Aloe Energy

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Power first, grid next: why mini-grids need a rethink

Most people still without power live close to the grid, at the end of weak lines. Mini-grids built to join the grid, with storage, can serve them now and strengthen the network when it arrives.

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Key messages

Mini-grids are still planned as if the grid will never come. In most of Africa it is coming, and the way we plan, finance and hand over mini-grids has to change with it.

1. **The people we are trying to reach are not far from the grid.** In Zambia, about 1.9 million unelectrified people live within 2 km of an existing medium-voltage transformer, and another 2 million within 2 to 15 km. They are neither "off-grid" nor served.
2. **The grid at the edge is weak.** Our open screening of Zambia's 66, 33 and 11 kV networks finds about a third of feeders below 0.95 per unit voltage at evening peak, and about one in ten below 0.90.
3. **Local supply fixes the grid it connects to.** Solar plus battery on about 210 constrained feeders cut medium-voltage and 66 kV losses by about 39% and evening peak draw by about 300 MW in the model.
4. **Storage is the difference.** Solar alone cut losses by about 23% but did not move the evening peak or fix low voltage at all. The battery is what turns a mini-grid into a grid asset.
5. **There is a safe limit.** Above roughly 150% of local daily demand, exports start to overload lines and push voltage too high, so every feeder needs a hosting cap.
6. **Other countries show what decides the outcome.** Where rules for grid arrival were put in place and used, as in Cambodia, mini-grids became part of the grid. Where there were none, as in Sri Lanka and Indonesia, most were abandoned. Where the rules are unsettled, building to the utility's standard is the lower-regret choice for sites the grid is likely to reach.
7. **So mini-grids should be planned as distributed energy resources (DERs):** built first where the grid will follow, handed over on clear terms when it arrives, with the battery and generation kept on as grid services. That needs an open planning platform, tenders, and transfer rules that mostly do not exist yet.

1 The problem: planned for isolation, overtaken by the grid

The standard mini-grid model assumes a site that stays isolated for 20 years or more. That assumption shapes everything: where sites are chosen, how tariffs are set, how debt is sized and what happens when the national grid arrives.

In practice the grid moves faster than the model expects. Governments now plan for universal access: Zambia's updated Rural Electrification Master Plan (REMP) 2025-2030 targets universal access by 2030 at an estimated cost of about US$1.52 billion (Zambia Monitor). Mission 300 commits the World Bank and African Development Bank to connect 300 million people across the continent by 2030.

When the grid reaches a mini-grid built for isolation, three things go wrong:

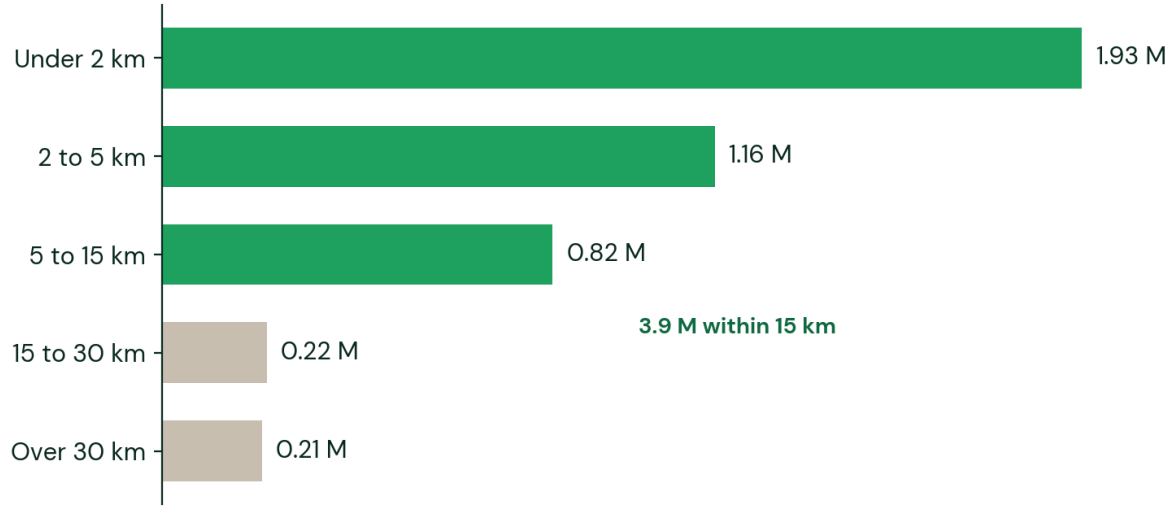
- **The asset is stranded.** There are rarely agreed terms for transfer or compensation, so investors price in the risk or avoid sites near the grid altogether.
- **Customers lose service quality or price.** Either the mini-grid tariff stays above the national tariff next door, or the utility takes over a network it did not plan for.
- **The grid loses a resource it needs.** Generation and storage that could support a weak feeder are switched off or removed.

The result is a gap in the middle. Developers avoid sites close to the grid because of encroachment risk, and utilities cannot reach them quickly because extension is slow and the existing network is already stretched. The people in that gap wait.

2 The people in between

Most of Zambia's unelectrified population lives close to the existing network, not far from it. Of about 4.3 million people in populated areas with no night-time light, about 3.9 million live within 15 km of a medium-voltage transformer.

Figure 1. Unelectrified people in Zambia by distance to the nearest medium-voltage transformer (millions)



Aloe Energy analysis of WorldPop 2020, gridfinder targets and ZESCO / World Bank MV transformers; populated cells with no night-time light.

This is the intermediary segment. These settlements are too close to the grid for a standalone mini-grid to be bankable on a 20-year view, yet too costly or too slow for the utility to connect now. Many sit at the

end of long, already overloaded feeders, so adding them as new load makes the grid worse before it gets better.

We count about 1.6 million people in 318 clusters of at least 2,000 people, each 2 to 15 km from the network. These are the natural candidates for mini-grids that are designed to join the grid, not to avoid it.

The counts use WorldPop 2020 population, gridfinder night-light electrification targets and the World Bank / ZESCO map of distribution transformers. Night-light data misses some connected households and counts some lit areas as served, so treat the figures as indicative.

Why this figure differs from our grid-edge atlas

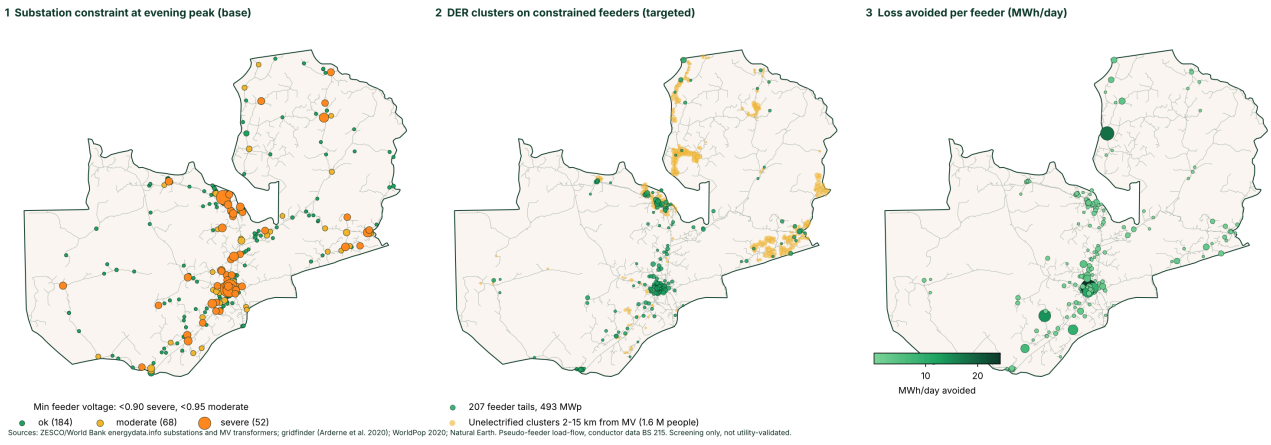
Aloe's grid-edge atlas puts about 6.5 million people in Zambia at 2 to 15 km from the grid; this paper says about 2 million. Both are right for what they measure. The atlas uses one method for all 39 countries it covers: distance to gridfinder lines, which include predicted lines, and it counts partly lit areas. This paper uses a stricter Zambia-only method: distance to mapped medium-voltage transformers from public utility data, with a threshold for what counts as lit. The atlas is built to compare countries; this paper is built to describe Zambia's network. We keep both methods and say which one each number comes from.

3 The grid at the edge needs local supply

Zambia's distribution network is already stretched at the evening peak, and the strain is greatest exactly where the intermediary segment lives. We built an open screening model of the 66, 33 and 11 kV networks to see where and by how much.

The model links about 17,500 ZESCO distribution transformers to 304 supplying substations, groups their load into about 650 representative feeders by direction and distance, and solves each one at four times of day. Demand is calibrated two ways, from installed transformer capacity and from electrified population, against a national peak of 2,194 MW (2018). We use the average of the two and keep the difference between them as a data-quality flag for each substation.

Figure 2. Zambia open distribution screening, 66, 33 and 11 kV



Constrained substations at evening peak (left), solar plus battery clusters on constrained feeders with unelectrified clusters near the network (center), and losses avoided per feeder (right). Aloe Energy open screening model.

At the evening peak, before any DERs:

Measure	Result
Substations with a feeder below 0.90 per unit voltage	52 of 304
Substations with a feeder below 0.95 per unit, or overloaded	a further 68
Feeders below 0.90 per unit	66 of about 650
Feeders above their thermal rating	38
Technical losses on 66, 33 and 11 kV lines	about 731 MWh/day, 5.4% of distribution demand, about 267 GWh a year

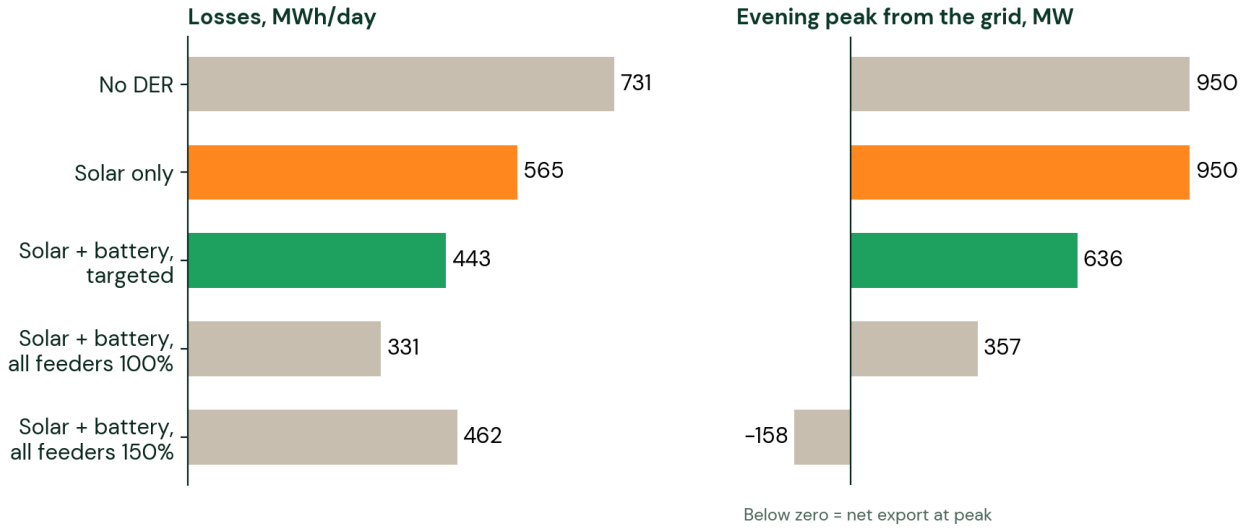
Long 33 kV lines are the main problem. The median 33 kV feeder in the model runs about 26 km, and one in ten runs more than 110 km. Voltage at the far end of these lines falls well below the usual 5% limit long before the conductors reach their thermal rating.

Every new connection added to the end of such a line deepens the problem. Grid extension alone, without local supply, connects people to a network that cannot serve them well at the hour they most need it.

4 Storage is the difference

Solar plus battery at the tail of constrained feeders cuts losses and peak load; solar alone does neither at the hour that matters. We tested each scenario across the whole Zambian network model.

Figure 3. Daily losses and evening peak draw by scenario



Aloe Energy open screening model of Zambia's 66, 33 and 11 kV networks; daily losses on modeled lines, evening peak at the supplying substations.

- **Solar only.** About 970 MWp of solar at feeder tails cuts daily losses by about 23%, but only in the middle of the day. Evening peak draw does not move, and the number of feeders below voltage limits is unchanged. Twelve feeders go over voltage at midday.
- **Solar plus battery, targeted.** About 490 MWp of solar with about 1.2 GWh of storage on about 210 constrained feeders cuts losses by about 39% and evening peak draw by about 300 MW. Feeders below 0.90 per unit fall from 66 to 6, and overloaded feeders from 38 to 6.
- **Solar plus battery everywhere.** Sized to 100% of local daily demand on every feeder, losses fall by about 55%. Above about 150%, batteries export so much in the evening that lines overload and losses rise again.

Two lessons follow. First, each kWh of local supply on a constrained feeder saves about 0.1 kWh of losses upstream, and the peak relief is worth more than the energy saved: it defers substation and line upgrades. Second, there is a safe hosting limit on every feeder. In the model it adds up to about 1,460 MWp nationally, but it varies widely, and 23 feeders had no safe level at the sizes tested.

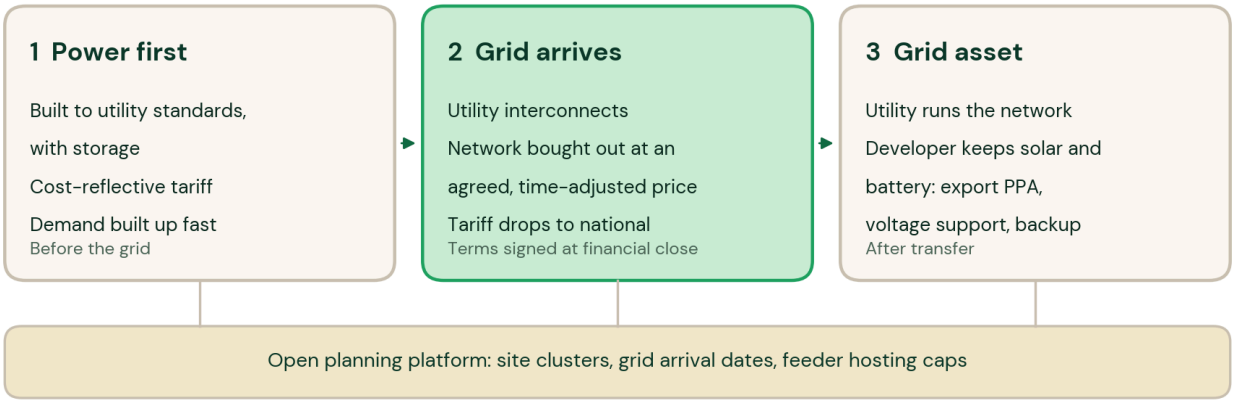
How does local supply compare with what a utility would usually do? On a representative 120 km, 33 kV feeder, solar with four hours of storage at the last six villages cut total losses by about 12% and lowered the substation's evening peak from 93% to 80% of its rating. Switched capacitors, a voltage regulator or a thicker conductor raised voltage at the end of the line, but none of them lowered that peak. This is a technical comparison only; it does not include costs.

This is why the battery matters to the model we propose. A mini-grid with storage is not just a supply for its customers; it is voltage support and peak capacity at the weakest point of the grid.

5 A different model: mini-grids as DERs

We propose planning mini-grids as distributed energy resources and short-term extensions of the national grid: power first, grid next. The mini-grid is built to grid standards where the grid is expected, serves customers until the grid arrives, then hands its network to the utility and keeps working as a grid asset.

Figure 4. A mini-grid planned as a DER serves first, then hands over and supports the grid



In practice that means four types of site, all of which the model has to serve:

DER model	Where	What the mini-grid does
Grid-ready	Grid expected within about 5 to 10 years	Built to utility standards, transfers on arrival
Undergrid / weak grid	Under or beside a weak feeder	Supplies customers and supports feeder voltage
Grid-arrival transition	Grid arriving now	Interconnects, tariff drops, network transfers
Interconnected DER fleet	After interconnection	Generation and storage aggregated for grid services

The commercial logic changes with it:

- **Tariff.** A cost-reflective tariff applies until transfer, then customers move straight to the national tariff.

- **Buy-out.** A transfer facility, backed by development finance institutions (DFIs), buys the distribution network at grid arrival. The price adjusts for timing, so early arrival pays more for lost revenue and late arrival less, in local currency indexed to the US dollar.
- **Generation and storage.** The developer keeps them after transfer and earns from an export power purchase agreement (PPA), weak-grid backup, grid services and, where host countries authorize it, Article 6 carbon credits.
- **Front-loaded demand.** Connection subsidies, appliance finance, tariff support and anchor-load deals build demand fast before the grid arrives. In a CrossBoundary trial at five mini-grids in Tanzania, tariff cuts of 50 to 75% raised customers' consumption to about 1.5 to 3 times baseline after two years, and it stayed there (CrossBoundary 2022).

The loss and peak savings in section 4 belong to the utility, not the developer. They are not a revenue line in this model; they are the reason governments and utilities should want it.

6 What happened when the grid arrived elsewhere

Zambia would not be the first country to face this. Mini-grids have met the arriving grid in South and Southeast Asia for two decades, and in East and West Africa more recently. The record points one way: where clear rules on grid arrival were put in place and used, mini-grids became part of the grid. Where they were not, most were abandoned.

What the record shows

Where rules were put in place and used, mini-grids survived. Cambodia's mini-grids were built with no grid-arrival rule. But from 2001 the new Electricity Law required every provider to hold a license, and the regulator made network upgrades a license condition. When the national utility's grid arrived, about 250 private mini-grids became licensed distributors: they kept their networks and bought power wholesale. Customers on these systems grew from under 100,000 in 2005 to over 1 million in 2015 (ESMAP 2018).

Where there were no rules, most were lost. In Sri Lanka, more than 100 of about 260 community hydro schemes disappeared after the grid arrived; three now sell power to the grid. In Indonesia, government-funded systems were barred from connecting until 2017, and "just 6 percent" of mini-grids stayed in business once the grid came (ESMAP 2018). In Bihar, India, the Dharnai solar mini-grid, built in 2014, lost its customers and collapsed after the grid reached the village (CSE 2026). The authors of the study of Sri Lanka, Indonesia and Cambodia found that in all three countries "no specific rules or policies were in place" when the systems were built.

Newer rules exist, but use is thin. Tanzania has had rules on grid arrival since 2017. A mini-grid may sell to the utility, keep its network and buy power in bulk, or do both. Its regulator reported in 2025 that no mini-grid has yet taken the distributor route, and developers report that the utility pays small producers less than the regulator's approved tariffs (EWURA 2025; AMDA 2025). Nigeria's 2023 regulations give a mini-grid 12 months' notice and the choice of keeping its network or selling it for its depreciated value plus 24 months of pre-tax profit (Legal 500 2024). Four interconnected mini-grids were running by 2025, and about 20 grid-connected projects had stalled in 2022 (RMI 2025; GEAPP 2026). Nepal allowed small hydro plants to connect in 2014; three had done so by 2018, while 34 plants had already been affected by grid extension by 2015 (Mallik 2018; energypedia 2018). Kenya's mini-grid regulations, drafted in 2021, had not been adopted as of November 2026.

Country	Rule on grid arrival	Options on arrival	What happened
Cambodia	None at first; licensing from 2001 made upgrades a license condition	Keep network, buy power wholesale	About 250 mini-grids became licensed distributors
Sri Lanka	No specific rule	Not set	More than 100 of about 260 schemes gone; 3 sell to the grid
Indonesia	Connection barred for government-funded systems until 2017	From 2017: sell to the utility on a 20-year contract	6% stayed in business; about 150 abandoned; 9 connected
India - Uttar Pradesh	State policy and regulations, 2016	Sell power at a feed-in tariff, run as franchisee, or sell the network at depreciated value	No public count of outcomes
India - Bihar	None found	Not set	Dharnai mini-grid collapsed after the grid came
Nepal	Decision of 2014 for plants under 100 kW	Sell power to the utility under a contract	3 connected by 2018; 34 affected by 2015
Tanzania	Rules from 2017, updated 2020	Sell power, keep network and buy in bulk, or both	No distributor conversions yet; payment below approved tariffs reported
Nigeria	Rules of 2016, replaced in December 2023	Keep operating, or sell the network for depreciated value plus 24 months' profit	4 interconnected mini-grids by 2025
Kenya	Draft rules of 2021, not adopted	Draft: sell power, distribute, or both, if built to the distribution code	No public outcomes

Sources: ESMAP 2018; CSE 2026; UPERC 2016; Mallik 2018; energypedia 2018; EWURA 2025; AMDA 2025; Legal 500 2024; RMI 2025; Bowmans 2021; EPRA regulations list (checked November 2026).

Five tests for whether the rules are ready

A rule on paper is not the same as a rule that works. Rather than label countries, we suggest five plain tests that anyone can apply.

1. Is there a published rule for what happens when the grid arrives?
2. Has it ever been used?
3. Is there a published standard a mini-grid can build to so that it can connect?
4. Is there a published tariff for power sold by small producers?
5. Does the utility pay its small producers in full and on time?

Country	1 Rule	2 Used	3 Standard	4 Tariff	5 Paid
Cambodia	Licensing, not a specific rule	Yes	License upgrade conditions	Wholesale tariffs set	Not found
Sri Lanka	No	3 cases	Rules made for large plants	Not checked	Not found
Indonesia	From 2017	9 cases	Not found	Yes, 2017	Not found
India - Uttar Pradesh	Yes, 2016	Not found	Not found	Set by the regulator	Not found
Nepal	2014 decision	3 cases	Yes, 2015	Contract by contract	Not found
Tanzania	Yes, 2017 and 2020	Producer route only	Yes	Yes, 2019	Below approved tariffs

Country	1 Rule	2 Used	3 Standard	4 Tariff	5 Paid
Nigeria	Yes, 2023	4 interconnected	Not found	Not found	Not found
Kenya	Draft only	No	Required in draft	Referred to in 2024 rules	Not found

"Not found" means the public sources we read did not say, not that the answer is no. The fifth test has the least public evidence anywhere, and it may matter most: a feed-in tariff "may not be enough" without clear payment terms and a creditworthy utility (World Bank 2019).

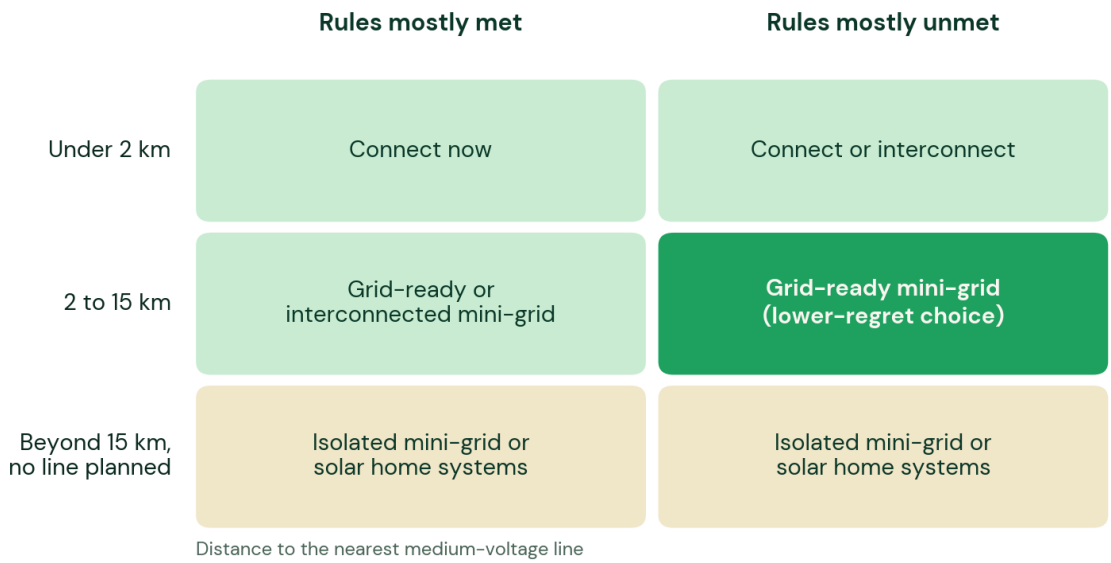
Why this favors building grid-ready now

Where the tests above are mostly unmet, a developer cannot wait for the regulator. What it can control is the network it builds. A mini-grid built to the utility's standard keeps every option open: it can become a distributor, sell its power, do both, or sell its network. One that is not built to standard is left with abandonment or running beside the grid. The World Bank's handbook puts it plainly: because mini-grids last 15 to 20 years and grid plans "can and do change, often for political reasons", it may be reasonable to assume that "nearly every mini grid built today should be prepared for the arrival of the main grid" (ESMAP 2022, p.255).

Missing rules also change where developers go. Without them, developers "may be choosing small sites farther from the main grid" (ESMAP 2022, p.56), which is how the people 2 to 15 km from the network, the intermediary segment in section 2, get left out. And rules that exist but have never been used still carry risk: "lack of experience" with a compensation scheme "creates a significant risk for investors" (ESMAP 2022, p.190). A built network that meets the standard gives the regulator something concrete to write terms around.

This makes grid-ready design the lower-regret choice for sites the grid is likely to reach, where arrival rules are unsettled. It is not the right choice everywhere.

Figure 5. Which kind of supply fits, by distance to the grid and the state of the rules



Adapted from the decision tree in World Bank 2019, Figure 3. "Rules mostly met" means most of the five tests above are met.

Where the case is weaker

- **It costs more up front.** In one reported case, meeting pole standards took 25% of a mini-grid's capital cost in Bangladesh, against 5% for an unregulated project in Nigeria (World Bank 2019). That is a single

developer's figure, but the direction is clear. If the grid never comes, the extra cost buys little.

- **Without subsidy there may be no good option.** Higher standards usually need support, and where integration is essential but no subsidy is available, "there is no good option" (ESMAP 2022, p.255).
- **Remote sites are different.** Well beyond 15 km, with no line planned, isolated mini-grids and solar home systems remain the better fit, and lighter standards make sense there.
- **The utility has to be a buyer worth trading with.** Selling power only helps if the utility pays. Tanzania shows the risk of tariffs set below what was approved.
- **The grid has to be reliable enough, and the mini-grid must still run alone.** In Nepal, connected plants cannot use or sell their power during grid outages (Mallik 2018), and outages of 8 hours or more a day are common in parts of India and Nepal (Smart Power India 2019; energypedia 2018).
- **Terms set too low can sink the business.** Buy-out values and bulk tariffs decide whether the end state is worth reaching.
- **We found no figure linking arrival rules to the cost of capital.** The link is widely argued, but we could not find it measured.

7 What has to be true

The model only works if four things are in place. None of them is technically hard; all of them need institutions to decide.

An open planning platform. Everyone has to see the same map: where the network is, where it is weak, where people are, and when the grid is likely to arrive. Today that picture is split across utility GIS files, donor studies and master plans, much of it closed. Our Zambia screening was built from open data only, which shows it can be done, but ZESCO's own line data and substation ratings would make it far more accurate. The platform should be open data, open source and neutrally hosted.

Tenders for site clusters, with hosting caps. Governments tender clusters of sites drawn from the platform, scored on subsidy needed, tariff, buy-out price and demand commitments. Each cluster comes with a hosting cap per feeder, so DERs relieve the grid rather than overload it.

Transfer terms agreed before construction. The buy-out formula, the tariff step and the export PPA have to be signed at financial close, not negotiated when the grid arrives. Without them, sites near the grid stay unbankable. Section 6 shows what happens otherwise.

Utilities able to run what they inherit. After transfer the utility owns and operates the network. Many rural utilities are stretched, so service can fall after handover. The developer's battery and generation become the backstop, which is why their grid-service role has to be contracted, with metering and dispatch rights for the utility.

There are real tensions here. Carbon credits under Article 6 need host-country authorization and may compete with national climate targets. Customers who had reliable mini-grid power may see more outages on a weak feeder. Who funds the gap between expected and actual grid arrival still needs an answer. The full study will work through each one.

8 What we ask

Each group can start now, without waiting for the others.

Who	What we ask
Governments and rural electrification agencies	Treat mini-grids near the grid as part of the grid plan. Use master plans such as Zambia's updated REMP to tender site clusters with transfer terms built in.
Regulators	Publish a standard transfer and buy-out framework, a tariff step at transfer, and a simple export PPA for DERs. Set hosting caps per feeder in tenders. Check your market against the five tests in section 6 and close the gaps, starting with a rule that has been used at least once and a tariff the utility actually pays.
Utilities	Share network data (lines, substations, ratings, losses) on an open platform. Name the constrained feeders where local supply would help most.
DFIs and funders	Back a transfer facility that buys networks at grid arrival, and fund the open platform as public infrastructure. Where the rules are unsettled, fund the grid-ready premium rather than waiting for them.
Developers	Build to utility standards, with storage, and price projects for transfer rather than for isolation. Where the grid is likely within the asset's life, say so in the financing case.

For Zambia specifically, the timing is good. The updated REMP 2025-2030 already uses least-cost geospatial planning, and the Energy Regulation Board launched an open access framework for transmission and distribution networks in 2025 (ERB). The pieces for a DER model are arriving; they need to be joined up.

9 Limits and next steps

The Zambia numbers come from a screening model built on open data, not from ZESCO's own network model. They show direction and order of magnitude, not values to plan a project on.

The main limits:

- **Feeder routes are approximated.** Feeders are built from where transformers are, not from mapped line routes. ZESCO's mapped MV lines, published as open data, would replace this.
- **Losses may be overstated.** The model uses one standard conductor per voltage level. Its 5.4% medium-voltage loss is high next to the 8.5% total system loss ZESCO reported for 2017 (Parliament of Zambia), which also covers transmission, low voltage and commercial losses. The percentage changes between scenarios are more reliable than the absolute MWh.
- **No substation transformer ratings.** These are not public, so substation overloading is not tested.
- **Demand is calibrated, not measured.** The 45% share of national peak on the distribution network is our assumption, as is the daily load shape.
- **REMP sites are not yet included.** The updated REMP 2025-2030 has no public GIS layer; we will add its sites from the published plan.
- **The representative feeder is a model, not a measured network.** It covers one day on one assumed feeder, with no costs.
- **The country cases rest on public reports,** several of them secondary summaries. The primary rule texts for Nigeria (2023), Kenya and Uttar Pradesh were not read in full. The five tests are a first pass, and the fifth has almost no public evidence.

The full Aloe Energy study, Mini-grids as DERs, will take this further: all Mission 300 compact countries, a technical sizing model, a financial model of the transfer, and the open platform itself. A natural next step is a grid arrival forecast: master plans and pipeline dates, adjusted for their delay record, joined to the grid-edge screening to show when the grid plausibly reaches each district.

Annex: method, data and sources

Zambia screening method. Each MV transformer and electrified population cell is assigned to its nearest supplying substation. Load is split into up to eight representative feeders per substation by direction, each with up to ten nodes by distance (route length = straight line x 1.3). Each feeder is solved with a radial load-flow at night, morning, midday and evening load levels. 11 kV results feed the 33 kV level, and 33 kV results feed a simplified 66 kV level. DERs sit on the outer 40% of each feeder, sized as a share of that section's daily demand, with batteries moving surplus solar to the evening (90% round trip).

Main assumptions. Distribution share of national peak 45%; power factor 0.9; ACSR conductors per BS 215 (Rabbit 11 kV, Hare 33 kV, Wolf 66 kV); 5.5 kWh/kWp/day solar yield; voltage limits 0.95 to 1.05 per unit.

Representative feeder. A 160 km 132 kV line (25 MW of other load assumed), a 15 MVA 132/33 kV substation with an 8 MW town, and a 120 km 33 kV feeder with 12 villages of 0.25 MW peak each; solar and a 1.5 MW, 6 MWh battery at the last six villages; one typical day, hourly, in pandapower. Capacitors and the voltage regulator are switched hourly.

Data	Use	Source
Distribution substations and MV transformers (ZESCO via World Bank)	Network nodes, installed capacity	energydata.info
gridfinder predicted grid, night-light targets	Line coverage, electrification	Arderne et al. 2020, Zenodo
WorldPop 2020, 1 km	Population	WorldPop
ZESCO peak demand 2018	Demand calibration	GET.invest
ZESCO system losses 2017	Loss check	Parliament of Zambia
Updated REMP 2025-2030	Policy context	Zambia Monitor
Open access framework	Policy context	ERB

Sources for section 6 and other cited works

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Code, GIS layers and results tables are available on request by email and will be published with the full study.