INENSUS

WORKING PAPER

Understanding demand (price elasticity) and supply (economies of scale) functions for a more financially sustainable rural electrification sector

September 2023

Executive Summary

Price elasticity of electricity demand has so far been widely neglected by most stakeholders in the mini-grid sector, leading to false conclusions regarding the **effect of tariff adjustments on revenue**, or the **impact of grant funding/RBF instruments on tariffs**. Collaterally, as demand was considered to be fixed, the potential benefits of **economies of scale in mini-grids** have also remained under-investigated.

This project proposal seeks to: a) generate a much better understanding of demand and supply patterns in mini-grids, and b) explore the regulatory and financial implications of such patterns.

A solid scientific understanding of price elasticity of demand and economies of scale in mini-grids may resolve some of the most pressing issues of the mini-grid sector:

- Cost of Service models used by **Regulatory Authorities**, which assume that revenues and tariffs are linearly linked, simply do not represent real life market behaviour. Accordingly, mini-grid companies are afraid of tariff regulation leading to financial losses. Therefore, many mini-grid companies shy away from tariff regulation and rather stay without regulatory protection for their assets at all than undergoing tariff regulation. With more knowledge about price elasticity in mini-grids, regulatory authorities' Cost of Service models could be improved to represent real market behaviour. This will re-establish trust between mini-grid companies, regulators and governments.

- **Donors** are trying to understand the effect of grants on tariffs, mini-grid system sizing, grant volumes required, and the effect of all of this on electricity demand saturation. Without a deep understanding of price elasticity and economy of scale patterns in mini-grids, donors are fishing in the dark. Once such knowledge has been generated, **grant funds/RBF instruments could be designed with higher precision**, a more solid integration of relevant institutions and potentially more impact per USD spent.

- A weak scientific basis on price elasticity and economies of scale creates insecurity for mini-grid **investors**. Even a decade after the first private sector mini-grids have been commissioned, there is still no proven theory about how profitability of the mini-grid business changes with tariff (and thus size) adjustments. This poses a high risk that investors shy away from. With more insight into demand and supply functions in mini-grids, risk mitigation instruments may be developed and implemented channelling more capital into the mini-grid sector.

It is understood that **such lack of knowledge is retarding the mini-grid sector's growth heavily**. This is why solid research about price elasticity and economies of scale in mini-grids is urgently required.

In order to address this gap, the proposed project seeks to develop and implement a comprehensive data collection strategy, building on existing databases and benchmarks, but also involving primary data-collection from mini-grid developers and energy regulators from a variety of geographies. The analysis of such data will allow the team to identify the main drivers behind supply and demand functions and to create a tool allowing everyone in the sector to model specific projects.

As described throughout the next section (and exemplified in the two annexed case studies), we strongly believe that such improved understanding of supply and demand patterns will have **substantial implications** in critical aspects such as mini-grids regulation, financing and planning, and thus in the broader efforts to achieve universal energy access.

Problem Statement

Introduction

Demand and supply functions in mini-grids have traditionally been poorly characterized, both in casual conversations (for example describing demand exclusively in kWh, regardless of tariff levels) as well as in the underlying logic that has shaped most regulations and financing approaches. In particular, the key relationship between demand levels and tariffs on the one hand, and between average costs (or LCOE) and project size on the other, are often neglected. Instead, demand is assumed to be fixed in kWh and LCOE is assumed to be constant. This results in conveniently simple demand and supply functions, as seen in figure 1.

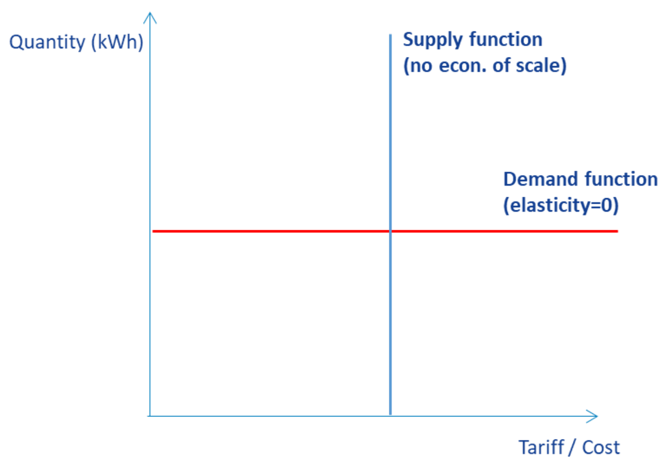

Figure 1: Supply and demand functions of mini-grids under the status quo logic

However, this logic fails to capture more complex patterns actually taking place, and thus leads to false conclusions. From a demand perspective, some initial experiments as well as anecdotal evidence from mini-grid developers show that consumers are in fact sensitive to tariff levels, adjusting their consumption if tariffs change. From a supply perspective, similar anecdotal evidence and preliminary cost analyses indicate that there are significant economies of scale in mini-grids. Figure 2 shows how these functions could actually look like based on assumptions presented in the next sections of the document.

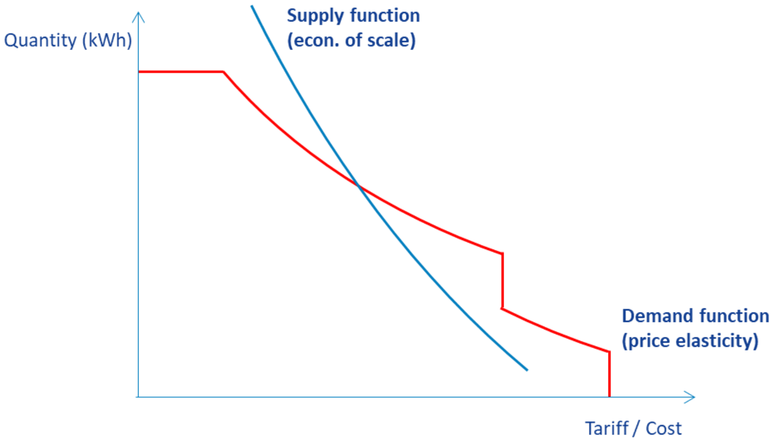

Figure 2: Indicative supply and demand functions of mini-grids (before this project starts).

While the integration of price-elasticity of demand **creates new challenges for the sector** (for example by suggesting that tariff regulation is not an all-powerful mechanism to adjust mini-grids profitability), **it also generates opportunities** to exploit economies of scale by adjusting tariffs and grant levels simultaneously. As it can be inferred from Figure 2, small displacements of the supply function (following the **introduction of a CAPEX grant/RBF instrument**), could result in comparatively larger displacements of the market equilibrium. Those mechanisms will be now discussed in more depth.

Price elasticity of demand

When a rural electricity supplier generates too little revenue to operate profitably, the regulator usually approves an increase in the residential electricity tariff, assuming that the supplier's profitability will be restored through an increase in revenue. This is an approach commonly applied by most African regulators. In rural areas, however, there is usually little increase in revenue after such a tariff increase, which eventually leads to the failure of electrification projects. The reason for this is an effect described in economics as the 'price elasticity of demand'.

Price elasticity of demand is the most underestimated factor influencing the profitability of rural electricity suppliers in Africa. Most electricity tariff regulation instruments to date do not take price elasticity into account.

Preliminary evidence

Results from specific experiments in Tanzania in 2019[1], as well as practical experiences of numerous mini-grid operators, describe the respective price-elastic electricity consumption behaviour of rural customers. INENSUS has gathered experience with price elasticity in mini-grids and came up with an understanding that is being supported by some individual data points from literature and own in-house research:

- **Residential electricity customers** and institutional customers (schools, health centers, etc.) have a constant weekly/monthly budget and therefore a price elasticity close to 1. This is true down to a demand saturation level, when price elasticity reduces drastically. On the other hand, if the tariff becomes more expensive than alternative sources (e.g., SHS), these customers will disconnect from the mini-grid.
- **Productive users** consume as much electricity as required to produce their goods, meaning that their price elasticity is close to zero. This applies until electricity become more expensive and/or less reliable than alternative power sources like diesel motors.

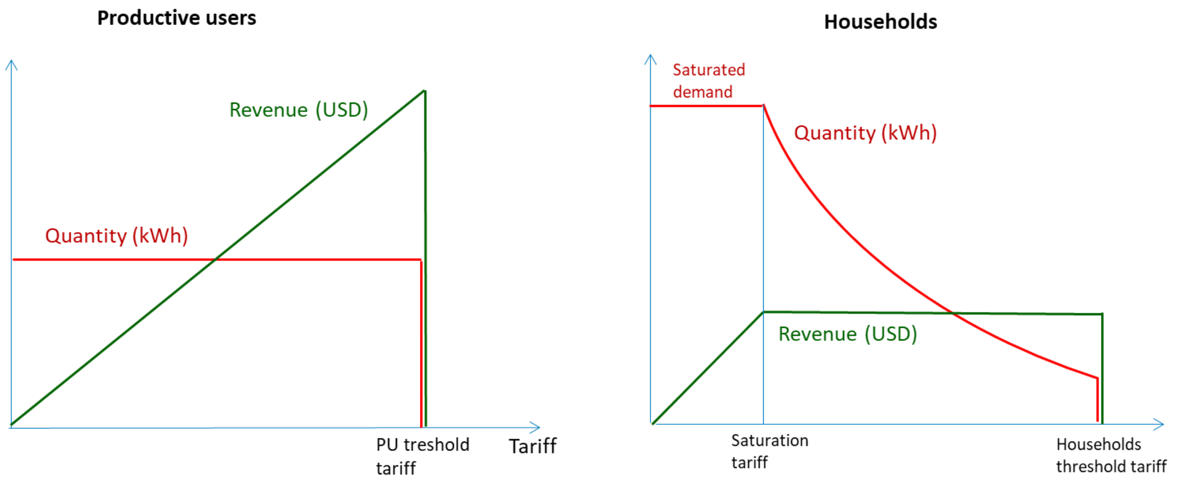

Figure 3: indicative demand functions for productive users and households.

[1] CrossBoundary, 2019. The price elasticity of power.

What happens when tariffs are 'too low' or 'too high'?

Looking at the electricity demand (and the resulting operator's revenue) as a function of an electricity tariff (see figure 3 above), the so-called 'electricity demand saturation point' is reached at the lower end of the scale. This is true for the first group, village households and public utilities, which have unitary elastic demand up to that point. From here on, a household's demand is saturated, and it will not increase its electricity consumption, even if the price drops further (demand becomes inelastic), thus the operator's revenues also begin to decline if the price of electricity is reduced further.

At the upper end of the electricity price scale, if the price of electricity continues to rise, a point will eventually be reached at which both customer groups have very elastic demand. Consumption declines radically, as customers switch to alternative sources of electricity whose cost is less than the price of electricity offered by the operator. Residential customers become interested in purchasing solar home systems or small diesel or petrol generators, while productive-use customers switch (back) to larger diesel generators. This so-called 'LCOE equivalence point' can occur even sooner, i.e. at lower tariffs, if unreliability or poor service from the operator alienates customers.

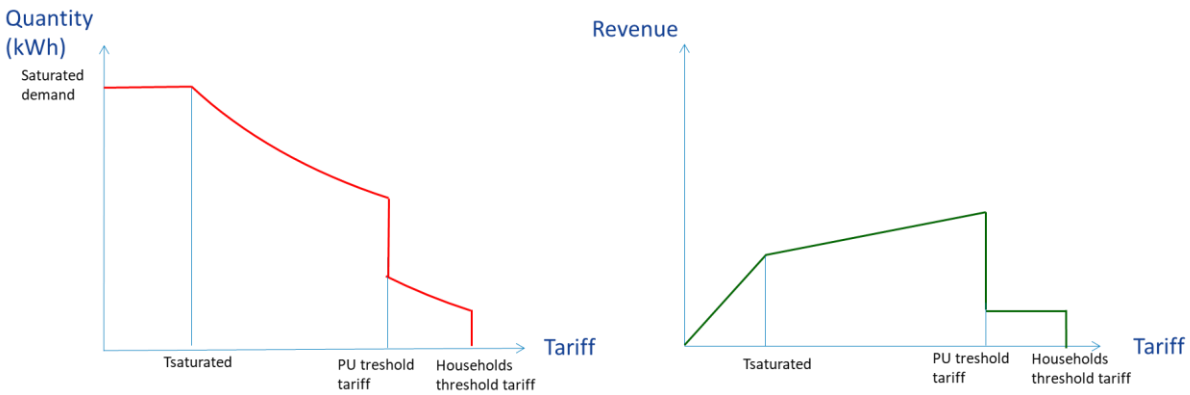

Figure 4: combined demand and revenue functions, integrating both customer groups.

Economies of Scale

In order to fully understand the implications of price elasticity of demand, it is necessary to consider the other ingredient of the market equilibrium, which is the supply function. As mini-grid size has often assumed to be fixed for a given location, there are not many studies or examples of projects where the potential impact of economies of scale in the supply function has been considered. Such impact might actually be larger than expected due to the shape of these functions, suggesting that even modest displacements in either demand or supply will have a broader effect in the market equilibrium.

This is particularly relevant in the context of CAPEX grants and/or RBF instruments. As exemplified in figure 5 below, the introduction of such a grant will displace the supply function, which will then intersect with the demand function at a higher demand level, which will then increase economies of scale effects and further reduce tariff levels. As seen in the figure, a small displacement of the supply function generates a larger shift in tariffs (plus an increase in total demand).

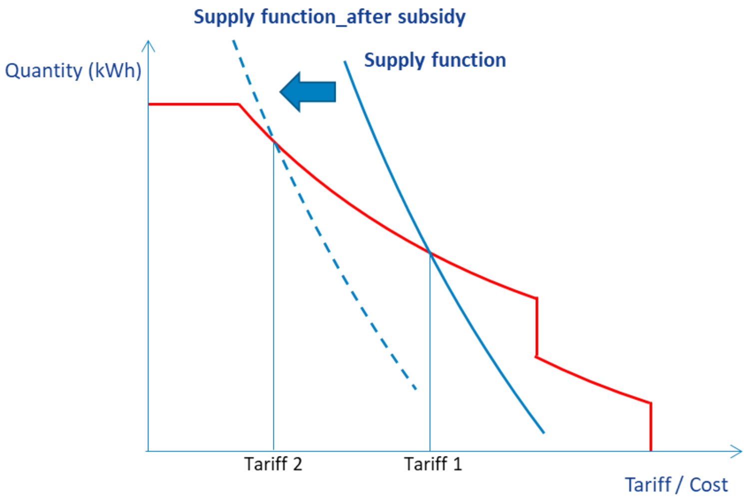

Figure 5: change in market equilibrium after introducing a CAPEX grant (shifting the supply function).

Preliminary evidence

The available evidence regarding economies of scale in mini-grids is rather limited. As a first approximation, it is possible to model such effects by disaggregating specific cost drivers and examining their relationship with project size. Usually, economies of scale should be expected in both CAPEX and OPEX:

- **The total mini-grid CAPEX** should not linearly increase with project size. By breaking down the total CAPEX into several sub-chapters, it is possible to derive a more accurate supply function. For example, while it could be assumed that generation CAPEX grows linearly with size, distribution assets, connection costs and project development costs might rather be fixed. Since generation costs usually correspond to 50% or less of mini-grid costs, a marginal CAPEX cost increase of 0.5% for a 1% increase in project size could be a realistic (conservative) assumption.

- **The total mini-grid OPEX** should also grow more slowly than project size. Given that, in the context of a PV mini-grid, it is mostly comprising “soft” costs (e.g. employees’ wages), marginal costs should be even more limited than for CAPEX Some preliminary calculations suggest an OPEX increase of 0.1% for a 1% increase in project size.

What are the implications for subsidization?

Based on such preliminary evidence, it becomes clear that subsidizing mini-grid projects will have broader implications that usually thought. More specifically, rather than assuming that a given CAPEX grant percentage will linearly reduce costs and tariffs, the combined effect of price elasticity and economies of scale will likely yield a larger reduction in tariffs, and an increase in demand (and thus project size). While one could think that such greater demand will require additional CAPEX grants/RBF volumes, due to economies of scale on both CAPEX and OPEX, every single USD of grants is indeed expected to deliver additional benefits than usually considered when ignoring price elasticity.

Such benefits can be modelled using the concept of consumer surplus, which captures the difference between the consumer's willingness to pay and the actual price paid (that is, the market equilibrium price). The increase in consumer surplus can then be compared to the total CAPEX grant volume, and a cost-benefit ratio can be calculated. Figure 6 shows the increase in consumer surplus (dashed area) after introducing a CAPEX grant. Based on preliminary analyses conducted by INENSUS, the cost-benefit ratio of CAPEX grants when accounting for economies of scale should be above 5 (meaning 5 USD of consumer surplus generated by each USD of CAPEX grant). Case study #2 in the Annex provides more details on this calculation.

In the context of an RBF instrument, the specific RBF modalities and payment timelines should be assessed in light of the above market dynamics. In particular, the question of how mini-grid developers "anticipate" the amount of the RBF payment at the project development and in their financial analyses would be key to ensure that price elasticity and economies of scale benefits are maximized.

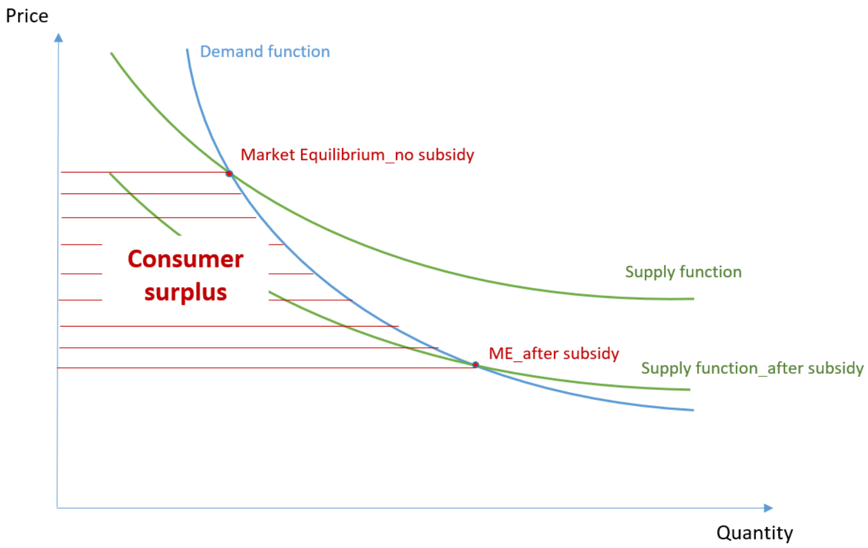

Figure 6: increase in consumer surplus following the introduction of a CAPEX grant/RBF instrument. [2]

[2] Note that the axes (price and quantity) are inverted when compared with previous diagrams.

Implications: where could we go from here?

As mentioned, price elasticity and economies of scale patterns have not yet been scientifically-studied and substantiated, but are largely based on the practical experience of mini-grid operators in various African countries. However, even if largely ignored so far, there is no question that they are already impacting electricity tariffs, demand levels and broader financial (un-)sustainability of mini-grid projects.

An increased understanding of such effects will allow the sector to move from ignoring them (and experiencing unintended results) to integrating them into policies, regulations and financing mechanisms. This should facilitate responding to the challenges and limitations that they impose (such as in the case of price-elasticity effects on tariff regulation) and also harnessing the opportunities identified (such as the amplifier impact of economies of scale). While some regulators (Nigeria and Mozambique, currently supported by INENSUS) have started integrating price elasticity factors into mini-grid tariff tools, increased awareness about these topics will provide broader benefits across the African continent.

In particular, **regulators** will need to acknowledge the constraints imposed by price elasticity, meaning that tariff adjustments are not an all-powerful mechanism to restore profitability. In addition, they could encourage the use of differentiated tariffs for households and productive users, and support rural industrialization efforts as the only reliable way to generate additional revenue in the medium term. Beyond acknowledging such limitations, alternative mechanisms to compensate mini-grid developers failing to meet their revenue requirements should be explored. These could include the creation of revenue/demand guarantees and/or the implementation of cross-subsidies (within the mini-grid sector or beyond it).

Finally, when it comes to **donors**, the preliminary evidence regarding the benefits of CAPEX grants provides a powerful rationale to support sector growth, in a context where funding gaps to meet 2030 universal access targets remain significant. It also seems to suggest that measures reducing up-front costs (CAPEX grants and RBF instruments, but also lower cost of financing, lower taxes and duties, etc.) have a comparatively higher impact than alternative schemes (such as OPEX subsidies).

Proposed project description

Data collection

The project will require a significant data collection effort, including internal data from project partners, previous studies on mini-grids demand/costs and primary data collection campaigns. In order to incentive data sharing, the benefits of the study for every participating stakeholder shall be clearly spelled out, and data privacy/anonymity considerations thoroughly addressed.

When it comes to demand patterns, a variety of data sources may be explored:

- JUMEME (INENSUS subsidiary) demand data from 10,000+ mini-grid customers in Tanzania.
- CrossBoundary data used in previous experiments in Tanzania and in on-going ones in Sierra Leone. Suitable approaches to accessing these data should be explored, as well as opportunities to collaborate with CrossBoundary.
- Broader mini-grid demand data from a variety of mini-grid developers and countries. This could be best achieved in collaboration with AMDA.
- Specific surveys conducted in mini-grids across several locations,

Beyond mini-grid specific data, it will be desirable to collect (and later analyse) demand data from rural consumers in grid connected areas. This could be explored in collaboration with energy regulators willing to share historical demand data, and would help inform demand patterns when tariffs are lower. It could also inform potential cross-subsidization solutions, and to what extent increasing tariffs for on-grid customers could result in additional revenue to be transferred to the mini-grid sector.

In case the availability and quality of demand data collected is not fully satisfactory, a potential solution could involve the implementation of specific surveys across several mini-grid locations, collecting data on current consumption/expenditure and exploring price elasticity patterns through scenario simulations. The usage of COMET software[3] could be particularly useful for this purpose.

As for supply data, economies of scale analyses could be based on three distinct data sources:

- Existing mini-grid cost reports and benchmarks (ESMAP, AMDA, RMI, etc.)
- Specific CAPEX and OPEX data reported by mini-grid developers. This data could be collected through AMDA, together with the demand data mentioned above.
- Disaggregated market prices of main mini-grid components, allowing to create a cost function and to benchmark reported costs.

[3] https://www.cometapp.net/

Data analysis

Once data have been collected, the main goal of the analysis will be to derive demand and supply functions and to identify which factors influence their shape across geographies and projects.

In the case of demand, the following specific questions should be answered:

- How do price elasticity and demand saturation change with increasing income of households?
- Is price elasticity in mini-grids the same all over Africa, Asia and Latin America? What are the region specific factors?
- How does family culture impact price elasticity? Does price elasticity change if various income earners contribute to electricity cost coverage? Does religion affect spending patterns?
- How fast does the demand respond to price signals under various constraints?
- How does reliability of electricity supply impact price elasticity behaviour?

In the case of mini-grid costs, some specific questions should be:

- How is CAPEX influenced by mini-grid average size? Are distribution and connexion costs indeed constant as demand increases?
- What are the main drivers behind OPEX patterns? Number of customers? Average demand?
- How do CAPEX and OPEX behave in projects with multiple mini-grids (bundling sites)?
- How different types of CAPEX grants and RBF instruments influence the supply function and thus the market equilibrium?

Results

Project report

The main results of the project would be included in a project report. The report will cover data collection, data analyses, findings and implications for the sector. Before publishing the report, such implications could be discussed with key sector stakeholders to collect feedback and increase support for adoption of related recommendations.

Modelling tool

In addition to the report, a modelling tool should be built allowing to generate supply and demand functions based on the specific inputs identified during data analysis. This tool could then be made available to the sector in order to maximize its impact.

Dissemination

Once results are available, dissemination efforts should be undertaken in order to ensure that this new knowledge is shared across the sector. This would benefit from a well-structured dissemination program including:

- Communication of results and available tools throughout the main sector platforms and events (ARE, AMDA, Sun-Connect, ESMAP conference, etc.).
- Organization of webinars presenting such results.
- Specific activities for more targeted audiences: training sessions for regulators, working groups with donors, etc.

Project timeline

The following chart provides an indicative project timeline covering 9 months, to be adjusted based on the final project concept.

	Months								
Tasks	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Kick-off									
Data collection									
Data analysis									
Report drafting									
Tool development									
Dissemination									

Annex: case studies

This Annex contains two illustrative case studies exploring the impact of price elasticity of demand and of economies of scale. The specific assumptions used in each case are only indicative, simply seeking to highlight the potential relevance of such patterns. The results were generated using a preliminary Excel-based model that INENSUS has developed internally.

Case study 1: implications of price elasticity on Cost-of-Service tariff regulation

This case study explores the (unfortunately common) situation in which a mini-grid developer is facing lower demand than expected and thus failing to meet the expected Cost of Service / Revenue Requirement.

Assumptions

- Current Revenue = 50% of CoS
- Current tariff (T1): 0.30 USD/kWh
- 75% of demand corresponds to price elastic (price elasticity = 1) customers. Those would be customers with a fixed budget for electricity.
- 25% of demand corresponds to price inelastic (price elasticity = 0) customers. Those would be customers with a fixed demand in kWh.

Tariff intervention

Under the status quo approach, the regulator will approve a tariff increase assuming that revenues will grow linearly.

New tariff (T2) = 0.30/50% = 0.60 USD/kWh

Expected results

New revenue = 100% of CoS

Actual results

The tariff increase only generates additional revenues from customers with inelastic demand. Thus, the new revenue increases by 25% but **still only represents 62.5% of CoS**.

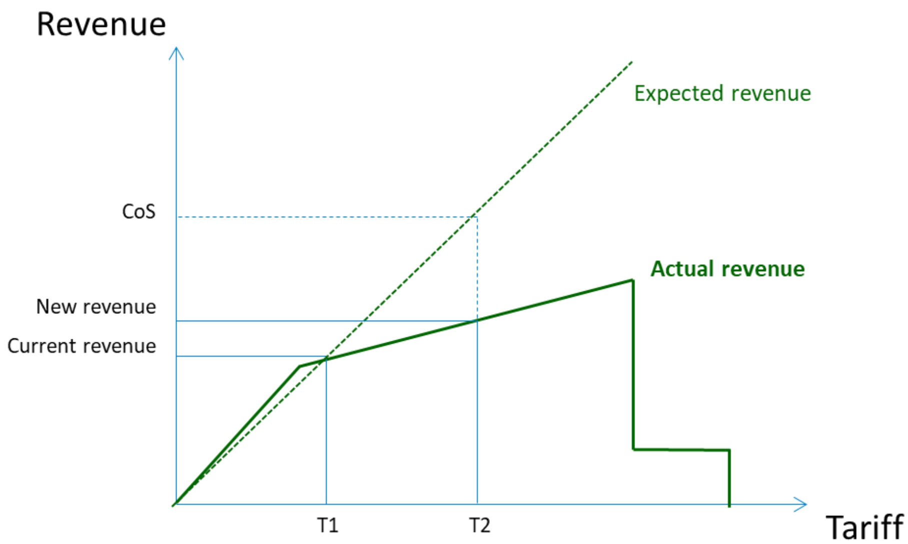

Figure 7: expected versus actual revenue after tariff adjustment

Case study 2: amplification of CAPEX grant/RBF instrument benefits due to price elasticity and economies of scale.

This case study explores the changes in market equilibrium after introducing a CAPEX grant/RBF instrument. More specifically, it seeks to describe how, thanks to the cumulative effects of price-elasticity and economies of scale, the impact of CAPEX grants is higher than expected (and thus the potential for reducing high mini-grid tariff levels to near-national grid levels).

Assumptions

- Current cost-reflective tariff: 1 USD.
  - CAPEX tariff: 0.80 USD (of which 0.25 USD/kWh pay back the assets and 0.55 USD/kWh correspond to the cumulated ROI over 20 years (IRR= 15%)).
  - OPEX tariff: 0.20 USD
- Price elasticity assumptions:
  - 75% of demand corresponds to price elastic (price elasticity = 1) customers. Those would be customers with a fixed budget for electricity.
  - 25% of demand corresponds to price inelastic (price elasticity = 0) customers. Those would be customers with a fixed demand in kWh.
- Economies of scale assumptions:
  - Marginal CAPEX cost: 0.5% for every 1% of size increase.
  - Marginal OPEX cost: 0.1% for every 1% of size increase.

- CAPEX grant/RBF instrument to be introduced: 50% of total CAPEX

Expected results

Under the status quo approach, where demand is fixed and there are no economies of scale, introducing a 50% CAPEX grant reduces the CAPEX portion of the tariff by a similar percentage. Thus, the resulting tariff is 0.60 USD/kWh with no changes in demand levels. The change in consumer surplus as a result of the grant can be easily calculated, providing a cost-benefit ratio of 3.2 (1 USD of CAPEX grant generates 3.2 USD of consumer surplus). In this sense, the economic returns of the grant match the IRR of the private capital it has replaced.

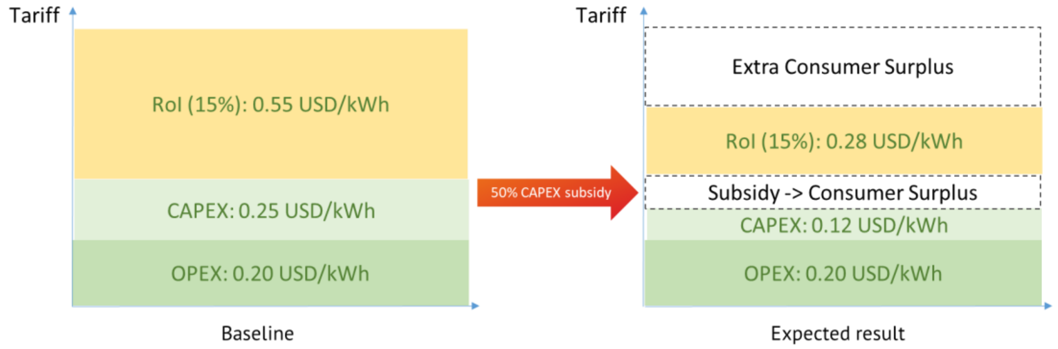

Figure 8: Expected tariff reduction and consumer surplus achieved as a result of CAPEX grant/RBF instrument.

Actual results

Once price elasticity and economies of scale are considered, the shape of both functions (demand and supply) is altered. As they no longer intersect forming a right angle, a given % reduction in the cost function is able to generate a comparatively larger shift of the market equilibrium.

Using the assumptions specified above, and adjusting the CAPEX grant percentage so its total amount is similar to the previous scenario, results in the following numbers.

- The grant portion now only covers 38% of the CAPEX
- Total demand increases by 83%
- Resulting tariff is **0.47 USD/kWh:**
  - CAPEX tariff: 0.35 USD (of which 0.11 USD/kWh pay back the assets and 0.24 USD/kWh correspond to the cumulated ROI over 20 years (IRR= 15%)).
  - OPEX tariff: 0.12 USD/kWh
- The **cost-benefit ratio[4] of the grant becomes 5.5** (5.5 USD of consumer surplus generated out of each USD of grant).

[4] In this case, the consumer surplus is calculated by mathematically defining the demand function and using an integral calculation function embedded into Excel.

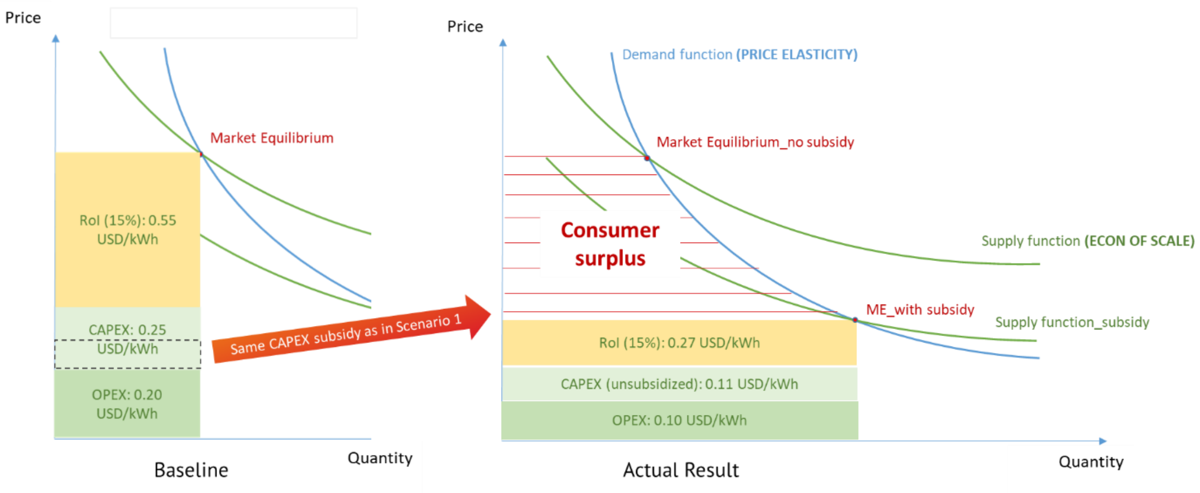

Figure 9: Actual tariff reduction and consumer surplus achieved as a result of a CAPEX grant/RBF instrument

Organization Profile

INENSUS GmbH

With over 17 years of experience as a consulting and engineering firm, INENSUS GmbH is a "one-stop-shop" for advisory on mini-grids and decentralised renewable energy systems. Being one of the **oldest and most experienced consultancies in the mini-grid space**, INENSUS provides unique insight into historic developments of business models, frameworks and financing schemes. This enables INENSUS to project the trajectory of future framework developments, as well as decisions of authorities and market players. INENSUS has indeed influenced and partly co-structured the frameworks or mini-grids in many African and some Asian countries. Building on a portfolio of projects in 40 developing countries across Africa, Asia and Latin America, and operation of its **own mini-grid labs** in Tanzania and Uganda, INENSUS knows the mini-grid business from all sides and is fully equipped to provide a wide range of services.

Any advice INENSUS sells through its consultancy services has been tested in the field with real power systems in mini-grids with real rural African customers.

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