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A Quantitative Analysis Of Different Tariff Designs For Mini-grids

Master thesis

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Abstract

To this date roughly 1 billion people lack the access to electricity, most of these people are living in rural areas of the developing countries. Reaching these rural areas with traditional grid-extension is often difficult and not a cost-effective solution for rural electrification due to large geographical distances. Instead of traditional grid extension it is expected that isolated small-scale grids (mini-grids) will play an important role in accelerating rural electrification. In order for mini-grids to actually play an important role in accelerating rural electrification it is necessary to solve the economic challenge of mini-grids. The economic challenge of mini-grids is related with the low income of the rural population. Most rural dwellers are not able to pay the electricity tariff of mini-grids. Resulting in that mini-grids are not economically sustainable due to insufficient revenues to cover the operational expenses. This thesis is set out to improve the economic sustainability of mini-grids by designing seven tariff types and quantitatively analyse which tariff design is the most affordable tariff design for a mini-grid. Three types of mini-grids are created based on a literature review on existing experience with mini-grids and elements that affect the economic sustainability of mini-grids. Mini-grid 1 has only residential user types, Mini-grid 2 has a mix of residential and commercial/governmental users and Mini-grid 3 has a mix of residential, commercial/governmental and industrial users. The tariffs which are designed for this thesis are; *the Energy Tariff, Capacity Tariff, Fixed & Variable Tariff, Fixed & Variable Tariff CT, Block Tariff, Block Tariff CT and Time of use Tariff.* A model (RETEP Tariff) is created for this thesis which calculates the *Levelized Cost of Electricity (LCoE)* per mini-grid, *tariff rates per tariff design* and the *Cost of Electricity (CoE)* for the end users. The tariff design which has the lowest CoE across all user types of a mini-grid is identified as the most affordable tariff design for a mini-grid. The results show that Mini-grid 3 has the lowest LCoE and lowest CoE for its users followed by Mini-grid 2 and then Mini-grid 1. With the most affordable tariff design for Mini-grid 1 being; *the Fixed & Variable Tariff, Fixed & Variable Tariff CT and The Block Tariff* CT. For Mini-grid 2 and 3 show the results that the Fixed & Variable Tariff is the most affordable tariff design.

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UN	United Nations
DESI	Decentralised Energy Systems India
OMC	Omnigrid Micropower Company
EDH	Electricité d'Haiti
BREP	Bamiyan Renewable Energy Program
PV	Photovoltaic
SHS	Solar Home Systems
AC	Alternating current
DC	Direct current
RES	Renewable Energy Sources
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
O&M	Operation and Maintenance
ESMAP	Sector Management Assistance Program
MFT	Multi-Tier-Framework
BTT	Base Telecom Tower
CoE	Cost of electricity
LCoE	Levelized Cost of Electricity
NPC	Net Present Cost
TAEC	Total Annual Energy Consumption
RR	Revenue Requirement
TIC	Total Investment Cost
GAE	Generation Asset Expenditure
DAE	Distribution Asset Expenditures
PDE	Project Development Expenditures
AAGCTR	Annual Allowed Generation Cost to Recover
AADCTR	Annual Allowed Distribution Cost to Recover
AASCTR	Annual Allowed Service Cost to Recover
AAF	Annual Adjustment Factor
ED	Energy Demand
PD	Peak Demand

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1 Introduction

One of the essential components in life is having access to electricity. Lack of access to electricity contributes to the already existing barrier to economic and social development in the developing world (Winkler *et al.*, 2011; Ahlborg and Hammar, 2014; Williams *et al.*, 2015; Bhattacharyya, 2018). Due to this fact, the United Nations (UN) declared the year 2012 as the "International Year of Sustainable Energy for All''. In that year the UN established three global objectives to be accomplished by 2030: ensuring universal access to modern energy services, doubling the global rate of improvement in global energy efficiency, and double the share of renewable energy in the global mix (Banerjee *et al.*, 2013). Since then, the portion of the world population with access to electricity has been increasing. The number of people living without electricity has dropped from 1.2 billion to roughly just below 1 billion in 2019 (Karplus and Von Hirschhausen, 2019). Most of the remaining 1 billion people are poor and located in rural areas of the developing world (Peters, Sievert and Toman, 2019).

The International Energy Agency projected in 2016 that despite the increased efforts, the objective of ensuring universal access to modern energy services that was set in 2012 will be missed. This means that more than a half billion people will still lack access to electricity by 2030 (Fioriti *et al.*, 2018). One of the main challenges in reaching this objective is providing clean and affordable electricity to the rural population of the developing countries. Large geographical distances make traditional grid-extension expensive, making traditional grid extension not a cost-effective solution for rural electrification (Ahlborg and Hammar, 2014; Baring-Gould *et al.*, 2016). Therefore, it is unlikely that the majority of the rural population is reached with the extension of national grids (Ahlborg and Hammar, 2014).

It is expected that instead of extending the national grid in developing countries, isolated small-scale grids (mini-grids) will play an important role in the electrification of rural areas and help accomplish the goal of the UN that was set in 2012 (Bhattacharyya, 2018). There are three reasons why high hopes are vested in mini-grids according to Ahlborg and Hammer (2014). First of all, mini-grids do not have a geographical barrier to overcome because it is now technically possible to build them in most rural parts of the world. Secondly, mini grids are able to provide sufficient capacity for productive uses but without the high-investment cost of extending high-voltage transmission lines. Thirdly, there may be one or more locations where there is an abundance in renewable energy sources such as solar power, wind power and hydro power.

Unfortunately, mini-grids have also a challenge to overcome. The challenge in the success of mini-grids for rural electrification is not technology-related but rather economically (Sustainable Energy for All Advisory Board, 2014). It has been proven that public and donor funds are insufficient to meet the universal access goals set by governments and international organizations (Williams *et al.*, 2015). In order to attract investors and private companies for increasing the rate of rural electrification with mini-grids. It is necessary to ensure sufficient revenues for mini-grid developers to cover their operational expenses and ensure some profits (Carvallo, Deshmukh and Gambhir, 2013). However, the rural population mostly has low income which leads to affordability issues when it comes to electricity tariffs of mini-grids (Peters, Sievert and Toman, 2019). While the presence of donors or subsidies cannot be ruled out, work is necessary to design tariffs that are both affordable for the consumers and provide sufficient revenues to the grid developers (''economically sustainable'' tariffs).

Hence, this study will focus on tariff design. In the research field of regulatory economics, previous research was mainly focused on one tariff design for a specific mini-grid in a specific country (Kimera *et al.*, 2012; Moner-Girona *et al.*, 2016; Herbert and Phimister, 2019). While this approach can improve rural electrification on specific locations, it does not help new mini-grid developers in other locations. Hence, this work looks at a number of exemplary mini-grids (differentiated in terms of the mix of end-users types) and alternative tariff designs in order to understand which tariff design(s) would ensure the economic sustainability of each type of mini-grid. This contributes to a first systematization of the knowledge needed to select the most appropriate tariff design in different locations. The outcome of such work would be directly helpful for mini-grid developers and, indirectly, to policy makers as well.

In short, the main objective of this thesis is *to analyse the economic sustainability of alternative tariff designs across a number of exemplary mini-grids*

In order to achieve the main research objective these sub-objectives are formulated:

1. *Finding examples of economic (un)sustainable mini-grids*

   It is necessary to research where mini-grids are located around the world and what makes them economic (un)sustainable. A lot can be learnt from previous experiences with mini-grid projects which can be used for the following steps.

2. *Identifying elements that affect the economic sustainability of mini-grids*

   Identifying and understanding these elements will help in constructing a few exemplary mini-grids.

3. *Identifying alternative tariff designs*

   Identifying the different tariff designs that are present in the literature and their main characteristics is instrumental to select the ones to be analysed in the thesis.

4. *Creating a number of exemplary mini-grids using the identified elements, as well as creating a number of tariff designs to be used for such mini-grids*

   A number of exemplary mini-grids can be created by combining different elements derived from point 2 and a number of tariff designs can be created from the information collected in point 3.

5. *Creating a tariff model that can quantify the economic sustainability of alternative tariff designs for exemplary mini-grids*

   The created tariff model will then be used for sub-objective 6.

6. *Using the created model for the analysis of the economic sustainability of different tariff designs for exemplary mini-grids*

   The model can be used for identifying the appropriate tariff design (one that is affordable for the users and provides sufficient revenue to cover expenditures for project developers) for different mini-grids.

2 Literature Review

This section contains the literature review of this thesis. The literature review is the basis of this thesis and provides information regarding existing mini-grids (Section 2.1), the elements that might affect their economic sustainability (Section 2.2), and tariff designs and tariff principles (Section 2.3). The lessons which were learned from these points are discussed in Section 2.4.

2.1 Existing, economic (un)sustainable mini-grids

This section contains examples of economic (un)sustainable mini-grids and the lessons that can be learned from these examples.

2.1.1 Decentralised Energy Systems India (DESI) Power

Decentralised Energy Systems India (DESI) Power is an independent rural power producer in India with six economically sustainable mini-grids. Three factors contribute to their success according to Schnitzer *et al.*, (2014). Firstly*,* Desi power serves a relatively small number of customers, most of whom are commercial ones. These commercial users have a productive daytime load in comparison with the residential users whom often only need electricity in the evening. Furthermore, the commercial users have a higher ability to pay than the residential users. Secondly, DESI sells power on a metered basis to customers, who pay an energy-based tariff. Which incentivizes their customers to use electricity efficiently. Thirdly, the company takes tariff collection very seriously. DESI Powers sends out its collectors on a daily basis, which gives their residential customers the chance to make payments. Furthermore, their collectors also visit their commercial customers once or twice a week in order to collect their payments.

The lesson that can be learned from DESI Power is that mini-grids with commercial customers can be economically sustainable due to their productive daytime load and higher ability to pay. Users with productive daytime load are crucial since rural households lack a productive daytime load. Rural households require energy for cooking, water heating, lighting and space heating often needed in evening hours. Which leads to a high energy demand during evening hours and low energy demand during the day, reducing the load factor of a mini-grid. The load factor of a mini-grid is an indicator often used to determine the efficiency of a mini-grid. It is the ratio of the average load to that of the maximum load available for a certain period of time. Mini-grids with a high load factor are therefore more efficient. Having commercial users with a productive daytime load increases the load factor making the mini-grid more cost-effective and therefore increasing its economic sustainability.

2.1.2 Omnigrid Micropower Company (OMC)

Omnigrid Micropower Company (OMC) is an independent rural power producer in India. OMC uses an alternative business model in order to make its mini-grids economically sustainable. The business model which OMC uses is the ABC Mini-grid model (Contejean and Verin, 2017). This model is based on an Anchor client, Businesses and a rural Community.

Anchor: An anchor client is a client with a continuous and predictable load in a rural area such as a telecom tower, mines and hospitals. Such clients sign contracts in order to guarantee purchase of electricity and demonstrate their ability to pay. Reducing the financial risk of a mini-grid project and increasing the load demand in rural areas where often the demand is low.

Business: The businesses near the Anchor client often with productive daytime load.

Community: The rural community (households) in the area near the Anchor client often with low energy demand and low ability to pay.

India has more than 150,000 mobile-telephone towers located in off-grid areas with unreliable electricity supply mostly based on diesel generators. OMC builds its mini-grids near mobile-telephone towers using these towers as an anchor client for its mini-grids (Tenenbaum *et al.*, 2014).

Another novel feature of their business model is that OMC does not always build traditional electricity distribution system with low-voltage lines and transformers for supplying rural households and business with electricity (Tenenbaum *et al.*, 2014). Which decreases the initial capital cost needed for building a mini-grid. OMC provides the rural population that lives near the OMC mini-grid with rechargeable battery boxes which they can rent for their energy needs. These battery boxes are returned to the OMC mini-grid in order to be recharged. The rural population which uses these battery boxes are not required to make mandatory fixed payments or pay any security deposit. Due to this novel feature, 30% of the potential households in the area signed up within 45 days of initial operation. Which is significantly higher than the households sign-up rate for traditional mini-grid projects (Tenenbaum *et al.*, 2014).

The first lesson that can be learned from OMC is that the ABC model can lead to economically sustainable mini-grid. Anchor and business clients can be used in order to improve the load factor and reduce the cost of electricity which results in more affordable energy for rural households. Furthermore, having a contract that guarantees the purchase of electricity makes the cash flows for a mini-grid project more predictable. The second lesson that can be learned from OMC is that novel business models can be affective in providing rural population with affordable energy services.

2.1.3 Electricité d'Haiti (EDH)

Electricité d'Haiti (EDH) is a government-owned utility which owns mini-grids in Haiti. Some of the mini-grids they own are economical unsustainable because of one main reason; poor cost recovery. The poor cost recovery is a result of low tariff levels and oversized generators. The tariff levels are too low to recover the operation and maintenance (O&M) costs, leading to that the local mini-grid operator lacks the funds to keep the mini-grid reliable. Furthermore, their generators are oversized by a factor of two to three for the loads they serve to their customers (Schnitzer *et al.*, 2014). Oversized generators consume fuel at very low efficiency, increasing the operational costs and leading to even poorer cost recovery. This leads to occasional maintenance problems which are caused by not having enough money. The maintenance problem results in a poor service for the customers which then leads to non-payment.

The lessons that can be learned from EDH is that the tariff levels should be high enough to cover the O&M costs and that it is very important to size the generators to the load demand of the area. Furthermore, that poor service leads to non-payment even in rural areas.

2.1.4 Bamiyan Solar Mini-grid

The Bamiyan Renewable Energy Program (BREP) developed a large scale solar photovoltaic (PV) mini-grid in Afghanistan's Bamiyan region. The mini-grid has diesel generators as a secondary source of electricity and batteries for storage. The Bamiyan mini-grid was funded by the New Zealand Ministry of Foreign Affairs. BREP is used to power an off-grid rural provincial center and has a system size of 1 MW (Foster, Woods and Hoffbeck, 2015). Due to its size it is possible to provide electricity to power commercial, governmental and household loads. Commercial and governmental users pay a tariff rate of $0.70 per kWh while the households pay a tariff rate of $0.25 per kWh. These tariff rates can be seen as a compromise between the national tariff rate (which are lower than these tariff rates) and the actual cost of electricity of the mini-grid (which is higher than these tariff rates). Prior to the arrival of the BRP mini-grid, the local population payed $1.95 per kWh for alternative energy services. BRP has reduced the cost of electricity for households from $1.95 per kWh to $0.25 per kWh (Foster, Woods and Hoffbeck, 2015). However, a tariff rate of $0.25 per kWh is insufficient for the long-term economic sustainability of this mini-grid since, the cost of fuel for operating the mini-grid on diesel backup is $0.30 per kWh (Foster, Woods and Hoffbeck, 2015). Which means that any time the diesel generators are generating power the mini-grid is operating at a loss. Current losses from operating diesel generators are covered with the surpluses which are made from running on solar PV. However, as the demand grows so grows the diesel consumption which means that with the current tariff rate the surpluses that are generated from running solar PV will diminish overtime.

The lessons that can be learned from the Bamiyan Solar Mini-grid is that setting a tariff rate lower than the operating costs can jeopardise the economic sustainability of a mini-grid in the long run.

2.2 Elements that affect the economic sustainability of Mini-grids

There are different terms such as Mini-grid, Micro-grid, Pico-grid and Nano-grid that distinguish the size of a grid. For this thesis a mini-grid is defined as: A system in where electricity providers supply electricity produced from local generating resources to local users, using local distribution network operating in an isolated mode with a size range of 100-150 kW.

2.2.1 Technical Configuration of a Mini-grid

A mini-grid has four technical features: electricity generation technology, a power distribution network, a storage unit and a balance-of-plant items (tracker, inverter, controller etc.) (Chaurey and Kandpal, 2010). The latter two are not mandatory since their presence depend on the type of generation technology is used for the mini-grid.

The generation of electricity can be done by using fossil fuel-based technologies, such as diesel generators or renewable energy resources such as wind, micro-hydro or solar PV. It is also possible to use a hybrid combination of the generation resources such as diesel-wind, diesel-PV-Wind and hydro-PV. Solar PV and hydro are the most common technologies used for off-grid electrification (S. C. Bhattacharyya and D. Palit, 2014). Selecting the most appropriate type of generation is very important as it affects the stability of the mini-grid and the total cost needed to build the mini-grid. On one hand, Renewable Energy Sources (RES) have an intermittent nature and higher investment cost compared to a diesel generator. This affects the stability of the mini-grid and the capital needed to build the mini-grid. On the other hand, choosing RES results in lower O&M costs (Rolland and Glania, 2016). Furthermore, the type of generation technology chosen decides whether the mini-grid is power or energy limited. Solar PV and Wind-powered mini-grids are energy limited systems while hydro and diesel generator powered mini-grids are power limited. Power limited mini-grids systems are limited by the maximum power their generator can produce. Energy limited systems are limited by the capacity of the storage systems since the instantaneous power availability of batteries and inverters will be higher than the level that can be sustained (S. C. Bhattacharyya and D. Palit, 2014).

Solar PV is often used for mini-grids because it is a mature technology and the cost of its components have drastically decreased in the last years making it an very attractive option (Hansen, 2017). One of the biggest advantages of solar PV is its modularity, if the demand of the mini-grid grows overtime new solar panels can be added. Which makes it easy to adjust the mini-grid for future demand. Furthermore, most areas where there is a need for rural electrification (Africa and Asia) have more than 300 sunny days per year which makes harnessing the energy from the sun attractive (S. C. Bhattacharyya and D. Palit, 2014). Hydro is also a mature technology but is geographically limited making it only applicable for certain areas. Asian countries have great potential for hydro-powered mini-grids while African countries lack that potential. Wind power is not a mature generation technology for mini-grids compared to solar PV and hydro.

Therefore, there is very little expertise and a lack of local reference plants, proven technical concepts and business models for standalone wind-powered mini-grids (Hansen, 2017).

Regarding the power distribution system, a choice must be made whether the distribution system will carry Direct Current (DC) or Alternating Current (AC) to the local dwellers. A DC distribution system operates at low voltages (12, 24, 48V) compared to an AC distribution system (220-240V). Operating at low voltages reduces the radius of which the mini-grid users can receive a reasonable quality of electricity supply because of voltage losses. Furthermore, the different voltage levels also make appliance choices and interconnection of the distribution grid difficult (S. C. Bhattacharyya and D. Palit, 2014; Bhattacharyya, 2018). The advantage of a DC distribution system is that it reduces the capital expenditure (CAPEX) of a mini-grid which is powered by solar PV or Wind energy since no inverters are needed. AC distribution system operates at high voltages which increases the area which can be covered by the mini-grid before voltage losses occur. Furthermore, an AC distribution system promotes productive electricity usage since most appliances are AC based.

Often a backup facility is needed for times when the demand or generation deviates from what was expected. The choice regarding a backup facility is often made between a storage unit (battery packs) and/or a diesel generator. Both technologies have their advantages and disadvantages which are shown in *Table 2.1*. As both technologies have their advantages and disadvantages combining them can lead to the best solution. Using only a diesel generator results in that it is always used when the load demand exceeds the generation capacity of RES, resulting in high O&M costs. Furthermore, if there is an abundance of generation capacity due to low load demand is it not possible to store it, making the mini-grid less efficient. Using only a storage unit reduces the reliability of the system and increases the chance of a black-out. A black-out occurs when the RES is not able to produce the generation capacity needed in order to keep up with the demand. For mini-grids which are powered by a solar PV system there is even a higher chance of a black-out during the night if only a storage unit is considered.

Table 2.1: Advantages & Disadvantages of a backup facility for a mini-grid (S. C. Bhattacharyya and D. Palit, 2014)

	Advantages	Disadvantages
Diesel Generator	• Low Investment cost • Increases mini-grid reliability	• High O&M Cost • Fuel dependency • Affected by diesel price fluctuations • Not a clean technology (Carbon emission)
Storage Unit	• Low O&M cost • Clean technology (no carbon emission)	• High investment cost • Reduces reliability of a mini-grid

Combining these two technologies results in that the efficiency of a mini-grid increases as abundant electricity can be stored. The O&M cost of the mini-grid can be kept low since the diesel generator is only used at extreme moments. Furthermore, the reliability of the mini-grid also increases since the chance of a black-out reduces.

2.2.2 User types of a mini-grid

A rural area can consist of different types of potential electricity users that have different contributions to the load size needs of that area. Four types of electricity consumers can be identified; residential, commercial, governmental and industrial users (Herbert and Phimister, 2019). Industrial users can be considered as Anchor clients if they are able to sign a contract to guarantee purchase of electricity and can demonstrate their ability to pay.

In order to make and keep a mini-grid economically sustainable, it generally needs a medium to large number of electricity users per area (Muchunku *et al.*, 2018). Commercial, governmental and industrial user types can increase the load factor of a mini-grid. Increasing the load factor results in that the mini-grid is more efficiently used reducing the Cost of Electricity (CoE) (Luc, Payen Mathieu, Bordeleau Young, 2015). Reducing the CoE is very important because most household in rural areas have a low ability to pay. An average African household has a monthly income of $180 (Baurzhan and Jenkins, 2016). Reducing the CoE leads to that electricity tariffs are more affordable and higher cost recovery can be reached which improves the economic sustainability of a mini-grid. Therefore, increasing the load factor can be a key factor in making mini-grids economically sustainable. Having multiple types of users not only increases the load factor but can also increase the revenue uncertainty. Commercial, governmental and industrial users have often a higher ability to pay compared to residential users which increases the revenue uncertainty of a mini-grid.

The need for mobile technology has been increasing in the last two decades (Rodríguez Gómez, 2013; Max and Berman, 2018). Therefore, large numbers of Base Telecom Towers (BTT) are located in rural areas of Africa and Asia and are often not connected to the grid. Diesel generators are often used for providing electricity to these towers resulting in a high OPEX and carbon imprint for the telecom providers (Goel and Majid Ali, 2014). Using these towers as an Anchor client for a mini-grid can help both the telecom providers and the mini-grid developers. For the mini-grid developers it increases the load demand and provides revenue security. For the telecom providers it reduces their OPEX and carbon imprint as most of the electricity is generated by RES. Therefore, A BTT which is an industrial type of user should be considered as an Anchor client for a mini-grid.

2.2.3 Load demand

The load demand needed in a given area is often forecasted prior to building a mini-grid. These forecasts help with designing the mini-grid system. Under or oversizing a system can lead to an economic unsustainable mini-grid. Oversizing a mini-grid reduces the financial viability of a mini-grid due to lower revenue generation than expected which eventually can lead to technical problems. Under sizing can lead to technical problems that can affect the reliability and availability of the system. If the reliability of the grid is lower than 95%, users can become frustrated and decide to leave the mini-grid for alternatives (Agenbroad *et al.*, 2017). Therefore, it is very important to have an accurate forecast of the load demand. Most of the mini-grid users will gain access to electricity for the first time of their lives, making predicting their energy consumption based on historic data impossible. The Energy Sector Management Assistance Program (ESMAP) has created a Multi-Tier-Framework (MTF). The MTF classifies the basic energy service needs of households in 5 of increasing power capacity ratings which is shown in *Table 2.2* (Bhatia and Angelou, 2015). *Table 2.2* shows for each tier what the basic energy service needs are regarding the peak capacity, availability, reliability, quality, affordability, legality and health & safety. The MTF can be used by mini-grid developers to assess the energy service needs of rural households in order to categorize them and forecast their load demand.

Another factor that can contribute to an unsustainable mini-grid is the failure to meet the expected load growth projections that are often made before building a mini-grid (Blodgett *et al.*, 2017). It is often expected that after a rural area has access to electricity, the electricity demand of that area will increase overtime. Even though this can be true, it is more often the case that the expected load growth is not achieved, leading to lower revenues than expected making the mini-grid economically unsustainable.

Table 2.2: Multi-Tier Framework for residential energy service needs (Bhatia and Angelou, 2015)

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Peak Capacity	Power capacity ratings[28] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
			Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhr/ day	Electrical lighting, air circulation, television, and phone charging are possible			
2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Afford-ability					Cost of a standard consumption package of 365 kWh/year < 5% of household income		
6. Legality						Bill is paid to the utility, pre-paid card seller, or authorized representative	
7. Health & Safety						Absence of past accidents and perception of high risk in the future	

2.2.4 Mini-grid site selection

The site selection of a mini-grid is an important element to consider since it determines the cost of the grid, the cost of competing alternatives and the potential of RES. An important factor that affects the economic sustainability of a mini-grid is its distance to the grid (Agenbroad *et al.*, 2017).

Agenbroad (2017) has made a least cost comparison between grid extension, mini-grids and Solar Home Systems (SHS) depending on the load size and distance from the existing grid. This is shown below in *Figure 2.1*. Since the costs of building a mini-grid is not affected by the distance from the grid, the costs of a mini-grid continue to be the same as the distance to the national grid increases. Multiple research papers concluded that when a rural area has a distance of more than 4 kilometres from the national grid with a load higher than 2.5 kWh/month per household, the least cost option for rural electrification would be a mini-grid (Agenbroad *et al.*, 2017; Reber *et al.*, 2018).

The closer a mini-grid is to a national grid the higher the chances are for a national grid extension and if a grid extension happens it could jeopardise the mini-grid investments. Seven mini-grid sites have been closed in India due to national grid extension which shows that the threat of grid extension is a factor that should be considered before building a mini-grid (Comello *et al.*, 2017).

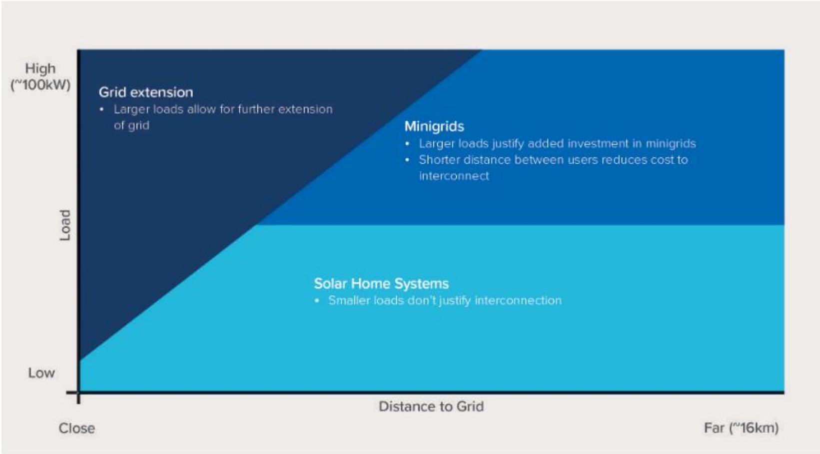

Figure 2.1: The least-cost option for energy access depending on load size and distance from existing grid (Agenbroad et al., 2017)

2.2.5 Ownership models of a Mini-grid

There are four different ownership models for mini-grids, Community-based model, Private sector-based model, Utility-based model and a Hybrid model (Rolland and Glania, 2016). Each of them has their benefits and drawbacks which are discussed here below and shown in *Table 2.3*.

Starting with a community-based model where the local community is the owner and operator of the mini-grid and also provides tariff collection, maintenance and management services. It increases the community self-sufficiency and self-governance and generates jobs regarding the operation, maintenance and management of the mini-grid. One drawback of the community-based model is that often communities in rural area's lack the technical and business skills to maintain a mini-grid which can make it unsustainable in the long-term. Another drawback is that it lacks capital as most rural communities are relatively poor. Furthermore, community based-model can be affected by corruption as a result of social and business relationships which overlap in the community.

A private-sector model has various arrangements when it comes to the ownership of the mini-grid, and contract types with the end-users. Overall, it can be stated that in such models a degree of profitability is needed. Sometimes just to recover the O&M costs and sometimes to recover the investment and O&M costs. The main advantage of such a model is that it provides electricity in a more efficient manner compared with the other ownership models (Rolland and Glania, 2016). This is a result of private companies having the technical ability to maintain the O&M of a mini-grid, having enough funds and a well-designed business plan which can ensure the economic sustainability of a mini-grid. Even though a private-sector model shows the most potential, in reality there is very low interest from the private sector when it comes to investing in a mini-grid.

A Utility-based model is where the utility operator of the country is responsible for the mini-grids operations. The utility operates the mini-grids in the same way as it operates the national electricity network. The users whom are connected to the mini-grid pay the same tariff rate as the customers connected to the main grid. Which is achieved by cross-subsidising the tariffs of the mini-grid users. Cross subsidization is when one group of users is charged a higher rate than they would otherwise be charged. This surplus in revenue is then used to subsidize lower rates for another group of users (Reber *et al.*, 2018). The Utilities do not invest voluntarily in mini-grids since it is not their core business. They are directed by the government to do so, whom are often politically driven (Tobergte and Curtis, 2014). Therefore, the funding is often obtained through the government. The main advantages of a utility-based model are that it can captivate funds easily, needs les regulation in order to protect the users and has affordable tariffs. The main drawback of the utility-based model is that it is very sensitive to political interference and corruption (Tobergte and Curtis, 2014)

The Hybrid model is a combination of the other three models where the ownership, investment and operation of a mini-grid is not carried out by the same actor. The responsibilities are split according to who builds, owns, operates and maintains the mini-grids (Tobergte and Curtis, 2014). The main advantage of such a model is that different actors contribute their strengths in order to make a mini-grid project economically sustainable. At the same time, it is also a major drawback since it has complex management structures and conflicts can arise between the different actors.

Table 2.3: Benefits & Drawbacks of the different mini-grid ownership models (Tobergte and Curtis, 2014)

Model	Benefits	Drawbacks
Community	• Increases community self-sufficiency & self-governance • Generates jobs • Creates local ownership	• Lack of technical & Business skills • Grants needed • Risk of corruption
Private sector	• High efficiency • High degree of Technical & business skills • Degree of profitability allows upscaling of operations • No political interference	• Higher tariffs • Lack of financial support • Investment risk due to grid extension
Utility	• Low tariffs due to the ability to cross-subsidize tariffs • Easy access to funding • Less regulation needed	• Inefficient • Not the core business • Sensitive to political interference • Risk of corruption
Hybrid	• Different actors contribute their strengths • Scalable & profitable	• Complex management structure

2.3 Tariff designs and tariff principles

Tariffs are derived from the so-called revenue requirements of a grid infrastructure. The revenue requirement (RR) refers to the total revenue, over the lifetime of the project, that must be realized through annual revenue collections, to cover total costs (Eltamaly and Mohamed, 2018). According to the definition adopted for this thesis, a mini-grid will be economically sustainable if tariffs are both affordable for its users and high enough that they recover the variable and fixed costs of the project. Section 2.3.1 provides a general overview, Section 2.3.2 introduces alternative tariff designs, and Section 2.3.3 discusses tariff principles.

2.3.1 An overview

In order for a mini-grid to be sustainable it must have a balance between the needs of three groups of stakeholders: governments, developers and users (Reber *et al.*, 2018). From this perspective three ‘tariff structures’ can be distinguished for mini-grids: uniform, site specific and hybrid.

A uniform tariff structure charges the users the same tariff without making a distinction whether they are connected to an urban utility grid, a rural utility grid, or a mini-grid. The goal of this type of tariff structure is providing fairness and equality for all the users. Such a tariff structure is very politically favourable for governments. According to Reber and Booth (2018), uniform tariff structure rates in Africa have a range of $0.05-0.30 per kWh, while a developer needs to charge between $0.50 and $1.00 per kWh in order to sustain a feasible business model for a mini-grid. Uniform tariff structures are kept low with cross-subsidization or are directly subsidized by the government, which is not sustainable in the long run. Furthermore, such tariff structures generate market-distorting effect whereby remote mini-grid users do not realise the true costs for providing rural electrification.

Site specific tariff structures allow the mini-grid operators to set their own tariff and payment structures which are high enough to recover their capital and operational cost. Making them higher than the tariff rates payed by user with a connection to the national grid and lower when compared to a user who is unconnected and pays for energy services in the form of batteries, candles and kerosene (Reber and Booth, 2018). International Finance Corporation (2017) estimated that unelectrified households in East Africa are paying $1.75 per kWh for these so called ''implied tariffs''. Mini-grids with site-specific tariffs are able to provide cleaner and cheaper electricity when compared to the implied tariffs rural households are already paying. However, these tariff structures are not without drawbacks. Rural household who are connected to a mini-grid could compare their tariff rate with somebody connected to the national grid and become upset, which could lead to lower revenue collection. Furthermore, what will happen if the national grid arrives near a rural village which is charged with site-specific tariffs by a mini-grid developer. Will the mini-grid developer keep the site-specific structure or lower the tariffs of the mini-grid? Keeping the site-specific tariff can result to disconnection by the users leading to lower cost recovery. Lowering the tariff will lead to ruin the business model of the mini-grid developer.

The hybrid between the two tariff structures is when site-specific tariffs are used in combination with subsidies or grants. This combination can reduce the gap between the site-specific tariff structure and uniform tariff structure. Nevertheless, relying on subsidies from a government that often lacks capital can lead to financial problems for a mini-grid operator and therefore make it economically unsustainable.

In accordance with the goal of this thesis (to provide guidance to mini-grid developers), the focus will be, from now on, on site-specific tariffs.

2.3.2 Tariff designs

A mini-grid operator has multiple options when it comes to choosing a tariff design. In practice, tariff design can be divided into energy-based, capacity-based or fee-for service tariffs.

An energy tariff is a volumetric tariff, based on the amount of kWh a user consumes. It has a fixed rate per kWh consumed, is easy to implement, load limiters are not required, encourages efficient use and is widely accepted. Energy tariffs are often used for energy-limited mini-grids (solar PV, Wind) where peak generation is only possible during the day and during the night there is a limited amount of energy available (storage volume of battery). A drawback of an energy tariff is that it can lead to revenue fluctuations since it is only based on the amount of kWh a user consumes (Mountouri and Döbeli, 2015; CEER, 2017; Reber and Booth, 2018). Furthermore, meters are required since the energy consumption of the users needs to be metered.

Then, there are capacity tariffs, which are based on the peak power (kW) consumed by a user rather than the amount of energy (kWh). Capacity tariffs are more often used for power-limited mini-grids such as hydro powered mini-grids that produce energy during the whole day at no extra cost but have a limited peak power. In contrast to energy tariffs, capacity tariffs offer more revenue certainty (Mountouri and Döbeli, 2015; CEER, 2017). The drawback of a capacity tariff is that it can encourage inefficient and excessive use since users are not paying for the amount of energy they consume.

Fee-for service tariffs are tariffs which are based on an energy-using services, this type of tariff captures a wide range of tariff types which all are based on charging a user for an energy-using service. Electricity is not sold per unit but priced for the service it provides. These services are defined by the mini-grid operator and the users are charged based on the services they use (Reber and Booth, 2018). An example can be that a user is charged on a set of appliances it has, one tariff for a refrigerator and another for the radio it owns. Such tariffs are very simple to understand for users who are not familiar with billing methods and do not require a meter. However, such tariffs are not encouraging efficient use of energy, hide the charge per kWh and need precise calculations of service prices.

To keep with the modelling capability and data availability of this thesis, only energy and capacity tariffs will be considered. Of course, these tariffs can also be fine-tuned in several ways.

Block tariffs are tariffs which divide the users of a mini-grid in different groups such as residential, commercial, governmental and industrial. Each group is charged with a different tariff rate which can be based on the level of consumption (the more a user group uses the higher or lower their marginal tariff will be) or power needs (a user group who has a higher power demand pays a higher tariff). Block tariffs can be complex because multiple factors are considered making them difficult to understand for an average user.

Time of use tariffs charge different rates which depend on the time a user consumes electricity. Higher tariff rates are charged at moments when the demand is high (peak hours) and lower rates are charged when the demand is low (off-peak hours). Using time of use tariffs can incentivize mini-grid users to consume electricity during off-peak hours promoting more efficient use of energy. Which can have a flattening effect on the load curve of a mini-grid. A drawback of such a tariff is that it needs sophisticated meters which increases the connection cost of a user.

Then there are binomial tariffs. Such tariff consists of two components one being a fixed tariff and the other being a variable tariff. The fixed tariff is often fixed for several years while the variable tariff changes from year to year. Fixed tariffs are often used to repay a part or all of the investment costs, while variable tariffs are often used to cover the variable expenses such as O&M cost. Binomial tariffs are favourable from a point of view of a mini-grid operator because they provide more revenue certainty (Tobergte and Curtis, 2014). Binomial tariffs are less favourable from the point of view of a mini-grid user since having a fixed cost reduces their financial flexibility.

2.3.3 Tariff Principles

There are different tariff principles that can be considered when assessing tariffs for a mini-grid. The literature clusters them into three main groups; System Sustainability Principles, Economic Efficiency Principles, and Protection Principles (Vivak S, 2010; Reneses and Ortega, 2014; Picciariello *et al.*, 2015).

The first group, System Sustainability Principles, focuses on the successful functioning of the infrastructure (e.g., cost-recovery) and on the incentives provided by the regulator.

The second group, Economic Efficiency Principles, includes:

- Productive Efficiency – energy services should be delivered to consumers at the lowest possible cost;
- Allocative efficiency – tariffs should incentivise the users to use the mini-grid efficiently;
- Cost reflectiveness – users should be charged in accordance with the costs of the services they have received, their contribution to the system peak and their position in the network.

And the third group, Protection Principles, includes:

- Transparency – the methodology and results of tariff allocations should be published and available to network participants, whose bills should clearly state each charged component;

- Non-discrimination – all users who demand the same network services and belong to the same group type should be charged the same tariff rate, regardless of their total energy consumption;
- Equity – certain categories of users, like low income users, or users that are located in remote areas, are charged a tariff which is lower than the cost of the services received;
- Simplicity – tariffs should be as easy as possible in order to be understandable for a user;
- Consistency – tariff regulation has to comply with the legislation in place;
- Stability – the tariff structure should result in stable electricity prices in the short-term, with gradual changes in the long-term.

In line with the focus of this thesis (the economic sustainability of mini-grids) the following tariff principles will be considered when evaluating alternative tariff designs:

- Cost recovery is an important tariff principle for mini-grid developers as they need sufficient revenues to cover expenses and ensure some profits. In particular, operational expenses need to be recovered in order to keep the mini-grid reliable over the long term of the project. Replacement costs need to be recovered since some assets (storage unit, diesel generator) need to be replaced after a while. Profits are important since a profitable mini-grid can secure financing from a bank and attract investors to fund future expansion (if necessary) of the mini-grid;
- Affordability which is specifically introduced for this thesis, and defined as the ability to pay for basic energy services (Piai Paiva, Jannuzzi and de Melo, 2019) – note that affordability is related to the *Allocative efficiency principle* (using the mini-grid efficiently reduces system costs) and to the *Productive efficiency principle* (providing the energy service efficiently reduces system costs);
- Cost-reflectiveness is important to consider because it ensures that the users payments for the energy service reflects their use of the system. For instance, users that contribute more to the peak demand will pay more as they increase the system costs. Not considering cost-reflectiveness allows the users to increase the system costs without any financial consequences. This can jeopardise the economic sustainability of a mini-grid;
- Non-discrimination principle assures that all users that belong to the same group are charged the same tariff. The aim of this principle is to ensure that the applied tariff do not provide one user any advantage over another user. Considering this tariff principle results in that the mini-grid users feel treated fairly, thereby increasing their satisfaction with the mini-grid and reducing the chance of disconnection;
- Simplicity principle ensures that tariffs are easy enough to understand for all mini-grid users. The simpler a tariff is the easier users of a mini-grid can respond to it.

It is important to note that each principle has its own objective and trade-off exist between the tariff principles. One of the trade-offs that should be considered between the tariff principles is between *simplicity* and *cost-reflectiveness*. Most tariffs which satisfy the *cost-reflectiveness* principle are not simple. Such tariffs often consider users contribution to the system peak which results in complex calculations making them hard to understand for rural dwellers. In order to design a proper tariff, (one that is in line with the objective that one has) one should prioritize some principles over the others.

Out of the 5 principles discussed here above *cost recovery* and *affordability* are prioritized. More specifically, this thesis assumes that *cost recovery* is always ensured by construction. Notably, to ensure a fair comparison across the exemplary mini-grids, the present value of all the costs sustained during the mini-grids' lifetime (the Net Present Cost, NPC) will be kept similar (clearly a project with a lower NPC has, all other things equal, a higher probability of being affordable for the end users). Furthermore, absent any information on each user's ability to pay (the thesis relies on exemplary mini-grids), individual affordability will be evaluated by looking at the annual cost incurred by each end-user for the energy service (a so-called Cost of Electricity, CoE, indicator). The simple assumption made for this work is that lower this indicator, the more likely that the user will be able to afford the energy service. To provide further realism to the evaluation, the CoEs resulting from the alternative tariff designs proposed in this work will also be compared with the CoE which would derive from the "implied tariff".

As for the *non-discrimination* principle, this will not be explicitly assessed *ex-post*: all tariff designs considered in this thesis will be built in a way that all users that belong to the same group are treated equally. The assessment of the other two principles (*cost-reflectiveness* and *simplicity*) will be qualitative.

2.4 Literature review findings

This section discusses sub-objective 1, 2 and 3 and gives a brief summary of the findings that were learned from the literature review.

Sub-objective 1: Finding examples of economic (un)sustainable mini-grids

There are very few examples in the literature of sustainable mini-grids (e.g., DESI Power and OMC), as well as examples of unsustainable ones (e.g., mini-grids of EDH). An example was also found of a mini-grid (Bamiyan Solar Mini-grid) which is currently economically sustainable but will become unsustainable in the future if the tariff rate is not changed.

Sub-objective 2: Identifying elements that affect the economic sustainability of mini-grids

It is possible from the literature to identify elements that affect the economic sustainability of a mini-grid. These are: technical configuration of a mini-grid, user types, load demand, site selection, ownership models and tariff design of a mini-grid.

Sub-objective 3: Identifying different tariff designs for mini-grids

The literature provides a clear taxonomy of tariff designs. The ones identified are: Energy tariff, Capacity tariff, Fee for service tariff, Block tariff, Time of use tariff and Binomial tariff.

In more details, the following learning points can be derived from the literature with regard to sub-objectives 1, 2 and 3 and can be used to guide the next steps of this thesis.

1. Considering multiple types of users is essential in making mini-grids economically sustainable.

Considering multiple types of users can improve the economic sustainability of a mini-grid because of two reasons. Firstly, developing a mini-grid only for residential users can be very challenging since residential users often have a low productive load during the day which reduces the load factor of a mini-grid. A low load factor means that the mini-grid is not used efficiently which results in higher Cost of Electricity for the users making the tariffs less affordable. Commercial, governmental and industrial user types can increase the load factor of a mini-grid because they have a higher energy consumption compared to the residentials. Secondly, the only revenue stream that a mini-grid has is from its electricity sales. Having multiple user types such as commercial and industrial users increases the number of revenue streams and reduces revenue uncertainty.

2. Anchor clients should be considered from year one when developing a mini-grid.

Anchor clients have a high and stable load demand. Which increases the load factor of a mini-grid making it more cost-efficient. Furthermore, they can provide revenue security for the mini-grid developer. Base Telecom Towers are located in large numbers in rural areas making them an ideal Anchor client for mini-grids.

3. Solar PV with battery storage and a diesel generator as backup shows the most potential as generation technology for a mini-grid.

Solar PV is a mature technology which is not geographically bound and countries in need of rural electrification often have an abundance of solar energy. Due to the modularity of solar PV is it easy to adjust the mini-grids system size on future demand growth. Combined with a battery storage system makes it possible to storage redundant electricity and use it during the night. Using diesel as a backup improves the reliability of the mini-grid system.

4. An AC distribution system should be considered in order to improve the economic sustainability of a mini-grid.

Productive electricity usage is very important as it increases the load demand of the mini-grid and therefore the electricity sales. An AC distribution system promotes productive electricity usage since most household appliances are AC based.

5. The private-sector based ownership model provides the most potential for an economically sustainable mini-grid.

A community-based ownership model does not show the most potential for a mini-grid. Since, most rural area's lack the technical and business skills which are needed for maintaining a mini-grid economically sustainable. The main advantage of community-based ownership is that it creates local ownership, generate jobs and increases awareness. Which can also be achieved with a private-sector model when the community is actively involved from the start of a mini-grid project. The utility-based model is also lacking potential since it is often inefficient and driven by a political agenda.

6. A site-specific tariff structure should be used for the mini-grid.

Using a site-specific tariff structure allows the mini-grid operator to set the tariffs high enough so that both capital and operational costs can be recovered. Recovering these costs is crucial for the economic sustainability of a mini-grid. These tariffs are often higher than the tariffs paid by users connected to the national grid and lower when compared to the "implied tariffs" paid by rural dwellers having no access to electricity at all.

7. "Implied tariffs" should be used for assessing the economic sustainability of mini-grids

The rural population pays for alternative sources of energy (kerosene, candles and cell batteries) with the so-called "implied tariffs". The CoE from the "implied tariffs" of the area where the rural population lives should be used as a benchmark to evaluate affordability. In order for a mini-grid to be economically sustainable it should have tariff rates lower than the implied tariffs.

3. Methodology

The methodology of this thesis can be divided in three steps. First, there is the design phase. In this phase a number of exemplary mini-grids and tariff designs are defined, based on the lessons learned from the literature review. Second, is the modelling phase. Third and last step, is the assessment, against the tariff principles, of the different tariff designs for the exemplary mini-grids.

3.1 Design Phase

This section discusses the design phase, this is the phase where the different exemplary mini-grids (Section 3.1.1) and tariff designs (Section 3.1.2) are defined.

3.1.1 Exemplary mini-grids

Three exemplary mini-grid are created based on the lessons learned and the findings from the literature review. These mini-grids are discussed here below and their characteristics are shown in *Table 3.1*. In order to improve the economic sustainability of a mini-grid different elements from objective 2 are combined. The elements that have the most potential are chosen for designing these three mini-grids. The technical configuration which shows the most potential is a Solar PV system with battery storage, diesel generator as a back-up and an AC distribution system. The ownership model which shows the most potential is a private sector based-model. Hence, all three mini-grids will have the same technical configuration and ownership model. What differentiates the three mini-grids is their user types and therefore also their load demand. This choice is made because multiple user types increase the revenue streams of a mini-grid and also reduce the revenue uncertainty. Considering multiple user types increases also the load factor of a mini-grid making the mini-grid more efficient thereby reducing the cost of electricity and making the tariffs more affordable. Furthermore, when multiple types of users are considered a wider variety of tariff designs can be used. The Block Tariff is an example of a tariff design which can be considered when a mini-grid has multiple types of users.

<u>Mini-grid 1</u> is a mini-grid serving only residential users with 2 types of households. The MTF (Table 2.2, Section 2.2.3) is used in deciding which type of residential user the mini-grids will have. The choice is made to only include residential type users who have an energy service need of Tier 1 and Tier 2. A Tier 1 type of residential user requires a minimum of 12 Wh of electricity on a daily base, often only needed for lighting. A Tier 2 type of residential user requires a minimum of 200 Wh of electricity on a daily base, often needed for lighting, refrigeration of food and mobile phone charging. This choice is made since, most residentials in rural areas need electricity only for lighting, charging mobile phones and operating small appliances. Furthermore, for most rural dwellers it is the first time that they experience having a direct electricity connection. Which makes it unlikely that they would have the appliances or the income to belong in a Tier higher than Tier 2. Mini-grid 1 is also going to be used as a base case in order to quantify how the difference in user types affects the economic sustainability of a mini-grid.

<u>Mini-grid 2</u> is a mini-grid serving residential, commercial and governmental users and, specifically, two types of household (same as Mini-grid 1), multiple commercial users (Barber, Carpenter, Kiosk, Market place, Pharmacy) and a governmental user (Primary school). The choice is made to include commercial and governmental user types in Mini-grid 2. With the lessons learned (point 1) during the literature review it can be concluded that a mini-grid with commercial and governmental users has more potential in being economically sustainable. Commercial and governmental users have productive day time load in contrast to residential users. Resulting in that the load demand of the mini-grid is increased which increases the cost efficiency of the mini-grid. Furthermore, commercial and governmental users have a higher ability

to pay in contrast to residential users. Which increases the sale of electricity resulting in higher revenues for the mini-grid developers.

Mini-grid 3 is a mini-grid type which contains residential, commercial, governmental, and industrial users. Notably, for Mini-grid 3 the choice is made to add an extra commercial user (Small Enterprise) and an industrial user (Base Telecom Tower). The Base Telecom Tower is chosen as an Anchor client since the need for mobile technology has increased and there are large numbers of these towers in rural areas. The choice is made to further increase the load demand during the day in order to quantify how the addition of an industrial user affects the tariff rates. Furthermore, an Anchor client provides even more revenue certainty than the commercial and governmental users since, it has a higher and more stable load demand during the year.

Table 3.1: User types, Technical Configuration and Ownership model of Mini-grid 1, 2 and 3

User Types	Mini-grid 1	Mini-grid 2	Mini-grid 3
Residential	Household (Tier 1)	Household (Tier 1)	Household (Tier 1)
Residential	Household (Tier 2)	Household (Tier 2)	Household (Tier 2)
Commercial		Barber	Barber
Commercial		Carpenter	Carpenter
Commercial		Kiosk	Kiosk
Commercial		Market Place	Market Place
Commercial		Pharmacy	Pharmacy
Governmental		Primary School	Primary School
Commercial			Small Enterprise
Industrial			Base Telecom Tower
Technical Configuration	Solar PV + Battery + Diesel Gen, AC distribution system	Solar PV + Battery + Diesel Gen, AC distribution system	Solar PV + Battery + Diesel Gen, AC distribution system
Ownership model	Private sector	Private sector	Private sector

3.1.2 Tariff Design

Seven tariffs were designed for this thesis. All of them ensure cost recovery, and non-discrimination.

3.1.2.1 Energy Tariff

The Energy Tariff is a volumetric tariff which is based on the annual energy consumption and annual Revenue Requirement (RR). The latter includes the annual generation, distribution, service and adjustment factor expenses of a mini-grid. The service expenses include the project development costs and staff costs which are needed to build and maintain the mini-grid and the adjustment factor expenses are costs as a result of uncollected payments.

The Energy Tariff is calculated using Eq. (3.1), where *y* refers to the year for which the tariff is calculated.

$$\mathrm{T_{EnergyTariff}} = \frac{(\mathrm{RR})_y}{\text{Energy consumption}_y} \quad (€/\mathrm{kWh}) \tag{3.1}$$

The cost driver of this tariff is the amount of energy a user consumes, the more energy a user consumes the higher their cost of electricity will be. Therefore, it incentivises the users to use energy efficiently.

3.1.2.2 Capacity Tariff

The Capacity Tariff is based on the *total individual peak* and the annual RR of a mini-grid, calculated using Eq. (3.2) with *I* being the number of individual users, and *Capacity* being the annual peak load of user *i*. The total individual peak is the sum of the peak of each user which can occur on different times. Therefore, the total individual peak has a low probability of ever occurring.

$$T_{CapacityTariff} = \frac{(RR)_y}{\sum_i^I Capacity_{i,y}} \quad (€/kW/year) \tag{3.2}$$

The cost driver for the users of this tariff is their annual peak load (kW): the higher their annual peak load, the higher their CoE. Notably, users can consume energy without any extra cost as long as they do not exceed their peak load.

3.1.2.3 Fixed & Variable Tariff and Fixed & Variable Tariff CT

The Fixed & Variable Tariff and Fixed & Variable Tariff CT are binomial tariff types which consist of a monthly fixed tariff and a volumetric tariff. The difference between the two tariffs is in the calculation of the fixed part. The Fixed & Variable Tariff does not consider the *Connection Type* (CT) of the users while the Fixed & Variable CT does.

Fixed & Variable Tariff

The fixed part of Fixed & Variable Tariff is calculated using Eq. (3.3) and the volumetric tariff is calculated using Eq. (3.4). The annual *Distribution cost* covers the distribution network and connections expenses. The annual distribution cost, together with the number of users, is used to calculate the monthly fixed tariff (Eq. (3.3)). The other expenses are used for the calculation of the volumetric tariff (Eq. (3.4)), together with the annual *Energy consumption* of the mini-grid.

$$T_{Fixed} = \frac{(\text{Distribution cost})_y}{(\text{Number of users} * 12)_y} \quad (€/month) \tag{3.3}$$

$$T_{Variable} = \frac{(RR)_y - (\text{Distribution cost})_y}{(\text{Energy consumption})_y} \quad (€/kWh) \tag{3.4}$$

Fixed & Variable Tariff CT

The Fixed & Variable Tariff CT has the same variable tariff as Fixed & Variable Tariff but a different monthly fee. The difference in the monthly fee is that it considers the *Connection type* a user has. There are three types of connections considered: Single phase Residential, Single phase Commercial/Governmental and Three phase Commercial/Industrial. The monthly fee of Fixed & Variable CT is calculated using Eq. (3.5) and the volumetric tariff is calculated using Eq. (3.4).

$$T_{Fixed\ ,Connection\ type} = \frac{(\text{Distribution cost})_{\text{connection type},y}}{(\text{Number of users} * 12)_{\text{Connection type},y}} \quad (€/month) \tag{3.5}$$

3.1.2.4 Block Tariff & Block Tariff CT

Block Tariff and Block Tariff CT split the users of the mini-grid into 3 *user groups*; Residentials (R), Commercial & Governmental (C&G) and Industrial (I). The difference between the two tariffs is that Block Tariff has only a volumetric tariff while Block Tariff CT has a volumetric and a fixed tariff.

Block Tariff

Block Tariff has a volumetric tariff, which is different for each user group and calculated using Eq. (3.7). The distinction between the user groups in their volumetric tariff is made based on their contribution to the daily system peak. The *Peak effect* of each user group is calculated using Eq. (3.6). The *System peak* is the hour during the day when the load demand of the system is at its highest. The *Contribution to the system peak* is the sum of the total load which is contributed by one of the identified *user groups* during the system peak. The peak effect of each group is then used for allocating a portion of the annual *RR* to each group based on their contribution to the *system peak*.

$$\text{Peak Effect}_{\text{user group}} = \frac{\text{System Peak}}{\text{Contribution to the system peak}_{\text{user group}}} \tag{3.6}$$

$$T_{\text{user group}} = \frac{RR_y * \text{Peak Effect}_{\text{user group}}}{(\text{Energy consumption})_{\text{User group,y}}} \quad (€/kWh) \tag{3.7}$$

Two cost drivers are considered for this tariff. The first cost driver is the group contribution to the system peak and the second cost driver is energy (€/kWh).

Block Tariff CT

Block Tariff CT has a volumetric tariff Eq. (3.8) and a monthly fixed tariff (Eq. 3.5). The monthly fixed tariff of the Block Tariff CT is the same as the Fixed & Variable Tariff CT.

$$T_{\text{variable,user group}} = \frac{(RR)_y - (\text{Distribution cost}_y * \text{Peak Effect})_{\text{user group}}}{(\text{Energy consumption})_{\text{user group,y}}} \quad (€/kWh) \tag{3.8}$$

3.1.2.5 Time of Use Tariff

The Time of use Tariff consists of two volumetric tariffs, one tariff for *peak hours* calculated with Eq. (3.14) and one for *off-peak hours* calculated with Eq. (3.15). *Peak hours* are the hours during a day when the load demand is at its highest (often during evening hours). *Off-peak hours* are all hours outside the peak hours.

In order to calculate the peak and off-peak tariffs multiple steps are taken. The *average peak during peak hours* is calculated using Eq. (3.9) and the *average peak during off-peak hours* is calculated using Eq. (3.10). The *total average peak* is then calculated using Eq. (3.11). The *peak factor* is calculated using Eq. (3.12) and the *off-peak factor* is calculated using Eq. (3.13). The *peak factor* and *off-peak factor* are used to allocate a portion of the annual *RR* during peak hours and off-peak hours.

$$\text{Average peak during peak hours} = \frac{\sum_{i=\text{start peak hour}}^{n=\text{end peak hour}} kW_i}{\text{Peak hours}} \quad (kW/Hour) \tag{3.9}$$

$$\text{Average peak during off peak hours} = \frac{\sum_{i=\text{start off peak hour}}^{n=\text{end off peak hour}} kW_i}{\text{off Peak hours}} \quad (kW/Hour) \tag{3.10}$$

$$\text{Total average peak (kW)} = \text{Average peak during peak (kW)} + \text{Average peak during off peak (kW)} \tag{3.11}$$

$$\text{Peak factor} = \frac{\text{Average peak during peak hours}}{\text{Total average peak}} \tag{3.12}$$

$$\text{Off Peak factor} = \frac{\text{Average peak during off peak hours}}{\text{Total average peak}} \tag{3.13}$$

$$T_{\text{peak}} = \frac{RR_y * (\text{peak factor})}{(\text{Energ consumption during peak})_y} \quad (€/kWh) \tag{3.14}$$

$$T_{\text{off peak}} = \frac{RR_y * (\text{off peak factor})}{(\text{Energ consumption during off peak})_y} \quad (€/kWh) \tag{3.15}$$

The focus of this tariff is incentivizing users to consume electricity during off-peak hours instead of peak hours by considering the system peak. This can have a smoothing effect on the load profile of the mini-grid and thereby reduce the energy demand during peak hour.

3.2 Modelling Phase

Two Rural Electrification Technical and Economic Planning (RETEP) models were used in this phase. RETEP Generation (Section 3.2.1) optimizes the generation (kW), storage size (kWh) and grid length (km) which are needed to cover the load, while minimizing the total cost of the mini-grid. RETEP TOTOX (Section 3.2.2) uses the outputs from RETEP Generation and calculates the Total Investment Cost (TIC) and annual Revenue Requirement (RR) of a mini-grid. RETEP Generation and RETEP TOTEX are both Excel based models and were developed by master thesis students DELL'ORTO (2017) and Braglia (2019) in collaboration with the Italian research institute CESI[1]. RETEP Tariff (Section 3.2.3) was built for the purpose of this thesis. It uses the outputs of RETEP generation and RETEP TOTEX in order to calculate the tariffs and quantify the necessary economic indicators.

3.2.1 RETEP Generation

RETEP Generation is the first model which was used in the modelling phase. RETEP Generation optimizes the generation, storage sizes and grid length in order to cover the load of a mini-grid while minimizing total cost. *Figure 3.1* shows the general overview of RETEP Generation. RETEP Generation needs three types of inputs: *technology*, *load demand* and *cost component inputs* which are shown in the upper part of *Figure 3.1*.

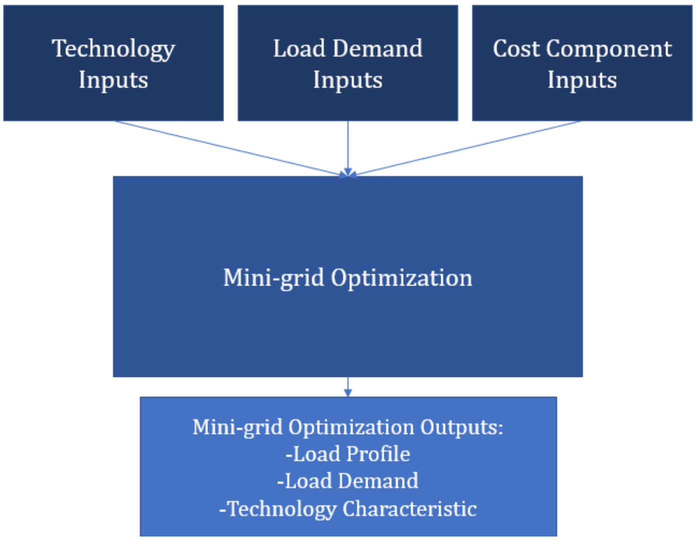

Figure 3.1: General overview of RETEP Generation

3.2.1.1 Technology inputs

The first step in performing the mini-grid optimization with RETEP Generation is choosing a generation technology. The generation technology chosen for the three mini-grids is solar PV with battery storage and a diesel generator as backup. The optimization of the three mini-grids in RETEP Generation are based on Solar PV combined with battery storage with a maximum Loss of Load Probability (LLP) of 5%. The LLP is an indicator which is used to define the mini-grid system reliability. RETEP Generation gives the LLP once the optimization is done.

Once the generation technology is chosen the next step is uploading the profile of PV generation into RETEP generation, it needs the hourly solar profile for a period of 1 year. The solar profile can be downloaded from an online platform[2] that provides the solar profile for the chosen location (Pfenninger and Staffell, 2016). Since, all three mini-grids are exemplary, one location in Tanzania

[1] https://www.cesi.it/
[2] https:///www.renewables.ninja

is chosen to use the solar profile from. The coordinates of the location which is used for the mini-grids in this thesis is (3°08'19.3"S 36°52'56.3"E). Once the solar profile is uploaded in RETEP generation, the next step is defining the battery storage and its input parameters. The battery technology chosen for this thesis is Lithium-ion and the input parameters which were set in RETEP Generation are shown in *Table 3.2* and are the same for all mini-grids.

Table 3.2: RETEP Generation input parameters

Mini-grid system parameters	**Inputs**	**unit**
Mini-grid Lifetime	20	Years
Maximum allowed Loss of load probability (LLP)	5	%
Energy storage parameters		
Minimum state of charge	0.1	%
Charge efficiency	95	%
Discharge efficiency	95	%
Maximum full cycles	3000	Cycles
Battery useful lifespan	10	Year

3.2.1.2 Load Demand inputs

RETEP Generation has a load generator which can generate the load demand of a mini-grid. It contains 15 default user profiles which represent the load demand of 15 different types of users and are shown in *Table 3.3*. It contains 8 household (R), 6 commercial (C) and 1 governmental (G) demand default profiles. Household 1-8 are also classified with the MTF based on their basic energy service needs. The daily load demand profiles of the default user profiles are shown in *Figure 3.2*. For this thesis it is assumed that the daily load profiles of all the user types are the same for the whole year. RETEP Generation generates the load of a mini-grid once the number of users per user type are defined in the load generator.

Table 3.3: User profiles and User types

Type of users	Annual Demand (kWh)	Annual Peak (W)
Household1 (Tier-1) **(R)**	70	22
Household2 (Tier-2) **(R)**	259	76
Household3 (Tier-3) **(R)**	1072	300
Household4 (Tier-3) **(R)**	1360	410
Household5 (Tier-4) **(R)**	1647	532
Household6 (Tier-4) **(R)**	2016	717
Household7 (Tier-5) **(R)**	2658	1028
Household8 (Tier-5) **(R)**	3135	1200
Barber **(C)**	894	209
Carpenter **(C)**	5737	1516
Kiosk **(C)**	2533	368
Market place **(C)**	9362	2775
Pharmacy **(C)**	2332	440
Primary School **(G)**	1319	343
Small Enterprise **(C)**	3272	939

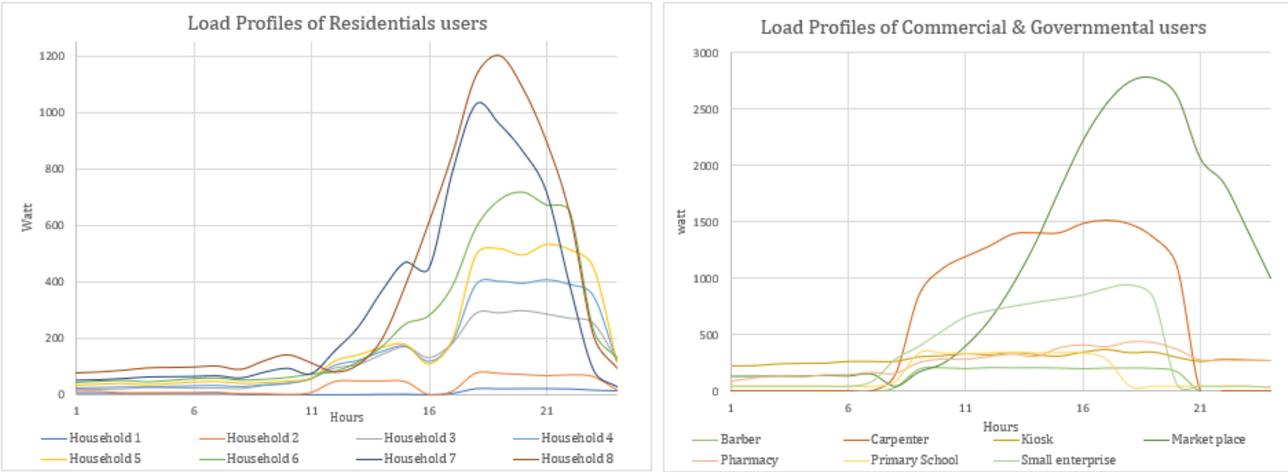

Figure 3.2: Load profiles of the default Residential, Commercial and Governmental user types in RETEP generation.

The load demand of Mini-grid 1 and 2 are generated with the use of the load generator within RETEP Generation. The load demand of Mini-grid 3 is created by adding the load demand of the BTT (shown in *Figure 3.3*) to the already existing default load profiles of RETEP Generation.

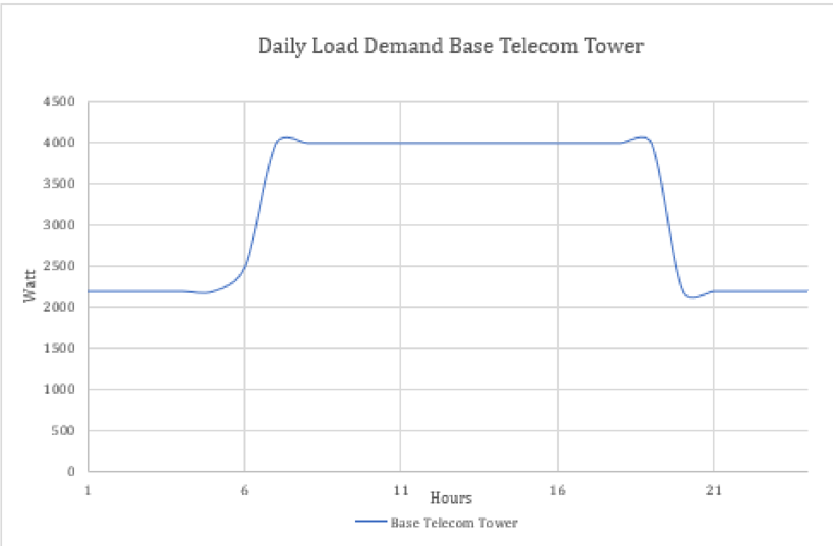

Figure 3.3: Daily load demand of the Base Telecom Tower (Rodríguez Gómez, 2013)

First the daily load demand of Mini-grid 3 is generated without the industrial user profile in RETEP Generation. Then this daily load demand profile of Mini-grid 3 is downloaded from RETEP Generation and aggregated with the daily load demand of the BTT (*Figure 3.3*). This aggregated daily load profile is then uploaded back to RETEP Generation. Furthermore, is it possible to set a yearly percentage of expected load demand growth for a mini-grid. The assumption has been made that all three mini-grids will have a yearly load demand increase of 1%.

3.2.1.3 Cost Component Inputs

Once the technology inputs are set and the load demand created for each mini-grid the next step is to set the cost component inputs. These cost component inputs which are set in RETEP generation are shown in *Table 3.4* and are the same for all mini-grids. All cost components are obtained from RETEP TOTEX except for the discounted interest rate. These cost component inputs were originally obtained from CESI's experts working in the field of mini-grids (Braglia , 2019).

Table 3.4: Cost Components input for RETEP Generation

Cost components	Input Parameter	Unit	Source
Mini-grid PV investment cost	1180	€/kWp	RETEP TOTEX
Solar PV O&M costs	2	%	RETEP TOTEX
Batter Energy Storage System investment cost	200	€/kWh	RETEP TOTEX
Batter Energy Storage System O&M cost	2	%	RETEP TOTEX
Cost LV line	5000	€/km	RETEP TOTEX
Connection cost per building	120	€/HH	RETEP TOTEX
Discounted interest rate	7.4	%	(Fernandez, 2019)

3.2.1.4 RETEP Generation Outputs

Once the inputs of RETEP Generation are defined, it optimizes the capacity planning of the mini-grids and provides its load profile and technical characteristics (*Table 3.5)*.

Table 3.5: RETEP Generation outputs

Mini-grid Load Demand	Unit
Total Annual Energy Consumption (TAEC)	kWh/Year
Daily energy consumption	kWh/d
Peak load	kW
Daily load (6 am - 6 pm)	kWh
Night load (7 pm - 5 am)	kWh
Technical Characteristics	
Solar PV size	kW
Battery Storage Size	kWh
Mini-grid grid length	km
Loss of Load Probability (LLP)	%

Once the optimization is done and the LLP is known, it is used for calculating the annual amount of diesel needed for the mini-grid. The assumption is made that the diesel generator is only used for providing the LLP percentage of the annual energy consumption. Equation (3.16) is used for calculating the annual amount of diesel needed per mini-grid. Diesel has an energy density of 10 kWh/L (University of Washington, 2005) and it is assumed that the diesel generator has an efficiency of 30%.

$$\text{Diesel} = \frac{\text{TAEC} * \text{LLP}}{\eta_{\text{Diesel}} * \eta_{\text{Diesel generator}}} \quad (\text{L/year}) \qquad (3.16)$$

TAEC = Total Annual Energy Consumption (kWh/year)

$\eta_{\text{diesel}} = 10$ (kWh/L)

$\eta_{\text{diesel generator}} = 30\,\%$

3.2.2 RETEP TOTEX

The second model which is used in the modelling phase is RETEP TOTEX which calculates the TIC, replacement costs, annual O&M costs and annual RR of the mini-grid. A general overview of RETEP TOTEX is shown in *Figure 3.4*. RETEP TOTEX needs the following inputs; *Mini-grid general inputs*, *Technical & non-technical cost inputs* and *Financing inputs*. The output for RETEP TOTEX consists of the TIC, replacement costs, annual O&M costs, and annual RR.

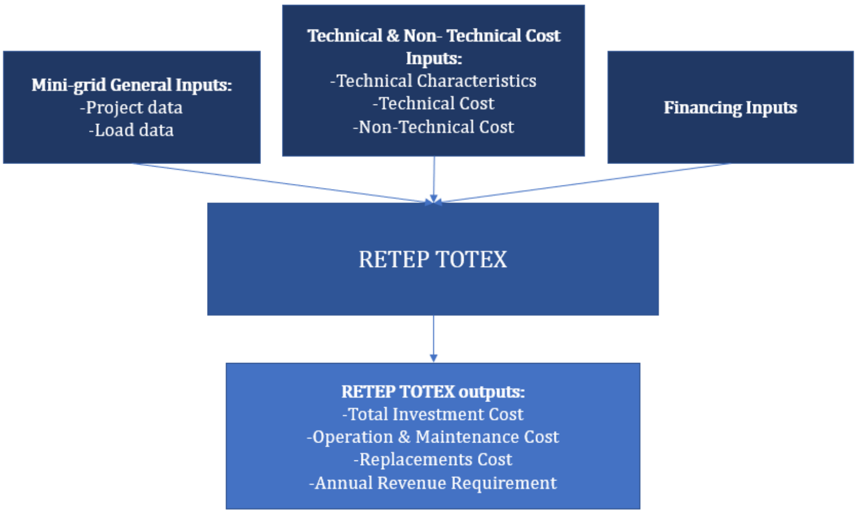

Figure 3.4: General overview of RETEP TOTEX

The first type of input RETEP TOTEX requires regard the mini-grid *project data* and the *load data*. The mini-grid project data used for this thesis are the same for all the three mini-grids and are shown in *Table 3.6*. The collection rate refers to the percentage of the annual cost to recover which is collected. It is assumed that 5% of the annual costs that need to be recovered are not recovered due to theft and difficulties in collecting bills. This amount is called the adjustment factor and is added to the annual cost to recover as a precaution in order to increase cost recovery. The mini-grid load data are unique for the three mini-grids. *Table 3.7* shows the users profiles available in RETEP TOTEX and the connection type of each profile. RETEP TOTEX considers 5 different connection types:

1. **Residential - Single Phase Low Voltage connection:** Voltage 240 V, frequency 50Hz, 1 phase plus 4 wires;
2. **Commercial / Governmental - Single Phase Low Voltage (LV) connection:** Voltage 240V, frequency 50Hz, 1 phase plus 4 wires;
3. **Commercial / Industrial - Three Phase Low Voltage (LV) Connection:** Voltage 415V, frequency 50Hz, 3 phase plus 4 wires;
4. **Single Phase Medium Voltage connection:** Voltage 240 V, frequency 50Hz, 1 phase plus 4 wires;
5. **Three Phase Medium Voltage connection:** Voltage 415V, frequency 50Hz, 3 phase plus 4 wires.

Only the first three connection types are used for this thesis since the exemplary mini-grids have only a low voltage distribution grid.

Table 3.6: General Inputs for RETEP TOTEX

Mini-grid Project Inputs	Input	Units
Project lifetime	20	Years
Construction period	1	Years
Yearly load growth	1	%
Collection Rate	95	%
Mini-grid load Data		
Daily Energy consumption	*	kWh/day
Peak load	*	kW
Daily Load (6 am - 6 pm)	*	kW
Night Load (7 pm - 5 am)	*	kW

* Depend on mini-grid type and are presented in Section 4.2, Table 4.2

Table 3.7: User profiles and Connection types of RETEP TOTEX

User profiles	Connection type	User types
Household 1 (Tier 1)	LV Single-phase (R)	Residential
Household 2 (Tier 2)	LV Single-phase (R)	Residential
Household 3 (Tier 3)	LV Single-phase (R)	Residential
Household 4 (Tier 3)	LV Single-phase (R)	Residential
Household 5 (Tier 4)	LV Single-phase (R)	Residential
Household 6 (Tier 4)	LV Single-phase (R)	Residential
Household 7 (Tier 5)	LV Single-phase (R)	Residential
Household 8 (Tier 5)	LV Single-phase (R)	Residential
Barber	LV Single-phase (C & G)	Commercial
Carpenter	LV Three-phase (C/I)	Commercial
Kiosk	LV Single-phase (C & G)	Commercial
Market place	LV Three-phase (C/I)	Commercial
Pharmacy	LV Single-phase (C & G)	Commercial
Primary School	LV Single-phase (C & G)	Governmental
Small Enterprise	LV Three-phase (C/I)	Commercial
Base Telecom Tower	LV Three-phase (C/I)	Industrial

RETEP TOTEX needs three types of technical and non-technical inputs; *technical characteristics of the mini-grid*, *technical cost* and *non-technical cost inputs*.

The technical characteristics of the mini-grids are obtained through RETEP Generation and are unique for the three mini-grids. The *technical cost inputs* which RETEP TOTEX requires are all the same for the three mini-grids and can be split into three types; Generation, Network and O&M costs. The *technical cost* inputs which were set in RETEP TOTEX are shown in *Table 3.8*.

Moreover, the choice is made to size the diesel generator based on the system peak of the mini-grid (*Table 4.2*). The diesel generator is initially oversized since a load demand increase of 1% is expected each year. The diesel generator must be able to maintain the maximum system needs without the solar PV and storage systems. Since, a situation might occur where both the solar PV and storage system are not working or are not able to provide the needed load demand. Therefore, the choice is made to have a diesel generator (for back up only) which has the capacity to provide the maximum system needs.

Table 3.8: Technical & Non-Technical inputs for RETEP TOTEX

		Input Parameter	Unit	Source
Technical Characteristics	Solar PV size	*	kW	RETEP Generation
	Battery Storage System Size	*	kWh	RETEP Generation
	Diesel Gen Set Size	*	kW	RETEP Generation
	Mini-grid Distribution Grid Length	*	km	RETEP Generation
	Solar PV System lifetime	20	Years	RETEP TOTEX
	Battery Storage System lifetime	10	Years	RETEP TOTEX
	Diesel Gen Set Lifetime	10	Years	RETEP TOTEX
	Mini-grid Distribution Grid Lifetime	40	Years	RETEP TOTEX
Technical cost				
Generation Cost	Total Solar PV plant Cost	1180	€/kW	RETEP TOTEX
	Lithium-ion Battery Cost	200	€/kWh	RETEP TOTEX
	Diesel Genset Cost	700	€/kW	RETEP TOTEX
	Diesel Fuel price	1.21	€/l	RETEP TOTEX
Network Cost	Distribution grid LV cost	5000	€/km	RETEP TOTEX
	Connection cost LV single phase (R)	120	€/connection	RETEP TOTEX
	Connection cost LV single phase (C/G)	120	€/connection	RETEP TOTEX
	Connection cost LV Three Phase (I)	200	€/connection	RETEP TOTEX
Operating Cost	Fixed O&M cost PV	2	% (of CAPEX)	RETEP TOTEX
	Variable O&M Cost PV	0	% (of CAPEX)	RETEP TOTEX
	Fixed O&M cost Battery	2	% (of CAPEX)	RETEP TOTEX
	Variable O&M Cost Battery	0	% (of CAPEX)	RETEP TOTEX
	Fixed O&M cost Genset	10	% (of CAPEX)	RETEP TOTEX
	Fixed O&M costs distribution grid	3.5	% (of CAPEX)	RETEP TOTEX
	Variable O&M distribution grid	1.5	% (of CAPEX)	RETEP TOTEX
	Service cost	55700	€/year	RETEP TOTEX

Non-Technical cost	Project Development cost	100000	€	RETEP TOTEX

*Depend on the mini-grid type

RETEP TOTEX requires financing inputs in order to calculate the annual RR of the three mini-grids. These are shown in *Table 3.9* and are for all three mini-grids the same. The TIC of the three mini-grids is financed 80% by debt. The pre-tax WACC is set to 7.4% (Fernandez, 2019) and the tax rate is set to 24% which is the worldwide average income tax for companies (Elke, 2019).

Table 3.9: Financing inputs for RETEP TOTEX

Financing Inputs	Value	Unit
Equity	20	% (Of total investment cost)
Debt	80	% (Of total investment cost)
Pre-tax WACC	7.4	%
Tax Rate	24	%

Once that the inputs of RETEP TOTEX are defined, it calculates the TIC, replacement cost, annual O&M costs and annual RR of the three mini-grids. There is only one year where there are replacement costs and that is in year 10. In that year both the diesel generator and the battery storage system need to be replaced. The assumption is made that the costs of purchasing a new diesel generator and a new battery storage system will decrease overtime as technology matures. The purchasing costs of both the systems decreases with 20% in 10 years. The O&M costs are calculated by RETEP TOTEX on a yearly base. RETEP TOTEX provides the user with a detailed cost breakdown regarding the TIC and the annual RR which is shown in *Figure 3.5*.

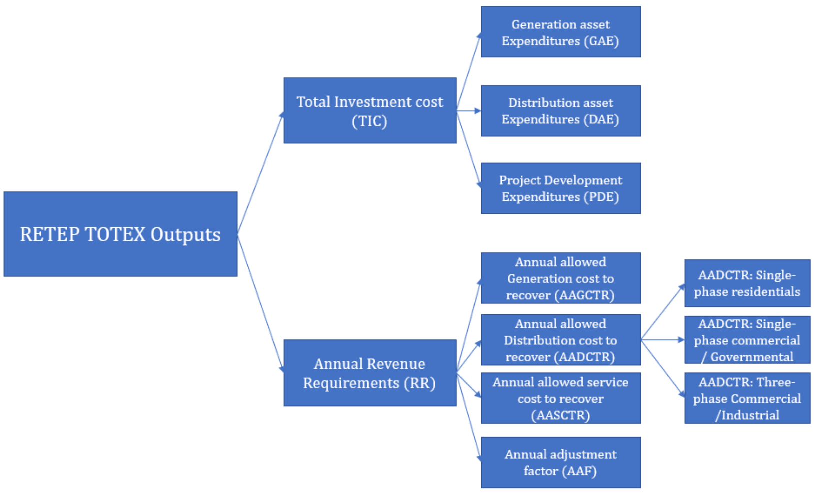

Figure 3.5: RETEP TOTEX; Total investment cost & Annual revenue requirements breakdown

The TIC is the sum of the *Generation Asset Expenditure (GAE)*, *Distribution Asset Expenditures (DAE)* and *Project Development Expenditures (PDE)*. The annual RR is broken down to the *Annual Allowed Generation Cost to Recover (AAGCTR)*, *Annual Allowed Distribution Cost to Recover (AADCTR)*, *Annual Allowed Service Cost to Recover (AASCTR)* and *Annual Adjustment Factor (AAF)*. The *AADCTR* is also calculated based on the connection types the users have. These outputs from RETEP TOTEX are used as inputs for RETEP Tariff.

3.2.3 RETEP Tariff

RETEP Tariff is an Excel based model and an addition to the other two RETEP models and built for this thesis. The general overview of RETEP Tariff is shown in *Figure 3.6*. The upper part of *Figure 3.6* shows the inputs which RETEP Tariff requires.

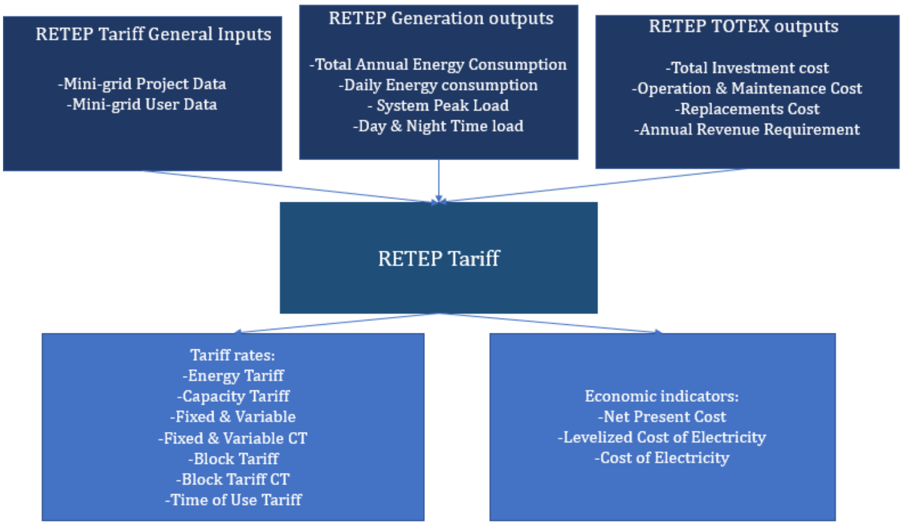

Figure 3.6: General overview of RETEP Tariff

RETEP Tariff requires two types of general inputs; *project and user data inputs*. The *project data* inputs which RETEP Tariff requires are the lifetime of the mini-grid and the discount rate. Both inputs are the same as used for RETEP Generation and RETEP TOTEX. The *user data* of RETEP Tariff is based on the same default user profiles as RETEP Generation with the addition of a Base Telecom Tower. *Table 3.10* shows these profiles, their connection type, annual energy demand, annual peak and user types. The *user data* inputs which RETEP Tariff requires are the number of users of a mini-grid.

Table 3.10: Default user profiles of RETEP Tariff

User profiles	Connection type	Annual Energy Demand (kWh)	Annual Peak (W)	User types
Household 1	LV Single-phase residential	70	22	Residential
Household 2	LV Single-phase residential	259	76	Residential
Household 3	LV Single-phase residential	1072	300	Residential
Household 4	LV Single-phase residential	1360	410	Residential
Household 5	LV Single-phase residential	1647	532	Residential
Household 6	LV Single-phase residential	2016	717	Residential
Household 7	LV Single-phase residential	3135	1028	Residential
Household 8	LV Single-phase residential	894	1200	Residential
Barber	LV Single-phase Commercial/Governmental	5737	209	Commercial
Carpenter	LV Three-phase Commercial/Industrial	5737	1516	Commercial
Kiosk	LV Single-phase Commercial/Governmental	2533	368	Commercial
Market place	LV Three-phase Commercial/Industrial	9362	2775	Commercial
Pharmacy	LV Single-phase Commercial/Governmental	233	440	Commercial
Primary School	LV Single-phase Commercial/Governmental	1319	343	Governmental
Small Enterprise	LV Three-phase Commercial/Industrial	3272	939	Commercial
Base Telecom Tower	LV Three-phase Commercial/Industrial	27922	4000	Industrial

The outputs of RETEP Tariff include three economic indicators; the NPC, the Levelized Cost of Electricity (LCoE) and the CoE.

The NPC is calculated using Eq. (3.17), with r being the discount rate (7.4%) and N the economic operational lifetime of the mini-grid (20 years).

$$\text{Net Present Cost (NPC)} = TIC + \sum_{y=1}^{N} \frac{(O\&M)_y + Replacementcost_y}{(1+r)^y} \quad (€) \tag{3.17}$$

The second economic indicator is the LCoE, representing the cost of a unit of electricity generated by the mini-grid over its entire lifetime, and calculated using Eq. (3.18).

$$\text{Levelized Cost of Electricity (LCoE)} = \frac{\text{NPC}}{\sum_{y=1}^{Ny} \frac{\text{Energy consumption(y)}}{(1+r)^y}} \quad (€/\text{kWh}) \tag{3.18}$$

As for the CoE, once the *tariff rates* are calculated (the actual payments due by the end-users for each tariff design), the following equations are used:

$$\text{CoE}_{\text{y,Energy Tariff}} = \text{T}_{\text{EnergyTariff,y}} * \text{ED}_{\text{user,y}} \quad (€/\text{Year}) \tag{3.19}$$

$$\text{CoE}_{\text{y,Capacity Tariff}} = \text{T}_{\text{Capacity,y}} * \text{PD}_{\text{user,y}} \quad (€/\text{Year}) \tag{3.20}$$

$$\text{CoE}_{\text{y,Fixed \& Variable Tariff}} = (\text{T}_{\text{Fixed,y}} * 12) + (\text{T}_{\text{Variable,y}} * \text{ED}_{\text{user,y}}) \quad (€/\text{Year}) \tag{3.21}$$

$$\text{CoE}_{\text{y,Fixed \& Variable Tariff CT}} = (\text{T}_{\text{Fixed,y,connection type}} * 12) + (\text{T}_{\text{Variable,y}} * \text{ED}_{\text{user,y}}) \quad (€/\text{Year}) \tag{3.22}$$

$$\text{CoE}_{\text{y,Block Tariff}} = \text{T}_{\text{usergroup,y}} * \text{ED}_{\text{user,y}} \quad (€/\text{Year}) \tag{3.23}$$

$$\text{CoE}_{\text{y,Block Tariff CT}} = (\text{T}_{\text{Fixed,connection type,y}} * 12) + (\text{T}_{\text{variable,y,usergroup}} * \text{ED}_{\text{user,y}}) \quad (€/\text{Year}) \tag{3.24}$$

$$\text{CoE}_{\text{y,Time of Use Tariff}} = (\text{T}_{\text{Peak}} * \text{ED}_{\text{peak,user,y}}) + (\text{T}_{\text{off-peak}} * \text{ED}_{\text{off-peak,user,y}}) \quad (€/\text{Year}) \tag{3.25}$$

ED = Energy Demand (kWh/year)

PD = Peak Demand (kW/year)

3.3 Assessment phase

The final step of the methodology is the assessment phase. In this phase are the different tariff designs assessed on their affordability (quantitatively), cost-reflectiveness and simplicity (qualitatively) for the exemplary mini-grids.

3.3.1 Affordability

The Affordability of the different tariff designs is assessed quantitively with the use of the results obtained through RETEP Tariff. RETEP Tariff calculates the CoE for each individual user of the exemplary mini-grids. The CoE of each individual user type is used to assess which tariff design is the most affordable for a mini-grid. A tariff design is identified as the most affordable tariff design for a mini-grid if it has the lowest CoE across all user types of a mini-grid. The identification of the most affordable tariff design for a mini-grid is done by summing up the CoE of one user per user type per tariff design . This CoE across all user types of a mini-grid is then compared between the different tariff designs in order to identify the most affordable tariff design for a mini-grid.

In order to benchmark how affordable the identified tariff design(s) actually is/are, a comparison will be made between the CoE of the identified tariff design(s) and with the CoE of an implied tariff. For this comparison an implied tariff rate of 1.46 €/kWh is used. This rate is paid by the rural population in East-Africa according to International Finance Corporation (2017). The implied tariff of East-Africa is used because half of the world's population who are without electricity are living in Africa, making it an realistic benchmark rate for the affordability of the tariff designs (Baurzhan and Jenkins, 2016). This comparison is only done for the residential user types since, the implied tariff rate only applies for them. The CoE of the implied tariff is calculated using Eq. (3.26).

$$\mathrm{CoE}_{y,\mathrm{Implied\ Tariff}} = \mathrm{T}_{\mathrm{implied\ Tariff},y} * \mathrm{ED}_{\mathrm{user},y} \qquad (€/\mathrm{Year}) \qquad (3.26)$$

3.3.2 Cost-reflectiveness & Simplicity

Once the most affordable tariff design is quantitively identified, it will also be assessed qualitatively on its cost-reflectiveness and simplicity. A tariff design which considers the contribution to the system peak of the users or the individual peak of the users is identified as a cost-reflective tariff design. The former one is considered more cost-reflective than the latter one since, the peak load of an individual user is often volatile and has a low correlation with the peak load of the other individual users. Resulting in that the peak load of one user is not directly related to the system peak. A tariff design which does not consider the users contribution to the system peak nor the individual peak will be identified as a non-cost-reflective tariff design.

The simplicity of the different tariff designs will be assessed based on how simple it is for the end-user to calculate its energy bill in advanced. A tariff design which only consists of a fixed tariff is considered the simplest tariff design. Fixed tariffs do not require any calculation from the user in order to calculate their energy bill and are therefore ranked the highest in terms of simplicity. A tariff design which considers the individual peak or the amount of energy consumed by the user will also be identified as a simple tariff design but less simple than a tariff design that consists of a fixed tariff. Such tariff designs require a simple calculation from the users in order to calculate their energy bill in advanced. The users can read their individual peak/the amount of energy consumed from the meter and by multiplying it with their tariff rate they can calculate their energy bill. A tariff design which considers the users contribution to the system peak is considered as a tariff design which is not simple. Users rarely know when the system peak occurs and how much they contribute to it making it impossible for them to calculate their energy bill in advanced.

4. Results

This section describes the results from RETEP Generation (Section 4.1), RETEP TOTEX (Section 4.2) and RETEP Tariff (Section 4.3). Section 4.4 contains the final remarks which directly address the main research objective.

4.1 RETEP Generation Results

The details of the demand side characteristics for the three exemplary mini-grids are shown in *Table 4.1* (types of users, numbers of users per type, connection type, annual energy demand and annual individual peak). Each mini-grid has its own colour, Mini-grid 1 is orange, Mini-grid 2 is yellow and Mini-grid 3 is green. Mini-grid 1 has 1000 users in total, Mini-grid 2 has 872 users in total, and Mini-grid 3 has 859.

Table 4.1: Demand side characteristics of the three mini-grids

Type of users	Connection type	Annual Demand (kWh)	Annual Peak (W)	Number of users	Number of users	Number of users
Household1 (R)	LV Single-phase residential	70	22	750	750	750
Household2 (R)	LV Single-phase residential	259	76	250	110	100
Household3 (R)	LV Single-phase residential	1072	300	0	0	0
Household4 (R)	LV Single-phase residential	1360	410	0	0	0
Household5 (R)	LV Single-phase residential	1647	532	0	0	0
Household6 (R)	LV Single-phase residential	2016	717	0	0	0
Household7 (R)	LV Single-phase residential	2658	1028	0	0	0
Household8 (R)	LV Single-phase residential	3135	1200	0	0	0
Barber(C)	LV Single-phase Commercial/Governmental	894	209	0	1	1
Carpenter (C)	LV Three-phase Commercial/Industrial	5737	1516	0	2	1
Kiosk (C)	LV Single-phase Commercial/Governmental	2533	368	0	5	1
Market place (C)	LV Three-phase Commercial/Industrial	9362	2775	0	2	1
Pharmacy (C)	LV Single-phase Commercial/Governmental	2332	440	0	1	1
Primary School (G)	LV Single-phase Commercial/Governmental	1319	343	0	1	1
Small Enterprise (C)	LV Three-phase Commercial/Industrial	3272	939	0	0	2
Base Telecom Tower (I)	LV Three-phase Commercial/Industrial	27922	4000	0	0	1
			Total number of users	1000	872	859

The daily load profiles of Mini-grid 1, 2 and 3 are shown in *Figure 4.1*, *4.2* and *4.3* respectively.

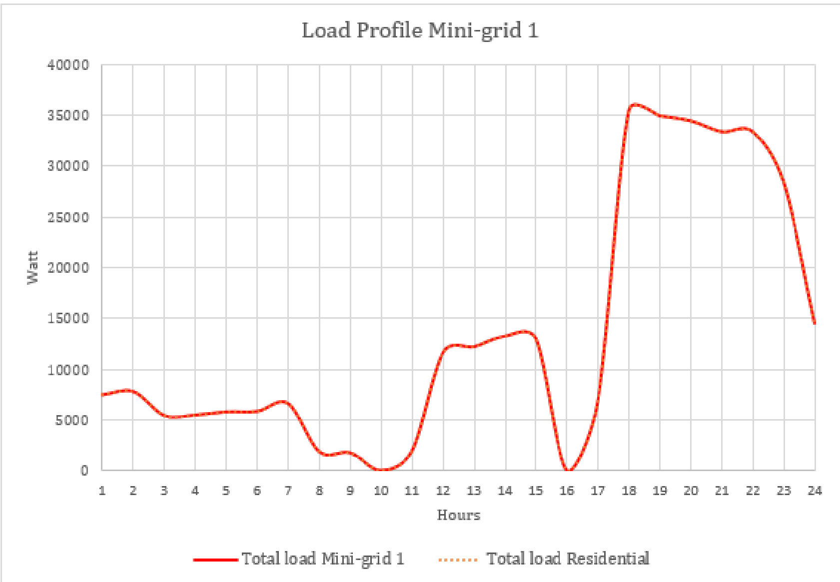

Figure 4.1: Daily Load profile of mini-grid 1

Looking at *Figure 4.1* it can be observed that the energy consumption of the residential users is at its lowest at 10:00 and at 16:00. Furthermore, it is noticeable that the energy consumption of the residential users is lower during the day than at night. The peak hours are from 17:00 to 24:00 and the off-peak hours are from 01:00 to 16:00 and the system peak occurs at 18:00.

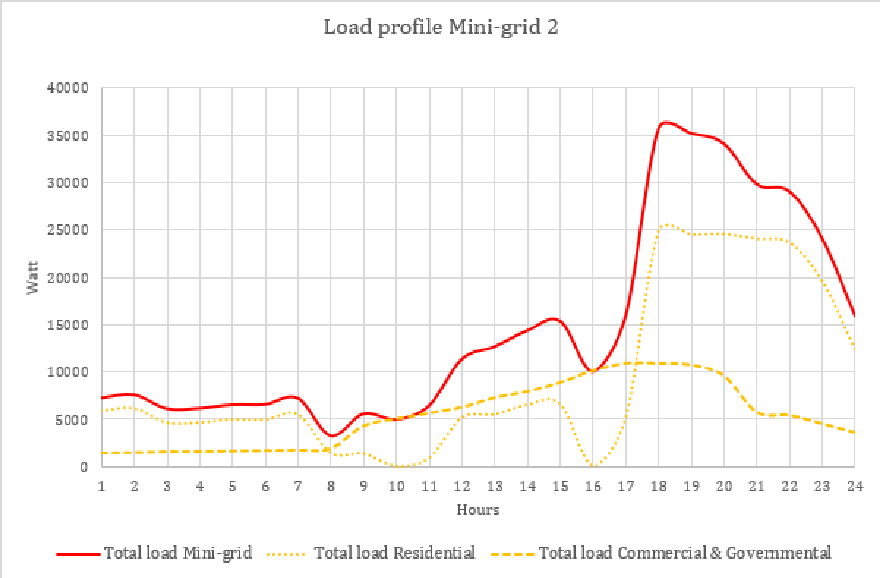

Figure 4.2: Daily load profile mini-grid 2

Figure 4.2 shows that the commercial & governmental users have a higher load during the day compared to the residential users. While, the residential users have a higher load during the night. Furthermore, it is noticeable that the commercial & governmental users have a more stable load during the day than the residential users.

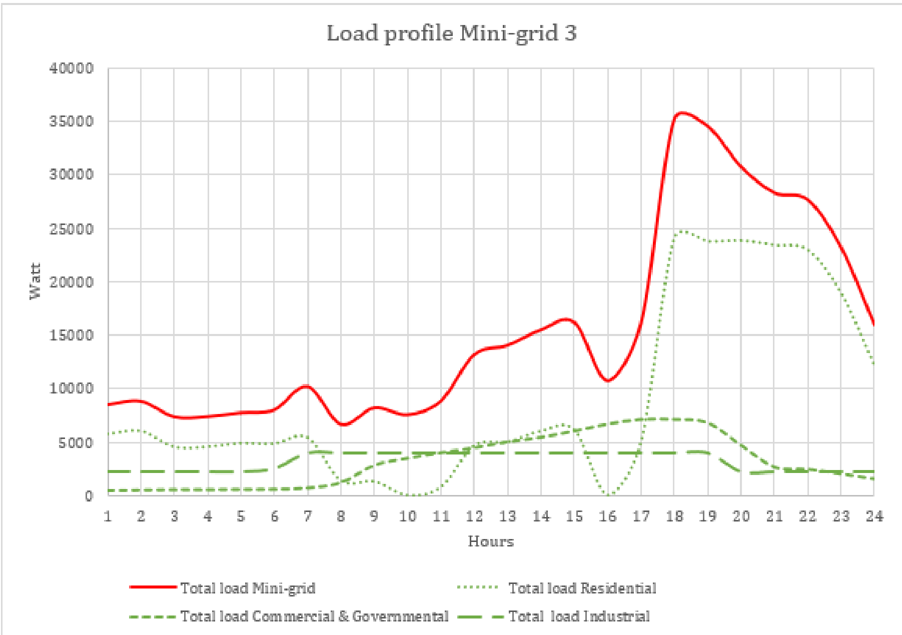

Figure 4.3: Daily load profile of mini-grid 3

As for *Figure 4.3* one should notice that the total industrial load is lower than the other two total loads but more stable. Furthermore, one should notice that Mini-grid 3 has the highest load during the day when compared to Mini-grid 1 and 2.

Table 4.2 shows the daily energy consumption, system peak, total individual peak, day-time load, night-time load and the Total Annual Energy Consumption (TAEC) of the three mini-grids for year one. Looking at the TAEC of the three mini-grids it is noticeable that Mini-grid 1 has the lowest followed by Mini-grid 2, with Mini-grid 3 having the highest (the day-time load of Mini-grid 2 and 3 are significantly higher than that of Mini-grid 1). Looking at the total individual peak per user type it can be noticed that Mini-grid 2 has the highest total individual peak. This is explained by the fact that Mini-grid 2 has the most commercial users.

Table 4.2: Load profile characteristic of the three mini-grids for year one

Mini-grid Load Profile characteristic:	Mini-grid 1	Mini-grid 2	Mini-grid 3	Unit
Daily energy consumption	321.0	352.0	370.2	kWh/Day
System Peak	35.5	35.7	35.2	kW_p/year
Total Individual Peak	35.7	36.5	35.9	kW_p/year
Day-time Load	140.0	178.5	196.7	kWh
Night-time Load	181.0	173.4	173.5	kWh
Total Annual Energy Consumption (TAEC)	117348.5	128471.0	135117.0	kWh/Year

Table 4.3 shows the optimised size of the PV system (kW), Li-ion battery size (kWh), Diesel Generator size (kW), loss of load probability (%) and the length of the distribution cables (km) needed for each mini-grid. Notably, Mini-grid 3 has the largest PV system (because of a higher day-time load). Mini-grid 1 has the largest Li-ion battery size (because of a large night-time load). All three mini-grids have a diesel generator with the same maximum capacity, based on the system peak (10% oversized in order to keep up with future growth in load demand).

Table 4.3: RETEP generation optimization results

Technology used	Mini-grid 1	Mini-grid 2	Mini-grid 3	Unit
PV system	116.2	127.2	133.8	kW
Li-ion Battery	367.4	341.6	345.2	kWh
Diesel Generator	39.0	39.0	39.0	kW
Distribution cable length (DCL)	31.9	29.9	29.6	km
Loss of load Probability (LLP)	4.2	4.6	4.5	%

The difference in DCL can be explained by looking at the total number of users the mini-grids have. Mini-grid 1 has the highest number of users which results in needing a larger DCL than the other two mini-grids. The LLP is similar across mini-grids.

4.2 RETEP TOTEX Results

The investment costs for the three mini-grids are reported in *Table 4.4*. Mini-grid 1 has the lowest GAE (the capacity of the PV system is the lowest) and the highest DCE (the number of users are the highest), and the highest TIC (the number of users has a significant effect on the distribution and connection cost).

Table 4.4: Investment cost for Mini-grid 1, 2 and 3

	Mini-grid 1	Mini-grid 2	Mini-grid 3	Unit
Generation Assets Expenditure (GAE)	255630	262334	271108	euro
Distribution & Connection Expenditure (DCE)	324690	304444	304758	euro
Project Development Expenditure (PDE)	100000	100000	100000	euro
Total Investment Cost (TIC)	**680320**	**666778**	**675866**	euro

Table 4.5 shows the annual RR and its components for year 1. By design, those are comparable for the three Mini-grids.

Table 4. 5: Annual revenue requirement for year 1 for Mini-grid 1, 2 and 3

	Mini-grid 1	Mini-grid 2	Mini-grid 3	Unit
Annual Revenue Requirement (ARR)	181844	179575	181401	euro
Annual Allowed Generation cost to recover (AAGCTR)	71192	72145	73761	euro
Annual Allowed Distribution cost to recover (AADCTR)	61294	58172	58282	euro
Annual Allowed Service cost to recover (AASCTR)	40594	40594	40594	euro
Annual Adjustment factor (AAF)	8764	8665	8764	euro

Table 4.6 shows the annual distribution cost to recover per connection type. The AADCTR of Mini-grid 1 consists only of Single-phase residential type users, which have the largest share also in the Mini-grid 2 & 3.

Table 4.6: Annual allowed distribution cost to recover for year 1 per connection type for Mini-grid 1,2 and 3

	Mini-grid 1	Mini-grid 2	Mini-grid 3	Unit
Annual Allowed Distribution Cost to Recover (AADCTR)	61294	58172	58282	euro
Single-phase residential	61294	39194	36670	euro
Single-phase Commercial/Governmental	0	6909	2720	euro
Three-phase Commercial/Industrial	0	12068	18892	euro

4.3 RETEP Tariff Results

Table 4.7 shows the results of the NPC and LCoE. As expected, the largest difference in NPC is only 1% (between Mini-grid 2 and Mini-grid 3). Looking at the LCoE, instead, a decreasing trend can be noticed. This is explained by the total energy consumption of the three Mini-grids.

Table 4.7: LCoE & NPC for mini-grid 1, 2 & 3

Economic indicators	Mini-grid 1	Mini-grid 2	Mini-grid 3	Unit
Net Present Cost (NPC)	1.625	1.608	1.626	Million Euro
Levelized Cost of Electricity (LCoE)	1.250	1.130	1.090	Euro/kWh

The tariff rates for year 1 are shown in *Table 4.8*. The lowest tariff rate per tariff design is shown with bold numbers. Furthermore, a comparison is made across Mini-grids: Mini-grid 1 is used as a base case in order to test how the tariff rates change when different types of users are added (Mini-grid 2 is used as base case when a specific rate is not available for Mini-grid 1).

Table 4.8: Tariff Results per type of tariff for year 1

Tariff type	Mini-grid 1	Mini-grid 2		Mini-grid 3		Unit
	Tariff Rate	Tariff Rate	Compared to base case	Tariff Rate	Compared to base case	
1: Energy tariff	1.55	1.40	-10%	**1.34**	-14%	Euro/kWh
2: Capacity Tariff	5089.22	**4919.72**	-3%	5059.11	-1%	Euro/kW/year
3: Fixed & Variable Tariff						
Fixed Tariff (Connection Cost)	**5.11**	5.56	9%	5.65	11%	Euro/Month
Volumetric Tariff	1.03	0.94	-9%	**0.91**	-12%	Euro/kWh
4: Fixed & Variable Tariff CT						
Single-Phase Residential						
Fixed Tariff (Connection Cost)	5.11	3.80	-26%	**3.60**	-30%	Euro/Month
Volumetric Tariff	1.03	0.94	-9%	**0.91**	-12%	Euro/kWh
Single-Phase Commercial/Governmental						
Fixed Tariff (Connection Cost)	-	71.97	0%	56.67	-21%	Euro/Month
Volumetric Tariff	-	0.94	-9%	**0.91**	-12%	Euro/kWh
Three-Phase Commercial/Industrial						
Fixed Tariff (Connection Cost)	-	**251.42**	0%	314.86	25%	Euro/Month
Volumetric Tariff	-	0.94	-9%	**0.91**	-12%	Euro/kWh
5: Block Tariff						
Residential						
Volumetric Tariff	1.55	**1.54**	-1%	1.58	2%	Euro/kWh
Commercial/Governmental						
Volumetric Tariff	-	**1.15**	0%	1.28	11%	Euro/kWh
Industrial						
Volumetric Tariff	-	-	-	0.74	-	Euro/kWh
6: Block Tariff CT						
Residential						
Single-phase Residential						
Connection cost	5.11	3.80	-26%	**3.60**	-30%	Euro/Month
Volumetric Tariff	**1.03**	1.04	1%	1.07	4%	Euro/kWh
Commercial & Governmental						
Fixed cost						
Single-phase Com/Gov Connection cost	-	71.97	0%	**56.67**	-21%	Euro/Month
Three-phase Connection cost		**251.42**	0%	314.86	25%	Euro/Month
Volumetric Tariff	-	**0.78**	0%	0.87	12%	Euro/kWh
Industrial						
Three-phase Connection cost	-	-	-	314.86	-	Euro/Month
Volumetric Tariff	-	-	-	0.50	-	Euro/kWh
7: Time of use Tariff						
Peak Tariff (17-24)	1.93	1.72	-11%	**1.71**	-11%	Euro/kWh
Off Peak Tariff (1-16)	**0.79**	0.86	9%	0.85	8%	Euro/kWh

In sum, there are several instances where moving from Mini-grid 1 to Mini-grid 2 and/or Mini-grid 3 implies a reduced tariff rate:

1. The volumetric part of the Energy Tariff, Fixed & Variable Tariff, and Fixed & Variable Tariff CT decreases by 9% and up to 14% when Mini-grid 2 and 3 are compared with Mini-grid 1. In fact, Mini-grid 1 has only residential users, presenting a relatively low energy consumption. The three mini-grids have a comparable annual RR which means that the main contributor to the decrease in the tariff rate is the increase in TAEC.

2. The Capacity Tariff has a tariff rate decrease of 3% (Mini-grid 2) and 1% (Mini-grid 3) when compared with Mini-grid 1 – indeed, Mini-grid 2 has the highest total individual peak.

3. The fixed part of the tariff of the Single-phase residential user for the Fixed & Variable Tariff CT and Block Tariff CT has a tariff rate decrease of 26% (Mini-grid 2) and 30% (Mini-grid 3)

compared to Mini-grid 1. This is explained by the fact that Mini-grid 2 and 3 have a significant lower AADCTR for the Single-Phase residential users.

4. The peak tariff of Mini-grid 2 and 3 decreases 11% compared to Mini-grid 1 while the off-peak tariff increases with 8%-9%. The peak tariff decreases because both mini-grids have commercial, governmental and industrial users who have higher peak during off-peak hours than the residential ones of Mini-grid 1. The difference in off-peak tariff is explained by the fact that Mini-grid 1 has the lowest average peak during off-peak hours compared to Mini-grid 2 and 3.

Differently, there is only one case where the reverse is true: the fixed part of the Fixed & Variable Tariff has a tariff rate increase of 9% (Mini-grid 2) and 12% (Mini-grid 3) compared to Mini-grid 1. Notably, Mini-grid 1 has the highest total number of users while the annual distribution costs are comparable across mini-grids.

The results of the CoE for year 1 are illustrated next, for each mini-grid separately. This is done to compare the different tariff designs in terms of total costs incurred by each end user. As before, the lowest CoE per type of tariff per user is shown with bold numbers. Furthermore, all the tariff designs are compared with the tariff design which has the lowest CoE per user type and the percentage of total cost increase is shown.

Table 4.9 shows the CoE per user type for Mini-grid 1. As expected, the Energy Tariff has the lowest CoE for Household 1 (a user with relatively low energy consumption - Tier 1 - such as Household 1, has the highest economic benefit from an Energy Tariff). Differently, the Fixed & Variable Tariff and Fixed & Variable Tariff CT have the lowest CoE for Household 2 (a relatively high energy consumption compared to Household 1 and therefore, the variable tariff has a significant effect on the CoE).

Table 4.9: Cost of Electricity of year 1 for Mini-grid 1 per user type

	Mini-grid 1						
Tariff	Energy Tariff	Capacity Tariff	Fixed & Variable Tariff	Fixed & Variable Tariff CT	Block Tariff	Block Tariff CT	Time of Use Tariff
Household 1	€ **108.60**	€ 113.50	€ 133.29	€ 133.29	€ **108.60**	€ 133.29	€ 113.59
Compared to the Lowest Cost	0%	5%	23%	23%	0%	23%	5%
Household 2	€ 401.58	€ 386.87	€ **327.52**	€ **327.52**	€ 401.58	€ **327.52**	€ 386.61
Compared to the Lowest Cost	23%	18%	0%	0%	23%	0%	18%

Table 4.10 shows the CoE for each user per tariff type in Mini-grid 2. As before, the Energy Tariff has the lowest CoE for Household 1 and the Fixed & Variable Tariff CT for Household 2 (as the annual energy consumption of Household 2 is significantly higher than Household 1, it benefits from a low volumetric tariff in the Fixed & Variable Tariff CT design).

Results for commercial and governmental users are more varied; the Capacity Tariff has the lowest CoE for the Kiosk and Pharmacy and the Fixed & Variable Tariff has the lowest CoE for the Barber, Carpenter, and Market Place. The Time of Use Tariff has the lowest CoE for the Primary school (which consumes energy mostly during off-peak hours).

Table 4.10: Cost of Electricity of Year 1 for Mini-grid 2 per user type

	Mini-grid 2						
Tariff	Energy Tariff	Capacity Tariff	Fixed & Variable Tariff	Fixed & Variable Tariff CT	Block Tariff	Block Tariff CT	Time of Use Tariff
Household1	**€ 97.95**	€ 109.72	€ 132.93	€ 111.80	€ 108.10	€ 118.66	€ 105.93
Compared to the Lowest Cost	0%	12%	36%	14%	10%	21%	8%
Household2	€ 362.22	€ 373.99	€ 311.59	**€ 290.45**	€ 399.74	€ 315.82	€ 364.52
Compared to the Lowest Cost	25%	29%	7%	0%	38%	9%	25%
Barber	€ 1,249.90	€ 1,027.94	**€ 911.72**	€ 1,708.69	€ 1,028.53	€ 1,559.02	€ 1,016.63
Compared to the Lowest Cost	37%	13%	0%	87%	13%	71%	12%
Carpenter	€ 8,019.78	€ 7,458.05	**€ 5,488.55**	€ 8,438.83	€ 6,599.35	€ 7,478.54	€ 6,657.33
Compared to the Lowest Cost	46%	36%	0%	54%	20%	36%	21%
Kiosk	€ 3,540.54	**€ 1,808.75**	€ 2,460.32	€ 3,257.29	€ 2,913.46	€ 2,833.35	€ 2,943.26
Compared to the Lowest Cost	96%	0%	36%	80%	61%	57%	63%
Market place	€ 13,085.71	€ 13,652.29	**€ 8,913.42**	€ 11,863.69	€ 10,768.03	€ 10,296.81	€ 13,403.12
Compared to the Lowest Cost	47%	53%	0%	33%	21%	16%	50%
Pharmacy	€ 3,259.95	**€ 2,166.09**	€ 2,270.63	€ 3,067.60	€ 2,682.56	€ 2,677.25	€ 2,870.29
Compared to the Lowest Cost	50%	0%	5%	42%	24%	24%	33%
Primary School	€ 1,844.24	€ 1,686.74	€ 1,313.53	€ 2,110.50	€ 1,517.60	€ 1,889.67	**€ 1,308.73**
Compared to the Lowest Cost	40%	28%	0.4%	61%	16%	44%	0%

Finally, *Table 4.11* shows the CoE for each user per tariff type for Mini-grid 3. As before, the Energy Tariff has the lowest CoE for Household 1 and the Fixed & Variable Tariff CT for Household 2. As for commercial and governmental users, the Fixed and Variable Tariff has the lowest CoE for most (Barber, Carpenter, Market Place, Pharmacy, Primary School and Small Enterprise). Notably, the Block Tariff CT has the lowest cost for the Base Telecom Tower. For an industrial user is it very important to have a low volumetric tariff because of its high energy consumption. Block Tariff CT presents this characteristic because a higher portion of the annual RR is allocated to the residential user group due to their higher contribution to the system peak.

Table 4.11: Cost of Electricity of Year 1 for Mini-grid 3 per user type

	Mini-grid 3						
Tariff	**Energy Tariff**	**Capacity Tariff**	**Fixed & Variable Tariff**	**Fixed & Variable Tariff CT**	**Block Tariff**	**Block Tariff CT**	**Time of Use Tariff**
Household 1	**€ 94.08**	€ 112.83	€ 131.70	€ 107.00	€ 110.79	€ 118.33	€ 105.12
Compared to the Lowest Cost	0%	20%	40%	14%	18%	26%	12%
Household 2	€ 347.91	€ 384.58	€ 303.98	**€ 279.27**	€ 409.68	€ 321.20	€ 361.75
Compared to the Lowest Cost	25%	38%	9%	0%	47%	15%	30%
Barber	€ 1,200.54	€ 1,057.06	**€ 882.67**	€ 1,494.86	€ 1,143.49	€ 1,456.14	€ 1,008.90
Compared to the Lowest Cost	36%	20%	0%	69%	30%	65%	14%
Carpenter	€ 7,703.05	€ 7,669.35	**€ 5,296.00**	€ 9,006.53	€ 7,337.02	€ 8,758.10	€ 6,606.70
Compared to the Lowest Cost	45%	45%	0%	70%	39%	65%	25%
Kiosk	€ 3,400.71	**€ 1,859.99**	€ 2,375.95	€ 2,988.14	€ 3,239.12	€ 2,878.47	€ 2,920.87
Compared to the Lowest Cost	83%	0%	28%	61%	74%	55%	57%
Market place	€ 12,568.90	€ 14,039.08	**€ 8,598.51**	€ 12,309.04	€ 11,971.67	€ 11,903.69	€ 13,301.19
Compared to the Lowest Cost	46%	63%	0%	43%	39%	38%	55%
Pharmacy	€ 3,131.20	€ 2,227.46	**€ 2,193.03**	€ 2,805.22	€ 2,982.41	€ 2,704.24	€ 2,848.46
Compared to the Lowest Cost	43%	2%	0%	28%	36%	23%	30%

Primary School	€ 1,771.41	€ 1,734.53	**€ 1,270.12**	€ 1,882.32	€ 1,687.23	€ 1,825.19	€ 1,298.77
Compared to the Lowest Cost	39%	37%	0%	48%	33%	44%	2%
Small Enterprise	€ 4,392.99	€ 4,748.19	**€ 3,049.42**	€ 6,759.95	€ 4,184.25	€ 6,618.28	€ 3,691.27
Compared to the Lowest Cost	44%	56%	0%	122%	37%	117%	21%
Base Telecom Tower	€ 37,486.20	€ 20,236.43	€ 25,510.17	€ 29,220.70	€ 20,613.22	**€ 17,768.81**	€ 31,018.25
Compared to the Lowest Cost	111%	14%	44%	64%	16%	0%	75%

The last set of results compare the alternative tariff designs for residential users (only) with the implied tariff. *Table 4.12* contrasts the CoE per tariff design for Household 1 and Household 2 with the CoE deriving from the implied tariff rate. The tariff designs which are less costly for Household 1 and 2 based on their annual CoE are shown with bold letters.

Table 4.12: Comparison of CoE per tariff design for Household 1 and Household 2 with the CoE derived from the implied tariff rate

Mini-grid 1		
Tariff Type	Household 1 Compared to implied tariff	Household 2 Compared to Implied Tariff
CoE Energy Tariff	6%	6%
CoE Capacity Tariff	11%	2%
CoE Fixed & Variable Tariff	30%	**-13%**
CoE Fixed & Variable Tariff CT	30%	**-13%**
CoE Block Tariff	6%	6%
CoE Block Tariff CT	30%	**-13%**
CoE Time of Use Tariff	11%	2%
Mini-grid 2		
Tariff Type	HH1 Compared to implied tariff	Compared to Implied Tariff
CoE Energy Tariff	**-4%**	**-4%**
CoE Capacity Tariff	7%	**-1%**
CoE Fixed & Variable Tariff	30%	**-18%**
CoE Fixed & Variable Tariff CT	9%	**-23%**
CoE Block Tariff	6%	6%
CoE Block Tariff CT	16%	**-17%**
CoE Time of Use Tariff	4%	**-4%**
Mini-grid 3		
Tariff	HH1 Compared to implied tariff	HH 2 Compared to Implied Tariff
CoE Energy Tariff	**-8%**	**-8%**
CoE Capacity Tariff	10%	**2%**
CoE Fixed & Variable Tariff	29%	**-20%**
CoE Fixed & Variable Tariff CT	5%	**-26%**
CoE Block Tariff	8%	**8%**
CoE Block Tariff CT	16%	**-15%**
CoE Time of Use Tariff	3%	**-4%**
CoE Implied Tariff (€/Year)	€ 102.32	€ 378.36

As for Mini-grid 1, none of the calculated tariffs are more affordable (present a lower CoE) than the implied tariff for Household 1. Differently, three tariff types (Fixed & Variable, Fixed & Variable CT and Block tariff CT) are more affordable when compared to the implied tariff for Household 2.

Looking at Mini-grid 2, there is one tariff design (Energy Tariff) which is more affordable than the implied tariff rate for Household 1 (-4%) while for Household 2 there are 6 tariff types which are more affordable than the implied tariff. The most affordable tariff for Household 2 in comparison with the implied tariff is the Fixed & Variable tariff CT.

Considering now Mini-grid 3, it can be observed that this mini-grid has the lowest CoE for Household 1 and Household 2 when compared to the implied tariff - the Energy Tariff being the most affordable tariff for Household 1 and the Fixed & Variable Tariff CT for Household 2.

4.4 Final remarks

Table 4.13 shows the sum of the CoE for all user types for all the seven tariff designs per exemplary mini-grid. The tariff design which has the lowest CoE across all user types of the exemplary mini-grids is shown in *Table 4.13* in bold.

Table 4.13: The sum of the CoE for all user types for all seven tariff designs per exemplary mini-grid

	Energy Tariff	Capacity Tariff	Fixed & Variable Tariff	Fixed & Variable Tariff CT	Block Tariff	Block Tariff CT	Time of Use Tariff
CoE for Mini-grid 1	€ 510.18	€ 500.37	**€ 460.80**	**€ 460.80**	€ 510.18	**€ 460.80**	€ 500.20
CoE for Mini-grid 2	€ 31,460.28	€ 28,283.57	**€ 21,802.69**	€ 30,848.84	€ 26,017.36	€ 27,169.11	€ 28,669.80
CoE for Mini-grid 3	€ 72,097.00	€ 54,069.50	**€ 49,611.55**	€ 66,853.03	€ 53,678.88	€ 54,352.44	€ 63,161.27

When a mini-grid is built to serve mostly residential loads as in exemplary Mini-grid 1, the tariff designs which ensure the lowest CoE for all types of end-users are the Fixed & Variable Tariff, Fixed & Variable Tariff CT and Block Tariff CT (shown in *Table 4.13*). Implementing one of these three tariff designs will result into that the group Household 2 will benefit the most (all three tariff designs have the lowest CoE for Household 2). Consequently, if one wants to ensure an overall affordability for the tariff design of a mini-grid there always will be winners and losers. The losers being the Household 1 group since all three tariff designs imply a minimum CoE for Household 2 but not for Household 1. The tariff design which would be more favourable for Household 1 would be the Energy Tariff or the Block Tariff.

When looking with a more realistic view at the three tariff designs in terms of affordability by using *Table 4.12*. It can be concluded that all three tariff designs are favourable from the point of view of Household 2 but not for Household 1. The tariff designs are favourable for Household 2 because all three are lower (-13%) than the implied tariff in terms of CoE. The tariff designs are not favourable for Household 1 because all three are higher (30%) than the implied tariff in terms of CoE. Therefore, implementing one of these tariff designs would not be advised for users such as Household 1. Users such as Household 1 might disconnect from the mini-grid and go back to paying the implied tariff.

Even though the Fixed & Variable Tariff, Fixed & Variable Tariff CT and the Block Tariff CT perform the same in terms of affordability they are not performing the same in terms of cost-reflectiveness and simplicity. The Block Tariff CT performs the highest in terms of cost-reflectiveness but the lowest in terms of simplicity since, it considers the users contribution to the system peak. The opposite is true for the Fixed & Variable Tariff and Fixed & Variable Tariff CT. The advantage of implementing a cost-reflective tariff design (Block Tariff CT) is that the tariff rate is based on the actual costs a user imposes on the system. Resulting in that every user is charged with their actual costs. The advantage of implementing a simple tariff design (Fixed & Variable Tariff and Fixed & Variable Tariff CT) is that most users will understand the tariff design and are able to calculate their energy bill in advanced. The disadvantage of implementing a simple tariff design is that it does not reflect the true costs a user imposes on the system. Resulting in that some users (users that consume energy during peak hours) are charged less than they should.

When a mini-grid is built to serve a mix of residential and commercial/governmental loads as in Mini-grid 2, the tariff design which ensures the lowest CoE for all the types of end-users is the Fixed & Variable Tariff (shown in *Table 4.13*). This choice would be favourable from the point of view of one group of commercial users (the Barber, Carpenter and Market place) making them the winners (lowest CoE). While, being unfavourable from the point of view of the remaining commercial/governmental users (Pharmacy, Kiosk and Primary School) and residential users

(Household 1 and Household 2) in terms of CoE and therefore making them the losers. The tariff designs which would be favourable for the residential group would be the Energy Tariff (Household 1) and the Fixed & Variable Tariff CT (Household 2). The tariff designs which would be favourable for the remaining commercial/governmental users would be the Capacity Tariff (Pharmacy & Kiosk) and Time of Use Tariff (Primary School).

When looking more realistically to the CoE for the Fixed & Variable Tariff and the CoE as a result of the implied tariff for the residential users. It can be concluded that choosing the Fixed & Variable Tariff would be favourable from the point of view of Household 2. Even though that the Fixed & Variable Tariff is not the most affordable tariff design for Household 2, it is still 18% lower than the CoE of the implied tariff. Choosing the Fixed & Variable Tariff would not be advised when looking from the point of view of Household 1. Since, the Fixed & Variable Tariff results to a higher CoE (30%) for Household 1 than the implied tariff. Resulting in that such residential users might be forced to disconnect from the mini-grid and go back to paying the implied tariff rate.

Moving on, the Fixed & Variable Tariff is not a tariff design which can be considered as a cost-reflective tariff design. Since, it does not consider the users contribution to the system peak. Resulting in a disadvantage that the users are not charged with the costs they impose to the system. The advantage of the Fixed & Variable Tariff is that it is a very simplistic tariff design. Resulting in that users are able to understand the tariff design and calculate their energy bill in advance.

When a mini-grid is built to serve a mix of residential and commercial/governmental loads and also presents an Anchor client as in Mini-grid 3, the tariff design which ensures the lowest CoE for all the types of end-users is the Fixed & Variable Tariff (shown in *Table 4.13*). Implementing this tariff design would be beneficial for all commercial/governmental users except for the Kiosk. Furthermore, this implementation would not be beneficial for the residential users since, the Fixed & Variable Tariff has a higher CoE for them. The same is true for the Anchor client (Base Telecom Tower) since, the Fixed & Variable Tariff results to a higher CoE than the Block Tariff CT. Resulting in that all the residential users, one commercial user (Kiosk) and the Anchor client (Base Telecom Tower) would be the losers when the Fixed & Variable Tariff design is chosen.

When comparing the CoE of the implied tariff with the CoE of the Fixed & Variable Tariff for Mini-grid 3. The same can be concluded as for Mini-grid 2. The only difference is the fact that the Fixed & Variable Tariff is now 29% higher than the CoE of the implied tariff for Household 1 and 20% lower than the CoE of the implied tariff for Household 2.

Finally, there are advantages for some user types in terms of affordability of the tariff designs when moving from Mini-grid 1 to Mini-grid 2 and 3. For the residential users an overall advantage (lower CoE) can be noticed for all the seven tariff designs when moving from Mini-grid 1 to Mini-grid 2. With Household 2 having the most advantages in terms of affordability when moving from Mini-grid 1 to Mini-grid 2. The most advantage in terms of affordability for the residential users is with the Fixed & Variable Tariff CT. While the lowest advantages in terms of affordability for the residential users is with the Block Tariff. Therefore, the addition of the commercial/governmental user types result to a lower CoE for the residential users. When moving from Mini-grid 2 to Mini-grid 3, four out of the seven tariff designs (Energy Tariff, Fixed & Variable Tariff, Fixed & Variable Tariff CT and Time of Use Tariff) have an advantage in terms of affordability for the residential group. This advantage is the largest when the Energy Tariff is applied. The other tariff designs (Capacity Tariff, Block Tariff and Block Tariff CT) have a disadvantage for the residential users in terms of affordability (higher CoE). With the Capacity tariff having the largest disadvantage for the residential users. Resulting in that the addition of the Anchor client leads to less advantages in terms of affordability for the residential users than the addition of the commercial/governmental users.

Moving on to the commercial/governmental users, an overall advantage can be noticed in terms of affordability when moving from Mini-grid 2 to Mini-grid 3. Three tariff designs (Energy Tariff, Fixed & Variable Tariff and Time of use Tariff) are more affordable for the commercial/governmental users in Mini-grid 3 than in Mini-grid 2. With the Energy Tariff having the most advantage in terms of affordability for the commercial/governmental users when it is applied. The tariff designs which have an overall disadvantage for the commercial/governmental users are; the Capacity Tariff, Block Tariff and Block Tariff CT. With the Block Tariff having the highest disadvantage in terms of affordability for the commercial/governmental users. When applied, the Fixed & Variable Tariff CT has an advantage for all of the commercial/governmental users in Mini-grid 3 except for the Carpenter and the Market Place. The Block Tariff CT has a disadvantage in terms of affordability for all commercial/governmental users in Mini-grid 3 except for the Barber.

5: Discussion

This chapter discusses the limitations of this thesis (Section 5.1), explains the contributions of this research and provides an avenue for future research (Section 5.2). Then, the recommendations which can be provided to the mini-grid developers based on the results of this thesis are discussed in Section 5.3.

5.1 Research Limitations

This thesis has multiple limitations which have influenced the results of this research. These limitations are a result of the methods used and the assumptions made during this thesis.

The first limitation of this thesis is the fact that only 3 types of exemplary mini-grids are created. An additional mini-grid type with multiple industrial type of users could have added value in the quantitative analysis of the tariff designs. For instance, the Block Tariff and Block Tariff CT would be more affordable for the residential users of the mini-grid when multiple industrial type of users are considered. Since, the contribution to the system peak of one industrial user type in Mini-grid 3 is not significant when compared to the contribution to the system peak of a group of residential users. Therefore, a large portion of the RR is allocated to the residential users resulting in a relatively high tariff rate for them. Which reduces the affordability of the Block Tariff and Block Tariff CT for the rural dwellers. The consideration of an additional mini-grid type with multiple industrial user types would have added quantitative insight on the affordability of the Block Tariff and Block Tariff CT for rural dwellers.

The second limitation of this thesis is the fact that only the CoE of year one for the end-users are used for identifying the most affordable tariff design for the exemplary mini-grids. As the RR of the exemplary mini-grids decreases each year and the energy consumption of the users increases each year. It is possible that a shift might occur in which tariff design is the most affordable tariff design for a mini-grid during the lifetime of the mini-grid. An improvement to this method would be to use the CoE for each type of user per year over the entire lifetime (20 years) of the exemplary mini-grids. This will result into that the identified tariff design is the most affordable tariff design over the entire lifetime of the mini-grid instead of only for year one.

The third limitation of this thesis is the assumption that all tariff designs assure full cost recovery. In reality, is it very difficult to assure full cost recovery since a large portion of the cost recovery depends on how the users actually consume energy. A user can change their energy consumption which results to revenue fluctuations and a lower cost recovery than expected. Therefore, even though the different tariff designs provide all full cost recovery in this thesis, in reality they might not. Out of the seven tariffs designed for this thesis, the one that would provide the highest cost recovery would be the Capacity Tariff since it charges the users based on their annual individual peak. Charging users based on their annual individual peak load leads to less revenue fluctuations and a high cost recovery. Even if mini-grid users reduce their energy consumption for a period of time during the year, it would not lead to a lower cost recovery. Since, consuming less energy for a period of time does not affect a user's already maximum peak power drawn from the mini-grid during that same year. The tariff design which would provide the lowest cost recovery is one that only has a volumetric tariff rate (the Energy Tariff, Block Tariff and Time of Use Tariff). Such a tariff design is very vulnerable to how a user consumes energy which can lead to revenue fluctuations and a low cost recovery.

The fourth limitation of this thesis is the assumption that the daily load demand profiles of the default users are the same for the whole year. In reality, the demand profile of the mini-grid users changes on a daily base often motivated by seasonal changes, personal needs and financial situation. This assumption affects the cost reflectiveness of the Block Tariff and Block Tariff CT as both tariff designs have only one tariff rate for year one. In reality, such tariff designs would have different tariff rates over a year since the demand profile of the mini-grid users change. Resulting in different daily tariff rates over the year which can confuse the users resulting in that the cost-reflectiveness of the tariff design is lost. In order for the Block Tariff and Block Tariff CT not to lose its cost reflectiveness, the users contribution to the average monthly system peak should be used. Furthermore, the same assumption affects also the cost reflectiveness of the Time of Use Tariff design since the peak and off peak hours are always known. Therefore, the peak hours coincide always during actual peak hours. In reality, peak hours are often forecasted, resulting in that there is a chance that the actual peak hours and the forecasted peak hours will not coincide. If that occurs users will be charged a lower tariff rate even if they are contributing to higher grid cost. Resulting in that the cost-reflectiveness of the Time of Use tariff design is lost.

5.2 Research implications

This thesis gives mini-grid developers more insight on how to improve the economic sustainability of a mini-grid and which tariff design to implement in order to make the tariffs more affordable for different types of mini-grids. A literature review was conducted on existing (un)sustainable mini-grids, elements that affect the economic sustainability of mini-grids and tariff designs for mini-grids. The findings from the literature review give mini-grid developers more insight on why some mini-grids are economically sustainable while others are not. These existing experiences help new mini-grid developers learn from the mistakes of other mini-grid developers, which can accelerate rural electrification. Furthermore, the findings from the literature review give mini-grid developers more insight on which technical configuration shows the most potential, which ownership model to apply and which tariff structure should be considered by mini-grid developers.

The quantitative analyses of this thesis give mini-grid developers a first systematization of the knowledge needed to select a tariff design. Mini-grid developers who develop mini-grids, with the same mix of user types as with the exemplary mini-grids of this thesis, can use the outcomes of this thesis to aid in implementing a tariff design which provides an overall affordability for that type of a mini-grid. Furthermore, this thesis not only provides an answer to which tariff design(s) provides an overall affordability for a mini-grid. It provides also the advantages and disadvantages regarding the affordability, cost reflectiveness and simplicity of implementing that tariff design. Which gives mini-grid developers the needed knowledge to make the right choice regarding a tariff designs for a mini-grid they develop.

During this thesis the main focus was solving the consumer's side of the economic challenge of mini-grids by designing multiple tariffs and quantitatively analyse their affordability for three exemplary mini-grids. The cost recovery (developers side of the economic challenge of mini-grids) of the tariffs which were designed in this thesis where assumed to be fully assured (one of the limitations of this thesis). Leading to that even though the identified tariff designs provide an overall affordability for the mini-grid users they might not provide sufficient cost recovery for the mini-grid developers. Therefore, future research should focus on quantitively analysing which tariff design provides the highest cost recovery for a mini-grid.

5.3 Research recommendations

From the results the following recommendations can be given to mini-grid developers. It is for mini-grid developers important to focus on rural areas that are medium to high densely populated. Such areas have often economic activities such as a marketplace with potential commercial users for the mini-grid. Furthermore, industrial activities in the area who are relaying on diesel generators should be used as anchor clients. Both the commercial and industrial users are able to increase the load factor of a mini-grid as it is very unlikely to have a rural household with a productive daytime load. Increasing the load factor of a mini-grid is very important since a mini-grid with a higher load factor is more cost efficient (lower CoE for the end-users).

Moreover, mini-grid developers are advised to choose solar PV combined with battery storage, a diesel generator as backup and an AC distribution grid. Solar PV shows the most potential as a generation technology since it is a mature technology. Furthermore, due to the modularity of solar PV is it easy to adjust a mini-grids system size for future demand growth. Combining it with a battery storage and a diesel generator as backup improves the reliability and efficiency of the mini-grid. The ownership model and tariff structure which would be advised for mini-grid developers to use is the private-sector based model and site-specific tariff structure.

As for the tariff design of a mini-grid the results show that there is not one tariff design which is the most affordable tariff design for all user types. Therefore, there always will be winners and losers when a tariff design is implemented for a mini-grid. Mini-grid developers who are developing a mini-grid which consists only out of residential users are advised to choose out of the following tariff designs; the Fixed & Variable Tariff, Fixed & Variable Tariff CT and Block Tariff CT. Choosing one of these tariff designs will result into that residential user types with a Tier 1 energy service needs will have a disadvantage in terms of affordability. While, a residential user with a Tier 2 energy service needs will have an advantage in terms of affordability. Mini-grid developers who are developing a mini-grid which consist out of a mix of residential and commercial/governmental users are advised to implement the Fixed & Variable Tariff. Implementing this tariff design will provide an advantage in terms of affordability for most of the commercial/governmental users and a residential user with a Tier 2 energy service needs. Furthermore, Mini-grid developers who are developing a mini-grid which consist out of a mix of residential, commercial/governmental and industrial users are also advised to implement the Fixed & Variable Tariff.

6 Conclusion

This thesis was set out to quantitatively analyse the economic sustainability of alternative tariff designs across different types of exemplary mini-grids (which differ only in the mix of users). In order to create different types of exemplary mini-grids and design alternative tariffs for mini-grids a literature review was conducted. Furthermore, two models (RETEP Generation and RETEP TOTEX) were used during this thesis and one model (RETEP Tariff) was created for the quantitative analysis of this thesis.

The elements that affect the economic sustainability of mini-grids are; technical configuration of a mini-grid, user types, load demand, site selection, ownership model and tariff designs of mini-grid. The generation technology which shows the most potential for mini-grids is solar PV combined with battery storage, a diesel generator as a backup and an AC distribution grid. The private sector-based ownership model shows the most potential for making a mini-grid economically sustainable. Furthermore, site-specific tariff structures should be used by mini-grid developers in order to recover sufficient revenues for making a mini-grid economically sustainable. The tariff designs which can be used for site-specific tariff structures are; Energy Tariff, Capacity Tariff, Fee for service tariff, Block Tariff and Binomial tariff.

The results from the quantitative analyses showed that the economic sustainability of a mini-grid with only residential users (exemplary Mini-grid 1) can be ensured when one of the following tariff designs are implemented; the Fixed & Variable Tariff, Fixed & Variable Tariff CT and Block Tariff CT. These three tariff designs ensure the lowest CoE across all types of end-users and therefore provide an overall affordability for the end-users. However, implementing one of these tariff designs will result into that residential users with a Tier 2 energy service needs (Household 2) have an advantage in terms of affordability over residential users with a Tier 1 energy service needs (Household 1). The residential users with a Tier 1 energy service needs would have a lower CoE with the implementation of the Energy Tariff or the Block Tariff. Moreover, when the CoE of the implied tariff rate is compared with the CoE of the Fixed & Variable Tariff, Fixed & Variable Tariff CT and Block Tariff CT for the residential users. It can be concluded that all three tariff designs are more affordable for Household 2 (all tariffs are 13% lower in CoE) but not for Household 1 (all tariffs are 30% higher in CoE). Therefore, implementing one of these tariff designs might force residential users such as Household 1 to disconnect from the mini-grid and go back to paying the implied tariff rate. Although all three tariff designs are equally in terms affordability, they are not in terms of cost reflectiveness and simplicity. The Block Tariff CT is a cost reflective tariff since it considers the users contribution to the system peak. The advantage of such a tariff design is that it charges the users the costs they impose to the system. The disadvantage of the Block Tariff is that it is not a simple tariff designs since it considers the users contribution to the system peak. For the Fixed & Variable Tariff and Fixed & Variable Tariff CT the opposite is true. Both tariff designs are simple but not cost reflective. Resulting in that when implemented, some users who consume energy during peak hours are not charged with the costs they impose to the system.

As for a mini-grid with only residential and commercial/governmental users (exemplary Mini-grid 2), affordability of the tariff design can be improved by implementing the Fixed & Variable Tariff. The Fixed & Variable tariff has the lowest CoE across all types of end-users and therefore provides an overall affordability for the end-users. Yet, implementing this tariff design will result into that some commercial/governmental users (Pharmacy, Kiosk and Primary school) and all residential users have a disadvantage in terms of affordability (higher CoE). Even though the Fixed & Variable Tariff design results to a higher CoE for Household 2, it is still very favourable for them in terms of affordability (18% lower in CoE than the implied tariff rate). This is not true for residential user such as Household 1, the Fixed & Variable Tariff design has a CoE which is 30% higher than the CoE of the implied tariff.

For a mini-grid with an Anchor client (industrial type of user), commercial/governmental users and residential users such as exemplary Mini-grid 3, the tariff design which ensures the lowest CoE is the Fixed & Variable Tariff. However, implementing this tariff design results into that one commercial user (Kiosk), the Anchor client (Base Telecom Tower) and both residential user types have a disadvantage (higher CoE) in terms of costs.

Furthermore, the results show that the residential users have an overall advantage in terms of affordability (all seven tariff designs have a lower CoE) when moving from Mini-grid 1 to Mini-grid 2. The most advantage in terms of affordability for the residential users is with the Fixed & Variable Tariff CT. While the lowest advantages in terms of affordability for the residential users is with the Block Tariff. The residential users have less advantage in terms of affordability when moving from Mini-grid 2 to Mini-grid 3 (four out of the seven tariff designs have a lower CoE). The Energy Tariff has the most advantage in terms of affordability for the residential users when moving from Mini-grid 2 to Mini-grid 3. Therefore, the addition of the Anchor client leads to less advantages in terms of affordability for the residential users than the addition of the commercial/governmental users. The commercial/governmental users have an overall advantage in terms of affordability when moving from Mini-grid 2 to Mini-grid 3, although not all tariff designs provide a lower CoE. Three tariff designs (the Energy Tariff, Fixed & Variable Tariff and Time of use Tariff) have a lower CoE for the commercial/governmental users in Mini-grid 3 when compared to Mini-grid 2. With the Energy Tariff having the most advantage for the commercial/governmental users.

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