BEYOND THE 100% ASSUMPTION: ADJUSTING OnSSET TO REFLECT GRID RELIABILITY COSTS

SUSTAINABLE ENERGY FOR ALL

Disclaimer

The findings presented herein are for illustrative purposes only to demonstrate the functionality of the model; they do not reflect actual site conditions and should not be used for investment planning.

ACKNOWLEDGEMENT

These developments were introduced into the OnSSET tool by **Julian Cantor**, an Energy Planning Analyst at Sustainable Energy for All (SEforALL), together with **Andreas Sahlberg**, Geospatial Data and Energy Modelling Officer, SEforALL and **Alexandros Korkovelos**, Energy Planning Senior Officer, SEforALL. This work is part of the Center of Excellence - Integrated Energy Access Planning, with funding from the Global Energy Alliance for People and Planet.

The methodological updates were inspired by similar, sophisticated techno-economic planning methodologies, particularly the **Reference Electrification Model (REM)**, developed by the MIT/Comillas-IIT Universal Energy Access Lab (UEA Lab) (R. Amatya et al., 2019).

We are also grateful to the Global Electrification Platform (GEP) team at the World Bank/ESMAP for their supportive brainstorming conversations, as well as to the broader OnSSET community for their continuous guidance on sector needs and tool development priorities.

At SEforALL, we remain deeply committed to advancing open, trustworthy and equitable modelling solutions aligned with the guiding principles for achieving SDG7. Feedback is very welcome as this is a community effort, and your insights will help make the tools better for everyone.

Integrated Energy Planning Unit

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EXECUTIVE SUMMARY

OnSSET (Open-Source Spatial Electrification Tool) is a GIS-based tool developed to support electrification planning and decision-making for the achievement of energy access goals in currently unserved locations. OnSSET chooses the "optimal" technology based on a Levelized Cost of Electricity (LCOE) comparison. While the reliability of power supply is explicitly reflected in the sizing of off-grid systems (e.g., mini-grids), the model does not account for (potentially) unreliable supply in new grid connections.

To address this, we have introduced two variations of the standard LCOE formula that serve as proxies for the cost of non-supplied electricity and test the model's reaction on a case study in Uganda. We observed that the:

1. **Cost of Non-Served Energy (CNSE) option** - which applied a parametric economic penalty for outages based on reliability indices (e.g., SAIDI) - caused minor technology shifts from grid connections towards solar home systems (SHS); it had only a limited impact on total investment estimates as it functions primarily as a shadow price.
2. **Diesel Backup option** - which models the explicit CAPEX and OPEX of backup generators required to cover supply gaps in each settlement - resulted in more evident shifts from grid extension to off-grid solutions and also increased the total estimated investment of the least-cost electrification scenario.

The analysis confirms that incorporating reliability metrics may alter the "least-cost" electrification pathway. When the (un)reliability-incurred costs are factored into the modelling process - whether through economic penalties or backup infrastructure costs - decentralized solutions could become a more suitable electrification option in areas with an unstable centralized grid network.

While both methods have limitations (e.g., CNSE is value-laden; diesel backups rely on broad customer assumptions), the new modification represents a long-awaited, critical step towards a more reality-reflective version of OnSSET. We invite planners, researchers, and policymakers to join us in strengthening the approach so that least-cost modelling continues to evolve and better reflect real-world technical constraints, policy environments, and country priorities.

CHAPTER ONE

INTRODUCTION

OnSSET (Open-Source Spatial Electrification Tool) is a GIS-based tool developed to support electrification planning and decision-making for the achievement of energy access goals in currently unserved locations. OnSSET chooses the “optimal” technology based on a Levelized Cost of Electricity (LCOE) comparison. That is, the cost of electricity - factoring in generation & distribution, where applicable - to meet the targeted demand at each location.

Off-grid technologies – such as mini-grids and solar home systems – are typically sized with stringent reliability requirements. For mini-grids, reliability of supply is often set to 95-99%, which drives up CAPEX and results in a higher cost of energy. In contrast, grid extension modelling is assumed to provide 100% reliability, yet this assumption is not explicitly reflected on the associated CAPEX needs or in the resulting cost of electricity calculations.

To address this, we have introduced two variations of the standard LCOE formula that serve as proxies for the cost of non-supplied electricity. The first incorporates a parametric Cost of Non-Served Energy (CNSE), essentially a monetary adjustment to account for failed grid service. The second assumes that non-served electricity is supplied by a backup diesel generator, with the adjusted cost reflecting the genset’s CAPEX and operational expenses. We tested both approaches for a selected area in the Eastern part of Uganda.

What is the unmet electricity demand?

We define the demand that is not covered due to grid system failure as unmet. The formula is simple, as shown below:

$$Unmet\ demand\ =\ Total\ demand \times (1 - grid\ reliability)$$

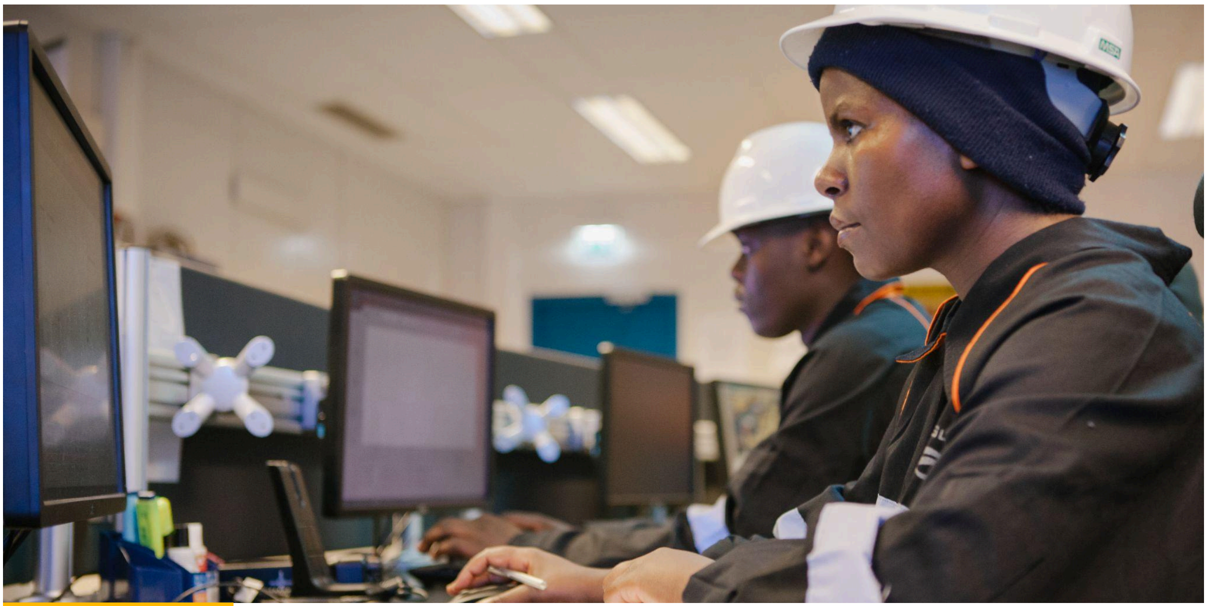
To give an example, a settlement with an estimated total demand of 5,000 kWh/year and a grid reliability level of ~90% will lead to an estimated unmet demand of 500 kWh/year in that settlement.

Ok, but how is grid reliability estimated then?

Ideally, grid reliability metrics would be provided directly by the utility or system operator. In practice, however, such data is not generally available, and seldom is there sufficient spatial granularity. Therefore, we often rely on indices such as the System Average Interruption Duration Index (SAIDI) and Frequency Index (SAIFI) (World Bank, n.d).

Note that SAIDI and SAIFI are usually reported at different temporal resolutions but are almost always spatially aggregated to a single value per country or utility/distribution company service area. A global average value underrepresents reliability in many specific areas. In an ideal scenario, SAIDI would be available at the MV substation level to better capture the spatial variations in grid configurations. For example, areas served exclusively by radial lines, with no redundancy, are far more likely to experience longer periods of unavailability in case of failure events.

The OnSSET code has been adapted to accept reliability inputs at any available spatial resolution, from national values to provincial, utility service-area level, or even settlement-level data where available. The model simply adjusts to whatever granularity is available.



CHAPTER TWO

METHODOLOGY: MODELING GRID UNRELIABILITY

There are two approaches to model the grid (un)reliability using OnSSET. The first one relies on the Cost of Non-Served Energy, while the second assumes that the unmet demand is provided by a diesel generator. The two methods are described in detail in this chapter.

2.1 Option 1: Modeling with CNSE (Cost of Non-Served Energy)

CNSE represents the economic value of the losses incurred due to electricity interruptions. It is a value used in medium-term/long term generation and transmission planning, technological up-gradation of assets, design of regulatory incentives and compensation mechanisms, etc. (Public Utilities Commission of Sri Lanka, 2024).

The yearly cost of non-served energy is calculated by multiplying the unmet demand by the assigned cost of non-served energy.

$$Annual\ CNSE \ = \ Unmet\ demand\ x\ CNSE$$

Coming back to the example of unmet demand of 500 kWh/year, and a CNSE-value of 0.50 USD/kWh, the annual CNSE would be 250 USD. For grid extension, this cost is added as a penalty to the LCOE function for the cost of grid extension as a penalty:

$$Grid_{LCOE} = \frac{\sum_{t=0}^{n} \frac{CAPEX_{grid} + OPEX_{grid} + Annual\ CNSE}{(1+r)^n}}{\sum_{t=0}^{n} \frac{Total\ Demand}{(1+r)^n}}$$

2.2 Limitations with the CNSE approach

- CNSE represents the broader economic value of lost load - such as lost productivity, spoiled inventory, and reduced welfare - rather than a direct financial expenditure (like the cost of purchasing backup fuel)(Bose, et al. 2006; Colambage and Perera, 2018; Gorman. W, 2022)[1]. High-value or critical services (e.g., hospitals or large employers) face much higher outage costs than residential users. For example, Namibia's Electricity Control Board estimates CNSE (termed COUE) at 0.65 USD/kWh for residential users, while business-sector estimates range between 2-150 USD/kWh, depending on the activity. Given that OnSSET operates at a settlement level, the current version cannot capture these sectoral differences, so the CNSE input is applied as a national average.
- Equally, there is no standardized or universally accepted method for calculating CNSE. Countries – and even individual institutions – apply different assumptions, data sources, and valuation approaches, leading to widely varying estimates. As a result, CNSE is inherently value-laden: its magnitude depends on the user's judgment and intuition about the economic cost of outages.
- In our approach, CNSE is basically incorporated as an additional OPEX (operational expenditures) cost, but this alone does not indicate how much extra CAPEX (capital expenditures) would be required to strengthen the grid. It only shows whether the added OPEX burden may shift new connections toward alternative supply options that, on paper, deliver higher system reliability; that is, if sized adequately, supply will always meet demand.

2.3 Option 2: diesel back-up system

This approach involves deploying a backup diesel generator to cover unmet demand. While **this is by no means an endorsement of this solution**, this approach does align with current market realities in many countries that continue to face frequent power interruptions (MarkNTel, 2024). Any analysis of diesel backup must account for the volatility of fuel markets and the likelihood of future price increases. These cost risks are often exacerbated in remote communities or unstable regions, where complex transport logistics can drive delivered fuel prices significantly higher than national averages.

So here, the required capacity of diesel gensets is calculated based on the estimated annual unmet demand in each settlement:

$$Installed\ Capacity\ [kW] = \frac{Total\ Unmet\ Demand\ (kWh)}{Capacity\ Factor * Hours\ per\ Year\ (h) * Average\ to\ Peak\ load\ ratio}$$

[1] There are similar concepts provided in the literature such as Cost of Unserved Power or Value of Lost Load.

Next, the diesel fuel requirements are estimated as follows:

$$Diesel\ fuel\ requirements\ [kWh/year] = \frac{Unmet\ Demand\ (kWh)}{Generator\ efficiency}$$

From there, the annual operation and maintenance costs, including fuel, can be calculated. The cost of operating a diesel generator is not just associated with the market price but includes transport costs, which impact settlements located in remote areas.

Next, both the diesel generator CAPEX and OPEX are added to the LCOE equation as shown below:

$$Grid\ LCOE\ [USD/kWH] = \frac{\sum_{t=0}^{n} \frac{CAPEX_{grid} + OPEX_{grid} + \boldsymbol{CAPEX_{diesel}} + \boldsymbol{OPEX_{diesel}}}{(1+r)^n}}{\sum_{t=0}^{n} \frac{Total\ Demand}{(1+r)^n}}$$

With this approach, we can capture not only how an unreliable grid affects the LCOE, but also the additional CAPEX required to deploy a backup diesel generator.

2.4 Limitations with the diesel backup approach

- We assume that all customers rely on generators to cover unmet demand - an assumption that may not hold universally and will vary depending on customer type and the actual reliability levels experienced. It is far more typical for income-generating or commercial customers to deploy backup diesel gensets than it is for households.
- The sizing of the generator is done based on an estimated peak load derived from the annual electricity demand using a generic *average-to-peak load ratio*. This can over- or under-estimate the true needs of different customer types. Critical loads, such as those in health facilities, are best sized on peak load and using an averaged ratio may undersize their backup capacity, leading to unmet demand during peak periods. Conversely, the same method may oversize systems for households or other users that do not require large backup capacity, resulting in unnecessarily high CAPEX. As noted above, backup generator use is far more common among commercial or income-generating customers than households, but the model assumes all customers behave similarly. Since OnSSET calculates demand at the aggregate settlement level, individual variations in customer behavior and peak loads are implicitly smoothened out. Therefore, we apply a unified backup assumption across the entire settlement rather than modeling specific customer types.
- Diesel fuel costs also vary widely across countries, within the country for remote and vulnerable communities, and over time, making it difficult to select an appropriate price for future years, as required by OnSSET for the target year. This adds another value-laden assumption, since fuel prices are sensitive to taxes, subsidies, logistics, global markets, and local supply constraints, all of which can significantly influence the model's outcomes.

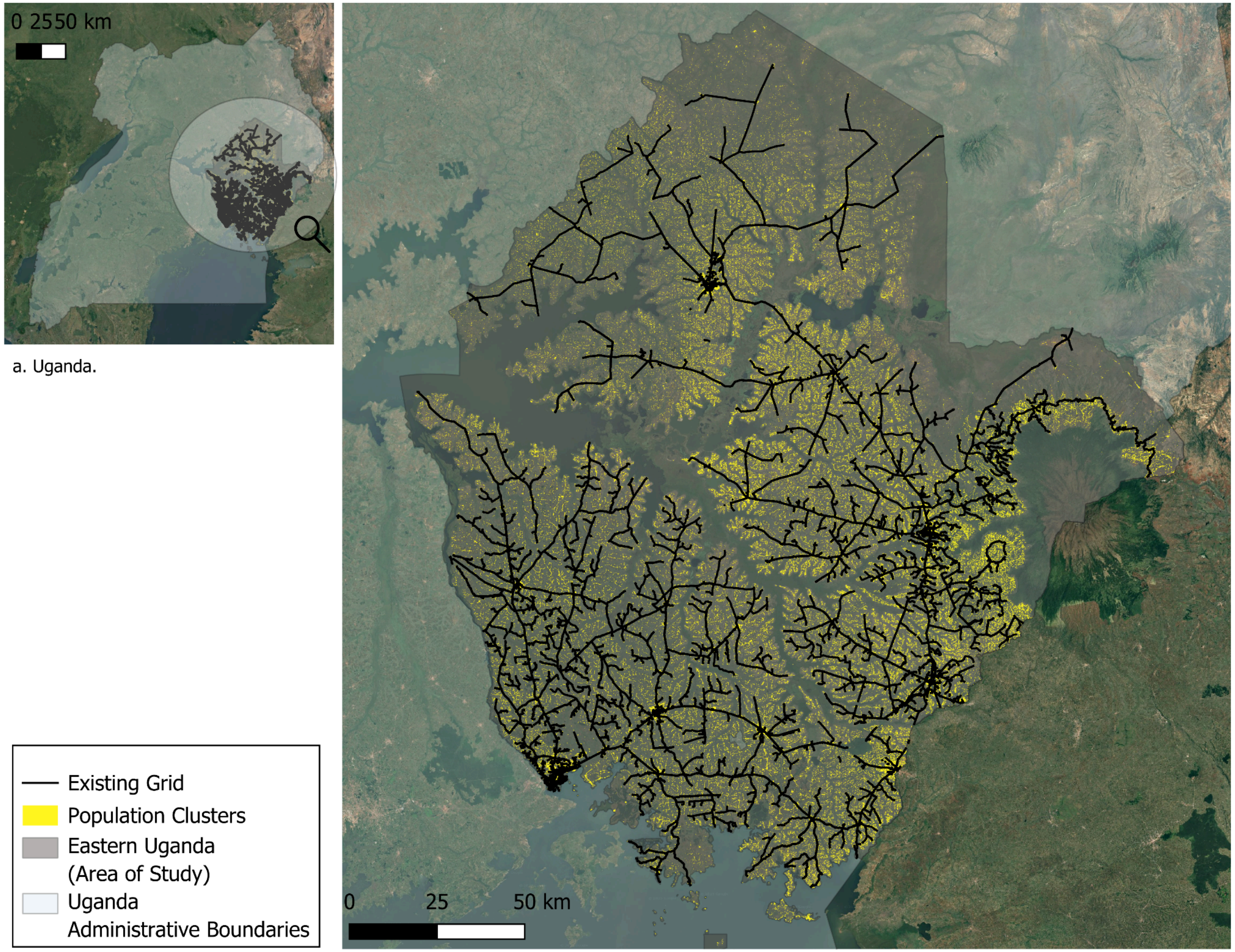
CHAPTER THREE

CASE STUDY: PERFORMANCE & SENSITIVITY IN UGANDA

We tested the two modelling modifications in a small region in eastern Uganda (see Figure 1). The area was selected arbitrarily based on the availability of previous research, relevant data, and existing models[2].

[2] These results are for demonstration purposes only; they are intended solely to illustrate model behaviour and should not be interpreted as representing actual conditions.

Figure 1: Map of the Area of Study (AoS) selected by the team to test the new OnSSET modifications. The area was selected arbitrarily based on the availability of previous research, relevant data, and existing models.



a. Uganda.

b. Area of Study (Eastern part of Uganda) with more granular view of the different layers.

With regards to electricity demand targets, we assumed:

- Urban settlements at Tier 4 (1,241 kWh/customer/year)
- Rural settlements:
    - Large at Tier 3 (365 kWh/customer/year)
    - Smaller at Tier 2 (73 kWh/customer/year)

Other assumptions related to technology specifications and costs were based on the team's experience and work conducted for the Global Electrification Platform (GEP).

In the base case scenario, we assumed grid reliability at 100% (that is SAIDI=0). The model run indicated a total capital investment of 2.2 billion USD; the investment goes mainly towards grids, with grid densification (4%) and grid extension (65%), while off-grid solutions include 24% for solar home systems and 8% for solar PV mini-grids.

3.1 Applying the CNSE approach

Using the references in Table 1, we decided to use two SAIDI values: 50 and 100 hours per year.

Table 1: SAIDI and SAIFI indices for Uganda

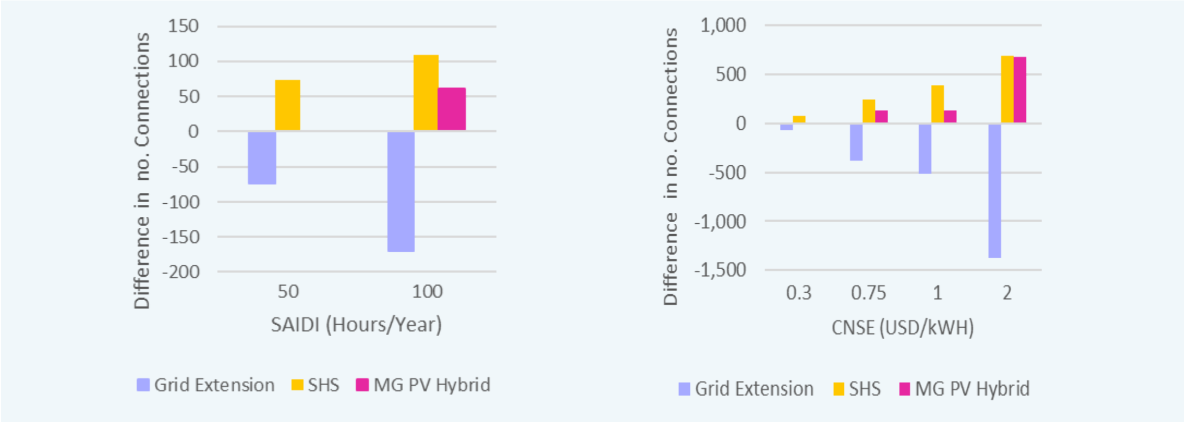
SOURCE	SAIDI	SAIFI
Utility Performance and Behaviour in Africa Today (World Bank, 2018)	50	35
Power Markets Database. (World Bank, 2021)	49.8	49.8
Uganda Energy Transition Plan (IEA, 2023)	56	38
Reliability Study of Electrical Distribution Network in Kampala East (Joshua et al.,2023)	100	68

The CNSE method required quantifying the monetary value of Non-Served Electricity, which – as mentioned above – is value-laden. In this example, we therefore drew on what the literature suggested. That is, a value of 0.3 USD/kWh for non-critical loads (Gonzáles-Garcia et al., 2022).

By introducing the SAIDI reliability proxy range, we observed a minor least cost technology shift from grid extension towards Solar Home Systems (SHS), the (originally) second-best option. This pattern was more evident, but still relatively small, at higher SAIDI values, with both solar home systems and mini-grids starting to substitute grid extension in some areas (Figure 2a).

With SAIDI at 50 hours per year, we then experimented with different CNSE values. Note that the selected range 0.3-2.0 USD/kWh is simply illustrative and was based on anecdotal information (Electricity Control Board, 2023). We found that lower CNSE values produce minimal changes in the technology mix, whereas higher CNSE levels -particularly beyond 1 USD/kWh – lead to more pronounced shifts from grid expansion toward off-grid solutions. (Figure 2b).

Figure 2: . (a) Least-cost technology shift for different SAIDI indices with CNSE=0.3 USD/kWh. (b) Least-cost technology shift for different CNSE with SAIDI set constant at 50 hours/year.



3.2 Key observations from the CNSE approach

We observed that the total estimated investment for electrification remains largely unchanged relative to the baseline. This is because CNSE is incorporated as an economic penalty that influences technology choice, rather than as a CAPEX reflected in the final investment totals. Several factors may explain this limited effect.

- First, SAIDI is used as a national-level proxy for reliability, which may not reflect much higher outage levels in particularly unreliable areas or may simply be an unrealistic approximation.
- Second, the modelling approach may not fully capture the magnitude of reliability-related costs.
- Third, the characteristics of the selected geographic area may not adequately represent locations where reliability issues drive more pronounced shifts.

As a result, while the 'shadow price' of CNSE does trigger some least cost movement from grid expansion to off-grid options, the scale of this shift remains limited under the current assumptions. However, with more representative reliability proxies and more realistic CNSE estimates, the impact could be substantially larger, potentially shifting anywhere from hundreds to several thousand connections from grid extension to off-grid solutions, depending on the underlying assumptions.

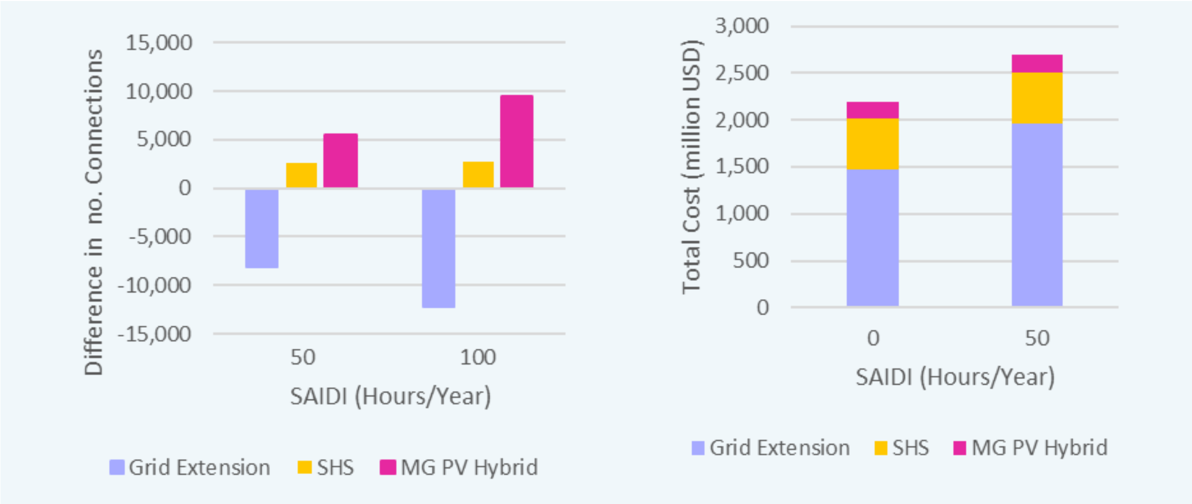
3.3 Applying the diesel back-up approach

We applied the same approach to the diesel-backup option, assuming that all unmet grid demand is supplied by diesel generators. We tested two scenarios, one assuming 50 hours/year and another 100 hours/year of interruptions based on SAIDI.

In this case, the differences become far more pronounced, with thousands of connections shifting from grid expansion to off-grid technologies, even at a moderate SAIDI value of 50.

A clear change (approx. +20%) in the final estimated investment becomes evident too, as the inclusion of backup systems substantially increases the capital expenditure – seen as a capacity substitute for new grid extension.

Figure 3: (a). Least-cost technology shift for different SAIDI indices and diesel as back-up for unmet demand. (b) Change in total investment requirements of the least-cost electrification plan if diesel gensets are used to account for unreliable grid service.



3.4 Reflections and next steps

Across both approaches – the CNSE penalty and the diesel-backup option – we observe shifts towards off-grid technologies in the least-cost technology mix once grid reliability is introduced into the analysis. This reinforces a key insight: incorporating reliability is essential for realistic electrification planning in contexts with unstable grids. However, the magnitude and direction of these shifts depend strongly on assumptions, data quality, and modelling choices.

At the same time, both approaches come with limitations that can shape how their results should be interpreted.

- For the CNSE case, the model cannot capture sector-specific outage costs: residential CNSE may be around 0.65 USD/kWh, but business values can be significantly higher (2–150 USD/kWh) depending on the activity. In our approach, CNSE is applied as a national average, masking these variations. Moreover, since there is no standardized way to calculate CNSE, estimates can vary widely across countries and institutions. As a value-laden parameter, CNSE depends heavily on user judgment around the economic cost of outages. In our implementation, CNSE functions as an additional OPEX penalty, which signals relative cost differences but does not indicate the level of CAPEX required to strengthen the grid. It identifies when alternative technologies appear more cost-effective under unreliability – assuming systems are correctly sized – but does not quantify the investment needed to improve grid reliability itself.
- For the diesel-backup case, constraints arise, too. The approach assumes that all customers rely on generators to cover unmet grid demand, even though this behaviour varies widely: commercial and income-generating users are far more likely to own gensets than households. Generator sizing is based on an average-to-peak load ratio, which may undersize critical loads (e.g., health facilities) during peak periods or oversize systems for households, leading to unnecessarily high CAPEX. While load aggregation at the settlement level smooths some variability, it cannot fully represent customer-specific

backup needs. Diesel fuel prices also vary significantly across countries and over time, making it challenging to select a future-year price, as required by OnSSET. This introduces another value-laden assumption, given the sensitivity of diesel costs to taxes, subsidies, logistics, and global market volatility.

- Despite these limitations, both approaches demonstrate that reliability considerations can meaningfully alter electrification pathways, especially when more realistic proxies and assumptions are used. In scenarios where CNSE or outage duration values reflect current local conditions more accurately, least-cost pathways shift from prioritizing grid extension to off-grid solutions, reaching hundreds or even thousands of connections. Likewise, if grid extension includes improved grid reliability, off-grid solutions can be less prevalent in least-cost pathways.

At SEforALL, we believe that open-source data and tools enable better and more transparent planning. The model, methodology, and code are all publicly available on OnSSET's official GitHub repository, and we welcome everyone's exploration, scrutiny, and use in their own geography.

This module represents a step forward, not the finish line. We actively welcome feedback on this methodology – what works, what needs refinement, and where data gaps limit realism. We invite planners, researchers, and policymakers to join us in strengthening the approach so that least-cost modelling continues to evolve and better reflect real-world technical constraints, policy environments, and country priorities.

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