Modelling financing schemes for energy system planning: a mini-grid case study

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Abstract:
Energy modeling has been playing a crucial role in defining solutions for effective energy planning. Bottom-up energy system planning models, namely those models characterized by high technological detail, typically present exogenous techno-economic parameters which rely on data gathered by the user, from specific costs to efficiencies. However, poor to no attention has been given to the date to the financial parameters of energy models, which are often assumed and barely justified (e.g., “discount rate equal to 10%”, full stop). Still, model outputs are drastically sensitive to variations of finance-related parameters and must provide the financing structure that a decision-maker should implement for funding the advised energy planning strategies. This results particularly crucial for mini-grid sizing in sub-Saharan African countries, where the challenge of the energy transition entails the construction of massive new capacities to improve energy access rates and tiers of service, demanding an enhanced collaboration between private and public sectors. The case study, applied on an off-grid mini-grid in Mozambique, proposes a comparison between scenarios with increasing financial detail and a possible conceptualization of the hard link between detailed financial modelling and a bottom-up energy model for mini-grid optimization. Different financing schemes are modelled and their impact on the energy modelling outputs assessed. Project finance hence emerges as a useful approach that could upgrade the financing structure of domestic power projects in African countries. This may lead to many benefits: more sustainable and affordable interest rates where corporate finance is missing, improved risk management, diversified funding mix, and facilitated financial support from international institutions.

Keywords:
Mini grid; energy planning; financing schemes; access to energy; Mozambique; project finance.

1. Introduction

The electrification of rural areas in developing countries is a critical challenge for achieving sustainable development goal 7 (SDG7) of United Nations’ Agenda 2030 [1], aimed to assure access to electricity and to clean fuels and technologies for all by 2030. Despite the significant progress that has been made in recent years, with global access to electricity rising from 83% in 2010 to 91% in 2020, still the 80% of world’s people without access to electricity lived in rural areas in 2020 [2]. This results in limiting the ability to develop local economies and reducing their chances of improving living standards. On the one hand, new technological solutions for decentralized generation such as mini-grids are increasing their viability for last-mile electrification [3], providing high standards of service for densely populated rural areas [4]. The use of such solutions grew significantly between 2010 and 2019: the number of people with access to decentralized solutions, including solar home systems and mini-grids, more than tripled, rising from 12 million in 2010 to 39 million in 2019 [2]. Alongside this, a large community of energy modellers specifically focused on the optimal sizing of decentralized solutions has raised in the last decade, bringing to several models and approaches for their effective planning [5,6]. On the other hand, new business models [7] and financing schemes [8] are emerging, evidencing the need of private sector involvement for fostering off-grid electrification. According to several scholars [5,9] and international organisations [10–12], the profitability and the attractiveness of investment in mini-grid solutions still remains one of the key barriers for their definitive market upscaling in developing countries, characterised by limited resource, governance and infrastructure. Moreover, as sub-section 1.3 will detail, there is an increasing interest, both at academic research and at international institutions levels, to understand to which extent assumptions on financial parameters affect the ouput of energy modelling scenarios. In fact, these parameters are crucial to provide the financing structure that a public or private decision-maker should implement for funding the advised energy planning strategies.

This paper proposes a modelling exercise able to test the suitability of different financing structures for triggering virtuous financing markets for mini grids in Mozambique. The methodology adopted will advance a possible conceptualization of the hard link between financing structures and a bottom-up energy model for

https://doi.org/10.52202/069564-0178

mini-grid sizing, thus assessing the impact of financial parameters on the energy modelling outputs. The first introductory sub-sections of the work have the scope of framing the problem of mini-grid financing in relation to mini-grid sizing. First, the state-of-art of mini-grid financing in Africa is briefly investigated, providing references and a non-exhaustive overview of the trends of the sector. Existing financing structures are hence introduced into the discussion. Second, sub-section 1.2 is devoted to summarising the state-of-art of energy modelling for mini-grid sizing in African contexts. The research gap is then identified in sub-section 1.3, where claims from recent literature are reported to push for the increase of financial detail in energy modelling research. The rest of the paper is structured as follows: section 2 details the modelling methodology adopted, inclusive of energy and financial modelling; section 3 draws the case study of Ndoro village in the Caia district of Sofala Province Mozambique; results are then discussed critically in section 4; finally; section 5 concludes the work providing outlooks derived from the exercise.

1.1. Financing mini grids in Africa

Even though mini-grids already represent a least-cost option for delivering high tiers of energy services in many contexts [4], the existing mini-grid sector in sub-Saharan Africa (SSA) is characterized by early-stage market fragmentation, lack of competition, high transaction costs, perceived investment risks, and high cost of capital. According to a market report by the Mini-grids Partnership [13], in 2020 a total of 5544 mini-grid projects have been mapped as installed and operative among Asia (60% of the total), SSA (39%), Island nations (1%) and Latin America (0.4%). Of these, more than 60% were powered by solar or solar-hybrid energy, the 21% exclusively by hydropower, the 11% by fossil-fuels and the remaining by biomass, wind, or other energy sources. Despite the very reduced current market, the suitability of mini-grid solutions towards universal access to electricity has been reproved by the International Energy Agency (IEA) in the Sustainable Africa Scenario (SAS) of the last Africa Energy Outlook [11]. In this scenario, aimed to give access to electricity to 90 million people in Africa each year on average from 2022 to 2030, the 32% of the new connections are established via renewable mini-grids and the 21% via renewable stand-alone systems. The Outlook shows how mini-grid systems could constitute a profitable business for small private companies in small and isolated communities, which would remain out of electrification policies planned by the national grid operators. However, according to Williams et al. [9], there are three main financial challenges for their definitive market upscaling: revenue insecurity, due to the capital-intensive nature of electrification investments and to the associated high costs of unincentivized energy tariffs, unaffordability to consumers, related to the spread inability to pay, and reduced access to finance, due to the poor local investment climate mostly associated to perceived risks.

The immaturity of the mini-grid market in Africa is reflected by the typical structure of financing of these systems. Traditional financing of power projects, including plans for off-grid electrification, usually sees the participation of the national government, through its national energy ministry or agency, as the major funder. The main source of the investment usually comes from the governmental development budget or from aided borrowing by multilateral and bilateral development agencies. In the current situation, the participation of the private sector is therefore very limited: it is involved at the stages of construction and first running of the power plant, but the property (and the associated risk of investment) is still owned by a national public utility, in most of the cases. In general, two types of financing can be employed in the mini-grid market for structuring a new investment:

Table 1. Types of financing in the African mini-grid market.

Type of financing	Description
Debt	Debt financing consists in the mini-grid developer borrowing capital from lenders such as banks, privates, or other financial institutions to fund the project. Debt must then be repaid at an agreed cost, called return on debt or interest rate, and within a certain time horizon, called maturity of debt. Debt repayment is generally independent from the performance and prioritary to equity repayment. As Smith summarises in his book [14], debt lenders that currently invest in African countries markets can be grouped into: private commercial lenders (domestic or international), foreign countries, African state-owned firms, multilateral commercial banks, and export-import banks. However, debt financing remains widely untapped in the mini-grid market due to its low attractiveness and bankability. As a result, rates of return on debt are still high: locally sourced debt often reaches interest rates up to 20% in SSA [9], but for the mini-grid market this figure can increase up to 30% for countries such as Sudan and Somalia [15].

 https://doi.org/10.52202/069564-0178

Equity	Financing by equity means that the mini-grid developer invests his own capital available (i.e., the residual cash flows from existing assets) into a new asset, namely the mini-grid infrastructure. Equity can also be supported by project promoters such as local banks who, in case of attractive projects, can enter the investment as shareholders. Equity is therefore derived from the company's shareholders' capital, which will be repayed according to a rate of return on investment called return on equity. Apart from private capitals, equity investors in mini-grids market in developing countries are mainly development finance institutions (DFIs) and impact investors [13]. It is worth mentioning that the return on private equity is usually high since it embeds several upfront uncertainties on the success of the investment, especially for high-risk projects such as mini grids in developing countries. For this reason, it is usually supported in blended finance with grants.

Grant financing can support both equity and debt. Donors (international institutions, regional development banks, governments through national cooperation agencies, private foundations, etc.) provide grants in highly concessional forms, meaning to null (donation) or negligible rate of return. This is the most common type of funding for the mini-grid sector in SSA and can subsidize the investment in various ways: reducing the upfront capital requirements, ensuring revenues and limiting their volatility, and reducing the interest owned to the debt provider [16], in case of blended commercial lending. Currently, two types of grants are adopted in mini-grid financing structures [13]: upfront grants (usually blended with equity from the developer or shareholders) and result-based financing grants (a type of public-private partnership including a commercial lender as third party between a public institution and private developer).

Finally, it is relevant to highlight that the technical solution chosen for a local electrification plan strongly influences the cost of capital and the possible financing structure. As Agutu et al. [15] argued, mini grid solutions represent a infrastructure-based system and imply a high initial investment. Their strong dependence on the local regulatory framework and on the political setting of the country makes them perceived as riskier with respect to stand-alone systems, thus requiring longer maturities and higher return rates and costs of capitals. Moreover, the specific components that constitute a mini grid system (i.e., PV panels, diesel generators, battery banks, hydropower turbines, wind turbines, etc.) have very diverse cost structures [17]: renewable energy technologies imply high initial investment cost, whereas fossil fuels-powered technologies will have greater operation and maintenance costs. As this study will reprove, the least-cost sizing of the mini-grid is relevantly affected by the cost structure of its components and especially by how the associated investment and operating costs will be paid back (i.e., by the financing structure chosen).

1.2. Energy modelling for off-grid planning

Energy modelling has proved, over the last 20 years, to be growing in relevance on providing evidence based and scientifically solid insights for energy strategy formulation [18]. Thanks to energy modelling it is possible to develop energy scenarios, assess the potential impact of the penetration of technologies in the market and identify optimal strategies to achieve energy related goals. However, as Debnath et al. highlighted in 2018 [19], the entirety of the existing energy system models originated in developed countries, and for this reason, some key issues that affect the developing world's energy systems are not considered in such models. Among such issues, the author's identifies lack of reliable data, and the issue of access to energy, urging for more attention dedicated to modelling suppressed demand and the socio-political feedbacks of developing countries.

Especially when it comes to mini-grid sizing and off-grid energy planning, a more specific set of challenges exists [5], the main reason for that being that off-grid energy system are not purely a technological challenge, but above all a social challenge, as the main goal of developing off-grid systems for access to energy is to trigger local development [20], which is complex phenomenon to include into modelling frameworks [21]. A set of specific models has been developed along the years for supporting off-grid energy planning [22], and can be classified into two categories: i) Off-Grid Strategy Selection Models, and ii) Off-Grid System Sizing Models. As for the second category of models, Akbas et al. [22] categorise them into models aiming to provide: optimal system configuration and unit sizing, optimal power dispatch strategy, and optimal network design. The present study specifically addresses the first two issues, involving the selection of types of energy resources and least-cost sizing of mini grid system components, which become crucial when considering costs and impacts of a project for rural electrification. Optimal power dispatch will come together with system configuration since the optimization will be run on the hourly availability of resources.

1.3. Research gap and article's scope

Recent literature has been highlighting how energy models must be tailored to the african specific context [19,23], specifically highlighting the diffused disregard of the cost of capitals for financing energy access options in the energy modelling discipline [5,15,24,25]. This absence brings to a general neglection of the impacts of financial parameters on the outputs of energy modelling exercises and eventually devaluates the research evidence that may outcome to support policy and decision makers. A contribution by Lonergan et al. [26] critically reviewed how the cost of capital is accounted in existing energy system models and found that, even though most existing models still rely on own assumptions and on expert elicitation for selecting an exogenous cost of capital, the literature trend is directing towards academic reference values, project data and financial data. This encouraging trend suggests that the energy modelling community is becoming more and more aware of the impact of the cost of capital to the model results. The International Energy Agency (IEA) is also moving in this sense: a "cost of capital observatory"[1] has been launched in 2022 to collect and update data on the cost of capital of renewable energy projects, with a specific focus on some developing countries. This work has the scope of complementing the existing literature providing a simple approach to expand the hard link between energy and financial modelling on the local scale. A new hybrid modelling methodology is hence proposed to reflect the financing structures of a mini grid investment.

2. Modelling methodology

2.1. Financial modelling approach

The financial modelling approach adopted in this work introduces some essential features of financial analysis for pushing beyond the traditional approach present in energy modelling. The modelling of the cost of capital is here presented to substitute the discount rate with the Weighted Average Cost of Capital (WACC). From this parameter, scenarios on the financing structures of the investments are produced.

2.1.1 Weighted Average Cost of Capital (WACC) and Leverage (L)

This parameter represents the cost of capital invested in the project averaged on its financing structure and can be intended as the minimum return over which the investment becomes profitable, given a certain structure. It must hence be minimized as much as possible. It is here defined as in Steffen [27] formulation:

$$WACC = R_D * (1-t) * \frac{D}{D+E} + R_E * \frac{E}{D+E} \tag{1}$$

Where the following definitions and units of measure hold:

D	Total level of debt	[kUSD]
E	Total level of equity	[kUSD]
R_D	Cost of debt (i.e., the interest rate)	[-]
R_E	Cost of equity (i.e., the return required by the equity shareholders)	[-]
t	Corporate tax deduction (debt is assumed as tax deducible)	[-]

Two complementary definitions follow in Eq. (2) and Eq. (3). To this work, the total asset value of the investment is defined as the sum of debt and equity invested in the project:

$$V = D + E \tag{2}$$

An additional parameter to be introduced is the Leverage ratio, also known as the debt-to-equity ratio. This parameter gives a proxy of the risk perceived by investors, or viceversa as the attractiveness of the investment to external debtors.

$$L = D/E \tag{3}$$

The Leverage ratio varies between 0 (the project is fully financed by equity) and $+\infty$ (the project is fully financed by debt). According to the definitions provided in Eq. (2) and Eq. (3), Eq. (1) can be reformulated as a function of the Leverage ratio, thus bringing to Eq. (4):

$$\begin{cases} \dfrac{D}{D+E} = \dfrac{1}{1+\frac{E}{D}} = \dfrac{1}{1+\frac{1}{L}} = \dfrac{L}{1+L} \\ \dfrac{E}{D+E} = \dfrac{1}{1+\frac{D}{E}} = \dfrac{1}{1+L} \end{cases}$$

[1] https://www.iea.org/data-and-statistics/data-tools/cost-of-capital-observatory

 https://doi.org/10.52202/069564-0178

$$WACC = R_D * (1-t) * \frac{L}{1+L} + R_E * \frac{1}{1+L} \tag{4}$$

$$WACC = f(L)$$

Eq. (4) represents the Weighted Average Cost of Capital as a function of the Leverage ratio (or debt-to-equity ratio), varying between 0 and 1. This explicit formulation allows to represent R_D, R_E and t as parameters, while L will be kept as the only variable of the financial model. It is worth noticing that being the leverage L in a [0; +∞) domain, WACC varies depending on the parameters above mentioned, and can be qualitatively depicted as in **Figure 1**.

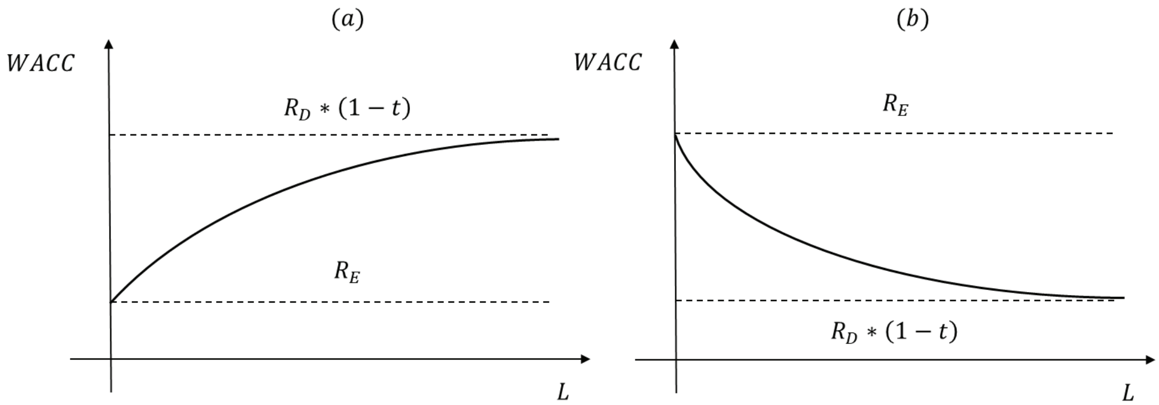

Figure 1. WACC as function of the leverage, for different values of return on equity and return on debt. In (a), the return on debt discounted of taxes is higher than the return on equity, and the WACC. The opposite works for (b).

In general, the higher the equity E is invested in a project, the less risk is perceived by new lenders and the more the cost of borrowing external capitals can reduce over the time, pushing for an increase of D. Consequently, as the above graphs reflect, the WACC can be minimized by:

(a) maximizing the level of equity E (i.e., minimizing L) in the case that the rate of return on debt (R_D) discounted of taxes (t) results greater than the rate of return on equity (R_E); or
(b) maximizing the level of debt D (i.e., maximizing L) in the case that the rate of return on equity (R_E) results greater than the rate of return on debt (R_D) discounted of taxes (t).

In the case of this study, the WACC will be minimized according to the scenario of interest, referring to configuration (a) or (b). Finally, it is worth mentioning that the figures of R_D and R_E strongly depend on the financing structure adopted for the project. As will be advanced in the following sections, a structure built with a project finance approach can help in maximizing the leverage while keeping the return on debt low, if the solidity of future cash flows is assumed [28].

2.1.2 Scenario setting

Three scenarios are here considered, stemming from the ones proposed by Agutu et al. [15]. As already mentioned, the leverage is generally high in SSA power projects, but the return rates on debt are still high, thus bringing to high costs of capital if borrowed through debt. The scenario setting must hence start from the consideration that, in the current mini grid sector in SSA, the most common condition is represented by the rate of return on debt (R_D) discounted of taxes (t) resulting greater than the rate of return on equity (R_E).

The first scenario represents a common *status-quo* situation for the mini grid sector, in which the whole costs are assumed to be covered by public funded equity (i.e., granted at very low rate of return). However, this situation hinders the participation of private lenders or shareholders and does not therefore contribute to develop the sector market, for the reasons already mentioned. For this, a second scenario is introduced, called *increasing private participation* scenario. In this scenario, the shifting from a 20% to a 100% debt-financed mini grid is represented, while keeping the rates of return fixed to the current condition. Finally, the third scenario foresees a *public intervention* in which the regulator intervenes to substantially increase the corporate tax discount (t) and to produce a rate of return on debt (R_D) discounted of taxes (t) lower than the return on equity (R_E). Sensitivity analyses, corresponding to different financing structures, will be performed to understand the impact of these parameters on the modelling outputs.

https://doi.org/10.52202/069564-0178

2.1.3 Assumptions

It is worth mentioning that the financial modelling approach above introduced entails two main assumptions that are far from being negligible in the context of this study. These are:

(i) the source of financing for the investment will provide 100% of the investment on due time, disregarding the upstream sources and markets, and

(ii) the investment will be paid back in its entirety, with assured revenues over the lifetime of the project.

2.2. Energy modelling approach

The open-source energy modelling approach applied in this work emulates the one adopted by Stevanato et al. [29]. It couples an open-source bottom-up energy planning model, MicrogridsPy [30], with an open-source stochastic load demand generator, RAMP [31].

MicrogridsPy is a two-stage linear stochastic mini-grid optimization software developed in python (pyomo) by several authors in the years (original version in 2019 by Balderrama et al. [30]; multi-energy system optimization by Stevanato et al. [32]; multi-year capacity expansion, or MicrogridsPy-MYCE, by Stevanato et al. [29]; last published version in Stevanato et al. [33]). MicrogridsPy requires as inputs: the load demand with hourly resolution, the time series of the variable renewable energy sources with the same time resolution of the demand, and other parameters of techno-economic and financial nature. Both the inputs and the outputs are meant to be user-friendly, being written in intuitive excel sheets. The most advanced version of MicrogridsPy (2.0, March 2023, published at [33]) allows the user to:

- choose the objective function of MicrogridspPy between economic ones (minimum Net Present Cost or non-actualized Operation Costs) or environmental ones (minimum CO2 emissions), or a weighted combination of the two (multi-objective optimization),
- implement stochastic optimization,
- implement multi-year evolving load demand and multi-step capacity expansion,
- account for possible future connection to the main national grid,
- account for existing capacity already installed (brownfield optimization),
- deal with data paucity issues by mean of built-in load archetypes for rural users and endogenous calculation of renewable energy sources production from NASA-Power database.

The code, available in GitHub [34] and in constant updating, is open-source under the EUPL v1.1 license and needs an external solver for the model resolution. The compatibility of MicrogridsPy with a stochastic load profile generator such as RAMP (Remote-Areas Multi-energy systems load Profiles, [31]) has been already tested in existing literature [29,35]: the coupling of the two models provides a powerful energy planning tool to account for stochasticity both on input and design sides of the problem, thus producing more robust modelling results. According to the financial modelling approach introduced in the previous section, some input parameters as well as structural equations of MicrogridsPy have been modified to realise the hard linking with the financial modelling and run the scenarios introduced. The updated code is available in a new branch of MicrogridsPy 2.0 [36]. The user is now allowed to insert the input parameters of **Table 2** in the "Model_data.dat" file.

Table 2. New input parameters to MicrogridsPy.

Parameter and default value	Comment
`param: WACC_Calculation := 1;`	`# 1 to select Weighted Average Cost of Capital calculation, 0 otherwise`
`param: cost_of_debt := 0.11;`	`# Cost of debt, i.e., rate of return on loaned debt capital`
`param: cost_of_equity := 0.12;`	`# Cost of equity, i.e., rate of return on equity capital from shareholders`
`param: tax := 0.02;`	`# Corporate tax to be discounted from loaned debt`
`param: equity_share := 0.10;`	`# Total level of equity as a share of the total investment cost [-]`
`param: debt_share := 0.90;`	`# Total level of debt as a share of the total investment cost [-]`
`param: Discount_Rate := 0.02;`	`# Generic discount rate to be applied if WACC_Calculation is not selected`

The parameters are hence used in a pre-processing function that computes the leverage and the WACC as in Eq. (4). Moreover, all the functions including any actualization of costs have been updated to use WACC instead of Discount_Rate, including the Levelized Cost of Electricity (LCOE). Above all, the objective function will be the minimization of the Net Present Cost (NPC), now defined as:

$$NPC = \sum_{y}^{N} \frac{Inv_y + Fix_y + Var_y - Salvage}{(1+WACC)^y} \quad (5)$$

https://doi.org/10.52202/069564-0178

3. Case study: Ndoro village

3.1. Mozambique off-grid energy context

According to the World Bank [37], Mozambique is among the top 20 access-deficit countries (7th in the world), with 22 million people lacking access to electricity in 2020. This share, corresponding to the 38% of the national population, is mostly located in rural areas under extreme poverty caused by lack of electricity, income, education, and healthcare [38]. Mini-grids are not a new phenomenon in the country: since almost more than 25 years, the public services have owned and operated off-grid diesel generators for remote villages [39,40]. Off-grid electrification via renewable-based or hybrid mini-grids is increasing in the region but at insufficient pace to meet economic and demographic growth [16, 18], because of several barriers that are being investigated in disciplinary literature and reports. Among these, Baruah and Coleman [42] indentify economic and financial barriers such as: high cost of capital from local banks (i.e., associated to high interest rates), short maturity of lending, underdeveloped microfinance options, reduced attractiveness for foreign capitals, and no national-led incentives to mobilize low-cost finance to private-sector led off-grid projects. As Soares et al. [43] proved in their recent investigation, private sector stakeholders in the mini-grid sector of Mozambique consider economic factors as the most limiting ones for the enabling of the national market. Particularly, the authors highlight how the five economic factors, including general economic stability, cost of investment, and positive economic environment, are mostly equally important, according to the stakeholders interviewed.

3.2. Materials

3.2.1 Ndoro village

The village of Ndoro is situated in the Administrative Post of Ndoro, in the Caia district of Sofala Province, at the geographical coordinates of 34°56'35.6"E 18°6'59.5"S, located 62 kilometers away from the nearest national electrical network. This distance has resulted in a lack of access to electricity for over 19,161 residents of the Ndoro community. The current village's energy sources are primarily dependent on diesel generators, solar panels, wood, dung, charcoal, waste, candles, kerosene, portable electric torches, and batteries (see **Table 3**). Due to the dispersed population of the village, it is difficult to plan and execute initiatives for installing a mini grid. The absence of electricity has resulted in numerous difficulties for the community, including limited access to education and healthcare, lack of communication facilities, and decreased economic opportunities. The community's reliance on traditional sources of energy has also contributed to environmental degradation and pose health hazards. Efforts to address this problem and bring sustainable electricity to Ndoro are underway, including the installation of solar home systems However, due to the challenges posed by the village's reduced economic opportunities and geographical location, these initiatives lack extensive planning and resources. Nonetheless, providing reliable and sustainable energy to the people of Ndoro remains crucial for their overall development and wellbeing.

Table 3. General information of Ndoro village

Location (lat., lon.)	Lat. - 18°6'59.5''S Lon. - 34°56'35.6''E; 62 km from Caia district, Sofala province, where the nearest national electricity grid is located
Population	19'161
Number of users interviewed	69
Social services	Hospitals, Schools, Church, Police office, Administrative post
Productive activities	Bars, Tents, Barbershops, Tailor workshop, Mills
Sources/devices used	Lighting – candles, kerosene, portable electric torches, and small lithium batteries Heating and cooking – wood, dung, residues, and charcoal

During the site visits, between 2019 and 2020, it was possible to collect data from households, public institutions, and commercial infrastructures, reaching an overall of 69 potential users. The local energy needs were investigated in two ways: first, through the field visit, which allowed for the observation of the village's actual condition; and second, through meetings with focus groups involving institutions and the local leadership. This second step allowed to define tailored scenarios of demand evolution, too. During the on-field visit, it was also possible to assess the viability of local renewable energy sources for generating electricity. The solar energy resource is unbounded, and its huge potential is freely available with few topological constraints. Relevant hydropower resource is absent. The load demand estimated from the data collected and the correspondent scenarios have been organized in a shared Zenodo repository, accessible at [44]. The following sub-section aims to detail the inputs that are provided to the model.

3.2.2 Model definition

Energy resource assessment

First, the potential of each energy source available in Ndoro has been evaluated. As for fossil fuels, the on-field visit confirmed the availability of diesel in the local market to supply diesel generators, provided by local sellers at a roughly constant price of 1.1 USD per litre. As for renewable energy assessment, the built-in feature for renewable energy assessment of MicrogridsPy 2.0 has been adopted to build the hourly resolution time series to provide as input. The solar resource potential found was characterized by annual average global horizontal irradiation of about 1712.72 kWh/m^2, with daily average of 400 Wh/m^2 and peaks of almost 1000 Wh/m^2. The potential of wind was evaluated at 23 m of height from the soil with the peak values over 14 m/s, and the yearly average wind speed of 4.055 m/s, in which is considered too low for efficient power generation.

Load demand definition

Even tough the current situation of Ndoro is far from being energy intensive, growth scenarios contained in [44] detail the perspective provided by local focus groups. High growth scenario has been chosen for the scope of this analysis, due to the willingness of investigating financing structures for a >100 kW of peak power capacity mini grid. In fact, this represents the most suitable case for a commercial-alike study. The output of RAMP software is depicted in **Figure 2**, showing the estimated evolution of Ndoro yearly load duration curves along the modelling horizon (2022-2041).

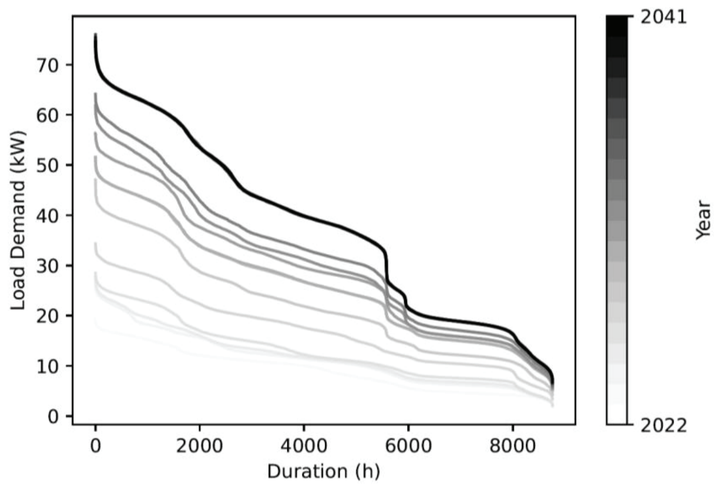

Figure 2. Estimated load duration curve evolution in Ndoro village.

Technology selection and techno-economic parameters

The model considers the possible technologies that could be employed for the construction of a 3rd generation hybrid mini grid [10]: solar PV panels, wind turbines, diesel generators and lithium-ion batteries. The techno-economic parameters for the definition of these technologies are available at [45].

Financial parameters and financing structures

The sensitivity analysis has been conducted on the parameters that characterize the scenarios drawed according to the rationale previously introduced. The combinations of these parameters correspond to a specific financing structure. Values for Mozambique market have been taken and adapted to the case study from the publication by Agutu et al. [15]. A summary and critical description of the financing structures are proposed in **Table 4**.

Table 4. Summary of financing structures associated to the scenarios considered.

Scenario	Description	R_D	R_E	t	D [%]	E [%]	WACC
Status quo	The scenario represents the business-as-usual case, characterised by total absence of private capital participation. The resulting WACC is low, due to the low rate of return required by public funding.	0.26	0.13	0.02	0	100	0.13

 https://doi.org/10.52202/069564-0178

Increasing private participation	The scenario represents an increasing of private capital participation from a partially public funded to a non-funded mini grid. However, since the market is assumed to be static, the rates of return are fixed to the status quo boundaries, and the overall WACC increases as D increases. The return on equity in this scenario is slightly increasing with respect to the status quo, due to the participation of private shareholders in the equity market, too.	0.26	0.17	0.02	20	80	0.187
					40	60	0.204
					60	40	0.221
					80	20	0.238
					100	0	0.255
Public intervention	The scenario shows how a substantial increase of t, consisting in a massive public incentivizing scheme, brings to a (1-t)*R_D lower than R_E. This changes the slope of the WACC curve (see Figure 1.) and makes the increase of D functional to the reduction of the WACC, thus pushing for the participation of the private sector.	0.26	0.17	0.4	20	80	0.167
					40	60	0.164
					60	40	0.162
					80	20	0.159

4. Results and discussion

The extent of impact of the financing structure is assessed observing the modelling outputs of the mini grid, i.e., the values taken by the decision variables of the model. The comparison of the results makes sense at scenario level and broader considerations can be made to provide an outlook for the research.

Table 5. Summary of results associated to the scenarios considered.

Scenario	WACC	PV [kW]	Diesel genset [kW]	Battery bank [kWh]	LCOE [USD/kWh]	NPC [kUSD]
Status quo	0.130	83.42	41.94	138.49	0.271	330.201
Increasing private participation	0.187	48.96	41.94	54.62	0.313	247.892
	0.204	38.3	60.21	12.91	0.321	227.569
	0.221	32.45	70.85	0.08	0.328	209.055
	0.238	28.98	74.17	0.05	0.335	192.876
	0.255	26.01	74.25	0.03	0.341	178.748
Public intervention	0.167	64.75	74.31	107.08	0.299	273.146
	0.164	65.93	46.79	107.42	0.297	277.203
	0.162	66.77	46.68	107.67	0.296	279.968
	0.159	68.55	46.6	111.97	0.294	284.196

In the *status quo* scenario the WACC has been taken at a value of 0.13 from [15], considering 100% equity financing sourced from public fund. As already debated in different literature, this scenario is not advisable since it excludes the participation of private capitals. However, the relatively low WACC provides high PV and battery bank capacity, corresponding to the greater NPC of all the scenarios.

As for the *increasing private participation* scenario, the resulting installed capacities are depicted in Figure 3. The five values of WACC considered correspond to a variation of the debt share from 20% to 100%. It is already evident from the depicted results how the PV technology, as well as the LCOEs, benefit from lower discount rates, in this case related to the lower debt shares. It is worth mentioning that the proposed configuration cannot raise debt penetration, being the return on debt still too high compared to the return on equity. Conversely, the *public intervention* scenario shows how in the case of a massive incentivizing intervention (t) by the regulator, the increase of debt share D can reduce the WACC. In this case, the modelling outputs are much less sensitive due to the reduced range of variation of the WACC.

https://doi.org/10.52202/069564-0178

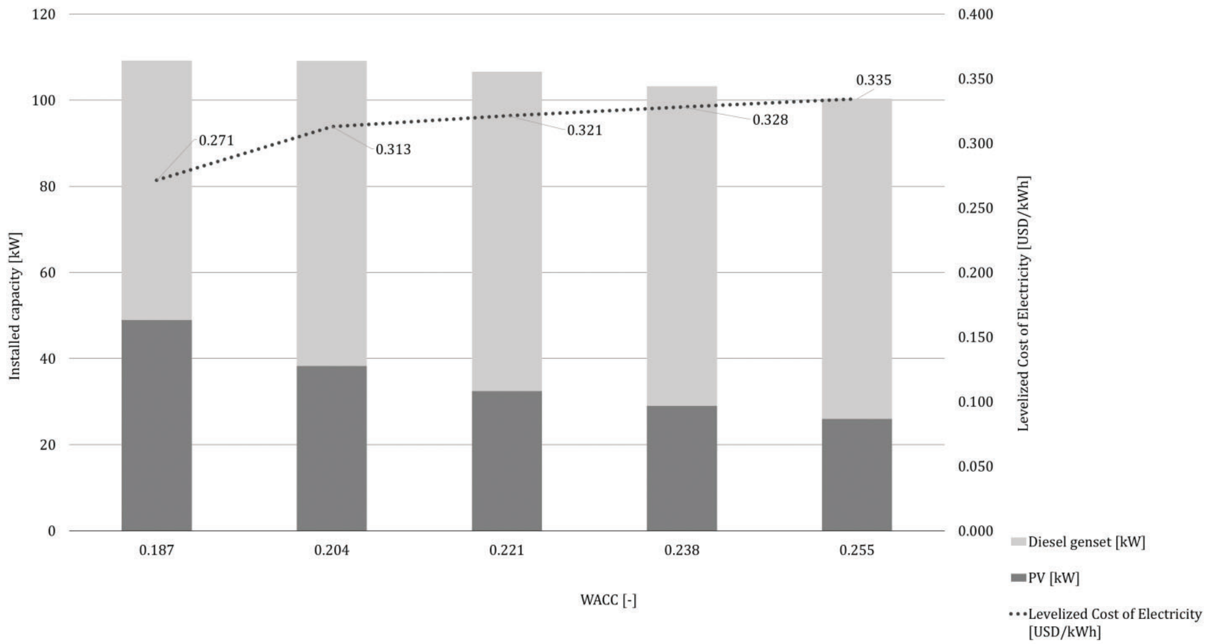

Figure 3. Capacities and LCOE as function of WACC in the *Increasing private participation* scenario.

All the above results are derived from scenarios with current rates of return, which are provenly inefficient and unattractive from a market perspective. The *public intervention* scenario moves in the sense of changing the slope of the WACC as function of the leverage L by varying the (1 – t) factor, i.e., switching from configuration (a) to (b) in **Figure 1**. On the one hand, this proves that, from the regulator perspective and to the goal of enhancing private participation, it would be more efficient to facilitate through a tax discount rather than through equity public funding. On the other hand, such a massive incentivizing intervention (correspondent to 40% of sourced debt) is far from being possibly realised in Mozambique.

5. Conclusion

The study conducted and the results proposed have some limitations to highlight. The limitations are strictly related to the assumptions already commented; for instance, the willingness to accept and wilingness to pay for the service have been assumed, granting that the capitals invested will be paid back. However, as Dibaba et al. [46] highlight, the effective financial sustainability of an off-grid solution cannot neglect the business model that interfaces with the users. Moreover, the financial modelling approach adopted in this study has disregarded the technolgy-specific rates of return, though national and scenario-related values for the costs of capitals have been taken. Out of the results obtained and referring to **Figure 1**, a massive public intervention would be needed to reach an efficient mini grid market in which the increase of the leverage L produces lower WACCs and higher penetration of renewables. The installation of renewables, characterised by lower variable costs and higher initial investment costs, is in fact favoured by lower WACCs in the actualization procedure. Another option to produce this effect is to directly tackle the rates of return and reduce R_D. To this scope, new financial approaches can be introduced. Project finance has been pointed out as a possible tool to upgrade the financing structure of domestic power projects in developing countries [28] and maximise the leverage while diversifying the sources. Such an approach could help in sourcing from climate finance, too, as suggested by Rai et al. [47], thus merging advantages of multiple investment streams while reducing the rates of return. In the case of mini grid financing, project finance is still almost unexplored and could be adopted for financing portfolios of several mini grids, able to ensure more solid cash flows and to mitigate the risk perceived by investors [13]. From the modelling perspective, this requires a more detailed representation of the cash flows and, possibly, a net present value-oriented optimization, able to account for the payback maturity and conditions of the different sources of financing.

Acknowledgments

Financial support from the European Commission H2020 funded project LEAP-RE (Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy), Grant Number 963530 is gratefully acknowledged.

 https://doi.org/10.52202/069564-0178

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