UPPSALA UNIVERSITET

UPTEC STS 19006

Examensarbete 30 hp

Mars 2019

Resilience-enhancement through Renewable Energy Microgrid Systems in rural El Salvador

Mathias Alarcón

Robin Landau

UPPSALA
UNIVERSITET

Teknisk- naturvetenskaplig fakultet
UTH-enheten

Besöksadress:
Ångströmlaboratoriet
Lägerhyddsvägen 1
Hus 4, Plan 0

Postadress:
Box 536
751 21 Uppsala

Telefon:
018 – 471 30 03

Telefax:
018 – 471 30 00

Hemsida:
http://www.teknat.uu.se/student

Abstract

Resilience-enhancement through Renewable Energy Microgrid Systems in rural El Salvador

Mathias Alarcón & Robin Landau

This Master thesis investigates how Renewable Energy Microgrid Systems (REMS) can enhance resilience for a rural grid-connected community in El Salvador. The study examines the optimally resilient design of a grid-connected PV-Wind-Battery hybrid energy system. The optimally resilient system configuration was determined based on energy affordability, defined as minimum net present cost (NPC) and energy reliability, which was defined as a 1% maximum annual capacity shortage. The system modelling and optimisation was performed in the HOMER (Hybrid Optimisation of Multiple Energy Resources) software, where the system was optimised for different scenarios.

The results of this study show that REMS can enhance resilience by lowering electricity costs for the community and thus increasing energy affordability. However, the REMS did not manage to make an equally substantial impact on energy reliability, due to the grid performance that proved to be high with few annual power outages. Besides the grid connection, the optimally resilient system was driven entirely by PV energy since it proved to be highly profitable. Wind power and battery storage were excluded from the optimally resilient system since they did not contribute to affordability and the capacity shortage limit was met already from the PV unit and the grid. Furthermore, the results show that self-sufficiency can be provided with REMS from the local energy resources, but that it is unrealistic with current costs due to the high battery prices. The study concludes that REMS should be considered as a legitimate resilience measure in rural El Salvador.

Handledare: Claudia Blanco
Ämnesgranskare: David Lingfors
Examinator: Elísabet Andrésdóttir
ISSN: 1650-8319, UPTEC STS 19006

Populärvetenskaplig sammanfattning

Centralamerika är en region som de senaste 20 åren drabbats hårt av naturkatastrofer och extremväder, och El Salvador är ett av de utsatta länderna i regionen. Den här rapporten syftar till att undersöka hur ett mikronät baserat på förnybar elproduktion kan bidra till att öka resiliensen för ett bostadskooperativ på landsbygden i El Salvador. Resiliens kan beskrivas som ett systems förmåga att förebygga utsatthet, klara av att utsättas för chocker och återhämta sig snabbt. Energitillgång är en faktor som brukar lyftas som central för resiliens, och Sustainable Energy for All (SE4ALL) och International Energy Agency har i sina definitioner av konceptet energitillgång lyft fram faktorerna ekonomi och tillförlitlighet. I den här studien undersöks hur dessa faktorer skulle påverkas om mikronät drivna av förnybar energi implementeras i det salvadoranska bostadskooperativet Cuna de la Paz. Det görs genom att simulera olika mikronätssystem och undersöka utfallen för de totala elkostnaderna och leveranssäkerheten.

Mikronät är en teknik som blivit allt mer populär till följd av att förnybara energitekniker baserade på lokala resurser har fallit i pris. Ett mikronät är ett energisystem i mindre skala som på ett kontrollerat och säkert sätt hanterar lokal elproduktion och elförbrukning. Mikronätet kan vara anslutet till ett regionalt elnät och har också möjlighet att operera i ett så kallat ö-läge, då systemet fungerar isolerat från elnätet. I denna studie har olika nätkopplade mikronätssystem bestående av solpaneler, vindkraftverk och batterilagring simulerats och optimerats för att se vilken kombination av energitekniker som sammantaget bidrar till mest resiliens.

Studien har genomförts i samarbete med den salvadoranska icke-statliga organisationen FUNDASAL som ansvarar för bostadskooperativet. Genom en fältstudie erhölls information kring bland annat bostadskooperativens elförbrukning, det regionala elnätet och kostnader för energiteknikerna i mikronätet. Därefter modellerades och optimerades systemet med hjälp av programmet HOMER Pro. Optimeringarna utfördes i tre olika nätscenarion, där ett av dessa fungerade som huvudscenario. Huvudscenariot byggde på nätdata från år 2017 med högre leveranssäkerhet medan det andra scenariot byggde på nätdata från år 2005 med lägre leveranssäkerhet. I det sista scenariot undersöktes om systemet med de lokala energiresurserna skulle kunna bli självförsörjande. I det scenariot kunde inte el köpas från det regionala elnätet.

Resultaten visar att mikronät kan bidra till att öka resiliensen för bostadskooperativet främst genom sänkta elkostnader. Elnätet i huvudscenariot visade sig vara tillförlitligt vilket gjorde att ett mikronät inte på samma sätt bidrog till att förbättra leveranssäkerheten. Resultaten visar också att solpaneler är den mest lönsamma energitekniken att investera i för bostadskooperativet. Varken vindkraft eller batterilagring visade sig vara motiverat att inkludera då kombinationen av solpaneler och elnät var tillräcklig för att skapa ett leveranssäkert system och medförde de lägsta totala kostnaderna. Simuleringarna i det tredje scenariot visar att bostadskooperativet skulle kunna bli helt självförsörjande med hjälp av ett mikronät. Däremot bidrog den uppskattade batterikostnaden till ett orimligt dyrt energisystem. Sammantaget visar rapporten att mikronät drivna på förnybar energi är en gångbar åtgärd för att öka resiliensen för landsbygdssamhällen i El Salvador.

Acknowledgements

There are many people that in different ways have been of great help to us in the process. First and foremost, without the dedication and drive of Claudia Blanco, Technical Director at FUNDASAL, our aspirations and ideas for the project might just have ended up as ideas. Claudia was absolutely vital for making the study happen, and we are eternally grateful for her support. Nina Larrea, We Effect's Regional Director in Latin America, belongs to the same VIP category. Thanks to her curiosity and willingness to let all important Regional Directorial duties aside to help some students realising a high-shooting idea, we got connected with FUNDASAL.

Our work in El Salvador was facilitated by professor Sandra Gutiérrez from the Central American University (UCA) who allowed us access to the university and introduced us thoroughly to important topics of the country (and her students). Roberto Melara, Civil Engineer at FUNDASAL, was a crucial support for us in our quest for different types of data: he arranged meetings, drove us there and tried to meet all our questions with great patience. Also Julio Meléndez, Assistant Director at FUNDASAL, drove us around and shared us his great hospitality. As the first Salvadoran face we encountered after the passport control at the airport, Julio's friendliness put its mark on our entire stay.

Many more people deserve to be mentioned: Diego Salcedo from AES El Salvador for providing valuable information and a good introduction to the energy sector of the country, Leticia Martinez, Mario Quezada, Isaac Seguro and Monica Hérnandez from FUNDASAL and We Effect for helping us out and introducing us to the Cuna de la Paz-project and Daysi for her friendship. Collectively, we want to praise the staff at FUNDASAL and We Effect, the cooperativists of Cuna de la Paz and the surfers of El Tunco.

Our university subject reader David Lingfors deserves a special recognition for bearing with us all along and correcting our direction in times of perplexion. So does Malin Frisk who got us inspired with her thesis, and gave us valuable inputs.

Finally, we want to acknowledge Emma Stenbacka for being our constant company and equally supportive regardless of our progression, and our families and friends for accepting our absence.

To all mentioned above and the people of El Salvador,

Thank you

Mathias Alarcón & Robin Landau,
Uppsala, March 2019

Abbreviations

AC – Alternating Current

ACOVIAMET – Asociación Cooperativa de Vivienda por Ayuda Mutua El Triunfo

ACOVICUPA – Asociación Cooperativa de Vivienda por Ayuda Mutua Cuna de la Paz

ARENA – Allianza Republicana Nacionalista

CEL – Comisión Ejecutiva Hidroeléctrica del Rio Lempa

CNE – Consejo Nacional de Energía de El Salvador

DC – Direct Current

DER – Distributed Energy Resources

DG – Distributed Generation

ETESAL – Empresa Transmisora de El Salvador

FMLN – Frente Farabundo Martí para la Liberación Nacional

FUNDASAL – Salvadoran Foundation for Development and Minimal Housing

HOMER – Hybrid Optimisation of Multiple Energy Resources

IEA – International Energy Agency

JICA – Japanese International Cooperation Agency

LCOE – Levelised Cost of Energy

LGE – Ley General de Electricidad

MER – Mercado Eléctrico Regional

NGO – Non-Governmental Organisation

NPC – Net Present Cost

O&M – Operation and Maintenance

REMS – Renewable Energy Microgrid Systems

SAIDI – System Average Interruption Duration Index

SAIFI – System Average Interruption Frequency Index

SIGET – Superintendency of Electricity and Telecommunications of El Salvador

PV – Photovoltaic

Table of contents

1. Introduction

When it comes to extreme weather events and climate catastrophes, less developed countries have been more afflicted than industrialised countries historically. A region that has been remarkably stricken by weather-related disasters the last 20 years is Central America, where several countries occupy the top ranks of the Global Climate Risk Index (Kreft et al., 2017). One of those is El Salvador, a country hit by natural disasters such as Hurricane Ida in 2008 (Shoda, 2012) and the extreme drought in 2015 which left over 3.5 million Central Americans in need of humanitarian assistance. The most vulnerable groups are the rural communities and small-scale agricultural producers who see their livelihoods and homes affected and often demolished (FAO, 2016). The country has also been affected by non-climate related natural disasters such as the 2001 earthquake, which reached 7.6 on the Richter scale and killed more than 1000 people (BBC, 2018). As a result of these problems, which are compounded with violence and criminal gang activity, many Salvadorans have to leave their communities in search of safety (OAS, 2015).

Because of the problems the country faces, the concept of resilience is of great importance in the modern context of El Salvador. Resilience can be defined as "*the ability of countries, governments, communities and households to manage change, by maintaining or transforming living standards in the face of shocks or stresses, while continuing to develop and without compromising their long-term prospects"* (Brooks et al., 2014, iii). This definition covers both a system's ability to cope with shocks and stresses (like earthquakes and droughts) and the ability to remain strong and continue to improve in the long run. Hills et al. (2018, 23) state that resilience management is a "*key strategy for managing disaster risk under climate change*". According to Kelly-Pitou et al. (2017), resilience measures are actions that should be taken today to protect communities from direct damage and at the same time help remove the long-term impacts of climate change. Such actions should make systems stronger and smarter than they were in the past.

Energy access is a vital factor in the resilience context, as argued by several sources. The International Energy Agency (IEA, 2019a) states that "*access to affordable and reliable energy services is fundamental to reducing poverty and improving health, increasing productivity, enhancing competitiveness and promoting economic growth"*. Hills et al. (2018) stress that energy access is crucial for people's livelihoods and wellbeing, and that a lack of energy access could be a key constraint in providing resilient occupations and be a cause of poverty for the most vulnerable communities to climate change. Perera et al. (2015) describe energy access as an enabler to poverty reduction. According to the Sustainable Energy for All's (SE4ALL) definition of energy access, two factors of crucial significance are affordability and reliability (Angelou, 2014).

As renewable energy technologies become less expensive, opportunities for increased energy access are emerging. The foreword of the 2017 edition of the World Energy Outlook describes the cost reductions of solar photovoltaics (PV), wind power and battery storage as one of the major trends that *"profoundly reshape the energy sector"* (IEA, 2017, 3). The International Renewable Energy Agency (IRENA) states that the strong business potential of renewable energy is the *"chief driver"* of the capacity growth of the technologies, and that it offers *"increasingly exciting economic opportunities"* (IRENA, 2018, 3), where the most evident example is the 80% cost reductions of PV modules between 2009 and 2018. They consider renewable energy to be a key opportunity especially in developing countries (IRENA, 2018). These renewable technologies are often utilised in microgrid applications (several examples are presented in this study). A microgrid can be described as an integrated electrical grid system, with local loads and energy production that is often (but not necessarily) renewable, and which can operate both in connection with a main grid and in isolation (Smith and Ton, 2012). Wu et al. (2016) express that community level microgrids can provide reliable and resilient electricity services with the aim to optimise electrical, economic and societal goals by serving critical loads. Kelly-Pitou et al. (2017) consider microgrids to play an increasingly popular role in discussions regarding electrical grid reliability. They further constitute renewable microgrids to be an effective local level action to contribute to long-term challenges of sustainability.

Resilience is a central focus of the work of the Salvadoran NGO FUNDASAL (the Spanish acronym for the Salvadoran Foundation for Development and Minimal Housing in English). FUNDASAL works on the ground in El Salvador with the mission to provide secure and dignified housing to the groups that are vulnerable to the contemporary hazards. The NGO has worked for 50 years with the construction and fortification of both rural and urban communities (FUNDASAL, 2017a). An ongoing rural project is Cuna de la Paz, where a grid-connected community village consisting of 62 homes and a community center along with the necessary infrastructure is under construction. The plan is to partially maintain the community through eco-tourism. FUNDASAL is recognised for their construction and integral project management expertise. Nevertheless, local energy solutions have not yet been considered or evaluated by the organisation.

The combination of the hazardous Salvadoran environment, the rise of business opportunities of renewable energy integrated in microgrid systems and the Cuna de la Paz project provide an interesting study case for assessing how a promising system solution could contribute to enhanced resilience. Perera et al. (2015) acknowledge that the concept of resilience needs to be understood as context-specific, which makes case studies ideal in developing the toolbox of resilience-enhancing activities in different geographic regions (also supported by Hills et al. (2018) and Stone (2013)). A research gap that they identify is the general need to specifically map the challenges and opportunities in different regions at different scales. Central America appears to be an under-investigated region regarding energy connection and resilience. Balint (2006) points out that most regional assessments tend to focus on Africa and Asia and that Central America has been left behind. Twelve years later, Madriz-Vargas et al. (2018) recognise the same issue, indicating that this region still needs attention.

1.1 Study aim

The aim of the study is to investigate if Renewable Energy Microgrid Systems (REMS) can provide enhanced resilience to rural Salvadoran communities, exemplified by the Cuna de la Paz project, and how a REMS should be designed to optimally do so. In accordance with the energy access definition presented by SE4ALL (Angelou, 2014) and IEA (2019), resilience is conceptualised as the energy- affordability and reliability, which is investigated with different premises in various scenarios presented in Chapter 3.

1.2 System setup and study delimitations

Cuna de la Paz is a community village under construction and described in detail in Section 2.3.2. It has already been connected to the main grid and a fortification is planned. The microgrid systems that were investigated in this study are simulation products and have thereby only been studied through computational models. They were modelled to work in times of power outages from the main grid as long as there is sufficiently available local energy resources (such as solar PV production or battery-stored energy). In compliance with the circumstances they were modelled as grid-connected, only providing electricity to the community. This was decided with FUNDASAL who did not consider a thermal demand for the project. Therefore, the systems do not provide thermal energy.

The modelled system designs consist of combinations of PV modules, a wind turbine, battery storage and a grid connection. The sizes, locations and orientations of the components are presented in Section 3.2.6. The study focuses on implementing renewable energy since it aligns with the planned eco-touristic profile of the Cuna de la Paz-project, besides the sustainability aspect of renewable energy that makes it comply with resilience. Consequently, fossil fuel-based electricity generation is excluded. Diesel generation was thereby excluded even though it has successfully been implemented in many rural microgrids with the benefit of being able to provide power when the renewable sources do not produce sufficiently (Eziyi and Krothapalli, 2014). The issue is nevertheless more critical in off-grid Microgrid systems where no main grid provision can be counted on. The PV modules and the wind turbine were chosen because of the recognised potential of solar insolation and wind energy in the studied area (further elaborated in Section 2.2.4**)**. Other renewable energy sources, such as biomass energy and hydro energy were excluded. Biomass energy normally consists of agricultural crop remain or forest bioenergy resources and were considered to be insufficient in the studied area since it lacks farming activity. Hydro energy was excluded since no suitable water streams were available in the vicinity. PV modules and the wind turbine were also chosen due to their advantage of being easily managed, with little harm to the vicinity and high social acceptability (Dawoud et al., 2018). The term for the system that is used in this report is Renewable Energy Microgrid System (REMS).

The modelled location of the production units in the community is presented in Section 3.2.6**.** Only rooftop spaces have been considered for the PV modules. However, the weight limit of the rooftops has not been considered within the study. Therefore, the decision making of choosing the most suitable rooftops for the installation of PV modules did not depend on construction boundaries.

The community is connected to a local grid. The modelled system's possibility to sell electricity to the grid was however not limited by restrictions regarding the capacity of the local grid. It was therefore assumed to manage all surplus electricity that the system generates in all simulations.

1.3 Disposition

This section gives an overview of the disposition of the thesis. The background chapter (2) begins by briefly introducing the country El Salvador in section 2.1, while Section 2.2 discusses electricity-related issues of the country. Section 2.3 outlines the organisation FUNDASAL and the project Cuna de La Paz. The background chapter ends with a discussion of microgrid technologies in Section 2.4.

The methodology and data chapter (3) presents the research methodology and data collection of the study. They were decided to be presented in the same chapter since the chosen methodology stemmed from the type of data that was available. The chapter introduces the modelling procedure and the simulation outline in section 3.1. In Section 3.2, the data acquisition of the study is described and discussed. Lastly, the selected sensitivity variables are presented in Section 3.3.

The results and analysis chapter (4) presents the results of the optimisations. The different results for the three scenarios (presented in Section 4.1, 4.2 and 4.3) are illustrated and analysed. The discussion chapter (5) aims to widen the results to a broader context. The chapter starts by highlighting the main lessons from the results in Section 5.1. In Section 5.2, the methodology of the study is discussed, and Section 5.3 contextualises the findings. The discussion chapter ends by recommending further research in Section 5.4 before the concluding Chapter 6.

2. Background

This chapter introduces the aspects that were considered relevant for the understanding of the study. Section 2.1 gives a general introduction to El Salvador. In Section 2.2 a more in-depth presentation of electricity-related issues of the country is presented, such as the electricity production, electricity prices and the current status of solar- and wind power. Section 2.3 presents FUNDASAL and the Cuna de la Paz project. Lastly, microgrid technologies are presented in Section 2.4.

2.1 El Salvador

El Salvador (see Figure 1) is the smallest and most densely populated country in Central America with an area of 21’000 km^2 and a population of 6.4 million (Landguiden, 2018a). Its neighbouring countries are Honduras, Guatemala and Nicaragua. The country is located in the tropical zone and has two seasons. The dry season extends from November to April, and the wet season from May to October, when the country receives heavy rain falls (Nations Encyclopedia, 2019).

Figure 1. Location of El Salvador (Source: OpenStreetMap, 2019. © OpenStreetMap’s donors, available under the Open Database Licence.)

Between 1979 and 1992, the country suffered badly due to its ongoing civil war and about 75’000 Salvadorans lost their lives. Years of social injustice and military-dominated rule caused a left-wing movement, led by guerrilla and paramilitary squads, to take up arms against the regime. The war reached its dramatic climax when archbishop Romero was assassinated in 1980 (Calvo-Gonzalez and Humberto, 2015). After the war, the country has stabilised, and the last presidential elections have been considered to be democratic. In February 2019, Nayib Bukele was elected president, the first candidate not representing the previously dominant parties constituted by leftists FMNL and conservative ARENA, which were the opposing sides in the civil war (NBC, 2019). The economy has traditionally been heavily dependent on the the agricultural sector, which accounted for 25% of the GDP in 1987 (Countrystudies, 2019). However, during the last decade, the service sector has dominated the economy. There is also a big informal sector in the country, and many families rely on money from Salvadorans who have migrated to the U.S (Landguiden, 2018b). Some sources claim that this kind of income accounted for 18.3% of the total GDP in 2017 (Orozco, 2017).

Another important and worrying issue for the country is the threat from gang criminality. El Salvador has had one of the higher murder rates in the world due to criminal gang activity, and the police forces have been struggling to cope with the situation since the early 1990s. (Woody, 2018).

2.2 Electricity in El Salvador

This section is an introduction to the Salvadoran electricity context and discusses the electricity generation (2.2.1), electricity system (2.2.2), electricity prices (2.2.3) and the current situation for solar and wind power (2.2.4). Before the Salvadoran electricity situation is entered in depth, a contextualisation of the electricity access in Central America is presented in Figure 2.

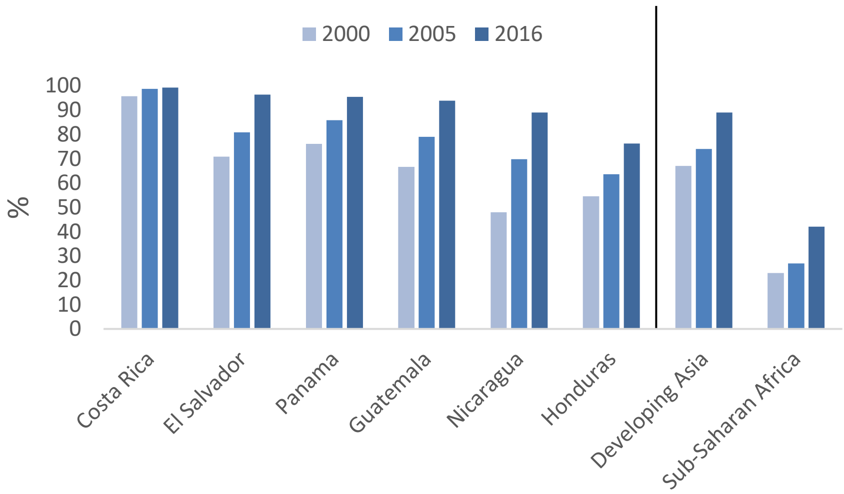

Figure 2. The national electrification rate of the Central American countries in 2000, 2005 and 2016. Developing Asia and Sub-Saharan Africa are included as a reference. Data source: IEA Energy Access Database (IEA, 2019b): National electrification rate.

Figure 2 shows that El Salvador in 2016 has the second highest electrification rate in Central America with 96%, after a rapid growth since 2000 (a growth that is shared by most of neighbouring countries). The electrification rate interval of the Central American countries in 2016 is between 76% (Honduras) and 99% (Costa Rica). Developing Asia (including for example China, India, Indonesia and South-East Asia) and Sub-Saharan Africa (including all African countries except for those fronting the Mediterranean) are included as reference. The statistics show that Developing Asia's rate relate to the lower scoring Central American countries Nicaragua and Honduras with 89% in 2016. Sub-Saharan Africa, with a 42% electrification rate in 2016, gives a completely different situation. The statistics imply that the Central American countries in general have experienced a quick electrification growth from 2000 with high rates in 2016 compared to other developing regions.

2.2.1 Electricity profile

The generated electricity in El Salvador originates from 3 major sources. Figure 3 demonstrates the Salvadoran electricity matrix in 2017.

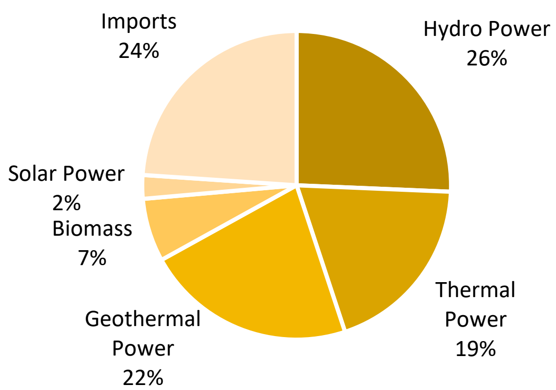

Figure 3. The sources of the electricity in the Salvadoran utility grid 2017. Data source: SIGET (2017): Cuadro r3, 37, 38B and 73.

As Figure 3 shows, the main electricity source is hydro power, although geothermal and thermal energy are not far behind (net imports disregarded). The electricity generation in El Salvador is heavily influenced by rainfall and hydroelectric potential, which becomes clear in a comparison with the 2016 electricity matrix, shown in Figure 4.

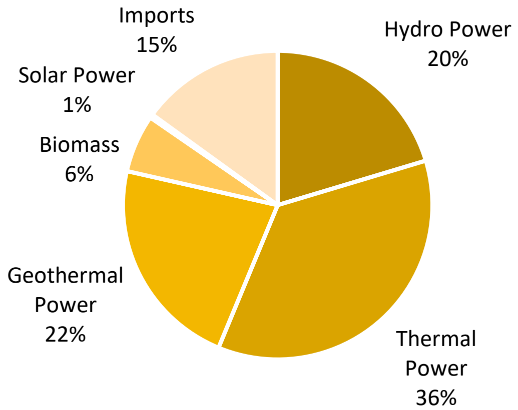

Figure 4. The sources of the electricity in the Salvadoran utility grid 2016. Data source: SIGET (2016): Cuadro 37 and 79 and SIGET (2017): Cuadro r3.

A dry 2016 paved the way for increased thermal energy production. With almost 40 percent of the injected electricity, the power system is clearly dependent on thermal power during dry years. Figure 5 provides a closer comparison of the year profiles of 2016 and 2017.

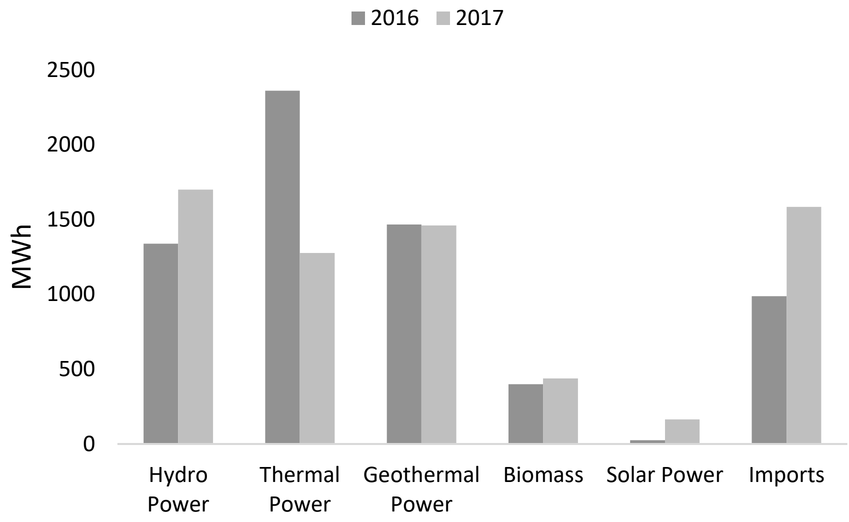

Figure 5. The sources of the electricity in the Salvadoran utility grid 2016 and 2017. Data source: See Figure 2 and 3.

Among the energy sources shown in Figure 5, hydro power is the prioritised energy source when available since it has the lowest production margin costs. The fluctuation in hydro power (caused by seasonal variations and year to year anomalies) is covered by thermal power. The domestic and relatively cost-effective geothermal and biomass power supplied base loads remain in largely unchanged between seasons and years (JICA, 2012). With 204 MW of installed geothermal capacity, the volcanic El Salvador is the largest producer of geothermal power in the region, as well as one of the world's leading countries in basing its domestic power system on the utilisation of the power source (with 22 percent of the injected electricity both 2016 and 2017) (World Watch, 2019). The first geothermal power plant was built back in 1976 (see data source for Figure 7**)**, and the installed power has grown steadily since then. The sugar cane-based biomass production is a more novel power source, with the first large-scale plant in production in the early 2000s. However, biomass power has experienced a rapid growth from 20 MW in 2003 to 264 MW in 2017, and with further investments in efficiency and the use of new crops, Salvadoran biomass power is expected to continue to increase (CNE, 2019a). Solar energy is presented in Section 2.2.4.

Figure 6 shows that El Salvador's net electricity imports have increased significantly in recent years: roughly 18 times between 2012 and 2017. This indicates that El Salvador has issues with the economic competitiveness of their domestic electricity. Since the formalisation of the Central American Regional Electricity Market (MER) in 1996, El Salvador has by far been the biggest importer of electricity in the region. The main exporter is neighbouring Guatemala, whose low electricity end price stems from their expansion of hydro power and biomass, and also their transition in thermal production from oil to coal (Molina, 2017). In El Salvador, on the other hand, the vast thermal power consumption (critical not least during the dry periods) is based entirely on oil combustion (IEA, 2018, Table 1.3). Besides increasing import dependency (El Salvador does not have large petroleum resources), reliance on oil makes for electricity price vulnerability, as will be discussed in Section 2.2.3.

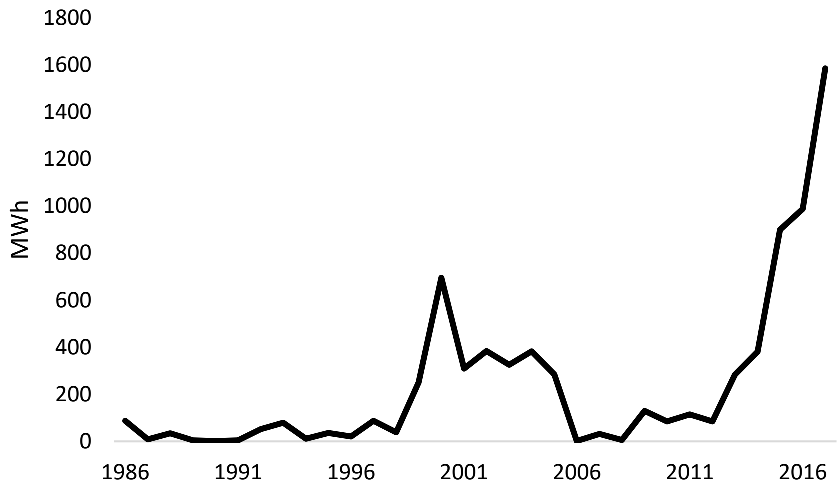

Figure 6. The Salvadoran net imports of electricity 1986-2016. Data source: SIGET (2017): Cuadro 09.

In order to provide some perspective on the Salvadoran electricity generation system, Figure 7 presents the installed capacity from the origin of the nation scale power system (1954) to the latest available data (2017).

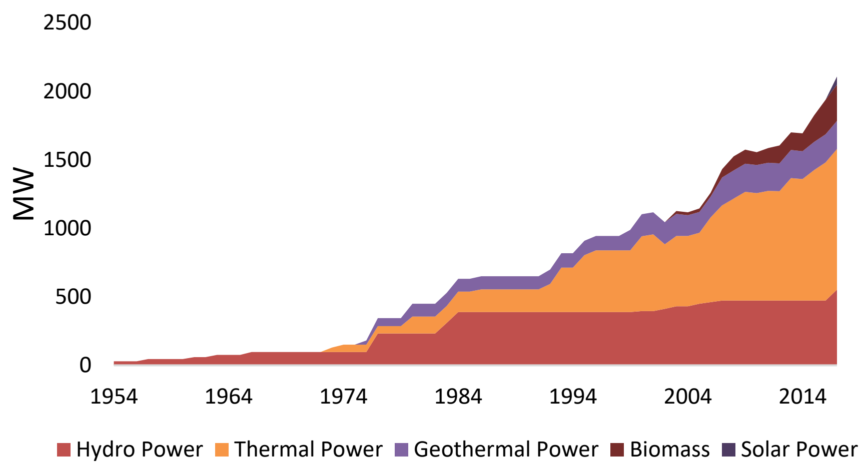

Figure 7. The development of the installed power capacity in El Salvador 1954-2017. Data source: SIGET (2017): Cuadro 07.

For the first 20 years all power generation mainly originated from the first two hydro power plants. In the 1970s thermal and geothermal production started contributing to an extended power capacity. Since then, all three power sources have been significantly expanded, although thermal power has had the most significant expansion (JICA, 2012). A trend that started at the turn of the century is the surge of the renewables, which so far has been most clearly manifested by rapidly increasing biomass power. The rise of solar PV and wind energy that has started in recent years will be discussed in Section 2.2.4.

2.2.2 El Salvador's electricity system

In the first half of the 20th century only a few communities had electricity access from local turbines, managed by local grid operators. 1954 gave birth to not only the inauguration of the first large scale hydro power plant of 30 MW, but also the vertically structured National Electrification Program and its ambition to provide electricity services to all of El Salvador (CNE, 2019b). The power system was managed publicly through la Comisión Ejecutiva Hidroeléctrica del Rio Lempa (CEL), who stayed in charge of both the major production plants and the operation of the national grid (CNE, 2017a). The first 20 years gave rise to a rapid growth of the national grid, and in 1970 most of the Salvadoran territory had electric supply (Grupo CEL, 2015). In 2016, briefly 60 years later, the Salvadoran national electrification rate was 96%, the next highest in the region behind Costa Rica (see Figure 2). Figure 8 shows an up to date Salvadoran map with the national transmission system and major power production plants, and Figure 9 shows the 230 kV grid that connects the Central American countries.

Figure 8: El Salvador's transmission system and main power plants. Source: CNE (2016) 14. Used with permission.

Figure 9: The interconnection of the Central American countries electricity systems. Source: CNE (2016) 15. Used with permission.

The transnational grid is in fact one line (see Figure 9), which makes it vulnerable. In July 2017 for example, a power outage caused by a downed Panamanian transmission line hit millions of users in Panama, Costa Rica and El Salvador (Sibaja, 2017). The vulnerable interconnection becomes problematic regarding the extreme weather events that regularly hit Central America (mentioned in Chapter 1). The transnational Siepac transmission grid has planned capacity reinforcements through a second power line that is to be operational in 2024, but there are indications that the expanded transmission capacity will not withstand the increase in demand that the Central American countries will face in the time to come (Dorothal, 2018).

The 1990s became a time of major energy sector reforms for many of the Latin American countries including El Salvador, driven by a development program from the World Bank. The first step was the foundation of the General Law of Electricity (LGE) which lay the juridical base of the system operation and provides the General Superintendency of Electricity and Telecommunication (SIGET, the main data source in the study regarding El Salvador's electricity sector) the regulation and supervision responsibility. With the superintendency in place, the restructuration continued with privatisation reforms where the previously governmental (i.e. CEL) driven thermal power plants and distribution grids where auctioned to private operators. The national high voltage grid was kept in government control through the newly constituted Transmission Company of El Salvador (ETESAL), and the new electricity market was managed through the Transaction Unit (UT) founded for the purpose. The new market is characterised by supply and demand-based spot pricing. An important role is provided to the distribution grid owners since they take responsibility for the delivery in their respective areas and the invoicing for the integral costs (CNE, 2019c).

2.2.3 Electricity prices

The end electricity price consists of various components which are charged by the distribution grid operators. The main cost covers the Energy Price Transferrable to Tariff (PET) which considers the marginal costs of production (virtually the spot price which makes up 85% of PET), power capacity readiness and maintenance of the national grid and the market (CNE, 2019c). Besides, the end customer is charged for the distribution grid operator's transmission costs and for extra fees, that practically can be considered as the operating expenditure. The invoices that have been presented to the authors have indicated that the PET makes out on average 75% of the total charged cost, meaning that approximately 64% of the end customer price covers the spot pricing.

The spot price covers the marginal cost of the electricity generation. As described in Section 2.2.1, the electricity production depends on the availability of the relatively cheap hydro power. Since the tropical climate of El Salvador provides two seasons (dry and wet), the availability is highly season based. Moreover, dry year anomalies provide an additional uncertainty. The peak month of hydro generation 2010 provided 294 GWh nationally, while the corresponding number the year before was 193 GWh (as pointed out by JICA (2012)). The availability of the cheapest electricity generation is therefore unreliable, which consequently opens for end electricity price variations, both on a seasonal and yearly basis.

The lack of hydro power availability is complemented by thermal power production from petroleum derivatives. The thermal production is significant in both seasons but dominates to a higher degree when the hydro power does not produce at its higher capacities. Thermal production is not weather dependent, but it provides a substantial element of price volatility in another way. The cost of electricity production in Salvadoran thermal power plants is depending directly on the international market price of crude oil: a price which has fluctuated dramatically the last decades. Figure 10 shows the development of the crude oil spot price 1997-2017, Figure 11 the mean annual electricity spot price in El Salvador and the crude oil spot price 2010-2017 on a yearly basis and Figure 12 the electricity spot price in El Salvador and the monthly crude oil spot prices 2016-2017.

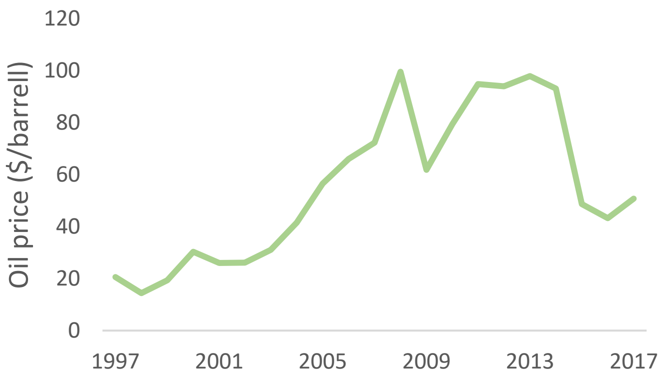

Figure 10. The spot price development of crude oil 1997-2017. Benchmark: Cushing, OK WTI. Source: EIA (2019).

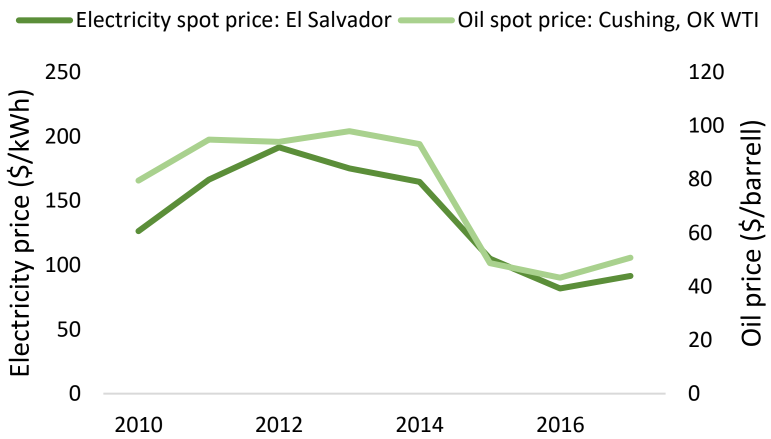

Figure 11. The development of the crude oil spot price (Benchmark: see Figure 10) and the electricity spot price in El Salvador 2010-2017. Sources: EIA (2019) and SIGET (2017) Cuadro 27.

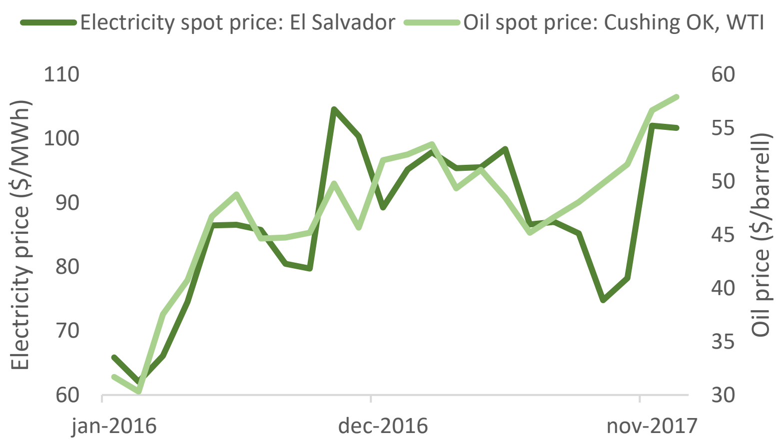

Figure 12. The development of the crude oil spot price (Benchmark: see Figure 10) and the electricity spot price in El Salvador January 2016 to December 2017. Sources: EIA (2019) and SIGET (2017) Cuadro 27.

The figures show not only that the crude oil market price is highly volatile, but also that El Salvador's electricity spot price has followed the crude oil price both on a yearly average the last 8 years and also to a high extent month to month in 2016 and 2017. Zummaratings (2017) affirm that the Salvadoran spot price depends to a high extent on the international petroleum prices and that this is the reason for the relatively low electricity prices the last years. JICA (2012) and CNE (2018) observe that the Salvadoran production capacity in the years following the electricity sector reform only expanded with oil-combustion plants since that type of production generated best profits as it is characterised by high marginal costs which are directly covered by the spot price – resulting in more expensive electricity. At the same time, the World Energy Outlook 2017 states that:

"The future trajectory for oil prices, both their average level and their volatility around this level, is a critical uncertainty for any forward-looking energy analysis." (IEA, 2017, 93).

Despite these currently low petroleum prices El Salvador has the highest electricity costs in Central America 2018, a factor that contributes to the rapidly growing competition driven electricity imports (Molina, 2018).

To mitigate the expenses of the poorest Salvadorans, the government issue electricity subsidies which can cover up to half of the total costs of electricity. The subsidies were expanded in 2018 and are expected to facilitate 950 000 families (CNE, 2017b). To be entitled subsidies there are a few criteria that must be met. Most notably, the consumer has to be an individual proprietary of no more than a single home with a total consumption of maximum 105 kWh per month (La Prensa Gráfica, 2017).

2.2.4 Solar and wind

There is an understanding of the need to produce less expensive electricity in El Salvador, and a way that has been highlighted is to strengthen renewable energy. In 2010, the National Energy Council (CNE) (with responsibility for the social and economic development strategies regarding the energy sector) issued a number of goals for the future. One of the most important goals was to diversify the energy production by expanding the renewable energy sector. The Japanese International Cooperation agency (JICA) was consulted for a thorough investigation in order to provide an integral plan for integrating renewable energy to the Salvadoran power sector (the so called "Master plan"). The report was released in 2012 and included for example energy potential measurements and strategy formulations which have been widely utilised in reports and projects that promote renewable energy. Figure 13 and 14 present the solar and wind power potential map respectively, where JICA points out zones where it is suitable to launch solar- and wind power projects.

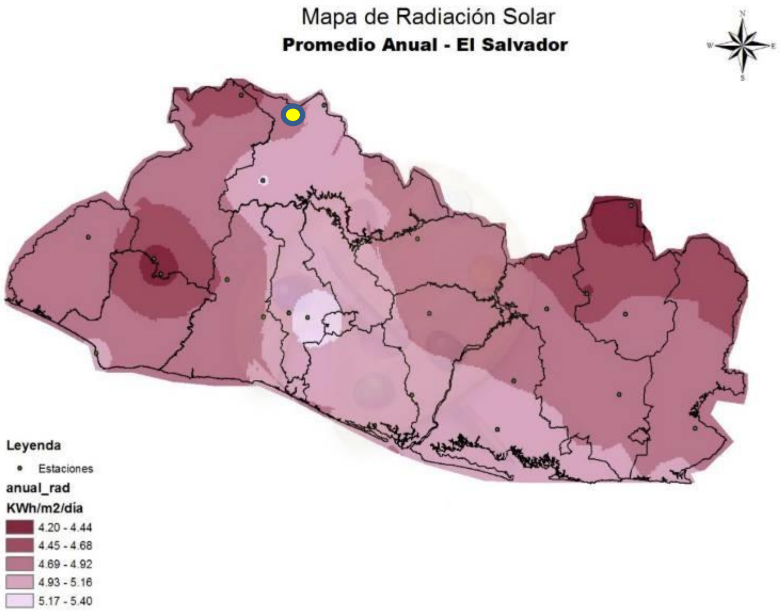

Figure 13. The solar potential in El Salvador. The yellow dot represents the location of Cuna de la Paz. Source: JICA (2012) 4-9. Used with permission.

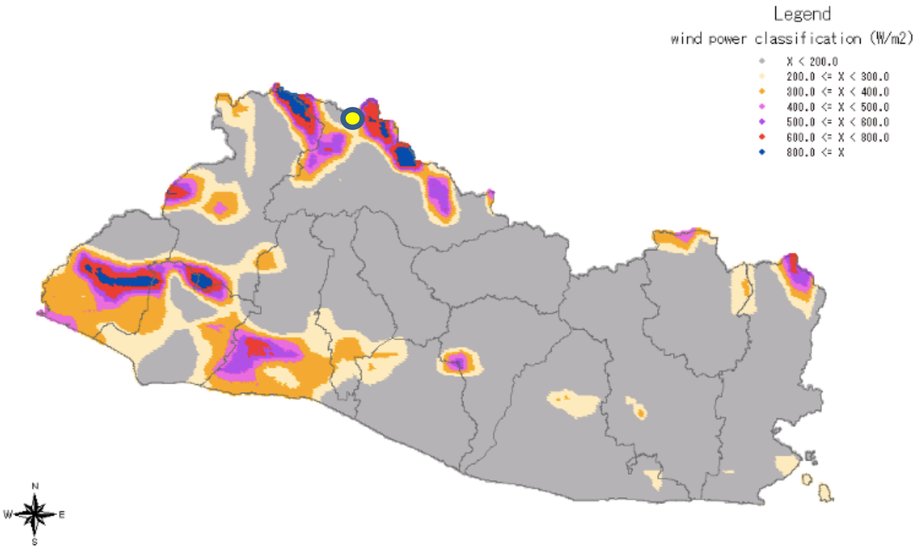

Figure 14. Sites with wind potential in El Salvador. The yellow dot represents the location of Cuna de la Paz. Source: JICA (2012) 7-2. Used with permission.

In 2018, CNE released a new plan (the "Indicative plan") that proceeded with the mission of diversifying the electricity production in El Salvador. The background of the report stated that the increased electricity demand in El Salvador will result in prices three times higher without an active expansion plan. The lead motive of the plan was to avoid even higher electricity prices in the future practically by any means necessary where all price reducing technologies were revised (from solar and wind to cheaper oil derivatives) (CNE, 2018).

The articulated goals of decreasing the electricity prices have resulted in various newly installed solar PV projects. The project type that has attracted most attention is the directly grid connected solar park in projects where global operators are invited by the government to give bids and thus enable major investments in the energy sector. The biggest solar park that is installed in early 2019 is the Providencia park of 101 MW, which is the biggest park in the Central American region (IndustryAbout, 2018). The other finalised parks are significantly smaller; aggregated with Providencia the total solar park capacity is 150 MW (SIGET, 2017, cuadro 35). The electricity price development depends on a variety of factors, but at least it seems like the injection of solar power has contributed to lower electricity prices according to a SIGET press release (Bellini, 2017). According to the earlier mentioned indicative plan, there are plans for a number of large solar parks yet to be installed in the following years, such as the Capella Solar-park of equal size as Providencia that is planned to be finalised in April 2019 (CNE, 2018). At the time of writing (February 2019) not a single utility scale wind power plant is finalised, but there is a financed project of 50 MW which is planned to be delivering power to the grid from April 2020 (Hernández, 2017).

Although considerably smaller in size, there are a number of PV-systems designed for self-consumption in El Salvador. Mainly installed on government buildings, schools and universities, a CNE summary shows that the installed capacity is 25 MW on approximately 130 locations, where most of them most likely are rooftop installations (CNE, 2019d). The JICA-report states that the potential for urban environment PV-systems is high due to the great solar radiation in the country as a whole and especially in the San Salvador metropolitan area (JICA, 2012). The installations of residential PV-systems have not yet started to get under way, only a small number have been performed in the high-class areas. Another type of PV-system solution is the off-grid system, where smaller loads are supplied by solar panels with an intermediate battery storage in areas not reached by the national grid. Two Salvadoran village examples are Caserío los Encuentros (AES El Salvador, 2016) and El Sauce (MITD-Lab, 2019). However, they remain nothing more than a parenthesis due to the high electification rate of the country (96%).

2.3 FUNDASAL

FUNDASAL (Salvadoran Foundation for Development and Minimal Housing) is a private non-governmental organisation that strives to create better homes for Salvadorans with scarce economic resources. With funding from both national and international organisations, they create housing projects throughout El Salvador. The organisation was founded in 1968, when a natural disaster eradicated many neighbourhoods in the capital, San Salvador. The neighbourhoods were mostly populated by impoverished families that lacked the economic capability to fund a rebuilding process. A group of Christians, that had the economic ability, helped the families to rebuild their homes. After finalising the rebuilding, the group started to mobilise a larger organisational structure, since the need to facilitate homes for similar groups of people (whom were either forced to move or to rebuild their homes due to natural disasters or violence) was much needed. Since the start, FUNDASAL has finalised 21 projects, giving over 3000 families new homes (FUNDASAL, 2017a).

2.3.1 Work and philosophy

FUNDASAL has different institutional programs that provides frameworks for how to operate depending on the qualifications for the project design. The “Neighbourhood improvement program” aims to reduce risk factors for violence and strengthen the environment of public spaces. The “New urban settlement program” and the “Rural habitat improvement program” attempts to facilitate new housing possibilities to families in rural areas and areas that have been affected by natural disasters (FUNDASAL, 2017b). All the programs have the intention of creating socially sustainable housing. Parts of the projects have been implemented with the idea of cooperativism. The idea of cooperative housing entered the organisation in the late 90s when FUNDASAL came in contact with the Swedish Cooperative Center (now We Effect). Instead of only building the houses, the cooperative approach creates opportunities for the families to be a part of the construction and maintenance process (FUNDASAL, 2017c). Before initiating a project, FUNDASAL provides training and education in how to construct and build the houses for the people part of the cooperatives. The homes are built by seismic resistant adobe bricks (a type of sun-dried mud bricks) which the cooperativists create, using resources that are normally abundant on the project site. Throughout the building process, FUNDASAL provides the cooperativists with technical expertise and other necessary support. The projects are funded by FUNDASAL and its partners with the aim of making the housing cooperatives self-managing (FUNDASAL, 2017d). As mentioned earlier, FUNDASAL has finalised 21 housing project and has various ongoing projects in different parts of El Salvador. The organisation is often engaged in the political debate, advocating for adequate housing habitat for all Salvadorans. In September 2018, the organisation celebrated its 50th anniversary by inviting collaborators and international organisations for a three-day long congress, containing lectures, workshops and field trips to the different housing projects (FUNDASAL, 2018).

2.3.2 Project Cuna de la Paz

The project Cuna de la Paz is located in northern El Salvador, in the municipality of La Palma, Chalatenango. La Palma had an important role during the civil war, where the town hosted the peace treaty between the guerrilla army and the military in 1992. Figure 15 shows the location of the project site. As Figure 13 and 14 show, the location of Cuna de la Paz has beneficial local energy resources.

Figure 15. Location of Cuna de la Paz (Google Maps, 2019).

The project consists of two cooperative groups (ACOVICUPA and ACOVIAMET) and they intend to build 62 family houses, creating a space for developing social activities, a community center and a water pump facility. The two latter are already built but none of the family houses are yet constructed and there is still no final date on when the project will be completed.

The project also strives to give the cooperativists a possibility to build artisanal workshops with the aim of attracting tourists to the location. The cooperativists have already created a tourist route, which gives a view over the nearby mountain landscape and there are plans to also start a small café. With the approach to attract tourists, the cooperatives are hoping to benefit the community economically and create job opportunities. They have also created a cultivation area with the intention of becoming self-sufficient to a high extent when it comes to vegetables. The family houses will all be built with the same design and each house has an area of 64 m^2, including two bedrooms, a kitchen, a living room and one bathroom.

Figure 16 consists of pictures of the project site with the community center, the water tank and the area where family houses will be built.

Figure 16. Community center, water tank facility, cultivation area and family house area. Source: the authors.

All the buildings within the project will have access to a local electricity grid which is operated by the company CAESS. The community center is currently connected, and Figure 17 shows a photo of the local electricity grid, taken from the community center.

Figure 17. Local grid in Cuna de la Paz. Source: the authors.

2.4 Microgrid systems

The concept of microgrids is defined by the U.S Department of Energy as local grids which consist of a group of interconnected loads and distributed energy resources (DER). The microgrid can be connected to the utility grid or be disconnected and work in island-mode, which means that it can meet the end-users demand by ensuring energy supply to the critical loads in a reliable manner. The ability to work independently from the grid mitigates outages and disturbances and therefore strengthens the grid reliability (Smith and Ton, 2012). DER can be different types of energy technologies, storage technologies or demand management applications. The separate elements together constitute distributed generation (DG) for end-use customers in the vicinity (Cultura, 2011) (Microgrid Institute, 2014). Furthermore, Cultura (2011) describes that the implementation of DERs can vary a lot between system designs. Some systems are designed for bigger communities or remote islands, where renewable energy resources are available, whereas some are planned for single or a couple of households. Microgrid Institute (2018) divides microgrids into five different categories:

1) Off-grid microgrids -which are not connected to a utility network, usually found on remote sites and islands.
2) Campus microgrids - which have a connection to a utility network but in the case of an outage to a certain level manages to maintain power on-site. Prisons, universities and hospitals are examples of such locations.
3) Community grids- that provide service to several customers within a specific community.
4) District Energy - microgrids that for multiple facilities can provide electricity and thermal energy for heating and cooling.
5) Nanogrids - defined as a single energy domain or a single facility that operates independently as a very small network.

The energy in microgrids that comes from DG can originate from both renewable and non-renewable energy technologies. Typical energy technologies that are used are photovoltaics, fuel cells, wind turbines, biomass, and diesel generators. When different sorts of technologies are integrated the whole system becomes a hybrid microgrid. DG can generate both AC and DC power, thus the hybrid microgrids have the advantage of producing both types (Nejabatkhah and Yun, 2015). A properly planned design is then necessary to integrate different AC/DC sources and loads. Patrascu et al. (2017) classifies the methods into three different categories; AC-coupled, DC- coupled and hybrid-coupled. In contrast to Nejabatkhah and Yun (2015), Patrascu et al. more emphasises the benefits with systems that are DC-coupled. In a configuration that is DC-coupled, energy sources are connected to a DC bus, and the bus voltage demonstrates the balance in the system. Several energy technologies (such as photovoltaics) naturally generates DC-current. Therefore, a more efficient connection can be obtained since the source can be connected directly via a DC/DC converter. But when the loads in the system needs AC, or the microgrid is connected to the utility grid, a bi-directional converter is needed (Patrascu et al., 2017).

In remote rural areas, Eziyi and Krothapalli (2014) states that the most common systems are based on various combinations of wind turbines, photovoltaics and diesel generators. Nejabatkhah and Yun (2015) highlights benefits of diesel generators, since they can cope with other DERs intermittency problems. However, Hubble, and Ustun (2017) points out that by removing fossil-based power generation (where diesel is the most common) more than environmental benefits are gained; the implementation of diesel generators into a microgrid requires a costly infrastructure, such as road building, fuel transportation, technical understanding of storage and maintenance.

Nevertheless, excluding the implementation of diesel generators and only relying on REMS can be challenging for the operation of the microgrid. Shuaixun et al. (2012) points out some key problems that come with microgrids only driven by renewable sources (such as solar and wind). The first problem is how to balance the intermittency of renewable energy sources with the microgrid loads. According to Katiraei (2008) the microgrid can handle intermittency more easy when connected to the utility grid as the latter can supply or absorb power differences of the microgrid generated power, to balance the system. However, when the microgrid must work in island-mode the power balance can be maintained through different strategies. Pinpointing critical loads within the system is one strategy in order to reassure that vital services work. A type of load that does not need instantaneous energy supply are the deferrable loads, which energy demand can be postponed when power is lacking. Water pumps are an example of a deferrable load within a community microgrid since their function often can be postponed until the power balance is restored.

As mentioned earlier, diesel generators are commonly used in microgrids, and they have the capability of meeting a mismatch between loads and the distributed generation. However, when excluding non-renewable energy sources from a microgrid, Chen (2010) highlights the importance of a good energy storage system. The energy storage system can shave the peak demand or store surplus electricity from DGs and thus work as dispatchable sources. The storage system can contain batteries, fuel cells, supercapacitors or flywheels.

To maintain the function of the microgrid and the balance between the loads and the DG a good control architecture is needed. As pointed out earlier and additionally by Rat (2018), fluctuations and weather dependent renewable energy sources pose a challenge to the balance of the system, as well as the cost of the equipment. Therefore, the author presents two different management approaches. The first approach is focusing on supply management and differ if the microgrid is isolated or not. The supply management intends to program the production of energy sources so that they meet given constraints for the system. In the first case, when the microgrid is isolated, the costs in order to meet the technical requirements are being minimised. In the second case the operating costs are being minimised and the profit of the DG, when selling to the grid, is being maximised.

The second management approach refers to decisions made with the intention of reducing the energy consumption from the local grid. Load control is part of the demand management and handles how to dispatch the generated electricity and prioritise the different loads. A common dispatch strategy is to always let the DGs operate at full power and serve the primary load. The surplus power can go to the lower prioritised objects, such as serve the deferrable loads or charging the storage system (Rat, 2018). Usually a controller makes decisions regarding the management of the system. Depending of the size of the microgrid, different control structures can be used. For smaller microgrids, sometimes only one controller is needed. When the microgrid is bigger, it can be divided into smaller subsystems.

3. Methodology and data

This chapter presents the different aspects of the methodology and data selection. A perhaps more traditional approach is to allow them two different chapters, since they represent different procedures where the methodology precedes and determines the data selection. It was decided to merge the subjects to one chapter since the work process partially has followed the opposite sequence. Prior to a field study it can be hard to predict what type of data that will be available. The field visit allows the researcher to determine the available data in a way that can be more difficult or at times impossible from afar. Sometimes one has to accept suboptimal data due to unexpected difficulties in acquiring the preferred. This turned out to be the case in a couple of instances in this project (primarily with the grid data acquisition), and when there is a lack of directly applicable data one must be creative. It was therefore considered most suitable to present the methodology and data together.

The chapter consists of 3 sections. Section 3.1 describes the model-related features with selection of optimisation software, the model creation and the outline of the result presentation. Section 3.2 presents the acquisition of the different inputs and how it was decided. Lastly, the sensitivity variables are presented in Section 3.3.

3.1 Modelling procedure and simulation outline

The aim of the study was to investigate how REMS should be designed to optimally enhance the resilience of Cuna de la Paz. Resilience is conceptualised as the energy-affordability and reliability. The key measurements of the REMS performances are therefore metrics that represent the total cost of the electricity over the system lifetime and the amount of the demanded total load that is being satisfied. In Section 3.1.2 the applied metrics are motivated. Another aspect of energy reliability is to examine the possibility for a self-sufficient REMS, where the community can rely entirely on the local system for the electricity consumption and thereby does not have to depend on the main grid performance. It can be seen as an energy assurance if the REMS can satisfy the load demand entirely by local renewable production. Therefore, this reliability aspect was also taken into consideration in the study. Section 3.1.3 Result outlines how the simulations were motivated and structured.

The study setup needs to be carried out as a balance act where local information and viewpoints are set against academic conventions. This understanding has been considered in the data collection and modelling- and optimisation processes and has led to an approach emphasising the use of local primary sources in the data collection, while the modelling and optimisation has followed established conventions in the hybrid energy system evaluation field.

3.1.1 Modelling and optimisation in HOMER Pro

Since the strive was to create and optimise the REMS model in a procedure similar to other studies in the field to make the results comparable, it was regarded as preferable to utilise a widely used integral software for the purpose. Evaluating affordability and reliability in REMS-models is a task that in itself is rather complex since various aspects need to be considered (such as different production setups, control system designs, grid performance, etc.) and thus leaves a wide range of design decisions and parameter selections to be estimated. Models created from scratch in softwares such as MATLAB or Python give the designer a full degree of freedom in the design which certainly can be of interest in projects where the subject of study is the performance of specific technical setups. This study however aims to evaluate optimal REMS setups on a more general level, which therefore makes a broadly used integral software for the purpose a suitable selection.

By examining the field of REMS evaluation in different site-specific cases it becomes clear that one specific modelling- and optimisation software is frequently used (for example in Hubble and Ustun (2017)**,** Sawle et al. (2017), Panhwar et al (2017), Frisk (2017), Li et al. (2018), Glania et al. (2016) and Silva (2011))**:** HOMER Pro, provided by HOMER Energy LCC and originally developed at the National Renewable Energy Laboratory (NREL) (referred to as simply HOMER in the report). The acronym stands for Hybrid Optimisation of Multiple Energy Resources and its website states: *"The HOMER microgrid software navigates the complexities of building cost effective and reliable microgrids that combine traditionally generated and renewable power, storage and load management.* (…) *HOMER is the established global leader for microgrid design optimisation and feasibility."* (HOMER Energy, 2019). Sinha and Chandel (2014) describe the edge of HOMER in comparison to other similar softwares as its simulation engine, which is designed to handle denser simulations, along with the possibility to combine off-grid and on-grid applications (which also is highlighted by Mishra et al. (2016)**)**. Zahraee et al. (2016) points out the software's ability to construct sophisticated sensitivity analyses with various factors. Those aspects are critical for a study like this, where the objective is to investigate optimal microgrid designs for resilience provision from a variety of approaches, and thus requiring the possibility to simulate multiple setups with various sensitivity cases.

HOMER simulates the system combinations, presents the configurations based on optimal economical result and provide sensitivity analyses for the defined sensitivity variables. The simulations are made with all allowed component sizes for all component combinations. In each time step, energy balance calculations are made where the energy demand and supplies (of the different sources) determine the flow between the components. In systems where non-momentary units are included, such as generators and batteries, the applied control parameters decide the components behaviour. Based on the selected performance specifications which give the user the option to regulate the simulations (such as allowed capacity shortage which was utilised in this study) the system configurations that do not fulfil the criteria are discarded. The total system cost over the specified lifetime for the eligible system combinations (including capital, replacement, operation and maintenance and fuel) are estimated as the Net Present Cost (NPC), a metric that is regarded as the primary economic figure and on which the optimisation is based. NPC is estimated as the total lifetime costs minus the present value of all the earned revenues over the system lifetime with a real discount factor that accounts for the change of value over time. HOMER presents the optimal system combinations and the optimal component sizes sorted on lowest NPC. The same procedure is made for every sensitivity case, and the results are presented as a hierarchy of the optimal system combinations for each sensitivity case. Various metrics such as levelised cost of energy (LCOE), payback time and capacity shortage are included in the presentation of each simulation.

3.1.2 System modelling

The Cuna de la Paz project was described in section 2.3.1. The cooperative structure that marks the project brings a combination of collective and private property which has implications for the ownership of the microgrid system. The ownership and economic benefit structure of the implemented REMS can be arranged in different ways. A setup which would go well together with the purpose of the project (and also with this study) to facilitate the situation for the cooperativists would be to fund the system centrally (a work suited for FUNDASAL), while the self-produced energy would prosper the cooperativists directly through cheaper electricity bills. There are certain trade-offs that would need to be resolved, not least the balance between the central ownership and the provided benefits to the households. These ownership issues are outside the scope of this study, nevertheless they need to be considered for the modelling. To not complicate matters more than necessary the community was modelled as one unit. That is a simplified approach, since the project will at least consist of 62 privately owned houses along with the cooperatively owned community center, water pumps and public lighting. However, modelling as a single unit has substantial benefits. Most importantly it provides simple and easily understood metrics for the performance of the whole system (including the total production, storage, control units and loads), which is desirable when investigating the potential on a general level. Besides, HOMER is not designed to handle a wide range of electrical load profiles or complex ownerships. Regarding the advantages that the software brings, the best suited choice was considered to simplify the community to one unit containing everything. The disadvantage is that this setup does not clarify how each cooperativist reaps the benefits of (supposedly) cheaper electricity. But again, that would not be possible since the ownership structure is not yet specified.

The constructed process model is adapted to suit with HOMER and is presented in Figure 18.

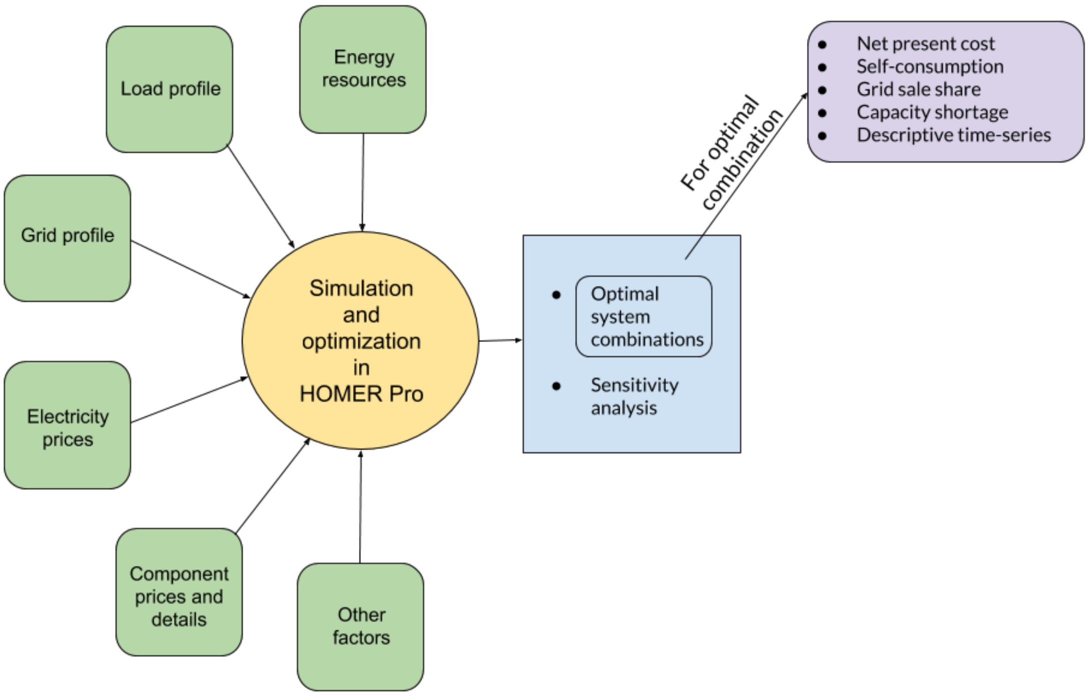

Figure 18. Schematic representation of the optimisation procedure.

The green boxes represent the various input factors that were the basis for the optimisation in HOMER that is illustrated by the yellow circle. The result of the optimisation is represented by the blue box where both the optimal system combinations and the different sensitivity analyses are provided. The purple box shows the information that is presented about the optimal system of the different scenarios that are described in the following sections. The selected data resolution was hour-based, since it makes the simulations run-time manageable (unlike the minute-resolution profiles tried, which demanded multi-hour run-times for simple setups).

The optimisations were executed with regard to net present cost (NPC) since it is an integral economic figure that takes all costs and revenues of the system lifetime into account and therefore fully accomplishes the measurement of the energy affordability aspect (very straight forward since HOMER's optimisation is based on NPC). To account for the energy reliability, the constraint of a maximum (yearly) capacity shortage is added. In HOMER, capacity shortage is defined as the difference between the required operating capacity and the available operating capacity in each time step. The required operating capacity is the load added up with the by the user chosen operating reserve (which is a safety measure to ensure that the system has marginals to provide more power than precisely what is needed). The unmet load-metric was considered to be better suited to correspond to the energy reliability aspect of resilience, since it is defined strictly by the difference between the load and the provided operating capacity and thereby gives a measure of the exact amount of energy that the system has failed to deliver to meet the direct demand (see HOMER Energy (2018)). By setting the operating reserve to 0, the unmet load and the capacity shortage becomes equal. This was done in some of the cases (see Section 3.1.3) in order to constraint the unmet load in the optimisations. Since capacity shortage and unmet load are synonymous in this setup, the report continuously refers to only capacity shortage.

The microgrid model that was implemented in HOMER is presented in Figure 19. It shows the schematic of the most complex system that includes all possible components. The green cells represent the energy resources and the orange cells the corresponding production units. The grey cell represents the power system component, the pink cell the grid, the purple cell the batteries and the blue cells represent the load units.

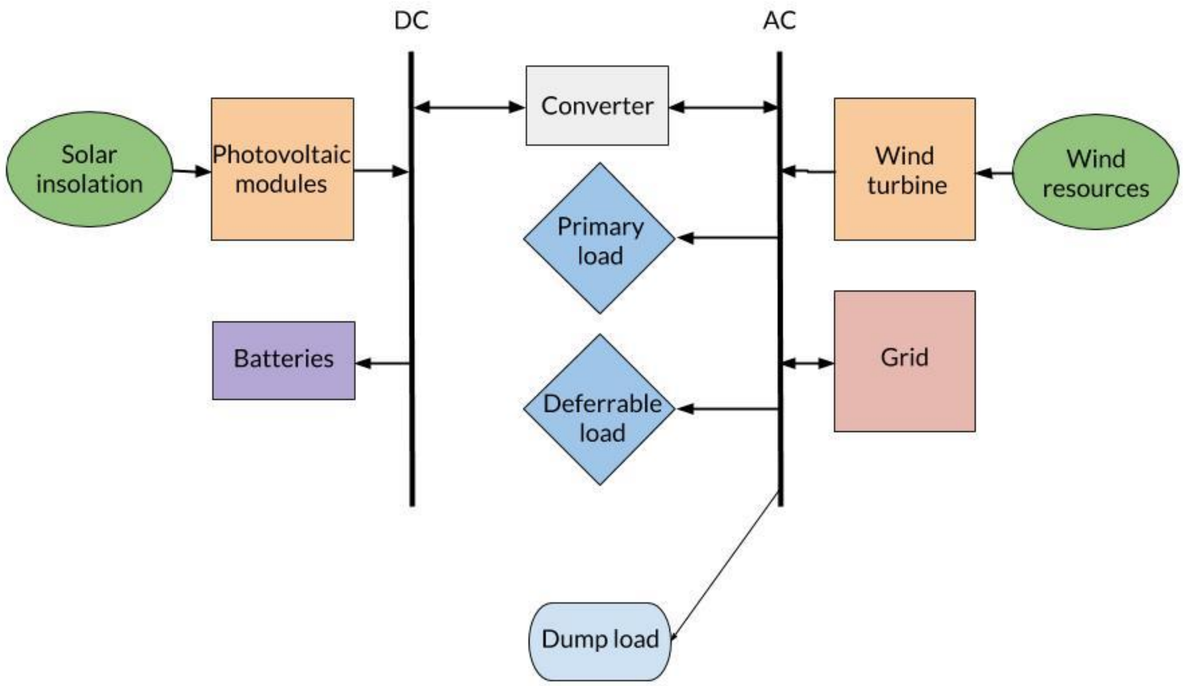

Figure 19. Schematic presentation of the most complex system combination.

The DC side consists of the photovoltaic modules that produce electricity from solar insolation and the batteries. The wind turbine (powered by wind energy) and the local grid are connected to the AC-side along with the deferrable load (i.e. the water pump) and the primary load (being the rest of the community). The grid is setup to both provide power when needed and to receive power through grid sales. The excess energy that is produced during grid failures, when the loads are met and the batteries fully charged, is accounted for by the dump load (a security measure which in practice can be regarded as light bulbs that consume excess electricity). The converter serves multiple functions: it converts DC power to AC to meet the loads, it controls the battery charge, it converts AC to DC power for battery charging, it regulates the microgrid's voltage and frequency and it runs the dispatch strategy (see next paragraph).

The dispatch strategy is the directive that is given to the microgrid system about how to run the controllable units, which typically are the generators and the storage units. It also decides the priority of the power sources. Since the systems modelled in this study are not connected to generators the dispatch strategy controls the charging and discharging of the batteries and the priority given between the local production units and the grid. Naturally, the local energy production is prioritised since the aspiration is to implement renewable energy, which in practice means that grid power is supplied when the locally produced power does not manage to serve the loads. The batteries are set to charge only with excess power produced locally (when the production is higher than the demand) and discharge in times of grid outages which implies that the batteries and the grid never operate the microgrid simultaneously. The batteries only discharge to a 10 percent state of charge to avoid deterioration. The deferrable load is served primarily when the microgrid has own production, and is being complemented with grid power at need. The purpose with the designed dispatch strategy is to allow the system to increase the self-consumption and at the same time increase reliability.

3.1.3 Simulation and result outline

For the model optimisation, two grid profiles were created **(**motivated and presented in the Section 3.2.3**)** to examine the importance of the grid performance within the model. Hence, two scenarios were created in order to allow the two grid profiles to be simulated independently. Therefore, the model was optimised with reasonable size boundaries (presented in Section 3.2.6) in the so-called Reliable grid scenario and Unreliable grid scenario (see Section 3.2.3 for details)**.** In addition to the two scenarios, a scenario was created were the self-sufficiency of the system was investigated (called the Self-sufficiency scenario). In this scenario, it was not possible to buy electricity from the grid, only to sell electricity. Therefore, it only relies on the components within the system to generate electricity in order to meet the demand. The motivation of the third scenario is based on the notion of investigating how self-sufficient the whole system is capable of being. The self-sufficiency is conceptualised as meeting the capacity shortage constraint described for the earlier scenarios. Since the third scenario only aims to give an answer theoretically regarding the potential of the local energy to satisfy the load, no restrictions regarding economic capacity or maximum size for the units (except for available space) or maximum cost was included within the optimisation.

For the two first scenarios, two optimisations were executed which were separated by the maximum allowed capacity shortage. In the first optimisation case (further entitled as the base case), the NPC was optimised without any constraints regarding the capacity shortage. The other case (the constraint case) strived to enhance the reliability of the system by counteracting power outages. In consequence, the NPC was optimised with the constraint of only allowing 1% of capacity shortage during the project lifetime. The end result from the reliable and unreliable grid scenarios is presented as The optimally resilient system. It was defined as the system with capacity shortage below 1% with the lowest NPC, which thereby best satisfies the affordability and reliability aspects, and therefore can be considered to contribute mostly to enhanced resilience.

The self-sufficiency scenario where a no-battery case and a battery-case are presented, illustrate the potential of microgrid systems of providing self-sufficiency to the community. The end result in that scenario is an evaluation of the potential for self-sufficiency. Table 1 visualises the different scenarios, their cases and the end result.

Table 1: Representation of the result outline. The three scenarios have two cases each, where the end result either is a specified optimally resilient system or a more general evaluation of potential.

Scenario	Scenario: Reliable grid		Scenario: Unreliable grid		Scenario: Self-sufficiency	
Case	Base case	Constraint case	Base case	Constraint case	No-battery case	Battery case
End result	*The optimally resilient system*		*The optimally resilient system*		Evaluation of potential	

3.2 Data

The continuation of this chapter describes and discusses the data acquisition and presents the obtained data.

3.2.1 Energy resources

The energy resources used in the modelling were solar and wind data. The resource data used in HOMER can be based on a monthly average or a time series with an hourly or minute-based time step.

Data discussion

HOMER lets the user fill in coordinates and provides wind and solar data collected by the NASA Surface Meteorology and Solar Energy website. HOMER then presents a monthly averaged value scaled from 22 years of data collection (NASA, 2018). HOMER also leaves the user with the option to import own resource data. Even though the data collection approach in this study emphasises locally obtained data, it was considered more reliable to employ data collected for 22 years by NASA (which in addition is the standard approach in HOMER simulations).

Solar resources

Figure 20 shows the downloaded solar data from NASA's Surface Solar Energy Data Set.

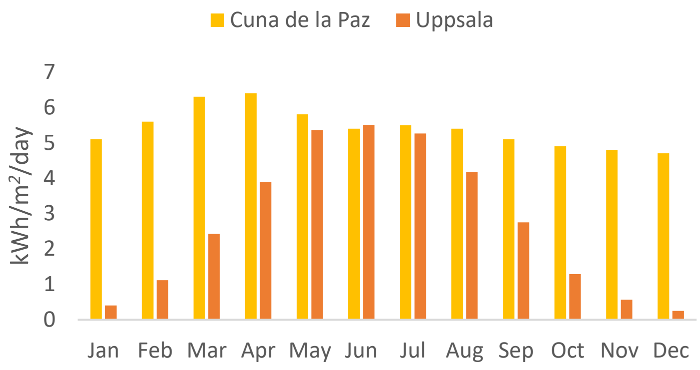

Figure 20: Solar insolation data for the location of Cuna de la Paz and Uppsala. Source: NASA (2018).

As presented in the figure, the solar radiation is relatively even throughout the whole year in contrast to the reference Uppsala, Sweden. The average solar radiation is 5.4 kWh/m^2/year in Cuna de la Paz and 2.8 kWh/m^2/year in Uppsala.

Wind resources

Figure 21 shows the monthly average wind speed used in the study with data from NASA's Surface Energy Data Set.

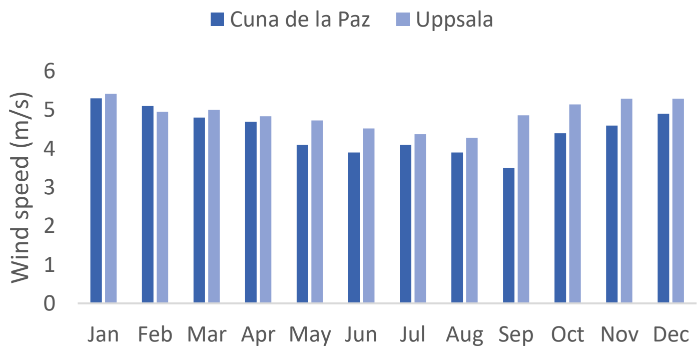

Figure 21. Wind speed data for the location of Cuna de la Paz and Uppsala. Source: NASA (2018)

The wind speeds vary slightly more than the solar radiation but are still somewhat even. The annual average wind speed is 4.4 m/s in Cuna de la Paz and 4.9 m/s in Uppsala.

3.2.2 Load profile

The load profile describes the electricity demand for the system model. HOMER can create generic load profiles or import hour- or minute-based time series data for a whole year. The software can classify loads differently, depending on their priority and importance. Within the presented system, two different load types were taken into consideration. The primary load was classified such as an electric demand that must be served directly according to an explicit time schedule. A deferrable load is requiring a certain amount of electricity within a given time period. Thus, the timing is not as important as for the primary load. The family houses, the community center and the public lighting was considered to represent the primary load. The water pump for the project was modelled as a deferrable load. In the load profile no difference between weekdays and weekends were considered, since the activities within the community are expected to be the same during the whole week. The load profiles were constructed in MATLAB with the assembled information.

Data discussion

When collecting the data for the load profile, a complicated obstacle that could not be overlooked was the fact that the family houses not yet were built. If the houses were built a convenient method to estimate the load would have been to collect the data from the family houses electrical bills. This was made when estimating the load for the already built community center and the water pump.

In order to handle the issue, different methods were considered to obtain information about the family houses. In HOMER there is a simple method for creating generic load profiles for both residential houses and communities. By estimating the peak load, the program creates a standard daily profile. There is also a possibility to download regional specific load profiles from databases. However, since the methodology for the data collection within this study strives to emphasise the local connection, the data was collected through interviews with five cooperativists and close collaboration with the civil engineer responsible for the ongoing construction in Cuna de La Paz. The selected method was considered more suitable for the study for creating a more authentic load profile. One can argue that it would have been a better approach to send surveys to the different families to get a wider range of information. This was considered difficult to carry out due to the different current habitations of the families involved (who yet have not moved to the community). The issue was discussed with the FUNDASAL staff, and the interviews was considered the best and most viable alternative.

Family houses

To estimate the load demand for the family houses five interviews were made and they lasted circa 20 minutes each (the questions are presented in Appendix B). The interviewees gave satisfying answers regarding their electricity usage and similar responses regarding which electrical appliances they would use in their home. Thus, an estimation on which appliance types to include in the load was made. The power of the appliances was estimated via the Salvadoran power company AES El Salvador, which provided an average number on their website based on local appliance and consumption data (AES, 2018). Table 2 presents the appliance types, their estimated power and hours used per day. It is notable that kitchenware such as oven or stove was not included since the kitchens are powered by gas. The refrigerator is only used 10 hours per day since the compressor (its power consumer unit) is turned on and off during the day.

Table 2. The appliances and usage that the load profile is based on.

Appliance type	Power (W)	Hours used per day
Refrigerator	200	10
Television	75	5
Mobile charging	150	3
Low energy light bulbs	200	7

With the appliances above considered, the estimated average load for a single household was estimated to 4.10 kWh/day with a 0.54 kW peak. In order to make it more realistic, an hourly 10% random variability was implemented for each family house demand (which is recommended as default in HOMER and exercised by Frisk (2017)). This results in an estimated 125 kWh monthly usage for each household.

Community center and public lighting

The community center was constructed 2017 and is used by the cooperativists every Sunday for community meetings. The activities in the community center that includes electricity usage are lighting, computer equipment and a speaker system. The cooperativists receive a monthly electrical bill for the electricity usage, where the monthly consumption is presented. To estimate the daily load for the community center, an average load was estimated based on electricity bills for six months usage. The estimated daily usage was then adjusted and verified with the help of the staff of FUNDASAL in order to create an adequate daily profile when the community center will not only serve as a location for Sunday meetings. The load was estimated to 5.4 kWh/day.

The public lighting is designed to illuminate certain areas within the community during evening and night time. Currently, no drawings have been made for location and number of light bulbs that will correspond to the public lighting. Thus, in collaboration with FUNDASAL, the public lighting was estimated to 4.7 kWh/day.

Aggregated primary load

Figure 22 shows the aggregated AC primary load profile that is used in the model. The time series that was imported consisted of 8760 points. It includes the community center, public lighting and the family houses. The variation of the hours is estimated from the interviews with the cooperativists and the FUNDASAL staff.

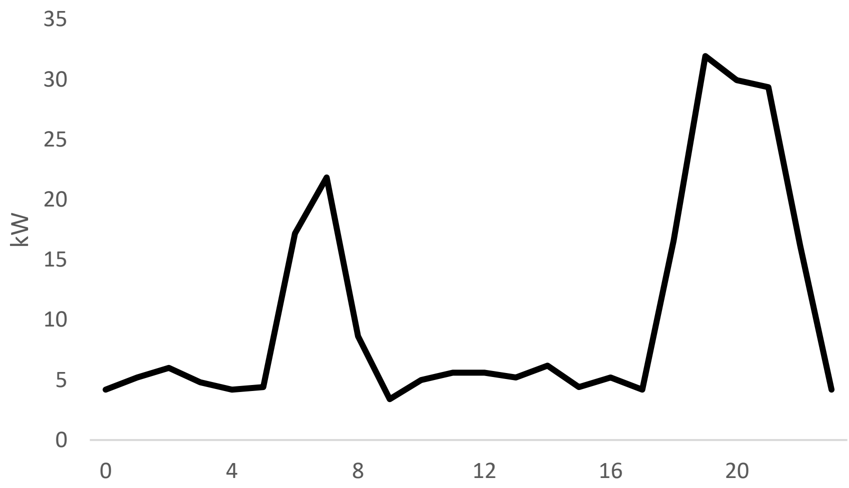

Figure 22. Aggregated AC load profile, presented as the average day.

The scaled annual average electrical load of the system is 260 kWh/day and the peak load is 34 kW. This gives an annual load of 95 500 kWh.

Deferrable load

The already built water pump is designed to work 16 hours per day. As mentioned before, the water pump is modelled as a deferrable load which means that it can be served at any time within a given period. Together with FUNDASAL staff, the load was estimated to 60 kWh/day with a 3.7 kW peak power.

3.2.3 Grid profile

The reliability of the local grid is a binary measure where the grid either works or is out of function. HOMER imports grid data as a binary time series of either hourly or minutely resolution.

Data discussion

Since the Cuna de la Paz-project is under construction and not a single family house is built yet there is no primary data to be found of the local grid, a grid that is yet to be expanded and dimensioned. Section 2.3.2 provides a picture of the present grid, which at this point is a line connected to the community center. The grid profile therefore had to be modelled with data that is not directly connected to the studied community.

CAESS is the distribution grid operator in the department of Chalatenango, where Cuna de la Paz is located. It was evaluated that the best data on which to base the grid profile would be real grid performance data from a hub in the proximity of the project, in a rural part of the municipality of La Palma or San Ignacio (the neighbour municipality), preferably several years of data. Unfortunately, the attempts to come across such data failed even though various attempts to get in contact with the owner of the distribution grid were carried out. An information source that turned out to be valuable in this pursuit was the Yearly Statistics Bulletin (Boletín de Estadísticas Eléctricas) publicated by the General Superintendency of Electricity and Telecommunication (SIGET**,** presented in Section 2.2.2), who has the responsibility of collecting official electricity sector statistics of El Salvador in cooperation with the distribution grid operators among others. SIGET has in every bulletin since 2003 presented quality indices of the distribution grid operators divided in the categories of urban and rural grids. These indices provide a long-term information source of the quality of the power supply in the Salvadoran grids, and this information was considered to be satisfactorily as a basis upon which to construct the local grid profile.

The main strength of this official statistics-approach is that even though there could be a risk of biased data, that risk is the least possible in this context since the information is regarded and presented by the authorities (there are occasions where data is presented as Not Applicable due to an unrealistic presentation by the data owner). The only way to get more reliable data would be through own measures, which would not be possible to conduct for an entire year due to the limited time of this study. The main weakness of the approach is that the presented data is a merge of all the grid operator’s urban data as well as rural data. CAESS operates a region at the size of 4 600 square kilometres, which makes the rural grid data rather unspecific. This has been regarded as an acceptable uncertainty for the purpose of the study, since it still is official data of rural grid performance in El Salvador.

Creation of the grid profiles

The indices that were used as basis of the grid data were SAIDI and SAIFI, which indicates the “behaviour” of the system outages. The System Average Interruption Duration Index (SAIDI) is a frequently used performance measurement for sustained interruptions and measures the total duration of an interruption for the average customer in a system. The System Average Interruption Frequency Index (SAIFI) indicates the average number of times that a system customer experiences an outage (Layton, 2014). Based on the index values a grid profile was created by randomising the outages based on the indicated probabilities from the SAIDI and SAIFI-data. The random approach was considered suitable since according to the SIGET bulletin (Gráfica 34) the vast majority of all the outages are spontaneous, i.e., not planned. The grid profile was created with hourly resolution since that was the selected resolution of the simulation.

Figure 23, 24, 25 and 26 present compilations of the SAIDI and SAIFI-data for CAESS rural grid from the SIGET-bulletins 2003-2017, where the data is presented on monthly and yearly basis.

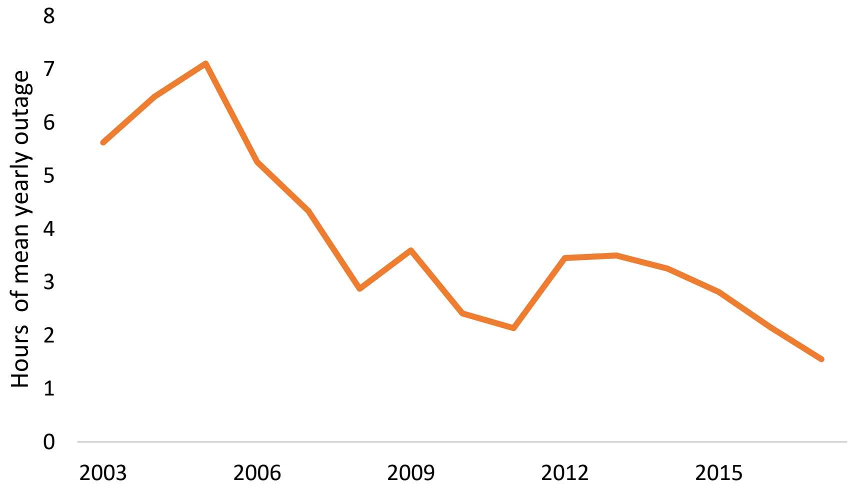

Figure 23. Mean SAIDI per year (2003-2017). Source: SIGET (2003-2017)

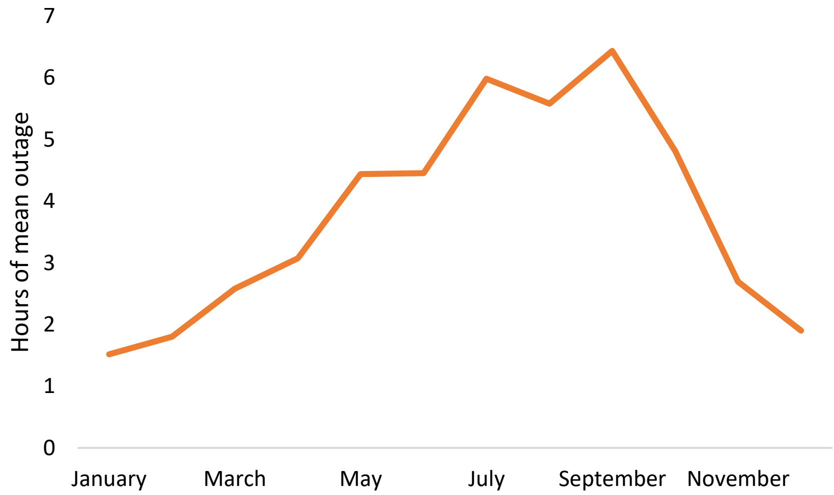

Figure 24. Mean SAIDI per month (2003-2017). Source: SIGET (2003-2017)

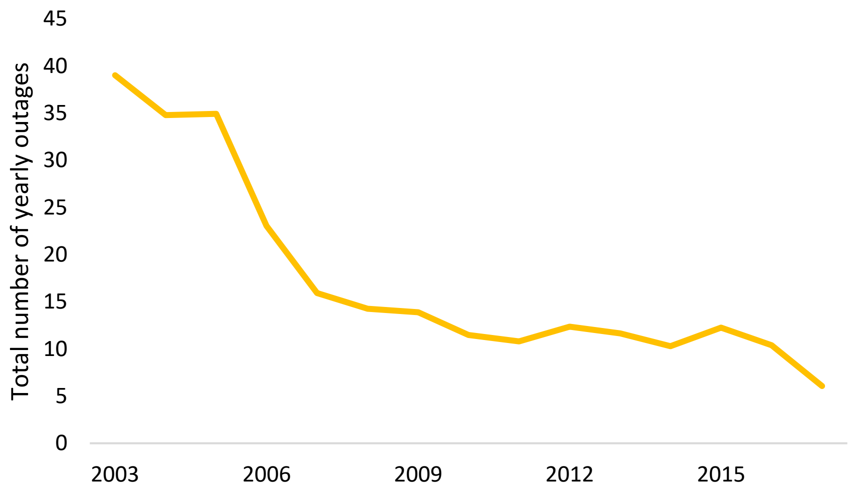

Figure 25. SAIFI per year (2003-2017). Source: SIGET (2003-2017).

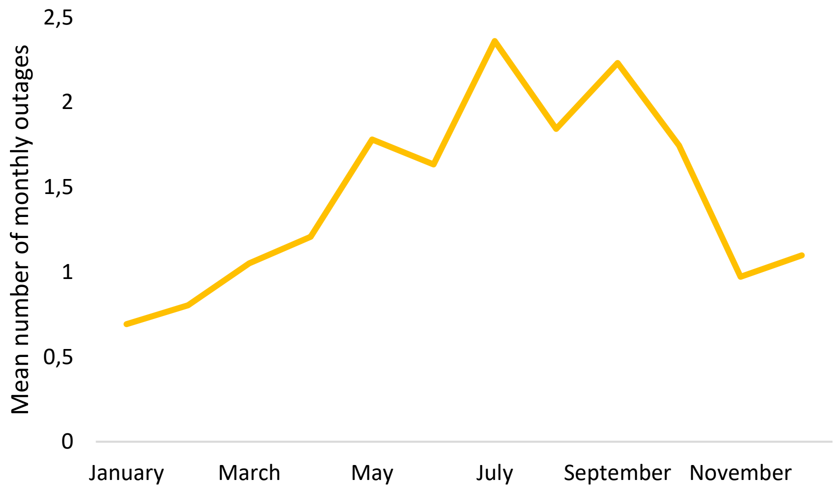

Figure 26: SAIFI per month (2003-2017). Source: SIGET (2003-2017).

It appears that both indices have decreased substantially during the time period, most clearly since 2005. The mean duration of a power outage in 2017 is a quarter of the 2005-value, and that the mean frequency in 2017 is five times lower than in 2005. At the same time the data indicates clear seasonal variations, with both longer and more frequent outages in the period of July-September (which coincide with the rain season) than the rest of the year.

Since the data indicates clear differences in the grid performance during the presented time, and the grid performance is a key factor in the modelling, it was considered important to create two grid profiles to the simulations. The first profile, the reliable grid, represents the recent grid performance (based on 2017-data) with fewer and shorter interruptions. The reliable grid is considered to be the more prevailing for the project, since the data it is based on is up to date. The unreliable grid-profile on the other hand is based on data from 2005 with the purpose of representing a grid with more and longer outages, to see if and how it affects the simulation results. By basing the simulations on very different grid profiles the optimal system solution can more clearly be determined along with its sensitivity to the grid performance.

The SAIDI and SAIFI for the two grid profiles were constructed by scaling the monthly average values 2003-2017 with the values of 2017 for the reliable grid and 2005 for the unreliable grid. It was considered wise to weight the profiles with the monthly average of the different years in order to decrease the impact of year anomalies. Figure 27 present the outcome for SAIDI and 28 for SAIFI.

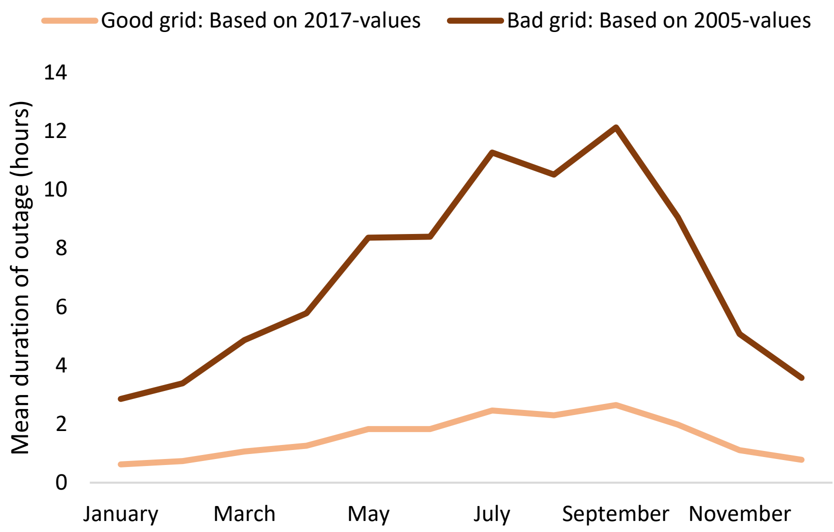

Figure 27. SAIDI profile for the grid in 2005 and 2017.

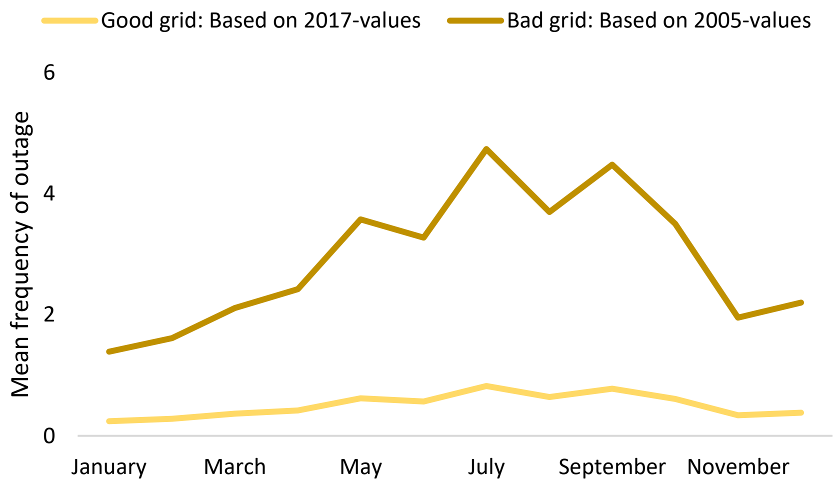

Figure 28. SAIFI profile for the grid in 2005 and 2017.

Finally, the grid data was constructed through an own written Python generator created for this purpose, which stochastically produces an hourly resolved year-profile with monthly SAIDI and SAIFI-data as inputs. Based on the inputs, the generator creates daily profiles where each day is characterised by the SAIDI- and SAIFI values of the month it belongs to. For each day, the generator determines if there is an outage by comparing a randomised uniformly distributed number between 0 and 1 with a generated poisson distributed number with the event rate λ, being the month's SAIFI-value divided by the month's number of days (which accounts for the daily outage frequency). If the uniformally randomised number is smaller than the poisson randomised, an outage occurs that day, which extension and timing is determined by a similar probability-based process. If not, the day is provided 24 data points of 1. Each day is added to a year list, which is the presented output in the end of the year generation. The validity of the generated grid data has been confirmed with officials from FUNDASAL who have been working in the region. The generated profiles that were imported into HOMER prior to the simulations are presented below.

Reliable grid-profile

The produced profile for the reliable grid is presented in Figure 29.

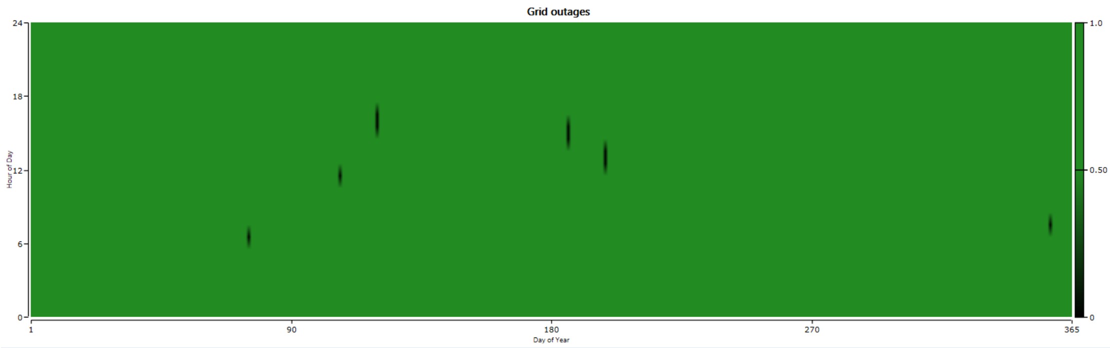

Figure 29. The profile of the reliable grid based on 2017 SAIDI and SAIFI data.

The chart should be understood in the following way: the x-axis indicates the day of the year (1-365) and the y-axis the hour of the day (0-24). Green indicates that the grid is in function, and black that there is an outage. That means that the generated reliable grid-profile includes totally 6 outages, with a duration of either 1 or 2 hours. A comparison with the SAIDI and SAIFI-profiles of the reliable grid indicates the validity of the generated data.

Unreliable grid-profile

The generated unreliable grid-profile is presented in Figure 30.

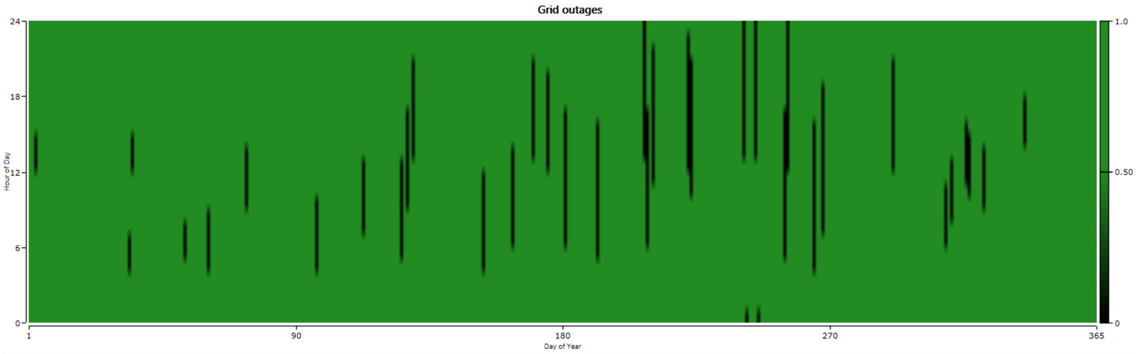

Figure 30. The profile of the unreliable grid, based on 2005 SAIDI and SAIFI data.

Compared with the reliable grid, this profile has several more outages (35 in total) and they are much longer (some up to 12 hours).

3.2.4 Electricity prices

The NPC calculation depends to a high degree on the price of the purchased electricity from the grid. High electricity prices make it more favourable to install higher production capacity since the relative gain increases (and the other way around). It is therefore important to be clear about how the grid electricity price has been modelled prior to the obtained results.

Data discussion

There is no way to precise the electricity prices for a consumer over a 25-year long future period without assumptions. The electricity price for the end user depends on a variety of factors, such as generation costs (see section 2.2), price structure (i.e. varieties depending on connected power capacity or consumer type, factors that affect Salvadoran consumers utility bills), distribution charges, taxes and subsidies. Instead of estimating each single factor with the risk of missing out on important circumstances that give the assumptions little validity a simpler approach was chosen, which still was estimated to be of high quality. In SIGET's Yearly Statistics Bulletin, information about the yearly average end electricity price of each distribution grid operator is presented over a 20-year period along with the average yearly price growth. The Bulletin also publishes the monthly average electricity prices (presented in Appendix C). The electricity prices in the model was based on this information. This gives a solid price approximation based on the actual average price of CAESS consumers with the long trend price development taken into consideration. The advantage of using a template price estimation based on long term data is that it is a safe way to assume a development in a complex environment, where one cannot be criticised of bald or un-based estimations. With this approach the general trend becomes covered in the safest possible way, although finer details remain unconsidered.

Section 2.2.3 describes the electricity subsidies of El Salvador, which is a significant political tool for decreasing the expenses of the poorest part of the population. Although the project of Cuna de la Paz is directed towards poorer groups, where many at the time being certainly are being granted electricity subsidies, the impacts of the subsidies have been excluded from the model. The main reason is that the approval of the subsidies is dependent on a number of terms (such as a maximum electricity consumption of 105 kWh/month, that the house is to be used only as a home and that the recipient is not owning other properties), and that there is no information about if the subsidies can be granted if the recipient has own energy production. Furthermore, the designed load profile of each household exceeds 105 kWh/month (whereas the estimation in the load profile is 125 kWh in a 30-day month), which disqualifies the customers from the subsidies.

Electricity prices

The average final electricity price for the CAESS customers 2017 is $0.1882/kWh (US dollar), and the average yearly price growth is 2.1% (SIGET, 2017, Cuadro 45). Based on this information, the first year average end electricity price in the model was the same as the average 2017 price, while based on the average yearly price growth the second year the average end electricity price becomes $0.1922, the third year $0.1962 etc.

However, the model is based on monthly electricity prices and not yearly. The basis for the monthly price profile was the data presented in (SIGET, 2017, Gráfica 32) scaled with the specific CAESS average price. Figure 31 present the month values used for year 1 in the model.

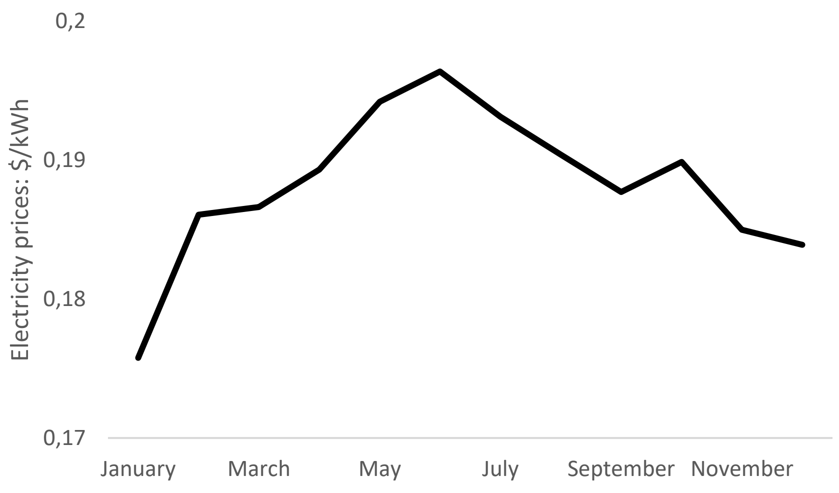

Figure 31. Electricity costs used year 1. Note the broken y-axis.

Naturally, in the same way as with the average yearly price, the month values increase with 2.1% per year in the model.

3.2.5 Component prices and details

The costs for the different components that HOMER requires are the capital cost ($/kW), replacement cost ($/kW) and operation and maintenance (O&M) cost ($/year). The capital cost represents the investment for the system component that has to be made initially. Except for the component price itself there are some examples of expenses that should be considered to be part of the capital cost (such as installation costs, necessary electrical components, shipping costs etc.). The replacement cost represents the cost if a part of the system component fails and needs to be replaced. O&M represents a yearly cost that is needed to maintain and operate the system component.

Data discussion

As described earlier in Chapter 1, prices on renewable energy technology have dropped significantly the last years. Previous studies have shown a wide range of estimated costs for different renewable energy components. For example, the capital costs for a PV system in Panhwar et al. (2017), Sigarchian et al. (2015) and Sen et al. (2014) differ between $900/kW and $6000/kW. It can therefore be rather complicated to estimate reasonable costs for a certain component, only relying on previous studies, especially since studies in many occasions are using prices and estimations based on their site-specific context. This is also pointed out by Seel et al. (2014), that highlights how PV system prices differentiate between Germany and the United States, and how different policies and market regulations may affect the costs for system components. It was therefore emphasised to attempt to find local retailers who had knowledge of the component costs in the search for suitable price estimations.

A valuable source in estimating the costs became the power company AES El Salvador, which had experience in implementing microgrids for rural Salvadoran communities. Two meetings were held with representatives from the company who had valuable information about component costs and microgrid solutions. The representatives provided prices for solar modules, converters, batteries and different installation costs for the components. The choice of using their estimated prices was considered important since it anchors the prices to the local area. Unfortunately, they did not have reference prices regarding wind power components. No other local retailer that offered small scale wind power systems was found. Hence, contact was taken with an international company that provided a proposal on what a small scale 3 kW wind power system would cost. However, it was considered important to compare the proposal with information from other sources. Another company was therefore found that offered the same system solution but far less expensive. Since none of the companies had a local connection, it was decided to use the cheaper wind system within the model. Comparing the price estimation with other studies, it is arguable that the utilised prices for the wind power system are underestimated (Panhwar et al., 2017; Frisk, 2017; Sigarchian, 2015).

The lifetime of some components was not provided by AES El Salvador. Therefore, other information was used which in most cases were previous research and suggestions from

HOMER. As mentioned earlier, HOMER requires an input value for a replacement cost for the system components. AES El Salvador did not provide this information, so the assumption was made that the replacement cost would be 10% lower than the capital cost for all components.

Solar modules

Table 3 shows the estimated different costs for the solar modules. The capital cost for the PV system includes solar modules, necessary electrical cable components, aluminium racking and labour costs for the system installation. All costs are estimations given by AES El Salvador. The company stated that the reference price for the solar panels was based on the solar panel Canadian Solar CS3U-355P (355W). The expected lifetime for the specific solar module was estimated based on manufacturer data (Canadian Solar, 2018).

Table 3. The utilised solar module prices.

Capital cost ($/kW)	Replacement cost ($/kW)	O&M ($/year)	Lifetime
1290	1161	17	25

The search space 0-54.7 kW was included in the optimisation for the PV system for the reliable and unreliable grid scenarios. The size for the self-sufficiency scenario was set to 484 kW (see section 3.2.6 for further discussion).

Converter

The converter costs were based on the Victron Quattro 5000VA-converter (Victron Energy, 2018). The product has all the functions that the modelled converter requires, such as DC-AC convertion, voltage and frequency control and battery charge control. Table 4 presents the costs for the converter. The capital cost estimation was given by AES, and the O&M cost is set to 0, since is assumed to be included in the O&M cost for the PV system. The expected lifetime is estimated from Panhwar et al. (2017), since AES did not provide that information.

Table 4. The utilised converter prices.

Capital cost ($/kW)	Replacement cost ($/kW)	O&M ($/year)	Lifetime
890	801	0	20

The search space for the converter was 0-40 kW in the optimisation for the reliable and unreliable grid scenarios. The search space for the self-sufficiency scenario was set between 0-460 kW.

Wind turbine

The capital cost for the wind power system included a wind power generator, a generator tower and the installation cost. The generator costs were estimated via Aleko (2018a; 2018b). The proposals from the company did not include installation and O&M costs. The installation cost was then assumed to be 30% of the wind power system proposal. The O&M cost was estimated through information from the Danish Wind Industry Association (2018). Expected lifetime was set to 15 years within the model. Table 5 presents the costs and lifetime that was implemented in the model.

Table 5. The utilised wind turbine prices.

Capital cost ($/kW)	Replacement cost ($/kW)	O&M ($/year)	Lifetime
2690	2420	53	15

Only one wind turbine is applicable in the model (see following section) and has a rated capacity of 3 kW and therefore makes the only available size estimation.

Batteries

The estimated capital cost for the battery system included battery cost, battery cable costs and battery rack costs, all estimated by AES. The prices from AES were based on the 4 kWh lead acid battery Trojan IND13-6V (Trojan Battery, 2016). However, HOMER only includes certain battery sizes and 4 kWh is not one of them. Hence, a generic 1 kWh lead acid battery, given by the HOMER catalogue, was used in the model and the costs given by AES was divided by four. The O&M cost was assumed to be 0 and lifetime was set to 10, as suggested by HOMER. The summarised costs are presented in Table 6.

Table 6. The utilised battery prices.

Capital cost ($/kWh)	Replacement cost ($/kWh)	O&M ($/year)	Lifetime
297	267	0	10

The search space 0-192 battery units was used in the optimisation for the PV system for the reliable and unreliable grid scenarios. The number of battery units for the self-sufficiency scenario was set to 10 000 (see section 3.2.6 for further discussion).

3.2.6 Other factors

Several factors affect the optimisation which are most suitable to put in a joint chapter since they were too small to have their own section but still very important.

Site specific parameters

Figure 33, obtained from the FUNDASAL staff, shows the site plan including the 62 family houses, the already existing community center and the water pump facility. As shown in the figure, the family houses are divided into six areas. In agreement with FUNDASAL the system is modelled as if the solar modules were installed on the rooftops within the project since no ground spaces were available for instalments. Thus, an important decision regarding which rooftops that should be selected had to be made. Two important parameter estimations were crucial to decide which rooftops to include. The first parameter was the rooftop angle, which with the latitude of the project site has the optimal angle of circa 13°, a sufficient angle to avoid accumulation of dirt (Solar Panel Tilt, 2017). All family houses have the same rooftop angle, which was estimated to 10° with the help of drawings provided by FUNDASAL, which can be seen in Figure 32.

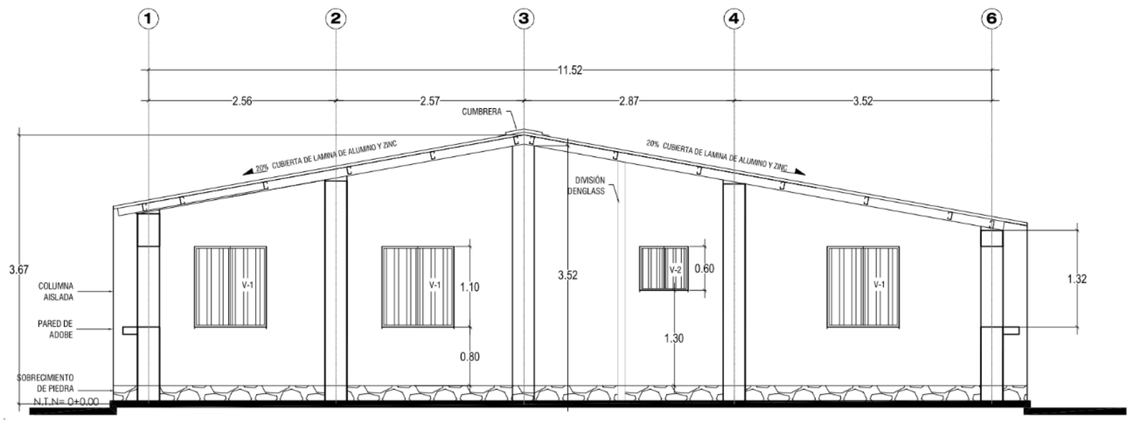

Figure 32: Drawing of a typical family house in Cuna de la Paz. Source: FUNDASAL. Used with permission.

The rooftop angle of the community center was estimated to 6°. As Figure 31 shows, a family house consists of a two-divided rooftop. According to the FUNDASAL staff, one part is fully rectangular and the other part is a smaller rectangle with a small extension (leading to less appropriate surface for the solar modules). To simplify the modelling, it was decided to only investigate the rectangular parts.

The second important parameter that was evaluated was the azimuth angle of the rooftops. The azimuth angle describes the west-east orientation in degrees. In the northern hemisphere, the value of the azimuth angle is 0° if the rooftop is facing directly to the south where the sun is, which is the optimal orientation since it gets the most out of the sun's energy (Civic Solar, 2011). The red marked family houses in Figure 31 have the azimuth angle 10° to the east, which is the lowest azimuth angle, compared with the other family houses. The community center has an azimuth angle of 13°. Since the family houses have a better rooftop angle and a better azimuth angle, the red marked rooftops in Figure 33 was chosen as the location for the PV system. The location of the wind turbine was selected in collaboration with the FUNDASAL staff, which is highlighted in green in Figure 33. It was considered to be the only suitable location for a wind turbine since no other spaces within the community were available.

Figure 33. Drawing of the Cuna de la Paz community. The red marked area shows the location of the family houses for the PV system. The blue box shows the used area the PV modules. The green marked area shows the location for the wind turbine. Source: FUNDASAL. Used with permission.

Size boundaries

To evaluate how big the PV system could be the areas of the red marked rooftops facing south were measured. The rectangular rooftop part of the red marked family houses in Figure 31 have an area of 44 m^2. The solar modules used in this study have the size of 1.99 m^2 (2003•995 mm) (Canadian solar, 2018). There are seven family houses within the red marked area and each rooftop can hold 22 modules. In total the rated capacity for each rooftop is estimated to 7.81 kW, leading to a total capacity of 54.7 kW for all the red marked rooftops.

To evaluate if the maximum capacity for the red marked rooftops were an appropriate estimation, national guidelines for how large private owned energy systems could be to be regarded as a micro production unit were searched for. Even though no explicit regulation policies were found, at least a guideline for grid connected PV-systems written by the Salvadoran national energy council was obtained. The recommendation of the maximum capacity for an installed PV-system according to the council stated that the system should be smaller or equal to the peak load demand for the owner, which in this case would be 34 kW (CNE, 2016). The information is a bit arbitrary since no validation of the information was carried out and since the system design is rather special in this study, so it was considered more as a recommendation of the order of magnitude. The optimal rooftop surfaces allow 54.7 kW which was set to the maximum size in the optimisation.

In the third scenario, the most suitable areas of all rooftops of the project were included. The total area of the rooftops was estimated to carry a total PV size of 484 kW. The azimuth angle was conceded as a rough estimate average angle since the purpose was to assess the potential rather than the exact production. The average azimuth angle was thus estimated as 20°. In the battery case, the size of the battery unit was set to 10 000 kWh, making sure that the size was big enough.

System assumptions

Since the project lifetime was set to 25 years several assumptions had to be made regarding some of the model parameters. The primary load is assumed to increase with 2% on a yearly basis to cover up for increased electricity consumption that may come with (potentially) cheaper prices, known as the "rebound effect" (UCUSA, 2015). As presented earlier, the electricity price has had a yearly growth of 2.1% and was assumed to continue during the project lifetime. The PV modules are expected to have an annual degradation rate of 0.5 % (Canadian Solar, 2018). Since surplus produced electricity can be sold to the local grid within the model, a price for the grid sale rate had to be estimated. No information regarding Salvadoran grid sell rates was found and thus the it was assumed that the profit for sold electricity would be $0.1. In comparison with Frisk (2017), the selected sales price can be regarded as rather conservative. A discount rate of 8% was used in the simulations. No penalisation of capacity shortage was included in the optimisation.

3.3 Sensitivity variables

The sensitivity variables in this study were selected to be the azimuth angle, the grid sale capacity, the hub height of the wind turbine, the average annual wind speed and the battery price. The alternative value for the azimuth angle (-10° in the model) was set to 95°. The value was motivated to test another PV production strategy, by postponing the peak in order to better match the load profile by producing more at times of higher consumption. The alternative grid sale capacity was set to 0 (unlimited in the original model), meaning that no excess energy could be sold to the local grid. This was tried to estimate the impact of the grid sales. The hub height, wind speed and battery price were tried with several iterations to find the points where the impact of the parameters changed the design of the optimised system.

4. Results and analysis

The following chapter combines the result presentation and analysis for the different scenarios listed in Table 1. The reliable and unreliable grid scenarios are presented in Section 4.1 and 4.2 respectively. The sections begin with the presentation of the case without the constraint regarding capacity shortage, the so called base case. Subsequently, the different system combinations are presented in a table that shows the optimal sizes for the system components and the NPC. Thereafter the optimal system combination is presented and analysed further, together with a sensitivity analysis. Subsequently, the constraint case with the constraint of maximum allowed capacity shortage is presented in the same manner as the previous. The optimally resilient system is highlighted, which meets the reliability requirement of less than 1% of capacity shortage with the lowest NPC. Section 4.3 presents the self-sufficiency scenario along with its no-battery case and battery case.

In the two first scenarios, only the system combinations that have a lower NPC than the grid-only system (i.e. the system for which all electricity is bought from the grid) are presented. Hence, the grid-only system serves as a reference system, showing which combinations that would be more profitable than the current (grid-only) setup.

4.1 Scenario: Reliable grid

This is the main scenario, where the optimisation is based on the reliable grid setting constructed with data from 2017 with few and short outages.

4.1.1 Base case

Table 7 shows combination hierarchy which is the result of the optimisation.

Table 7. Combination hierarchy of the base case in the reliable grid scenario.

SYSTEM COMB.	PV (kW)	Wind (kW)	Size battery (kWh)	Converter (kW)	NPC ($)
PV-GRID	54.7			38.0	298’000
PV-WIND-GRID	54.7	3		38.0	+1’360
PV-BATTERY-GRID	54.7		4	38.0	+2’010
PV-WIND-BATTERY-GRID	54.7	3	4	38.0	+3’370
GRID-ONLY					+117’000

The optimisation shows that the combination of PV modules, converters and the grid have the lowest NPC and is therefore regarded as the optimal system combination. The preferred size of the PV system (54.7 kW) is the maximal allowed in the settings. It is further shown that all the system combinations with lower NPC than grid-only contains the maximised PV system. The PV-wind-grid combination is the second most optimal combination in this scenario, with an NPC which is only 0.5% higher than the optimal PV-grid system. The wind turbine has a 3 kW size, which is the only applicable size in the simulation. PV-battery-grid follows up as the third most optimal combination. The battery size is 4 kWh which corresponds with the minimal possible battery unit. The system's NPC is not much higher than the optimal PV-grid combination, but the battery's relatively low unit cost tells that the unit does not contribute significantly to the system profitability. The battery size is the same in the fourth most optimal combination which adds wind power to the system. The PV-wind-battery-grid system is followed by the grid-only system which represents the scenario of no microgrid implementation. Its NPC is significantly higher than all the microgrid versions.

All the optimised microgrid systems contributes with substantial profitability through energy savings in comparison with the standard grid-only setup: the NPC decreases with 27.3% to 28.1% with the four microgrid system combinations. It is therefore a considerable saving to install any of the presented optimised systems. However, the result must be understood as primarily a declaration of the PV unit's high profitability. The other units do not do much more than freeriding on the PV system since they only increase the NPC through making the systems more expensive than they contribute to savings. For instance, the reason that the PV-battery-grid system has an NPC that is close to the optimal system combination is that the batteries are relatively inexpensive, which is why the battery size is the minimum possible allowed. HOMER suggested bigger PV units since the software computed the absolute optimum outside the allowed PV size range.

Table 8 shows technical information about the optimal system combination.

Table 8. Technical information about the optimal system combination.

Measurement	Value
PV-production (kWh/year)	94’700
Grid purchases (kWh/year)	82’100
Grid sales (kWh/year)	48’200
Self-consumption (%)	39.7
Grid sale share of own energy production (%)	50.9
Capacity shortage (%)	0.03
Capacity shortage grid-only (%)	0.0697

The total annual energy produced by the PV unit is 94’700, a higher amount than the yearly energy that is purchased from the grid (although slightly lower than the total primary load the first simulation year on 95’500 kWh). However, a considerable amount of the produced energy is sold to the grid, over half of the production, which implies that most of the PV production does not coincide with the consumption which is illustrated in the example day in Figure 33. Even though the PV unit produces more electricity than the system purchases from the grid, only 39.7% of the own consumption is covered by the self-produced electricity (which obviously also means that the grid purchases are reduced with 39.7% which is significant).

The capacity shortage is 0.03 percent, which means that more than 99% of the load is covered. The reliability requirement is a capacity shortage of max 1%, and here it can be seen that an explicit simulation to reach the requirement is not needed: the most economic system also provides a sufficiently low capacity shortage. In fact, even the capacity shortage of the grid-only system remains below 1%, which implies that the grid alone provides an acceptable capacity shortage due to the restrictions. Nevertheless, since the NPC is (considerably) lower for the PV-grid system, that becomes the optimally resilient system in the reliable scenario.

Figure 34 shows the PV production and the aggregated load an example day with the optimal system.

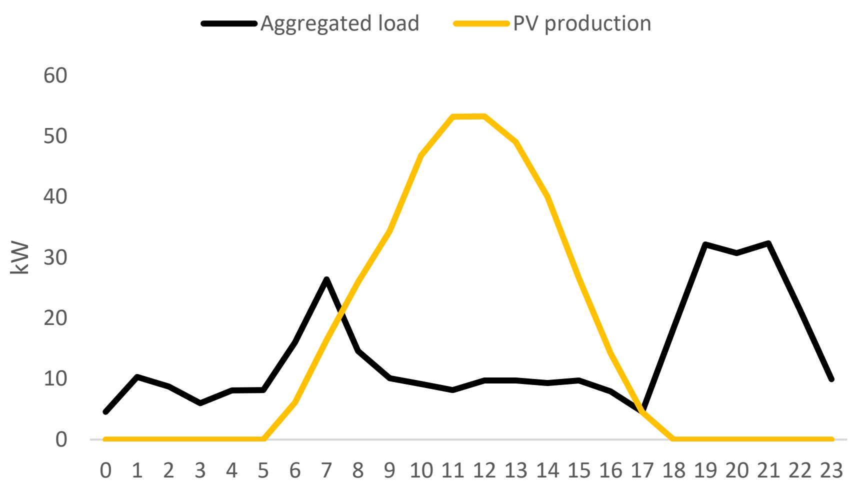

Figure 34. An example day with the optimal system, with the PV production and aggregated load presented.

As stated previously, the match between the PV production and the load is far from optimal. The PV modules manage to deliver a part of the morning peak but entirely misses the more extensive evening peak. The relatively low mid-day consumption is completely served by the PV energy. Figure 32 illustrates the potential for supplementing battery storage to the microgrid, since a big enough storage could provide complete self-sufficiency (which is tested in the upcoming self-sufficiency scenario). But again, the optimisation showed that batteries with the current prices are too expensive when affordability is of interest. Another solution could be to direct the PV array to the west to postpone the production to later hours. The result of such attempt is presented in the sensitivity analysis in the next section.

4.1.2 Sensitivity analysis

The sensitivity analysis shows how parameters of interest influence the optimisation. In following tables the first row presents the parameter value that is used in the presented optimal system, while the second row presents the effect that the alternative parameter value has on the output.

Table 9 shows the result of the sensitivity analysis with the alternative azimuth angle (which represent PV installation on another family house section).

Table 9. Sensitivity case with different azimuth angle.

Azimuth (°): (0=directly south)	Optimal system combination:	NPC for optimal system ($)
-10	PV-Grid	298’000
95	PV-Grid	+7’190

The PV system with a -10° azimuth provides a lower NPC than the system with a +95° azimuth. That means that the system that is oriented more to the south is a better option, even though it increases the production at times when the power consumption is low. The optimal system combination is hence unaffected by the changed azimuth angle.

Table 10 shows how not being able to sell excess energy to the grid affects the optimisation.

Table 10. Sensitivity case with different grid sale capacity.

Grid sale capacity	Optimal system:	NPC for optimal system ($)	PV-size (kW)
Unlimited	PV-Grid	298’000	54.7
0	PV-Grid	+99’800	23.4

The inability to sell excess energy to the grid affects the optimal system design, but only in the sense that the optimal PV-size is not the max size allowed (54.7 kW) but significantly reduced to 23.4 kW. PV-grid is still the optimal system though. NPC increases substantially, which clearly indicates the big impact the sales has on the profitability.

The impact of the wind power hub height is presented in Table 11.

Table 11. Sensitivity case with different hub height.

Hub height (m)	Optimal system	NPC ($) for optimal system
9.1	PV-Grid	298’000
20	PV-Wind-Grid	-199

With a 20 m hub height (with equal cost as the main scenario) wind becomes a part of the optimal system. This is only a theoretical result, since the increased hub cost is not included in the analysis (if included, the increased cost would make it preferable to avoid the turbine). The difference is also minimal, which makes it arguable if it in practice is worth the extra complexity.

Table 12 illustrates the impact of higher wind speeds.

Table 12. Sensitivity case with different annual average wind speed.

Annual average wind speed (m/s)	Optimal system	NPC ($) for optimal PV-Wind-Grid-system
4.44	PV-Grid	298’000
5	PV-Wind-Grid	-378

When increasing the annual average wind speed to 5 m/s the wind turbine becomes a part of the optimal system. That means that wind is really on the verge of being a part of the most rentable solution in our model with the selected costs.

The last sensitivity analysis discovers the impact of the battery price, presented in Table 13.

Table 13. Sensitivity case with different battery price.

Battery price ($/kWh)	Optimal system	NPC ($) for optimal PV-Battery-Grid-system
297	PV-Grid	298’000
29.7	PV-Grid	Same system

Batteries do not even contribute to the optimal system with a price of 10% of the original price. Batteries are thus far from being an economic complement to renewable energy systems in these circumstances, despite the production and consumption mismatch.

4.2 Scenario: Unreliable grid

The unreliable grid-scenario is based on grid inputs with longer and more frequent outages that stem from grid data from 2005. The purpose is to illustrate how the optimisation is affected by the grid data.

4.2.1 Base Case

As in the previous scenario, this case illustrates the optimisation results with no explicit capacity shortage constraint. Table 14 presents the optimal system combinations and the optimised unit sizes.

Table 14. Combination hierarchy of the base case in the unreliable grid scenario.

SYSTEM COMB.	PV (kW)	Wind (kW)	Size battery (kWh)	Converter (kW)	NPC ($)	NPC ($) from reliable grid scenario
PV-GRID	54.7			37.5	296’000	298’000
PV-WIND-GRID	54.7	3		37.5	+1’440	+1’360
PV-BATTERY-GRID	54.7		4	37.5	+2’170	+2’010
PV-WIND-BATTERY-GRID	54.7	3	4	37.5	+3’610	+3’370
GRID-ONLY					+106’000	+117’000

The results are identical with the reliable grid scenario except for the converter size and the NPCs. The same conclusions can be drawn from these results: any optimised microgrid with PV units is highly profitable and it is all because of the high value of the solar energy. The higher degree of grid outages affects the NPCs in the different combinations in different ways, some increase and some decrease. It is due to the inability of the grid in times of outages to deliver and receive power, which affects the various combinations in different ways. This is also the reason to why the batteries do not manage to contribute to a decreased NPC (since the optimal size is the smallest allowed) even though the presence of grid outages is substantially higher. An interesting consequence of the slightly different circumstances is the optimal size of the converter which in all cases is 37.5 kW (compared to 38 kW in the reliable grid scenario). This is most certainly a result of the decreased possibility to sell excess solar power to the grid (since it is out of function more often), which makes it more profitable to slightly decrease the converter size with more power wasted as a consequence.

Table 15 presents technical information about the optimal system combination in the unreliable grid scenario.

Table 15. Technical information about the optimal system combination.

Measurement	Value	Value in the reliable grid scenario
Grid purchases (kWh/year)	80’200	82’100
Grid sales (kWh/year)	45’800	48’200
Self-consumption (%)	41.7	39.7
Grid sale share of own energy production (%)	48.4	50.9
Capacity shortage (%)	1.6	0.03
Capacity shortage grid-only (%)	2.9	0.0697

Compared to the reliable grid scenario, the grid purchases and sales are slightly decreased (due to the higher outage presence that disables transmission). Naturally, with less grid purchases and sales, more of the own production is consumed internally and less is sold. The capacity shortage is remarkably increased and exceeds the 1% boundary which is the limit to meet the reliability criteria. Compared to the grid-only system though, the capacity shortage is decreased with 44% which is quite a bit. Nevertheless, as opposed to the reliable grid scenario, this case cannot be classified as the optimally resilient system in this scenario and requires a conditioning of the profitability to decrease the capacity shortage. Therefore, another simulation is demanded with the explicit capacity shortage constraint of 1%. The result of that simulation is presented in the following section.

4.2.2 Constraint Case

The optimisation results with the explicit capacity shortage constraint of 1 % is presented in Table 16.

Table 16. Combination hierarchy of the constraint case in the unreliable grid scenario. Grid-Only represents the Base Case, which does not fulfil the capacity shortage constraint.

SYSTEM COMB.	PV (kW)	Wind (kW)	Size battery (kWh)	Converter (kW)	NPC
PV-BATTERY-GRID	54.7		96	40.0	348’000
PV-WIND-BATTERY-GRID	54.7	3	96	40	+1’430
GRID-ONLY					+54’000

The result here is much different from the previous optimisations. According to the system configurations, the only way to increase the served load and decrease the capacity shortage with a fixed grid profile is with battery storage. Not exactly surprising (considering the previous results), the optimal combination becomes a PV-battery-grid combination. The smallest allowable battery unit to meet the requirement turns out to be 96 kWh (consisting of 24 4 kWh-batteries). The PV-size is again maximised in both combinations, but the converter size is increased to 40 kW to maximally help providing power to the served load (it is cheaper to increase the converter size than adding even more batteries). The profitability of these combinations is substantially lower than in the systems without the capacity shortage constraint, natural since the batteries have proved to be expensive. The grid-only option is presented only to compare the NPCs – it does not fulfill the reliability criteria. It is still cheaper to install a system combination with a large battery unit than not installing an optimised microgrid.

Table 17 shows technical information of the provided case, and a comparison with the base case.

Table 17: Technical information about the optimal system combination for the constraint case with the base case as reference.

Measurement	Value	Value in the base case
Energy out from battery (kWh/year)	1‘300	NA
Grid purchases (kWh/year)	80’200	80’200
Grid sales (kWh/year)	45’700	45’800
Self-consumption(%)	48.2	41.7
Grid sale share (%)	48.2	48.4
Capacity shortage (%)	0.6	1.6

The batteries provide 1’300 kWh/year, which satisfies the capacity shortage constraint. Therefore, this PV-battery-grid system is classified as the optimally resilient system in the unreliable grid scenario. The grid purchases and sales are further slightly decreased because of the capacity to store the surplus of the own production. The share of self-produced energy is increased with 6.5 %-units which is quite a bit but still not a significant change, which implies that a large addition of batteries still does not manage to store a substantial part of the evening peak (illustrated in Figure 33). The battery sizing is further explored in the following section.

Figure 35 presents the variations of an example day (presented from 9 AM to 8 AM to highlight the load peak behaviour) with a grid outage between 1 PM and 11 PM. The plots show the primary load, the state of charge of the batteries and the capacity shortage of the primary load.

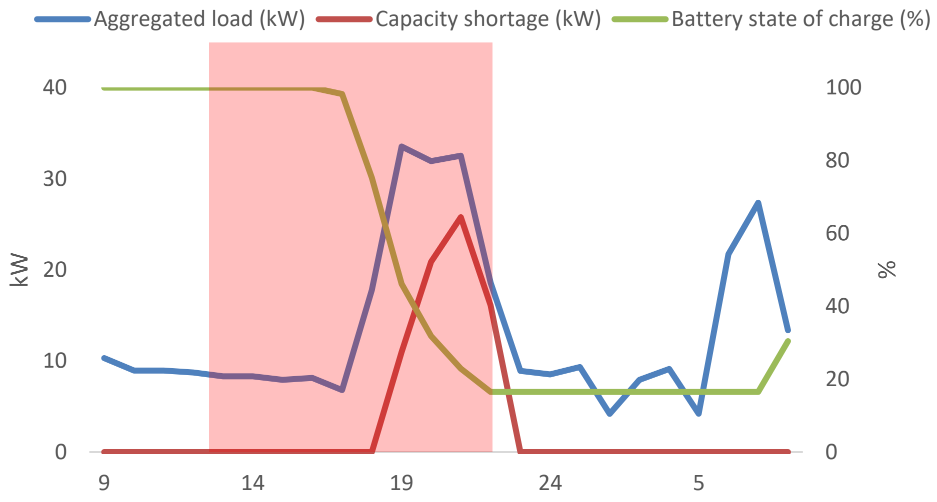

Figure 35. An example outage day with the optimal system, with the battery state of charge, aggregated load and capacity shortage presented. The red surface represents the power outage.

The outage occurs at daytime when the PV production is higher than the load, thus the batteries remain unaffected initially. It is first in the evening when the PV production ends and the evening load takes off that the battery starts discharging. The batteries achieve to decrease the capacity shortage to an acceptable level, although most of the capacity shortage remains unaffected since the batteries only manage to supply the load for a short amount of time. Thus, the capacity shortage increases during the evening which in practice leaves the community without electricity.

4.3 Scenario: Self-sufficiency

This scenario is constructed to illustrate the theoretical potential of microgrid systems driven on local energy sources to provide self-sufficiency to the community. All the energy use is covered by the local production, and the grid's only function is to receive excess energy through sales. The NPC serves no other functions than sorting the optimal combinations without and with battery (which are presented more in detail further down) and illustrating the order of magnitude of the costs. Table 18 shows the results.

Table 18. Combination hierarchy of the battery- and no-battery cases in the self-sufficiency scenario.

SYSTEM COMB.	PV (kW)	Wind (kW)	Size battery (kWh)	Converter (kW)	NPC
Optimal no-battery case: PV-grid	484			450	363'000
PV-WIND-GRID	484	3		450	+3'390
Optimal battery case: PV-BATTERY-GRID	484		10'000	450	5'140'000
PV-WIND-BATTERY-GRID	484	3	10'000	450	+1'510

In the same way as the previous scenarios, the optimal systems are the ones provided by only PV energy. Since no energy is delivered to the microgrid from the grid, the NPC is calculated without grid power purchases. Table 19 shows that the capacity shortage of the no-battery system is over 50%, which makes the system a bad choice (even though the NPC is not substantially higher than the optimal system in the reliable grid scenario). The battery-backed system has a capacity shortage of only 0.3% which classifies it as self-sufficient, but the installation costs of the enormous battery unit raises the NPC to astronomous levels. Nevertheless, it concludes that the system based on PV modules on all available roofs can provide self-sufficiency with unlimited storage capacity.

Table 19. Technical information about the optimal system combinations.

Measurement	No-battery case	Battery case
PV production (kWh/year)	837’000	837’000
Energy delivered from battery (kWh/year)	NA	75 900
Grid purchases (kWh/year)	0	0
Grid sales (kWh/year)	671’000	582’000
Self-consumption (%)	100	100
Grid sale share of own energy production (%)	80.2	69.5
Capacity shortage (%)	58.3	0.3

Table 19 also shows that the grid sale amount is clearly lower in the battery case which is logical since more of the production can be stored in the batteries. The grid sale share is lower in the battery case, but both cases have remarkable numbers: more than half of the produced power is sold to the grid. This implies that the PV units are clearly over-dimensioned. The gap is illustrated in Figure 34. It means that the available rooftops can provide the surface needed for self-sufficiency with big marginals. The energy delivered from batteries is approximately 70 times higher than in the unreliable grid scenario, which implies that the batteries contribute significantly.

Figure 36 illustrates the PV production, the primary load and the battery state of charge an example day.

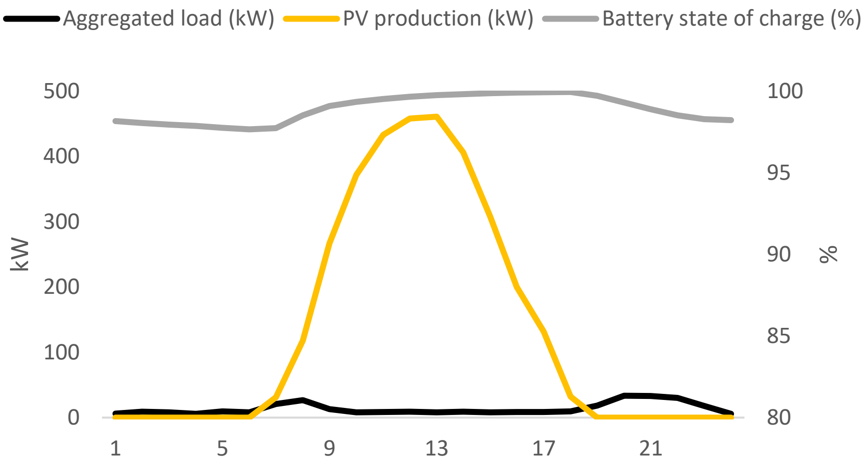

Figure 36. An example day with the optimal battery case system, with the battery state of charge, PV production and aggregated load presented.

The PV production can meet the load demand during the morning until the afternoon. During the day, there is a huge electricity production where almost everything is sold to the grid. During the evening peak and night when the PV production is non-existent the system is not able to meet the electricity demand directly without the battery contribution. The battery is charged each day with the produced PV energy and partly discharged during the evening peak and the night until the solar production starts with the morning sun.

5. Discussion

In this chapter the implications of the results are discussed in a wider sense. Section 5.1 discusses the reliability of the results and highlights its key aspects and is followed by a methodology discussion (5.2). Thereafter the result is contextualised in the Salvadoran environment in Section 5.3. Lastly, in Section 5.4, recommendations for further research are presented.

5.1 Main lessons

The most obvious finding to emerge from the study is that an implementation of a REMS driven by PV can enhance resilience for the community, by making electricity more affordable (since almost 30% of the electricity costs can be cut). These results echo those of Eziyi and Krothapalli (2013) and Rajbongshi et al. (2017), who also emphasise PV systems as a suitable option for rural microgrids with high solar insolation. An unanticipated finding was that the generated main grid profile had a high reliability, with only 0.07% capacity shortage. Thus, a more simplified PV-system that cannot operate “off-grid” with cheaper components (such as a simpler, non-MG compatible converter) could be of more interest for the community. A simpler, non-microgrid solution would lead to lower initial capital costs, since a less advanced converter that does not include a battery charge controller could be utilised. This notion is supported by the findings of Li et al. (2018) who have investigated feasibility of grid-connected PV systems in five different climate zones in China.

However, the size of the PV system heavily depends on national regulations and the grid sale capacity, which needs to be investigated further. As shown in the sensitivity analysis, the optimal size of the PV array decreased significantly and led to a higher NPC value when the grid sale capacity was set to 0. On the other hand, this would mean that the initial capital costs would decrease for the system. The sensitivity analysis also showed that the intention of changing the azimuth angle in order to meet the evening load more thoroughly did not improve the NPC for the system. A load profile with peak demand earlier in the evening could possibly benefit from changing the azimuth angle to be more west-oriented.

The results show that batteries are not particularly appropriate for the intended system. The high reliability of the main grid in combination with the high capital cost of the battery units rule out their usefulness. Nonetheless, the result shows that there is much surplus electricity generated from the PV system during the day and therefore a high potential of storage. This possibility is however partially prevented by the opportunity of selling the electricity to the grid. As the sensitivity analysis shown, even when the capital cost is only 10% of the original estimation, the batteries do not provide any value for the system. In the constraint case for the unreliable grid scenario, 24 batteries were included in the optimally resilient system leading to a capacity shortage of only 0.6%. The base case only had 1.6% of capacity shortage and therefore almost meets the reliability criteria.

Thus, the marginal utility of installing 24 batteries in order to avoid 1% capacity shortage is questionable. Therefore, it is reasonable to conclude that batteries can provide more value for communities where the grid reliability is significantly more unstable than presented in this study, which has been shown in Barbour et al. (2018) and Panhwar et al. (2017).

The sensitivity analysis also showed that the wind turbine becomes part of the optimal combination when the annual average wind speed is set to 5 m/s and when the hub height is set to 20 m. Nevertheless, the data discussion regarding the price of the wind turbine highlights a rather optimistic estimation. With a more conservative approach, the wind turbine would most certainly not be part of the optimal combination regardless of a slightly better windspeed or a higher hub.

The results of the self-sufficiency scenario show that it is possible for the community to rely solely on their own electricity production, since the total PV production far exceeds the total load demand as there is enough space on the rooftops for the PV modules. The main problem is the mismatch between production and load demand, since the PV modules only produce electricity during the day. As shown in the result, batteries then become essential to avoid an inconvenient capacity shortage, which leads to investment costs of gargantuan proportions. Energy storage is therefore a bottleneck for providing economically justifiable self-sufficient solutions.

5.2 Methodology discussion

Almost every power outage in the generated reliable grid profile occurs during the day, which can be seen in Figure 29. This is also when the PV production reaches its maximum output and the load demand is low. In the final phase of the study it was noticed that the grid profile generator had a bias towards locating outages during day time. This is a clear flaw, since it affects the capacity shortage. If the generated power outages would instead occur during the evening or night time, it would not be met by the PV production and therefore lead to a higher capacity shortage. Thus, the need of storing the daily produced electricity could be more relevant in order to meet the 1% constraint. This aspect could however be seen as rather arbitrary since the grid reliability to date (2017) is high. With only 6 outages occurring, no major capacity shortage increase could be expected if the outages were located at times of no PV production. On the other hand, the data does not include the impact of possible future climate disasters, which could lead to more power outages and a different result. This is partially presented in the unreliable grid scenario, since the batteries become necessary to not allow a capacity shortage higher than 1%. As mentioned earlier, one could question the necessity of installing 24 batteries in order to lower the capacity shortage with 1%. Nevertheless, if the number of climate disasters would increase, leading to a more unreliable grid and if the allowed capacity shortage would be set to 0, storage or alternative renewable energy sources could be necessary to meet the needs. At the same time, this study does not penalise power outages economically, they only affect the capacity shortage. Estimating a cost for non-delivered electricity would enhance the need of storage in the optimisation. The cost of non-delivered electricity can represent important activities within the community that cannot function without electricity. From a system perspective, the decision of not penalising power outages only leads to decreased NPC since less electricity is bought from the grid.

The grid sell rate estimation was rather conservative, and it could be argued that a more realistic rate would be higher. In that case, the NPC would decrease with an increased affordability as a result. Nevertheless, the PV system would not have been affected since its size is maximised, although it could be of interest to analyse if the wind turbine could be a more profitable component.

5.3 Contextualisation

The results imply that REMS solutions based on PV energy is a highly viable alternative for a community like Cuna de la Paz. It is mainly because of the significant electricity cost savings that are enabled but also because of the security it entails of having a running grid system unaffected by external conditions. This study can therefore be seen as a motivation for rural communities in El Salvador to implement REMS and especially PV energy. A main threshold is the high capital costs that characterise these types of solutions, and that can rule out investments that over time would have been both profitable and of high social values. By finding viable economic models to get around the issue and spread out the costs over the lifetime, countries like El Salvador can consider a potent measure for fortifying rural communities. The results also imply the profitability of residential PV systems, since the model's load profile has similarities with a typical household profile. The potential for increased residential solar PV in El Salvador is therefore recognised, although the upfront cost obstacle is the same as with the rural communities. Buildings and communities with load profiles more similar to the typical PV production profile with high consumptions during mid-day have even higher potential for profitability, since more of the produced energy can be consumed internally.

Zooming out to a national perspective, the results imply possibilities for cheap electricity production from renewable domestic sources. By implementing more PV (and wind) power to the system, the production costs (which, as seen in Section 2.2.3, makes up more than half of the final customer electricity price) can be decreased and thereby make electricity cheaper for the Salvadorans. As previously presented, this is already in progress, as several PV and wind projects are under construction at the time of writing. This should be seen as a confirmation of the statement regarding the renewable energy potential in the Master plan and Indicative plan presented in Section 2.2.4. Consequently, by proceeding with PV and wind implementation, El Salvador can decrease its dependency on oil-based imported electricity generation and keep more hydropower in storage during times of high PV and wind production. It would further provide more spare capacity in the hydropower dams during dry seasons which would stabilise the electricity costs.

Another interesting aspect is the result from the self-sufficiency scenario showing that a Salvadoran community like Cuna de la Paz easily could be self-sufficient with local PV energy, with the battery price being the economic bottleneck. The electricity consumption density in such a community is relatively low with large production areas (many rooftops) for a relatively small aggregated load. The result should be regarded as an indication of the vast self-sufficiency potential there is for alike communities. It is not to be considered as a viable option under current circumstances, but that could be changed by breakthroughs in energy storage technologies or prices. If so, regions that today are, and in the future will be even more, affected by nature- and climate hazards have a promising solution for increasing the resilience (through energy- reliability and hopefully also affordability).

Nevertheless, Cuna de la Paz has a grid connection (something that its residents share with 96% of the rest of the Salvadorans). The grid is of considerable importance, especially since the expensive energy storage possibilities rules out complete self-sufficiency with the present prices. Since grid access is highly widespread in El Salvador it is important to recognise its accessibility and plan the resilience measures of more frequent climate catastrophes from the premiss that most communities have a high energy accessibility (especially since the grid of today seems to be of high reliability). This study presents the performance of one type of measure, with the main result that it makes the electricity significantly cheaper but where the reliability already seems to be of high level and only marginally can be decreased by REMS-implementation with affordability aims. The authors therefore encourage to proceed the search for resilience-enhancing measures for exposed communities.

As presented in the initial part of Section 2.2, the Central American countries generally have relatively high electricity access rates. Assuming similar external conditions (such as electricity price, energy resources and consumption habits) it can be concluded that the lessons learnt in this study (that PV-driven grid-connected REMS is a good measure to increase the resilience) may be applicable also to the neighbouring countries to some extent. It was showed that Sub-Saharan Africa has significantly lower electricity access rates. Resilience enhancing measures aimed for typical rural Sub-Saharan African communities therefore need to account for a situation with no main grid connection (which most likely makes energy storage inevitable), which thus differs from the main scenarios of this study. The findings should therefore be considered relevant mainly for Central America, as a suggested local resilience enhancing activity requested by Perera et al. (2015).

In the introduction a notion from Kelly et al. (2017) was presented. It constituted resilience measures as actions that should be taken today to protect communities from damages and that helps remove the long-term impacts of climate change at the same time. Additionally, it stated that the actions should make systems stronger and smarter than they were in the past. To wrap up, this study has shown that REMS in El Salvador can prevent direct damages since the energy supply can be maintained even though the main grid is out of function. It helps remove long-term impacts of climate change by decreasing the demand of fossil produced electricity. By adding an extra layer of grid infrastructure, the community remains stronger and smarter than before. Renewable Energy Microgrid Systems should thereby be considered as a legitimate resilience measure in El Salvador.

5.4 Further research

This study has raised many questions in need of further investigation. The implementation of wind turbines seems to be an unexplored area within the region and the results shows that the technology is not feasible with current conditions. Lower prices on wind power components and new findings of suitable installation areas, could enhance the chances of making the technology successful. The study should also be repeated using a simpler system approach that does not necessarily have the benefits of a microgrid. By using simpler components without the possibility to operate in island-mode, even more cost-effective solutions could be obtained. Furthermore, studies need to examine more closely the links between electricity savings and how to share or distribute them within the community. How to finance the initial capital costs of REMS for NGOs like FUNDASAL could also be of interest. Further work is also suggested to fully understand the implications of the grid reliability in the area. Research that investigates grid capacity and the necessity of grid enhancement when installing a REMS should be conducted. Lastly, the concept of resilience can in further studies be widen with the aim of studying other aspects from the definition presented by Angelou (2014) that can be affected with the implementation of a REMS, such as capacity, legality and health and safety.

6. Conclusions

In this study it was investigated if Renewable Energy Microgrid Systems (REMS) could provide enhanced resilience to rural communities in El Salvador through the Cuna de la Paz-project and how a REMS should be designed to optimally do so. Resilience was conceptualised as energy- affordability and reliability. The study showed that REMS can enhance resilience by lowering electricity costs for the community and thus increase affordability. The energy reliability proved to be high due to reliable grid delivery with few annual outages, which made energy affordability the main contribution from the optimised REMS. The study also showed that PV systems are the most beneficial renewable technology in the region. The optimally resilient system excluded wind power and battery storage from the system design, since they did not contribute to affordability and the capacity shortage limit was met from the PV unit and the grid. Therefore, the suggested REMS for Cuna de la Paz is grid-connected and PV-driven, without wind power or battery storage. The results further show that self-sufficiency can be provided with REMS from the local energy resources, but that battery storage is an economical bottleneck, which makes it unrealistic with current costs. To conclude, the study shows that Renewable Energy Microgrid Systems should be considered as a legitimate resilience measure in rural El Salvador.

7. References

AES El Salvador. 2016. AES El Salvador inaugura proyecto de energía rural solar. Available online: http://www.aes-elsalvador.com/comunidad/noticias/noviembre-2016/energia-rural-solar/

AES El Salvador. 2018. Simulador de consumo. Available online: https://www.aeselsalvador.com/simulador/swf/Simulador2.html (2018-10-24)

Aleko. 2018a. Wind Power Generator 3000W. Available online: https://www.alekoproducts.com/Wind-Power-Generator-3000W-48V-p/wg3000w48v-ap.htm (2019-02-15)

Aleko. 2018b. Wind Generator Tower Wind Turbine Pole. Available online: https://www.alekoproducts.com/Wind-Generator-Tower-Wind-Turbine-Pole-30-Feet-p/p30-ap.htm (2019-02-15)

Angelou, N., 2014. A New Multi-Tier Approach to Measuring Energy Access. Available online: http://www.esmap.org/sites/esmap.org/files/DocumentLibrary/Multi-tier%20BBL_Feb19_Final_no%20annex.pdf (2019-02-15)

Balint, P.J. 2006. Bringin solar home systems to rural El Salvador: lessons for small NGOs. *Energy Policy* 34. 721-729. Available online: https://www.sciencedirect.com/science/article/pii/S0301421504002241 (2019-02-15)

Barbour, E., Parra, D., Awwad, Z., & González, M. C. 2018. Community energy storage: A smart choice for the smart grid? *Applied Energy, 212*. 489–497. Available online: https://doi.org/10.1016/j.apenergy.2017.12.056 (2019-02-15)

Bellini, E. 2017. Solar brings down power tariff in El Salvador. *PV Magazine*. July 17, 2017. Available online: https://www.pv-magazine.com/2017/07/17/solar-brings-down-power-tariff-in-el-salvador/ (2019-02-15)

British Broadcasting Corporation (BBC). 2018. 2001: Earthquake devastates El Salvador. Available online: http://news.bbc.co.uk/onthisday/hi/dates/stories/january/13/newsid_2554000/2554149.stm (2019-02-15)

Brooks, N., Aure, E., Whiteside, M. 2014. Final report: Assessing the impact of ICF programmes on household and community resilience to climate variability and climate change. *Evidence on Demand*. doi: 10.12774/eod_cr.june2014.brooksetal

Calvo-Gonzalez, O. and Lopez, J. H. 2015. El Salvador : Building on Strengths for a New Generation. Systematic Country Diagnostic;. World Bank, Washington, DC. World Bank. Available online: https://openknowledge.worldbank.org/handle/10986/22034 (2019-02-15)

Canadian Solar. 2018. KuMax. Available online: https://www.canadiansolar.com/fileadmin/user_upload/downloads/datasheets/en/new/2018-4-16_Ku-v5.571/Canadian_Solar-Datasheet-_KuMax_MBB_5BB__CS3U-P_High_Efficiency_v5.571_EN.pdf (2018-12-10)

Chen, W., Shi, J., Ren, L., Tang, Y. and Shi, Y. 2010. Composite usage of multi-type energy storage technologies in microgrid. Dianli Xitong Zidonghua/Automation of Electric Power Systems. 34. 112-115. Available online: https://www.researchgate.net/publication/285943662_Composite_usage_of_multi-type_energy_storage_technologies_in_microgrid (2019-02-15)

Consejo Nacional de Energía (2016). Electricity Sector of El Salvador. Available online: http://estadisticas.cne.gob.sv/wp-content/uploads/2017/07/electricity-sector-of-el-salvador-2015.pdf (2019-02-15)

Consejo Nacional de Energía (CNE). 2017. Política Energética Nacional. Available online: https://www.cne.gob.sv/wp-content/uploads/2017/09/poltica_nacional_de_energia.pdf (2019-02-15)

Consejo Nacional de Energía (CNE). 2017b. Gobierno beneficia a 950 mil familias con mejor subsidio a la energía eléctrica. Available online: https://www.cne.gob.sv/?itrans-slider=gobierno-beneficia-a-950-mil-familias-con-mejor-subsidio-a-la-energia-electrica (2019-02-15)

Consejo Nacional de Energía (CNE). 2018. Plan indicativo de la expansión de la generación eléctrica de El Salvador 2018-2035. Available online: http://estadisticas.cne.gob.sv/wp-content/uploads/2018/03/Plan-indicativo-de-la-generaci%C3%B3n-de-la-expansi%C3%B3n-2018-2035.docx.pdf (2019-02-15)

Consejo Nacional de Energía (CNE). 2019a. Biomasa. Available online: https://www.cne.gob.sv/?page_id=540 (2019-02-15)

Consejo Nacional de Energía (CNE). 2019b. Mercado Eléctrico. Available online: https://www.cne.gob.sv/?page_id=645 (2019-02-15)

Consejo Nacional de Energía (CNE). 2019c. Mercado Eléctrico Nacional. Available online: https://www.cne.gob.sv/?page_id=660 (2019-02-15)

Consejo Nacional de Energía (CNE). 2019d. Proyectos con Energías Renovables. *Portal para proyectos con Energías Renovables*. Available online: http://energiasrenovables.cne.gob.sv/index.php?option=com_content&view=article&id=37&Itemid=65 (2019-02-15)

Countrystudies. 2019. El Salvador. Agriculture. Available online: http://countrystudies.us/el-salvador/53.htm (2019-02-15)

Civic Solar. 2011. Calculating your optimal azimuth angle. Available online: https://www.civicsolar.com/support/installer/articles/calculating-your-optimal-azimuth-angle (2019-02-15)

Cultura, A.B.,,II. 2011. *Design, modeling, simulation and evaluation of a distributed energy system*, University of Massachusetts Lowell. Available online: http://ezproxy.its.uu.se/login?url=https://search-proquest-com.ezproxy.its.uu.se/docview/897141514?accountid=14715 (2019-02-19)

Dawoud, S.M., Lin, X. and Okba, M.I. 2018. Hybrid renewable microgrid optimization techniques: A review. *Renewable and Sustainable Energy Reviews* 82. 2039-2052. Available online: https://www.sciencedirect.com/science/article/pii/S1364032117311383?via%3Dihub (2019-02-15)

Danish Wind Industry Association. 2018. Operation and Maintenance costs for Wind Turbines. Available online: http://drømstørre.dk/wp-content/wind/miller/windpower%20web/en/tour/econ/oandm.htm (2019-02-14)

Dorothal, M. 2019. White paper /// Solar Energy Snapshot: Mexico and Central America. *Solar Asset Management*. Available online: https://www.solarassetmanagement.mx/solar-facts-figures-2018/ (2019-02-14)

U.S. Energy Information Administration (EIA). 2019. Petroleum & Other Liquids: Cushing, OK WTI Spot Price FOB. Available online: https://www.eia.gov/dnav/pet/hist/rwtcD.htm (2019-02-19)

Eziyi, I., and Krothapalli, A. 2013. Sustainable Rural Development: Solar/Biomass Hybrid Renewable Energy System. *Energy Procedia* 57:1492-1501. Available online: https://www.sciencedirect.com/science/article/pii/S1876610214015082 (2019-02-15)

Food and Agriculture Organization of the United Nation (FAO). 2016. Drought in the dry corridor of Central America. Available online: http://www.fao.org/emergencies/crisis/dry-corridor/en/ (2019-02-15)

FUNDASAL. 2017a. Historic Review. Available online: https://fundasal.org.sv/resena-historica/# (2019-01-29)

FUNDASAL. 2017b. Institutional programs. Available online: https://fundasal.org.sv/institutional-programs/ (2019-01-29)

FUNDASAL. 2017c. ¿...Y Mi Derecho a La Vivienda?. San Salvador. 1st editon.

FUNDASAL. 2017d. CPM. Available online: https://fundasal.org.sv/cpm-2/ (2019-01-29)

FUNDASAL. 2018. Information. Available online: https://congreso.fundasal.org.sv/ (2019-01-29)

Frisk, M. 2017. Simulation and Optimization of a Hybrid Renewable Energy System for application on a Cuban farm. Uppsala University. Available online: http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1083428 (2018-09-25)

Glania,G., Rolland, S. and Wiemann, M. 2016 .(2016). for Rural Electrification : Hybrid Mini-Grids for Rural Electrification: Lessons Learned. *Alliance for Rural Electricifation*. Brussels, Belgium.

Google Maps, 2019. Chalatelango Department. Available online: https://www.google.com/maps/@14.2528011,-89.4793553,9.93 (2019-02-15)

Grupo CEL. 2015. Historia de la CEL. Available online: https://www.cel.gob.sv/historia-de-cel/ (2019-02-15)

Hernández, G. 2017. El primer parque eólico del país implica inversión de 110 millones de dólares. *El Salvador*. January 31, 2017. Available online: https://www.elsalvador.com/noticias/negocios/309915/el-primer-parque-eolico-del-pais-implica-inversion-de-110-millones-de-dolares/ (2019-02-15)

Hills, J.M., Michalena, E. and Chalvatzis, K.J. 2018. Innovative technology in the Pacific: Building resilience for vulnerable communities. *Technological Forecasting and Social Change* 129: 16-26. Available online: https://www.sciencedirect.com/science/article/pii/S0040162517302093 (2019-02-15)

HOMER Energy. 2018. Capacity Shortage. Available online: https://www.homerenergy.com/products/pro/docs/3.10/capacity_shortage.html (2019-02-15)

HOMER Energy. 2019. About HOMER Energy LLC. Available online: https://www.homerenergy.com/company/index.html (2019-02-15)

Hubble, A. H. and Ustun, T. S. 2017. Composition, placement, and economics of rural microgrids for ensuring sustainable development. Sustainable Energy, Grids and Networks, 13, 1–18.Available online: https://doi.org/10.1016/j.segan.2017.10.001 (2019-02-15)

IndustryAbout. 2018. Providencia Solar Power Plant. Available online: https://www.industryabout.com/country-territories-3/3026-el-salvador/solar-energy/51941-providencia-solar-power-plant (2019-02-15)

International Energy Agency (IEA). 2017. World Energy Outlook 2017. Available online: https://www.iea.org/weo2017/ (2019-02-15)

International Energy Agency (IEA). 2018. Electricity Information. Available online: https://webstore.iea.org/electricity-information-2018-overview (2019-02-15)

International Energy Agency (IEA). 2019. Modern energy for all. Available at: https://www.iea.org/energyaccess/modernenergyforall/ (2019-02-15)

International Energy Agency. 2019b. Energy Access Database. Available online: https://www.iea.org/energyaccess/database/ (2019-02-15)

International Renewable Energy Agency (IRENA). 2018. Renewable Power Generation Costs in 2017. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf (2019-02-15)

IRENA - International Renewable Energy Agency. International Renewable Energy Agency. https://doi.org/10.1007/SpringerReference_7300 s.14-15

Japan International Cooperation Agency (JICA). 2012. The Project for Master Plan for the Development of Renewable Energy In The Republic of El Salvador Final Report (Summary). Available online: http://open_jicareport.jica.go.jp/pdf/12057261.pdf (2019-02-15)

Kelly-Pitou, K.M., Ostroski, A., Contino, B., Grainger, B., Kwasinski, A. and Reed, G. 2017. Microgrids and resilience: Using a systems approach to achieve climate adaptation and mitigation goals. *The Electricity Journal* 30: 23-31. Available online: https://www.sciencedirect.com/science/article/pii/S1040619017303007 (2019-02-15)

Kreft, S., Eckstein, D. and Melchior, I. 2017. Global Climate Risk Index 2017 – Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2015 and 1996-2015. Germanwatch. Available online: https://germanwatch.org/sites/germanwatch.org/files/publication/16411.pdf (2019-02-15)

La Prensa Gráfica. 2017. Gobierno reduce el monto del subsidio a la energía eléctrica. Available online: https://www.laprensagrafica.com/economia/Gobierno-reduce-el-monto-del-subsidio-a-la-energia-electrica-20170221-0049.html (2019-02-15)

Landguiden. 2018a. Befolkning och språk. Available online: https://www.ui.se/landguiden/lander-och-omraden/nordamerika/el-salvador/befolkning-och-sprak/ (2019-02-06)

Landguiden. 2018b. Fakta- ekonomi. Available online: https://www.ui.se/landguiden/lander-och-omraden/nordamerika/el-salvador/oversikt/ (2019-02-15)

Layton, L. 2004, Electric System Reliability Indices. Available online: https://www.researchgate.net/profile/Majeed_Samieefard/post/What_is_definition_of_distribution_system_reliability/attachment/59d63b5279197b80779985f9/AS%3A410161068953600%401474801427090/download/Reliability_Indices_for_Utilities.pdf (2019-02-15)

Li, C., Zhou, D. and Zheng, Y. 2018. Techno-economic comparative study of grid-connected PV power systems in five climate zones, China. Energy, Volume 165. 1352-1369. Available online: http://www.sciencedirect.com/science/article/pii/S0360544218320528 (2015-02-15)

Madriz-Vargas R., Bruce, A. and Watt, M. 2018. The future of Community Renewable Energy for electricity access in rural Central America. *Energy Research & Social Science* 35. 118-131. Available online: https://www.sciencedirect.com/science/article/pii/S2214629617303432 (2019-02-15)

Molina, K. 2017. El Salvador compra más energía a Guatemala. *El Salvador*. December 10, 2017. Available online: https://www.elsalvador.com/noticias/negocios/428097/el-salvador-compra-mas-energia-a-guatemala/ (2019-02-15)

Molina, K. 2018. La energía eléctrica en El Salvador es la más cara de la región. *El Salvador*. August 19, 2018. Available online: https://www.elsalvador.com/noticias/nacional/510872/salvadorenos-paga-la-energia-mas-cara-de-centroamerica/ (2019-02-15)

Microgrid Institute. 2014. About Microgrids. Available online: http://www.microgridinstitute.org/about-microgrids.html (2019-02-15)

Mishra, S., Panigrahi, C.K. and Kothari, D.P. 2016. Design and simulation of a solar–wind–biogas hybrid system architecture using HOMER in India. *International Journal of Ambient Energy.* 37, 184-191. Available online: https://www.tandfonline.com/doi/abs/10.1080/01430750.2014.915886 (2019-02-15)

MITD-Lab. 2019. Off-Grid Solar in El Salvador. Available online: https://d-lab.mit.edu/research/energy/solar/grid-solar-el-salvador (2019-02-15)

Nations Encyclopedia. 2019. El Salvador – Climate. Available online: https://www.nationsencyclopedia.com/Americas/El-Salvador-CLIMATE.html (2019-02-15)

National Aeronautics and Space Administration (NASA). 2018. POWER Project Data Sets. Available online: https://power.larc.nasa.gov/ (2019-02-15)

Nejabatkhah, F. and Yun, W. L. 2015. Overview of power management strategies of hybrid AC/DC microgrid. IEEE Transactions on Power Electronics, 7072-7089. Available online: https://ieeexplore.ieee.org/document/6994843 (2019-02-15)

National Broadcasting Company News (NBC). 2019. Latino. Nayib Bukele is elected president of El Salvador, vows to end corruption. 4th february. Available online: https://www.nbcnews.com/news/latino/nayib-bukele-elected-president-el-salvador-vows-end-corruption-n966566 (2015-02-15)

Openstreetmap. 2019. Avaialable online: https://www.openstreetmap.org/?mlat=13.66889&mlon=-88.86611&zoom=6#map=7/14.291/-89.797&layers=H (2015-02-15)

Organization of the American States (OAS). 2015. Migración Internacional en las Americas: Tercer informe del Sistema Continuo de Reportes sobre Migración Internacional en las Américas. Available online: https://www.oas.org/docs/publications/sicremi-2015-spanish.pdf (2019-02-15)

Orozco, M. 2017. Remittances to Latin America and the Caribbean in 2017. The Dialogue. Avaliable online: https://www.thedialogue.org/wp-content/uploads/2018/01/Remittances-2017-1.pdf (2019-02-15)

Panhwar, I., Sahito, A. R., and Dursun, S. (2017). Designing Off-Grid and On-Grid Renewable Energy Systems Using, 12(4), 270–276. Available online: http://www.jieas.com/volumes/vol171-4/abs17-v12-i4-1.pdf (2019-02-15)

Patrascu, C., Rat, C., Hulea, D., Vitan, D. and Muntean, N. 2017. Mixed PV-wind small power microgrid. 699-704. doi:10.1109/OPTIM.2017.7975050.

Perera, N., Gill Wilkins, E.B. and Phillips Itty, R. 2015. Literature Review on Energy Access and Adaption to Climate Change. *Evidence on Demand*. Available online: https://assets.publishing.service.gov.uk/media/57a0896b40f0b652dd0001fe/LitRev-EnergyAccessandAdaptation-Final-2.pdf (2019-02-15)

Rajbongshi, R., Borgohain, D., and Mahapatra, S. 2017. Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER. Energy, 126, 461–474.Available online: https://doi.org/10.1016/j.energy.2017.03.056 (2019-02-15)

Rat, C., Vasar, C., Gana, O., & Prostean, O. (2018). Microgrid supply management. Procedia - Social and Behavioral Sciences, 238, 46–52. Available online: https://doi.org/10.1016/j.sbspro.2018.03.006 (2019-02-15)

Reyes, M., 2018. ¿Cuánto cuesta instalar paneles solares en una casa? *El Salvador*. February 18, 2018. Available online: http://energiasrenovables.cne.gob.sv/index.php?option=com_content&view=article&id=37&Itemid=65 (2019-02-15)

Sawle, Y., Gupta, S. C., & Bohre, A. K. 2017. Optimal sizing of standalone PV/Wind/Biomass hybrid energy system using GA and PSO optimization technique. In Energy Procedia. Available online: https://doi.org/10.1016/j.egypro.2017.05.183 (2019-02-15)

Seel, J., Barbose, G. L., & Wiser, R. H. (2014). Energy Policy An analysis of residential PV system price differences between the United States and Germany. Energy Policy, 69, 216–226. Available online: https://doi.org/10.1016/j.enpol.2014.02.022 (2019-02-15)

Sen, R., and Bhattacharyya, S. C. 2014. Off-grid electricity generation with renewable energy technologies in India : An application of HOMER. Renewable Energy, 62, 388–398. https://doi.org/10.1016/j.renene.2013.07.028

Shuaixun, C., Beng Gooi, H. and Wang, M. 2012. Sizing of Energy Storage for Microgrids. IEEE Trans. Smart Grid. 3. 142-151. doi: 10.1109/TSG.2011.2160745.

Shoda, E. 2012. Ready for the worst of nature. The Guardian. Available online: https://www.theguardian.com/journalismcompetition/el-salvador-disaster-planning (2019-02-15)

Sibaja, M. 2017. Central America hit by massive power outages. *Yahoo.* July 2, 2017. Available online: https://www.yahoo.com/news/massive-power-outage-hits-central-america-235450851.html (2019-02-15)

Sigarchian, S. G., Paleta, R., Malmquist, A., & Pina, A. (2015). Feasibility study of using a biogas engine as backup in a decentralized hybrid (PV/wind/battery) power generation system - Case study Kenya. Energy, 90, 1830–1841.Available online: https://doi.org/10.1016/j.energy.2015.07.008 (2019-02-15)

Silva, S. B., De Oliveira, M. A. G., and Severino, M. M. 2011. Sizing and optimization of hybrid photovoltaic, fuel cell and battery system. *IEEE Latin America Transactions*. Available online: https://doi.org/10.1109/TLA.2011.5876425 (2019-02-15)

Sinha, S. and Chandel, S. 2014. Review of software tools for hybrid renewable energy systems. Renewable and Sustainable Energy Reviews. 32. 192–205. Available online: https://www.sciencedirect.com/science/article/pii/S136403211400046X (2019-02-15)

Solar Panel Tilt
https://www.solarpaneltilt.com/

Smith, M. A. and Ton, T. D. 2012. The U.S Department of Energy´s Microgrid Initaitve. *The electricity Journal.* (8). 84-94. Available online: https://www.sciencedirect.com/science/article/pii/S1040619012002254?via%3Dihub (2019-02-15)

Stone, J. 2013. Climate change: Adaption, resilience and energy security. *Expert response by Jeremy Stone*.

Superintendencia General de Electricidad y Telecomunicaciones (SIGET). 2016. Boletín de estadísticas eléctricas No 18 año 2016. Available online: https://www.siget.gob.sv/?wpdmact=process&did=NDA3LmhvdGxpbms (2019-02-19)

Superintendencia General de Electricidad y Telecomunicaciones (SIGET). 2017. Boletín de estadísticas eléctricas No 19 año 2017. Available online: https://www.siget.gob.sv/?wpdmact=process&did=NDM4LmhvdGxpbms (2019-02-15)

Union of Concerned Scientists (UCUSA). 2015. What is the Rebound effect Available online: https://blog.ucsusa.org/peter-oconnor/energy-efficiency-what-is-the-rebound-effect-946 (2019-02-15)

Victron Energy. 2018. Quattro Inverter/Charge 120V. Available online: https://www.victronenergy.se/upload/documents/Datasheet-Quattro-3-10kVA-120V-EN.pdf (2019-02-15)

Woody, C. 2018. These were the 50 most violent cities in 2017. *Business Insider.* 7th of March. Available online: https://nordic.businessinsider.com/most-violent-cities-in-the-world-2018-3?r=US&IR=T (2019-02-15)

World Watch. 2019. El Salvador: The "Land of Volcanoes" and Geothermal Energy. Available online: http://www.worldwatch.org/el-salvador-%E2%80%9Cland-volcanoes%E2%80%9D-and-geothermal-energy (2019-02-15)

Wu, L., Ortmeier, T and Li, J. 2016. The community microgrid distribution system of the future. *The Electricity Journal* 29. 16-21. Available online: https://www.sciencedirect.com/science/article/pii/S1040619016302123 (2019-02-15)

Zahraee, S. M., Khalaji Assadim, M. and Saidur, R. 2016. Application of Artificial Intelligence Methods for Hybrid Energy System Optimization. *Renewable and Sustainable Energy Reviews.* 66. 617-630. Available online: https://www.sciencedirect.com/science/article/pii/S1364032116304609 (2019-02-15)

Zummaratings. 2019. Informe del sector electrico de El Salvador. Available online: http://www.zummaratings.com/SectorElectricoSV.pdf (2019-02-15)

Appendix A - Who did what?

Table 20. Overview of who was responsible for each Section. Every Section has been read and edited by both authors.

Section	Author
Abstract	Both
Populärvetenskaplig sammanfattning	Both
1. Introduction	Robin Landau
1.1 Study aim	Both
1.2 Study setup and system delimitations	Both
1.3 Disposition	Mathias Alarcón
2.1 El Salvador	Mathias Alarcón
2.2 Electricity in El Salvador	Robin Landau
2.3 FUNDASAL	Mathias Alarcón
2.4 Microgrid systems	Mathias Alarcón
3.1 Modelling procedure and simulation outline	Robin Landau
3.2.1 Energy resources	Mathias Alarcón
3.2.2 Load profile	Mathias Alarcón
3.2.3 Grid profile	Robin Landau
3.2.4 Electricity prices	Robin Landau
3.2.5 Component prices and details	Mathias Alarcón
3.2.6 Other factors	Mathias Alarcón
3.3 Sensitivity analysis	Both
4. Results and analysis	Both
5. Discussion	Both
6. Conclusion	Both

Appendix B – Interview questions

- Where do you live now?
- What is your occupation?
- How many people live in your household?
- How much do you pay for your electricity today?
- How do you consider your electricity bills?
- Do you receive electricity subsidies?
- Which appliances do you have in your home that require electricity?
- At what times during the day are people at home in your household?
- At what hours are the appliances used during the day?
- Do you expect your electricity consumption will change when you move to Cuna de la Paz, and if so how?

Appendix C – Electricity prices

Table 21: The average yearly electricity price for the end customer in the CAESS grid

Year	$/kWh
1998	0.0979
1999	0.0942
2000	0.1045
2001	0.1097
2002	0.1004
2003	0.1072
2004	0.1040
2005	0.1084
2006	0.1207
2007	0.1289
2008	0.1272
2009	0.1681
2010	0.1694
2011	0.2138
2012	0.2170
2013	0.2176
2014	0.2138
2015	0.1786
2016	0.1404
2017	0.1882

Table 22: The average month electricity price for end customers in all El Salvador 2017 without subsidies.

Month	$/kWh
January	0.162
February	0.1715
March	0.172
April	0.1745
May	0.179
June	0.181
July	0.178
August	0.1755
September	0.173
October	0.175
November	0.1705
December	0.1695