key aspects should be set based on the country's specific needs and constraints.

Example 1: In a rural community, some customers could be 'sparsely' located, causing higher voltage drops. However, if these customers are households with basic lighting needs then, up to a certain voltage drop, good quality appliances, like LEDs with active power drives, will function reliably. Country example: Zambia has many unelectrified localities with 'sparse' households.

Example 2: Consumers could be highly sensitive to changes in tariffs. Usually, households can afford a fixed monthly amount. Tough requirements on availability will increase the tariff which, in turn, will dissatisfy the customers. It is important to understand the baseline affordability of the communities and their perception of tariffs.

Example 3: Once set, the requirements must be verified to ensure compliance with the technical requirements. Some countries have a designated authority to set the technical requirements, and another to verify. With clear guidelines and trained personnel, a streamlined process could help in ensuring the expected compliance level.

Country example: In Nigeria, the Standards Organisation of Nigeria (SON) sets the technical standards, and the Nigerian Electricity Management Services Agency (NEMSA) verifies the installations.

4 Beyond the Triangle: The Impact of Other Aspects on Affordability

Other technical aspects, which are outside the triangle of reliability, safety and affordability, like grid-interconnection requirements and technical reporting, also have a direct impact on the affordability. The interconnection readiness, and its impact, are discussed here for the regulators to appreciate the topics beyond the triangle, along with guidelines on how they can be carefully defined.

4.1

Interconnection Readiness

Mini-grids may be required to be grid-interconnection ready, particularly if they are built within a certain vicinity of the main-grid (5-20 km depending on the pace of grid advancement). Interconnection readiness requires that the distribution network and the customer connection points are compliant with the grid code which could be costly for a mini-grid in the beginning. As an example, a nine-metre pole might be required by the national grid code. Instead, a 7.5-metre pole can be easily used in rural areas, as clearance for large vehicles is not an issue in deep rural areas. This could reduce the CAPEX, which has a positive impact on the tariff. However, if there is a plan in place that the main-grid will arrive within a defined time frame, then some grid compliance could be enforced from the designing phase.

The cost can increase up to 25% to be grid compliant[2] . Costs will increase further if the transformer is needed to connect to a Medium Voltage (MV) grid network. This has an impact on the tariff, which is illustrated in Figure 14.

The additional components or upgrades needed to be grid compliant may include:

a) Greater cross-section of cables
b) Transformer with MV switchgear and accessories
c) Low Voltage (LV) switchgear, and
d) Higher-rated breakers at the customer end (e.g. 16A).

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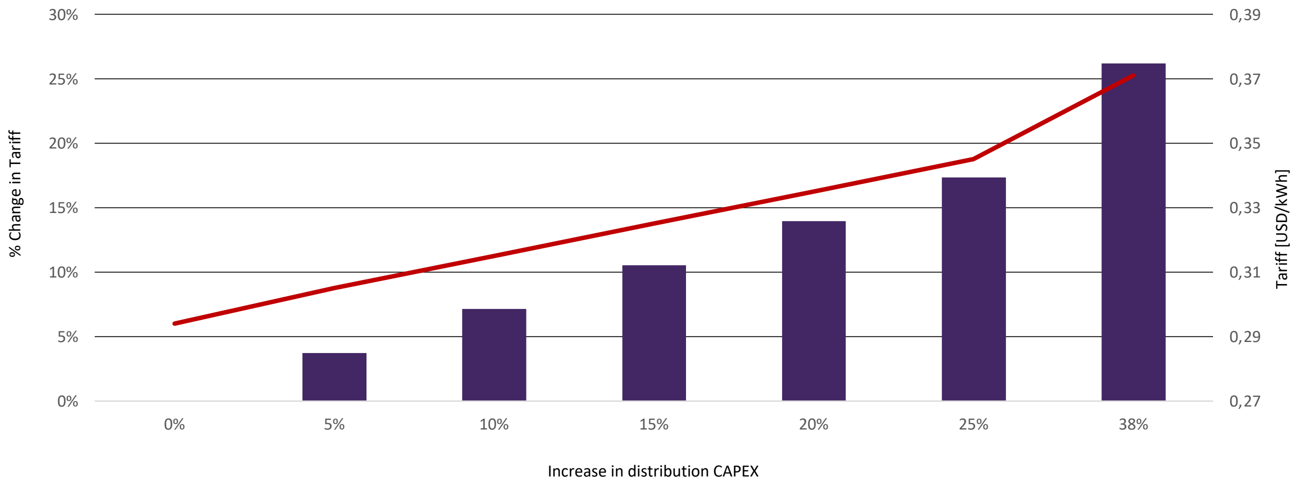
2) https://openknowledge.worldbank.org/handle/10986/31772

Figure 14
Impact of grid-interconnection readiness on distribution cost and tariff



The increase in distribution CAPEX may reach up to 38% if transformers are considered. This may result in a higher tariff from 0.27 US$/kWh to 0.37 US$/kWh.

Apart from that, the installation practices also affect the tariff. The regulator should therefore be cautious in setting a definite requirement. High-quality installation might require hiring personnel from outside the country which increases costs and, in return, the tariff. To improve the local capacity, training the technicians is possibly the most cost-efficient option. One way is to deploy a training institute to achieve this, however, that comes with a risk of monopoly. To carefully set the requirements of interconnection readiness, the regulator must take the following approach:

- **How far is the grid?** The regulators may refer to the rural electrification strategy or plan (if available) for selecting the unelectrified area, and find out which areas are within 5 to 20 km of the main-grid (this could also be 25 km depending on how fast the grid is approaching). These areas, if considered for mini-grids, should be main-grid compliant at some point for interconnection.

- **Find the interconnection readiness and its impact in your country.** It is important to design the system with and without grid readiness to find the differences in CAPEX and OPEX. The available tariff tool can be used to find the difference in tariff. If the difference is insignificant, the mini-grids can be interconnection ready from the beginning; otherwise, the systems can be upgraded once the grid arrives.

- The regulators should define different levels, based on the above two steps, to provide clarity on when the mini-grids should be made interconnection ready.

5 Conclusion

Mini-grid regulations are a critical tool to unlock the potential of renewable energy-based mini-grid solutions, to develop a sector by de-risking the investments and ultimately providing safe, reliable and affordable electricity to the rural unelectrified parts of Africa. The regulators, while setting the technical requirements within the regulations, must also consider their impact on other aspects, particularly affordability. The recommendation is that the regulators take inspiration from the best practices and standards, but ultimately follow a systematic and data-driven decision-making process in setting up the requirements which suit the local needs and capacity of their geographical locations.

The ideal pathway would be if mini-grids were to serve as a development nucleus to start providing electricity to the rural communities, and are able to constantly adjust to their growing demand. The steps along the way need to be taken in a cost-efficient way. Once the main-grid arrives, the mini-grids must have the option to continue serving as grid interconnected systems. In such a scenario, mini-grid regulations must support this transition by means of the technical compatibility of the assets, without putting the security of the investment in jeopardy and compromising the safety of the clients.

6 Annex I

The following table summarises the key underlying assumptions of the simulations. The simulations were conducted by GET.transform experts.

SIMULATION	ASSUMPTIONS
Availability and Affordability	• Homer simulations, with a defined X% system reliability. For example, a system reliability of an 80% simulated system resulted in a 32 kWp PV system with 68 kWh battery and 12 kW inverter, whereas a 90% reliable mini-grid system is a 39 kWp system with 76 kWh of battery storage and a 10 kW of battery inverter system for a typical load profile (123 kWh/day). • Technical and commercial losses, and a reserve margin of a total of 25%, are considered to determine the tariff. • Project lifetime: 20 years. • 75% grant for capital costs (base-case). The share of the grant varies, depending on the total CAPEX requirements. • Total number of customers: 205 (Single phase 200, three phases 5). • CAPEX, OPEX and project development costs were assumed, based on industry insights from the GET.transform experts and available cost benchmark studies, such as: o ESMAP (2017). Benchmarking study of solar PV mini-grids investment costs. o AMDA (2020). Benchmarking Africa's mini-grids. o Rocky Mountain Institute (2018). Mini-grids in the money. Six ways to reduce mini-grid costs by 60% for rural electrification.
Allowable Voltage Drop and Affordability	• Homer simulations with 90% system reliability are considered. The base load profile (123 kWh/day) is then scaled to simulate the losses throughout the distribution line (as a proxy of the different voltage drops). For example, a mini-grid with a 10% voltage drop from the nominal values results in a 40 kWp PV system, whereas to allow a 30% voltage drop, the capacity rises to 52 kWp to cover the losses and still serve the same demand. • Technical and commercial losses, and a reserve margin of a total of 25%, are considered to determine the tariff. • Project lifetime: 20 years. • 75% grant for capital costs (base-case). The share of the grant varies, depending on the total CAPEX requirements. • Total number of customers: 205 (Single phase 200, three phases 5). • CAPEX, OPEX and project development costs as per industry standards. • Distribution cost is adjusted linearly with the capacity (cross-section) of the overhead cables. This assumption considers not only the cable costs, but also the installation and supplementary materials (e.g. stronger poles). Based on this understanding, the distribution cost is adjusted linearly.

Impact of Power Quality

- Homer simulation results with a 90% system reliability are considered. The inverter cost (10 kW) is adjusted, assuming that the CAPEX/kW of the inverter is linearly connected with the number of failures. The relations might be different in actual performance. The figures should therefore only be used to comprehend the concepts.
- Technical and commercial losses, and a reserve margin of a total of 25%, are considered to determine the tariff.
- Project lifetime: 20 years.
- 75% grant for capital costs (base case). The share of the grant varies, depending on the total CAPEX requirements.
- Total number of customers: 205 (Single phase 200, three phases 5).
- CAPEX, OPEX and project development costs as per industry standards.
- OPEX is connected with the inverter performance. The higher the number of failures, the more OPEX also increases. The OPEX levels are the same as the other simulations discussed in Section 3.1.1.

Impact of Component Standards

- Homer simulation results with a 90% system reliability are considered. Different CAPEX scenarios are created with the defined combinations (smart meter + rural indoor installation, smart meter + urban indoor installation, prepaid meter + rural indoor installation, prepaid meter + urban indoor installation, post-paid meter + rural indoor installation, post-paid meter + urban indoor installation).
- Technical and commercial losses, and a reserve margin of a total of 25%, are considered to determine the tariff.
- Project lifetime: 20 years.
- 75% grant for capital costs (base-case). The share of the grant varies, depending on the total CAPEX requirements.
- Total number of customers: 205 (Single phase 200, three phases 5).
- CAPEX, OPEX and project development costs as per industry standards.

Interconnection Readiness

- Homer simulation results with a 90% system reliability are considered. To find the impact of interaction readiness, the distribution cost is increased by 5% steps up to 25%. The tariffs are documented. If a small transformer is considered, the distribution cost can increase up to 38% which is also shown.
- Technical and commercial losses, and a reserve margin of a total of 25%, are considered to determine the tariff.
- Project lifetime: 20 years.
- 75% grant for capital costs (base case). The share of the grant varies, depending on the total CAPEX requirements.
- Total number of customers: 205 (Single phase 200, three phases 5).
- CAPEX, OPEX and project development costs as per industry standards.

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