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A field study assessing changes of load curve characteristics in San Francisco Libre, Nicaragua

Master of Science Thesis in the Master Program Industrial Ecology

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Cover:
House in El Bihague, San Francisco Libre, Nicaragua
The village will be connected to the main grid 2014.

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Abstract

Low population densities, low income and low electricity demand make rural electrification through grid extension a difficult and costly business. This study assesses if small-scale, decentralized electricity production from solar energy could constitute a sustainable energy supply option for rural areas. The aim is to gain understanding of how load curve characteristics for rural households develop over time in order to estimate if solar home systems could meet the demanded electricity over an extended period of time at a viable cost.

A field study was carried out in Nicaragua, acquiring information from three communities, El Obraje, Madroñito and Villa Esperanza, with different electrification times. Data on the electricity use of the individual households in the communities were collected, together with qualitative information on local perceptions and expectations of electricity services. The quantitative data were organized into load curves, showing average electricity demand distribution over the course of the day. Load curve characteristics of the three communities were subsequently compared and prominent features were explained based on the use of the major household appliances. Costs for grid extension, including electricity generation, were compared to costs for solar home systems covering the necessary electricity demand.

Load curves showed the same characteristic behavior in all three villages: fluctuating, relatively low demand during the day, a prominent peak from six to ten at night, and constant, relatively low demand during the night. The total amount of energy demanded increased with the electrification time. The increase could mainly be attributed to the use of less efficient light bulbs and higher abundance of fridges and fans in the villages with longer electrification times and not socio-economic development.

The outcome of the cost comparison of grid extension and SHSs showed to be highly dependent on the distance from the community to the next grid connection point, on the energy demand per day and the PV system cost per W_P. This dependence was illustrated in a break-even distance plot.

In this study no major load curve characteristic changes over a 15-year time period were observed. This indicates that SHSs could constitute a sustainable rural electrification option for communities with load characteristics expected to be similar to those in El Obraje, and located at a similar distance to the closest grid connection point.

Resumen

Las bajas densidades de población, los bajos niveles de ingreso así como la escasa demanda de electricidad hacen que la electrificación por medio de una extensión de la red eléctrica sea un negocio difícil y caro. El presente estudio evalúa si la producción de electricidad proveniente de la energía solar, a menor escala y descentralizada, podría constituir una opción de suministro de energía sustentable en áreas rurales. El propósito es obtener una mayor comprensión sobre cómo se desarrollan las características de curvas de carga en los hogares rurales para así poder estimar si *"solar home systems"* podrían satisfacer la demanda de electricidad por un periodo extendido de tiempo a costos viables.

Por medio de un estudio de campo en las comunidades el Obraje, Madroñito y Villa Esperanza, que tienes diferentes tiempos de estar conectada a la red, en Nicaragua, información sobre el uso eléctrico fue adquirida, junto con información cualitativa sobre percepciones locales y expectativas sobre los servicios de electricidad. Datos sobre el uso de la electricidad fueron organizados en curvas de carga que muestran la distribución de electricidad promedio sobre el curso del día. Las características de curvas de carga de las tres diferentes comunidades fueron comparadas subsecuentemente y los rasgos prominentes fueron explicados con base en el uso de los electrodomésticos en los hogares. Así mismo, los costos de la reja de extensión, incluyendo la generación de electricidad, fueron comparados con los costos por *"solar home systems"* que cubren la demanda necesaria de electricidad.

Las curvas de carga mostraron las mismas características de comportamiento in las tres villas: fluctuantes, con una demanda relativamente baja durante el día, con un pico prominente de seis a ocho de la noche y durante la noche, una demanda constantemente baja. La cantidad total de energía en demanda se incrementó con el tiempo de la electrificación. Dicho incremento podría ser atribuido al uso de focos de luz menos eficientes así como a una mayor abundancia de refrigeradores y ventiladores en las villas con tiempos más largos de electrificación.

La comparación del costo de la extensión de la reja y SHS mostraron ser altamente dependientes de la distancia de la comunidad al siguiente punto de conexión de la reja, en la cantidad de demanda de energía por día y el costo del sistema solar por W_P.

En el presente estudio ninguna característica de carga de curva cambia significativamente en el periodo observado de 15 años. Esto indica que SHS podría constituir una opción sustentable para la electrificación rural de comunidades con cargas características similares como en El Obraje y localizadas a distancias comparables al punto de conexión a la reja más cercana.

Contents

List of acronyms

ESS	Energy-Saving Scenarios
ENATREL	Empresa National de Transmission Electrica (National electricity transmission company)
GRUN	Gobierno de Reconciliación y Unidad Nacional (Nicaragua’s National Government)
INE	Instituto Nicaragüense de Energía (Nicaraguan Institute of Energy)
INIDE	Instituto Nacional de Información de Desarrollo (National institute for development)
LCC	Life Cycle Cost
MDG	Millennium development goals
MEM	Ministerio de Minas y Energía (Ministry of mines and energy)
SFL	San Francisco Libre

1 Introduction

Low population densities, subsistence agriculture, low income and no access to electricity are characterizing features of the rural developing world. 1.3 billion people in the world still do not have access to electricity, most of them live in rural parts of Africa and South Asia, but also in Latin America (IEA, 2013). In the strife for economic growth and poverty alleviation, access to electricity is often considered to be of utmost importance, although there has not yet been found a consensus on how this important linkage works (Kirubi et al., 2009).

The electrification process in the developing countries is, by many actors, thought to be of great importance; however until very recently little attention has been paid to related environmental issues. In a time where anthropogenic climate change is being established and the necessity of a global commitment is getting apparent, mitigation measures are no longer solely the responsibilities of developed nations. In the long term, sustainable solutions have to be found and implemented in every part of the world. Projections estimate that the greatest growth in electricity supply from renewable energy sources will be in the developing countries (IEA, 2013). In the attempt to achieve the sustainable socio-economic development and environmental sustainability that the Millennium Development Goals call for, rural electrification from renewable energy sources has entered the international agenda.

When planning the electrification of rural areas, there is a variety of fundamentally different options to choose from. A wide range of factors need to be taken into account to find a sustainable solution that leads to the optional outcome. The decision often has to be made between grid extension and small-scale, stand-alone electricity production, either as micro-grid or individual household solutions, as well as between fossil fuel based energy and renewable energy. Small-scale production from renewables, especially solar PV, is often considered less adequate compared to grid extension; this is mainly due to perceived high front-up costs, since the installed capacity is relatively low, and due to the inherent intermittency and connected storage problem. However grid extension to remote settlements is a highly costly business (Ahlborg and Hammar, 2014) and if sustainability is to be achieved, costs, user opinions as well as environmental impacts have to be considered.

1.1 Purpose and Aim

The purpose of this study is to assess if small-scale, decentralized and thereby local electricity generation from solar energy, especially solar home systems, could constitute a sustainable energy supply option for rural areas. Given that grid extension and a localized solution based on solar power have about the same costs or that grid extension costs exceed the costs of small scale energy projects, can a decentralized solar-energy based electricity generation system constitute an optimal solution by covering the electricity demand expected in the decade following installation and at the same time reduce environmental pressure?

The aim of this study is to map the development of the electricity demand over time in three newly electrified rural villages and the corresponding households. The study intends to understand the underlying drivers of this development, by analyzing the change in users' perception of and attitude towards the electricity service supplied. Once demand and demand changes over time have been identified, the possibility to meet a rural settlement's demand in its first decade after electrification with small-scale, solar-based electricity generation solutions is analyzed.

1.2 Research questions

In order to meet the objective of this study, the following four specific research questions have been worked with:

1. How do the characteristic load curves of rural, remote households and communities change over time, i.e. is there a change over time of how, how much and when electricity is used?
2. Is there a change in area of use and total amount of electricity used, when comparing recently electrified communities with communities that have had electricity access for several years?
3. Do attitudes and perceptions of electricity services change over time?
4. Would it be possible to meet the electricity demand by decentralized, solar-based solutions? If so, are there other disadvantages or obstacles for supplying the electricity by solar based solutions as compared to from the grid?

1.3 Limitations

When considering the study's value in making general evaluation of the rural electrification process in developing country, its main limitation is that conclusions are based on a field study solely including three villages from one single country, even from one single region.

When disregarding the general shortcomings of generalizing the outcomes of field studies, the main limitations, elaborated on in Chapter 3, have been identified as the amount of communities investigated, time limitations as well as representativity of the interview samples.

1.4 Method

The project started with a brief literature study conducted in order to get an overview of the current state of knowledge and in order to choose relevant research questions so that the study adds further knowledge in the field. By presenting a short overview of the parts of the literature study that are directly relevant for this study, the research gap is identified and the study put into academic context with current research.

The main part of the study was carried out as field work in the municipality of San Francisco Libre, Nicaragua. Data was collected through 1) structured and semi-structured user interviews in three rural communities, 2) participant observation conducted in these rural communities by staying in some of the investigated households and observing everyday community life, and 3) through interview with relevant government bodies and private companies, which were/are involved in the electrification process of the investigated villages.

The data collection is followed by data analysis, both qualitatively and quantitatively. Information obtained on the amount of electricity used is presented in individual and aggregated load curves, which are subsequently compared. The semi-structured interviews are analyzed for relevant information on perception and attitudes, by assessing the content and paying particular attention to phrasing and word choice of the interviewees.

The methodology is further elaborated in Chapter 3.

2 Background

2.1 General demographic data

In order to be able to put obtained results into context, relevant demographic data will be presented below.

2.1.1 Nicaragua

Nicaragua is situated in Central America, bordered by Honduras in the north, Costa Rica in the south, the Atlantic in the east and the Pacific in the west. On an area of about 130.000 km^2, Nicaragua has a population of almost six million people (2013), 67% are mestizos (2005), 30% under the age of fourteen (2013) and 57% live in urban areas (2010) with over 900 000 people living in Managua alone (2009) (CIA, 2014). With a GDP of 4.400$ PPP (2012) Nicaragua is Latin America and the Caribbean's second poorest country (after Haiti) with 42.5 % of the population living below the poverty line (2009) and 28% of the labor force working in agriculture (CIA, 2014) .

The country is divided into 17 different regions, hereafter referred to as departments, of which two that are autonomous. Departments are further divided into municipalities. All three investigated communities are located in the municipality San Francisco Libre in the Department of Managua, see Figure 1.

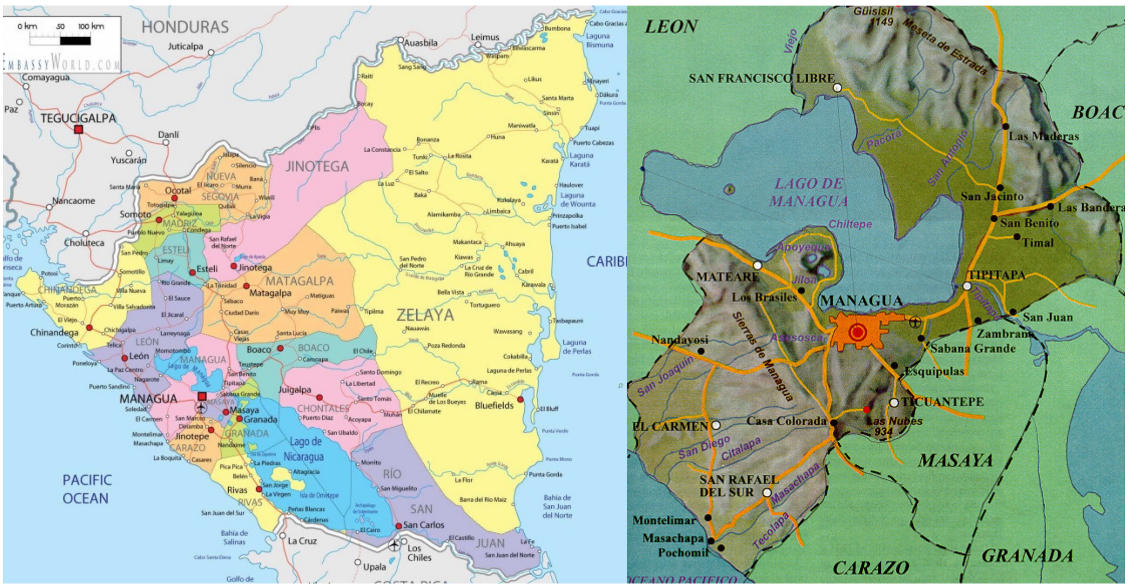

Figure 1 - Map of Nicaragua's 15 departments (Embassy World) and of Department Managua (Managua Online, 2014)

The population density in Nicaragua varies greatly between and within different departments as well as municipalities, with the least populated areas being the autonomous regions (RRAN and RRAS) in the eastern part of the country.

2.1.2 Municipality San Francisco Libre

All three investigated communities are located in the municipality of San Francisco Libre, about 70 km northeast of the capital Managua. The municipality is part of the greater department of Managua, which has an area of 3465 km^2. It is the country's most densely populated department, but only due to the fact that the capital is located here. The municipality consists of one major settlement (a port) with the name San Francisco Libre, located at the shore of Lake Managua, and of 31 smaller communities with populations ranging from 50 up to 400 inhabitants. A typical household is comprised of two to eight people. According to official government statements, in 2005 there were 2477 housings in the municipality of which only 1966 (~80%) were inhabited (INIDE, 2008). There are 32 primary schools in the municipality, providing a 100% of the municipalities inhabitants and it is assumed that 98% of all children in primary school age are enrolled in primary education (INIDE, 2008).

Figure 2 – Map of the municipality San Francisco Libre (INIDE, 2008)

The port San Francisco Libre is located 79 km from the capital Managua and had in 2012 an estimated population of 5081 people, corresponding to 47% of the total inhabitants of the municipality. The population density of the municipality is, with 16 inhabitants per square kilometer, less than half the countries average. The territory's altitude varies between 40 and 900 mamsl and is characterized by mountainous landscape and dry and hot climate (mean temperature of 30 degrees Celsius) most of the year, with annual precipitation levels of about 1000 mm. There are three major and four minor rivers crossing the territory, all of them running dry at the end of summer. (INIDE, 2008)

The main employment type of the men in the communities is subsistence agriculture, collection and sale of firewood as well as seasonal work in a mango export company. The main crops cultivated are corn and red beans. The majority of families have monetary income almost solely through remittances from family members, living in mainly Costa Rica or the United States of America.

2.2 Energy situation in Nicaragua

The Nicaraguan energy sector consists of several important stakeholders. The ministry of mines and energy (MEM) is the actor that is responsible for the planning work in the energy sector. Their major objective is to ensure that the development of the energy sector complies with the objectives of the national government, Gobierno de Reconciliación y Unidad Nacional (GRUN), and its plan for the national humanitarian development. Furthermore the Nicaraguan institute of energy, Instituto Nicaragüense de Energy (INE), the national electricity transmission company, Empresa National de Transmission Electrica (ENATREL), a private electricity transmission company, Dissnote-Dissur and the local municipality government are relevant actors in the part of the energy sector this study is concerned with.

Nicaragua has an interesting electricity generation history. In 1991, almost half of the installed power capacity connected to the grid in the country came from renewables (177MW) and 195 MW from fossil fuels. Since then demand and production have been steadily increasing and the renewable energy share has fallen to only about 25%, this despite the fact that a completely new form of renewable energy, wind power, has entered the energy matrix. (INE, 2013)

In 2013, the maximum power demand of the country was estimated to be 635 MW (installed power generation capacity in 2012: 1,3 GW), and the amount of electricity generated and subsequently distributed by the main grid was estimated to 3,9 TWh, which was complemented by 50 GWh generated by isolated systems (mainly from fossil fuels with solar power production not even named in calculations) (INE, 2013). The mean power and energy growth was estimated to be around 4,5% per year for the coming 15 years (MEM, 2013). GRUN has decided that by 2027, over 90% of the country's electric energy should come from renewable energy sources[1]. In order to achieve this and to cover projected, future electricity demand, the following new electricity generation is planned: 40 MW wind energy, 108 MW biomass, 1095 MW hydro and 527 MW thermal (MEM, 2013).

The Nicaraguan electricity grid is part of the greater Central American electricity grid but Nicaragua imports/exports only minor amounts of energy from/to its neighbor countries.

While installed production capacity has increased rapidly, load factors have been rather constant over the last 20 years at around 65% (INE, 2013).

Grid extensions in the country have been of low priority[2], which can be seen in that the length of the country's transmission lines has only increased with around 10% in the last 20 year, from a total of 1848 km in 91 to a total of 2060 km in 2012 (INE, 2013). However the government has now refocused and promised to provide universal access to electricity services.

[1] Interview with Antonio Roman, Managua, 2014
[2] Interview with Elvin Cruz, San Francisco Libre, 2014

The main electricity consuming sector in Nicaragua is the residential sector (~1/3 of total consumption in 2012), followed by the commercial sector and the industry, which are of about the same size (~980 GWh corresponding to ~25% of total consumption respectively) (INE, 2013). For comparison, in Sweden the domestic and the industry sector are about the same size and consume ~150TWh respectively (Ekonomifakta, 2013). The Nicaraguan average for domestic use was 1.17 MWh per year and household (INE, 2013).

In the municipality of San Francisco, the government's focus on rural electrification is evident. In 2008, only five of the 31 rural communities and the port had access to electricity services, in 2010 ten communities had access and in March 2014 the figure had increase to 17 communities[3].

2.3 Theoretical framework

Electricity can be generated in many ways. Today our electricity demand is almost exclusively met by large-scale, centralized and fossil-fuel based electricity generation plants. Developed countries have over the course of decades constructed enormous infrastructure projects, consisting of thousands of kilometers of transmission lines drawn from huge, high-power electricity generation plants to end users, living ever further from the production site. For energy security and stability reasons, the individual grids have become more and more interconnected, resulting in large-scale, centralized power production being seen as the supreme solution for electricity service provision.

2.3.1 Grid versus small-scale solutions

The situation in the rural countryside of developing countries is different, where "[t]he increased cost of generation, transmission and distribution losses (technical as well as non-technical like pilferage) and the high cost of a centralized management system for small loads make supply of grid power unattractive for remote places" (Mahapatra and Dasappa, 2012, Kirubi et al., 2009). Here the idea of small-scale, decentralized energy production has been given new attention.

In the last decades the need to shift to renewable energy sources for electricity production has become more and more apparent. This challenge, together with the challenge of electrifying rural communities with low population densities in developing countries, might result in that small-scale, local solar, hydro or biomass energy conversion facilities might constitute a new, sustainable and economically feasible option.

Kaundinya et al. (2009) present an extensive literature overview on the subject of grid connections versus decentralized power solutions and find that there is a lack of literature on general approaches to assess whether stand-alone, decentralized and small-scale electricity production facilities or grid connections are the more suitable choice.

[3] Interview with Elvin Cruz, San Francisco Libre, 2014

2.3.2 Comparing costs

In the literature, a variety of attempts to judge the economic viability of local, small-scale power production can be found. This has been done either by comparing different types of small-scale electricity generation or by comparing one type of small-scale electricity production option to conventional grid extension. Most encountered attempts are based on case studies.

Already more than two decades ago, Sinha and Kandpal (1991) made an attempt to evaluate cost effectiveness of small-scale, local electricity production in India. They compared the costs of different small-scale options with each other and with the costs of conventional grid extensions. They found several of the small-scale options to be economically competitive, even preferable. Further, they identified the major factors influencing their economic viability to be 1) distance to the grid, 2) demand and 3) load factor. By developing a simple cost model they could compare viability for locations with different characteristics.

Ten years later, Nässén et al. (2002) compared local, small-scale, solar-based electricity generation to extensions of the main grid and found that the factors 1) distance to the grid and 2) peak electricity demand of individual households are crucial when trying to evaluate which is the more economic viable option. They developed a model based on life cycle costs (LCC) in order to be able to not only estimate the costs of the different options, but also to compare the costs in a discounted manner. One localized option that Nässén et al. investigated was the implementation of individual solar home systems (SHS), which is of relevance for this study. They found that for individual households' peak demands, which could be covered with a $140W_p$ SHS, this option becomes cost competitive regardless of the distance to the grid. They also found that a major cost factor for the SHS option is the price of the accompanying battery pack, which needs to be changed every couple of years.

In the last ten years, a variety of papers assessing the viability (not only economically) of different decentralized electricity supply options, has been published. In a recent paper by Mahapatra and Dasappa (2012), the concept of LCC for assessing economic viability of small-scale, solar-based electricity generation is further developed and the model is adjusted to the situation in today's rural India. They constructed a model to find the economical distance limit, "defined as the distance where the LCC of energy (… US$/kWh) of the renewable energy systems matches the LCC of energy from grid extension" (Mahapatra and Dasappa, 2012). They also point out that it is difficult to compare small-scale, local and renewable energy with grid-supplied energy, due to the fundamental differences in the characteristics of input energy and the maturity of the respective technologies. They find that for their localized, solar PV based electricity production, LCC per kWh are almost independent of system capacity, but the sought-after economic distance level is highly dependent on the desired system capacity and on grid availability time. They find economic distance levels between 40 to more than 200 km for grid availability time of 12 hours, and half those values for grid availability of only six hours.

2.3.3 Solar home systems

Already in 1982 the United Nations received finance, capacitation and technical assistance requests from developing countries that saw stand-alone, solar PV electricity production as a possible way to meet the poor, rural populations' energy needs (Arungu-Olende, 1982). Since then the solar home systems (SHS) have developed and found application mainly in rural parts of developing countries. Solar home systems are small photovoltaic electricity generation systems for one household. They generally consist of one or several solar panels with an aggregated power output of between 100W_p and 300W_p, an AC-DC converter (if requiered), a battery, a charge controller and the required wiring. In 2000, more than one million SHS had been installed in the world (Nieuwenhout et al., 2000).

Chaurey and Kandpal (2010) give an extensive literature overview of different aspects of decentralized, solar-based electrification projects. They identify poor technology - user interaction to be as much of a challenge to successful implementations as access to credits for low-income households and the absence of sufficiently skilled technical personal.

Rebane and Barham (2011) assess the adoption and knowledge on SHSs in the rural countryside through a field study. They find that the adoption of SHSs is predicted by higher income and that knowledge about SHSs is mainly acquired by other SHSs in the neighborhood (Rebane and Barham, 2011). They also find that there is a connection between (more) knowledge of SHSs and higher adoption likelihood.

A prominent characteristic of SHSs is that they can not only work as a cost-effective means to electrify rural households that are located too far from the grid to justify grid extensions, but that they also can act as a possible, electricity demand stimulating measure.

2.3.4 Electrification as driver for socio-economic development

In the process of trying to reach the Millennium Development Goals, the access to energy services has been given vast attention by NGOs and the United Nations alike. The report of the World Summit on Sustainable Development in 2002 in Johannesburg considers higher rural electrification rates and improved access to reliable and affordable forms of energy for the poor a crucial prerequisite for poverty alleviation and thereby meeting the MDGs (UN, 2002). The development program of the United Nations expresses its standpoint on the connection between access to energy services, in particular electricity, and socio-economic development more carefully by stating that the "lack of access to affordable, reliable, and environmentally-benign energy is a severe constraint on development" (UNDP, 2005) and that the linkages between development and energy are just beginning to be understood.

A report by Ahlborg and Hammer on the subject of rural electrification and sustainable energy production in developing countries considers it a fact that the access to energy and electricity services is crucial to and brings about socio-economic development (2014). Kaundinya et al., who have conducted an extensive literature study on the subject of grid connection versus decentralized energy production options, consider electricity access even as the major driver for economic development (2009). However, they do not present an explanation for what they base this hypothesis on.

No literature has been found that presented a credible "proof" of how and that electricity access is a sufficient condition for socio-economic development. However, a case study in Nicaragua has shown that once electricity services are provided, under certain circumstances, some development of the investigated parts could be observed (Grogan and Sadanand, 2013).

2.3.5 Former work on rural electrification

There is a considerable amount of literature treating the challenging task of finding a low-cost, cost-efficient, reliable and sustainable way of electrifying the rural population in developing countries, still lacking access to adequate energy services.

In a recent paper, Casillas and Kammen assess the possible benefits and economical savings of replacing the fossil fuel based energy supply to rural villages by low-carbon and low-cost alternatives (2011). They do this mainly by analyzing the demand load. An interesting result they find, which is of direct interest for this study, is that 90% of all electricity demand is for domestic purposes, dominated by lighting, TV and refrigeration. They identify switching to more energy-efficient lighting options such as compact fluorescent light and the installation of meters that are directly visible to the user, as major possibilities to reduce electricity demand and to use the electricity more effectively.

Ahlborg and Hammer (2014) identify important drivers and barriers for the rural electrification process through a comparative field study of Mozambique and Tanzania. When analyzing the change of load curve characteristics of rural communities over time it is important to have an understanding for these underlying and process governing drivers and barriers. They found that the major obstacle to rural electrification was costs, for both decentralized power production as well as grid extension, whereas the major driver for both was identified to be political priorities alongside development policies (Ahlborg and Hammar, 2014). They find community (bottom-up) demand to be a less significant driver.

2.3.6 Research gap

An economically, socially and environmentally sound electricity generation system is not automatically also a sustainable one. A crucial factor for sustainability is the consideration of time. A sustainable option has to be economically, socially and environmentally viable over a considerably long time frame. In order to be able to make informed decisions on the optimal rural electrification option for a site, one not only needs to consider the economic viability of the electrification process today, but also whether or not the chosen option delivers reliable and sufficient energy services over an extended amount of time.

The literature study has shown that there has been extensive work done on the economic aspects of the different possible rural electrification options as well as on their social and environmental favorability and preference by the end-users. The option of renewable, small-scale solutions is covered as well as assessed and analyzed also with respect to economic viability. However, in order to be able to determine if decentralized, low-power electricity generation is a sustainable option, it is necessary to assess the development of rural communities' and individual households' electricity demand over time. Only when it can be assured that the electrification option considered is able to meet even future demand projections, can it be deemed a sustainable option. The understanding of the development of load curves and characteristic changes over time is therefore where this study seeks to contribute.

3 Methodology

This thesis was conducted as a transdisciplinary research project, combining methods from social science and engineering, in an attempt to get a holistic understanding of the development of the electricity demand in the studied, rural communities. By quantitatively analyzing the load curves of different households as well as entire communities, by studying possible demand change over time and by qualitatively assessing reasons for that behavior, the study combines two fundamentally different scientific approaches in order to achieve the best possible result. The user-based interviews in the relevant communities were complemented by informal interviews with other stakeholders, such as the local government and private electricity company representatives as well as with participant observations. The field work was preceded by a literature study in order to position the thesis in a research gap.

3.1 Literature study

The study was initiated by a literature study, focusing on understanding the current state of knowledge in the area of sustainable, rural electrification processes in the developing world as well as on the current costs of implementing small-scale, local, solar-based electricity generation options and grid extensions. This was complemented by a thorough investigation on the demographic and energetic situation in the planned field work territory. The results from the literature study have been presented in Chapter 2 and based on them the aim and purposes of the study as well as the detailed research questions have been developed.

3.2 Field study

In order to collect the data needed to answer the specific research questions, a nine-week field trip to Nicaragua was made. The time was spent in the department of Managua. Semi-structured user interviews and participant observations in three similar communities were complemented with informal interviews of other relevant stakeholders in the electrification process of the rural communities in San Francisco Libre (SFL).

3.2.1 Choice of data collection locations

In order to be able to assess the change and development of the electricity demand and the respective load curves, communities that have had access to electricity for different amount of times had to be found. To be able to ensure that possible load curve changes are due to the fact of different electrification times, other factors potentially able to influence load curve behavior had to be identified. The information necessary to make an informed decision about appropriate communities was acquired by informal conversation with the local population, who knew about different communities, and from inquiries with the Instituto Nacional de Información de Desarollo (INIDE), the national institute for development. Based on the obtained information, three different communities were chosen.

3.2.2 Choice of research method

The area of interest of this study is a multidisciplinary field. The study does not only intend to find and present changes in demand / load curve behavior over time, but aims also at understanding the underlying drivers and thereby finding possible explanations for the observed behavior. This required tackling the data collection as well as the analysis with tools from engineering and with tools most often used in social science. The complementation of qualitative and quantitative methods makes it possible to get a more holistic understanding of the situation (Brikci and Green, 2007).

Due the transdisciplinary nature of the research questions, different data collection methods were chosen. For the quantitative as well as qualitative data acquisition in the field, different types of interviews and participant observations have been chosen as the preferred methods.

To answer the research question: “How do the characteristic load curves of rural, remote communities and those of the individual households change over time?”, as well as when inquiring about the total amount of electricity used, a purely quantitative result is of interest. Data have been acquired by performing structured interviews, containing purely quantitative interview questions on domestic and (where applicable) commercial electricity use, with all the households in the relevant sampling group.

Figure 3 - Interview in Madroñito

To answer the research questions focusing on habits and perceptions of electricity use as well as concerning personal opinions on supply options, semi-structured interviews and informal conversations have been used as the preferred method of data acquisition. Semi-structured interviews give space to the interviewees to elaborate on their own thoughts and to furthermore add new information that was not anticipated beforehand. The answers received from this method are mainly qualitative and enable a deeper understanding of the underlying processes governing change in energy use and demand (Brikci and Green, 2007). The semi-structured interviews were complemented with participant observations on electricity use habits, conducted by staying in the respective villages several days. Participant observations were made in order to put actual and stated habits into comparison.

In order to be able to acquire more general information on the electrification process of the three communities, as well as of the country as a whole, unstructured interview with relevant stakeholders has been chosen as being an appropriate method.

3.2.3 Data collection in the field

3.2.3.1 User-based data acquisition

After having identified different types of interviews and participant observations as appropriate methods for data acquisition concerning electricity demand and users' perception and attitudes towards different supply methods as well as prospects of future demand and demand changes, interview guides incorporating all these aspects have been developed. They were continuously further developed and adjusted during the data acquisition process.

The user-based interviews consisted of two parts, the first part being a structured interview including questions on the users' daily routines concerning electricity use, on the electro domestics they have and regularly use in their home, as well as on personal electricity costs. The second part of the interview being of semi-structured nature and focusing on why households use electricity the way they do, if users themselves had observed a change in how and when they use electricity, and what their opinions, attitudes and perception of the electricity service they receive were. A full interview guide, used in E Obraje, can be found in Appendix A.

In order to be able to get a better understanding of the users' living situation and to be able to put electricity use and personal needs and habits into context, the user-based interviews were complemented by participant observation. This involved choosing a representative household and following the members' everyday life, closely observing electricity use practices. To get a representative sample this was done for an approximate amount of ten days per community.

3.2.3.2 Stakeholder investigation

For the investigation of the outer circumstances of the electrification process, contact to relevant stakeholders was established. The main areas of interest have been understanding and finding out about costs of the electrification projects, reasons for the choice of communities for the projects, reasons and expectations for the electrification and information about electricity prices and demand / use in the investigated areas. In order to find relevant stakeholders, all governmental and major private actors/companies that are involved in the energy sector in the relevant department as well as on state level have been investigated. Unstructured interviews as well as extensive Email conversations, concerning specific quantitative data requests, have been held with representatives of all the identified, relevant stakeholders that were willing to cooperate.

3.3 Data analysis

Since the data acquired during the literature study and the field work is of quantitative and qualitative character, different analysis tools have to be used in order to do them justice.

3.3.1 Load curves

A major part of the study focused on finding data in order to be able to construct load curves for the electricity use of different households as well as of the communities as an entity and subsequently compare them. The analysis of this part of the obtained data is therefore solely quantitative. The applied analysis strategy applied has been organizing the obtained information on electricity use for every individual household investigated according to time of day and then presenting it graphically as a load curve. The electricity use of the individual households has thereupon been added up to generate approximate mean load curves for each community. Comparison has been done based on total load, peak load, and characteristics of the curve, between different households within a community, different households between communities and between entire communities. The so calculated monthly amount of electricity used is compared to data on measured electricity use (for two communities) obtained from the electricity distribution companies.

By finally analyzing the load curve profile, statements can be made on whether or not the required electricity demand could be met by small-scale, local and solar-based electricity generation solutions, which could present a more sustainable option than large grid extensions.

3.3.2 Underlying drivers for load curve development

A more qualitative approach is needed for the investigation of underlying drivers of the observed load curve behavior and its development. The interviewees' answers have been transcribed and analyzed based on content, choice of words and phrasing, indications for insecurity in between the lines, attitudes as well as believes. The results from the participant observations found during the stays in the communities and the information obtained from informal conversations with users are incorporated in the analysis.

3.4 Cost calculations

In order to be able to compare costs of different electricity supply options, one has to decide on which approach to use. There are a variety of different approaches possible. In the literature in this field from the last 20 years, most often different decentralized solutions have been compared with each other and not to the extension of the main grid. In these cases, a recurrent approach has been to compare front-up investment costs and running costs.

A major approach in the literature discussing comparisons between small-scale, localized option with grid extensions has been life cycle cost analysis. This approach handles the discrepancy between costs occurring in the future and costs today, by introducing the concept of discounting into the calculation. However this makes the outcome highly dependent on the chosen discount rate, the value of which is still debated (Sterner and Persson, 2008). It also needs to be taken into account that the life cycle cost approach (LCC) incorporates the total costs occurring during a project's life time, which makes it difficult to compare options with different life times.

In this study the life cycle approach was chosen as the main cost comparison approach; however, it was complemented with a user cost approach for the different options, which considers the costs of the different options for the individual households.

3.4.1 Solar home systems

The decentralized electricity production option investigated in this study is SHSs. In order to calculate the costs of this option, a highly simplified cost model based on a life cycle cost approach has been developed. The model approximates the complete cost per household for a SHS that would cover the average electricity demand of one household.

$$LCC_{PV} = d_e u^{-1}(C_{PV} + C_B) + \alpha(d_e u^{-1} C_{PV})p + d_e u^{-1} C_B \sum_{i}^{T/\gamma} p_{i*\gamma}$$

LCC_{PV} refers to the aggregated cost for the whole life cycle of the system as if they were to be paid today; d_e is the daily demanded energy per household, based on the current average demand per community and day; u is the utilization factor, which depends on the solar irradiation at the specific site of installation, hours of sunlight, the overall system performance, shadowing etc.; C_{PV} and C_B are the costs of the solar PV system (excluding battery) and the costs of the battery per W_p respectively and α is a factor describing the yearly maintenance costs. p is the net present value factor, calculated according to

$$p = \sum_{t=1}^{T} \frac{1}{(1+r)^t}$$

with r being the discount rate. T refers to the time of the life cycle and $p_{i*\gamma}$ is the net present value factor of the $(i*\gamma)^{th}$ year and with γ being the lifetime of the battery.

The above cost model correctly adjusts both PV system and battery capacity and thereby price to the electricity demand. It does not take into account that panels are only sold in 50 W_P steps and that batteries are only available with certain specifications. Therefore the actual system cost calculated for a specific power supply is slightly underestimated.

3.4.2 Grid extension

In order to estimate the costs for the extension of the main grid as well as to be able to compare these to the costs of individual SHSs, a life cycle approach over a period of the same length has been chosen even here. This might not be the most obvious way of calculating grid extension costs, however in order to be able to compare the two options' cost over a predetermined time frame, this constitutes a good option. The main factors considered in the life cycle costs for the grid connection are generation, extension and maintenance costs. Costs that might result from higher load and thereby the need for new capacity generation are not included, since the increase in load is only marginal. However when (planning on) connecting all the unelectrified households in Nicaragua (around 60% (MEM, 2010) of the population) to the main grid, this cost should be taken into account since it will be considerable. The grid extension, life cycle cost model developed is based on the models from Nässén et al. (2002) and Mahapatra and Dasappa (2012):

$$LCC_{grid} = \frac{C_{gen} + C_{ext}(1 + \alpha p)}{N}$$

LCC_{grid} are the aggregated life cycle cost for the grid extension and electricity supply per household over the entire projects life time T. C_{gen} are the electricity generation costs, C_{ext} are the cost for the actual extension of the grid, α describes the maintenance costs as a share of the total extensions costs, p is the net present value factor (calculated as described in Chapter 7) and N the amount of households in the village under investigation.

C_{gen} is calculated according to

$$C_{gen} = t_{gen} d_e N \, p \, (1 - \delta)^{-1} * \, 365$$

where t_{gen} is the cost of producing 1kWh of energy, d_e the average demanded energy per household and δ the transmission and distribution losses.

C_{ext} is calculated according to

$$C_{ext} = l * C_{TL} + C_T + C_c * N$$

and incorporates the actual costs of the transmission lines that need to be put up, the transformer and either the connection of the individual households or the construction of several poles in different locations in the communities, so people can connect themselves. Here l is the length of transmission lines that need to be installed, C_{TL} the kilometer cost of the transmission lines, C_T the cost of the transformer and C_c the cost for the connection of the individual households.

3.5 Limitations

In order to be able to draw viable conclusions, the major limitations of this study have been identified. The main limitation of the study is the fact that only three different communities are investigated. It is therefore important to understand this study to be a case study and not statistically representative for generalization purposes. Further it is important to consider that the load curves have been constructed based on people's own appreciation of their everyday electricity use, partly adjusted for the results obtained from personal observations, and that the load curves are not based on quantitative electricity measurements, averaged over time.

Another limitation identified is that the investigated communities are not perfect for comparison, in the sense that conditions are not identical. However they offer very similar conditions for a real world system, apart from different electrification dates, which is intended. Beyond naturally occurring differences, they three communities are, geographically, very close to each other (and within the same country), making it difficult to generalize results for other geographical locations.

A limiting factor concerning the identification of costs for different electricity generation types and the actual grid extension realized was the unwillingness of involved stakeholders (private companies as well as government agencies) to reveal their own calculation on costs and actual spending. Therefore cost calculation could only be based on information from related articles and publically available, general figures.

4 Choice and characteristics of investigation sites

In order to ensure that changes in the observed load curve behavior are caused by the time that a user/community has had access to electricity services and not by other, interfering factors, a list of parameters that should be comparable in all the investigation sites has been developed. The following list contains parameters that could affect electricity demand, as well as electrification costs. The list was complemented with situation specific parameters (marked *), considered possibly relevant by local stakeholders.

1. Amount of housings in the community
2. Amount of people in the community
3. Distance of community to next major settlement*
4. Access to the community
5. Area of the community
6. Geographical situation of the community
7. Main employment type* [4]
8. Proximity to the next major employment facility*[4]
9. Income level
10. Level of education *[4]

Based on information obtained from an interview with Elvin Cruz, representative of the local government of San Francisco Libre, the communities El Obraje, Madroñito and Villa Esperanza were chosen. All three villages are located in the same, very small (in terms of area) municipality, ensuring good compliance with requirement 3, 6, 7, 10. Table 1 summarizes the characteristics of the three chosen communities.

Table 1 - Characteristics of the chosen communities

	El Obraje	**Madroñito**	**Villa Esperanza**
Year of electrification[5]	2013	2008	2000
Number of housings according to -INIDE (2008) -Own investigation (inhabited)	 77 43*	 61 47	 74 41
Amount of people (INIDE, 2008)	327	235	394
Distance to SFL (Google maps)	Ca. 15 km	Ca. 12 km	Ca. 12 km
Access (observations)	Gravel road, public transport twice per week	1 km off the main road (gravel) connecting SFL with Pan American	Gravel road (connection road between Leon and SFL), Public transport 5 x per week

[4] Interview with Pedro and Elielka Salinas, San Francisco Libre, 2014
[5] Interview with Elvin Cruz, San Francisco Libre, 2014

		Highway, public transport on main road various times per day	
Area (observation)	Two parts, houses very spread out	Very compact; 5 houses far away	Two parts, compact
Main Employment (INIDE, 2008)	Subsistence agriculture	Collection and sale of fire wood	Seasonal factory work, agriculture
Proximity to employment facility	SFL	SFL	10-15 km (Mangosa)
Income level (interviews)	0	0-50$	0-200$/month

The figures on housings and people are approximates; there are no official, up-to-date numbers of inhabitants or housings. Central government numbers, numbers from the local municipality government and observed numbers differ widely. Numbers presented above are from the 2005 government census. All three communities show high emigration rates, especially of the young population.

El Obraje is the community that has undergone the electrification process most recently. It is situated in a more remote location than the other two villages, e.g. not on the main road. It consists of the main village and a smaller satellite, separated by about two kilometers. The satellite was not included in the study and therefore the number of inhabited houses in El Obraje was found to be 43.

Demographically, the community is very similar to the other two and to most communities in the municipality, with a very young population (40% below the age of 15,) and a high level of illiteracy (half of the population over 15 can neither read nor write); only 30% have attended primary school (INIDE, 2008).

Madroñito is very compact, with only five houses located at a considerable distance from the center. These houses were included in the study.

Villa Esperanza was electrified in 2000; out of the three communities investigated, it is the only one where households have running water. It is located right on the municipality's main road, where also the area's only major factory Mangosa (a transnational mango export company) is located. Villa Esperanza's electrification process differed from the others, in the sense that the grid was only extended to the village border and that no connections to the individual households were made. Therefore the households have privately erected homemade poles and connected wiring in order to connect the houses to the main transmission lines. No mediators are installed and electricity bills here are based on a legal minimum electricity cost, which depends on the electric appliances that a household possesses. However, the inhabitants of Villa

Esperanza refuse to pay their electricity bills until they have proper connections and mediators installed.

4.1 Interviewee sampling

Sampling of the user-based interviews was done based on availability. The intention was to interview one person from each household; however, due to limited time in the field this could not be achieved and a mean share of 15% per village could not be interviewed. Table 2 presents characteristics of the sample from each community.

Table 2 - Sampling characteristics of the interviews in the three communities

	El Obraje	Madroñito	Villa Esperanza
Number of inhabited houses	40	47	35
Interviewed	38	38	31
Share of male interviewees	31%	18%	30%
Average age	43	43	42
Average amount of people per household	4,3	3.8	4
Number of households that operate a business (all shops)	6	6	2

All conducted interviews included a structured, semi-structured and an unrecorded, informal conversation part. Table 2 shows that in all cases the majority of interviewees were female and that the average housing is home to four people. All the businesses identified were minor shops in the families' homes.

5 Electricity demand

5.1 Electrical appliances

The first focus of the structured interviews lay on investigating the individual households' electrical appliances. Figure 4 shows the distribution of the electrical appliances owned in the different communities. Appliances are categorized into three different groups. The first group (the first four distributions shown in Figure 4) consists of appliances with low power demand, which are used over extended periods of time or even continuously. The second group shows the most common high-power appliances, which however are not used on a regular basis and when used then only for short periods. The third group consists of appliances that only very few households possess but which were desired by the other interviewed households.

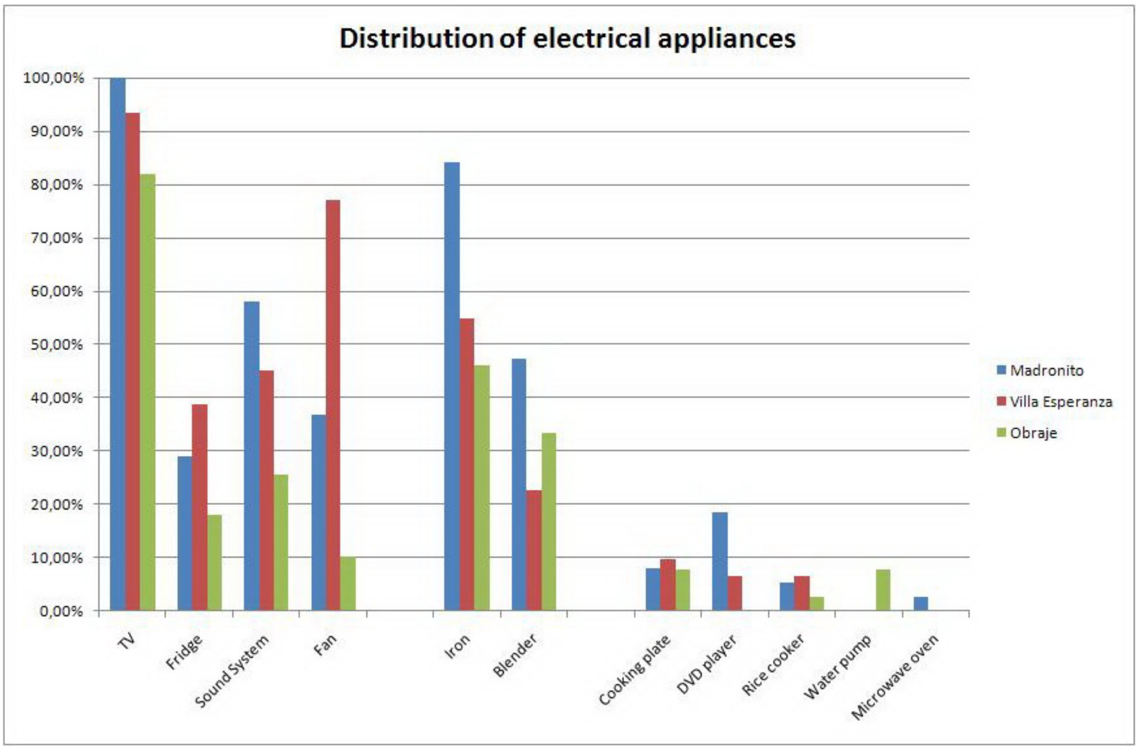

Figure 4 - Distribution of electrical appliances in the communities

Furthermore, 100% of the interviewed households have at least one light bulb installed. The average amount of light bulbs per household (2,6) and average hours in use (3,1) is similar in all three communities. In the communities El Obraje and Madroñito, all light bulbs installed are of 9W, energy-saving type, whereas in Villa Esperanza there are no energy-saving light bulbs, only normal 100W-type light bulbs.

Figure 4 shows that almost every household has a TV and that the amount of fridges and fans is higher in the communities with longer electrification times. The size and type of TVs varies, with the majority using between 70W and 150W, averaged to 100W in the calculations. The biggest difference in the abundance of a specific appliance between the villages is for fans; Villa

Esperanza has about eight times as many as El Obraje. Villa Esperanza also has more than twice as many fridges. The power demand of a typical refrigerator is assumed to 200 W. This high assumption is based on the types of fridges encountered and the way the fridges are used. All encountered fridges (except for two) were bought used and were therefore several years old. Fridges in the investigated communities are opened frequently for longer periods of time and normally do not contain more than one or two items at a time. This implies higher power demand.

5.2 Load curves

The data on electricity use and power demand obtained from the structured interviews was categorized, organized and subsequently plotted as load curves. The energy demand was organized in tables in order to make a comparison possible. Figure 5 shows the average, daily load distribution for the three communities.

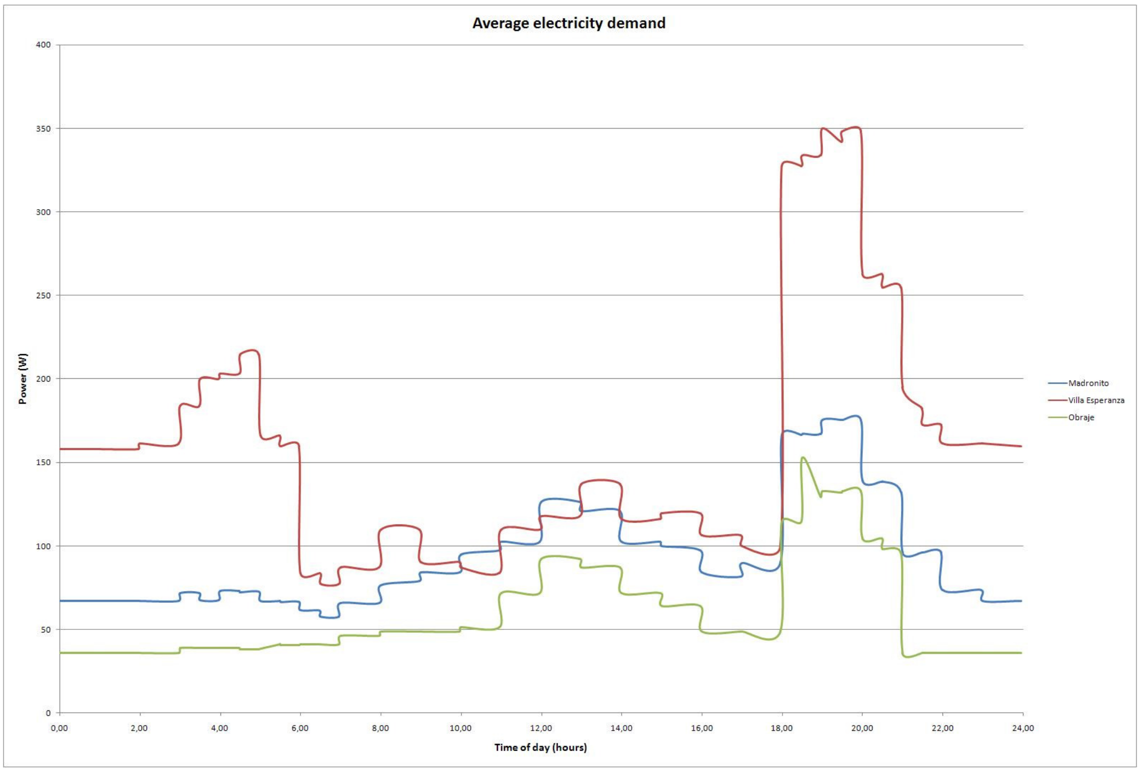

Figure 5 - Average electrical power demand for the communities over the day

All three load curves show similar behavior but different absolute values. Three major characteristic phases can be distinguished in the graph above. Phase 1, from 6AM to 6PM, is characterized by fluctuations over a community-specific mean value of approximately 60W in El Obraje, 90W in Madroñito and 110W in Villa Esperanza. A minor peak in the period from about 12AM to 2PM is distinguishable in all three curves. Phase 2 is characterized by a prominent peak, starting at 6PM with a very sharp increase in power demand. The higher power demand is maintained for approximately three hours and declines sharply thereafter. Phase 3, from 9PM to 6AM, is characterized by a stable, community-specific power demand. The load curve of Villa Esperanza shows a minor peak from 3AM to 6AM, which the other two villages do not show. For both Madroñito and El Obraje, the average power demand of phase 1 is slightly higher than that of phase 3, whereas it is vice versa for Villa Esperanza.

These three phases concur with the measured municipal power demand distribution shown in Figure 6, supplied by Tipitapa Power[6]. However, phase 1 and 3 show about the same mean electricity demand and a minor peak between 4AM and 6AM. When extrapolating the average data obtained from the three villages on the total amount of people in the San Francisco municipality, the power demand is of the same order of magnitude as shown in Figure 6.

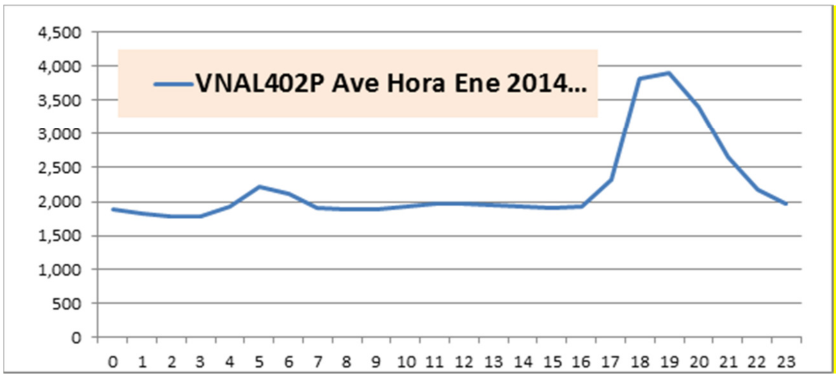

Figure 6 - San Francisco Libre municipality load curve, power in kWh

Table 3 presents important data found on average power and energy demand for the three villages. The average energy demand per household increases with the time that a community has been electrified. In all communities the share of energy demanded at night is higher than during daytime, approximately 63%. The highest instant power demand is considerably larger for Villa Esperanza than for the other two communities.

Table 3 – Household-specific energy and power demands

	El Obraje	Madroñito	Villa Esperanza
Average energy demand per household Daily/monthly/yearly	[kWh] 1,4/43/518	[kWh] 2,2/67/816	[kWh] 3,7/114/1270
Average daily energy demand per household 5PM to 7PM	[W] 0,8	[W] 1,3	[W] 2,98
Highest instant individual power demand	[W] 354	[W] 350	[W] 800

[6] Interview with Miguel Cruz, Tipitapa Power

5.3 Comparing average electricity demand

Figure 5 shows that there is a considerable difference between the communities in the level of power demand. It is highest for Villa Esperanza, which is the community that was electrified 15 years ago, and lowest for El Obraje, which was electrified last year. In order to explain the differences and similarities in the load curves, the absence of energy-saving light bulbs in Villa Esperanza has to be considered. Figure 7 presents the “real” load curves and a potential one for Villa Esperanza, if all 100W light bulbs were to be replaced with 9W energy-saving light bulbs.

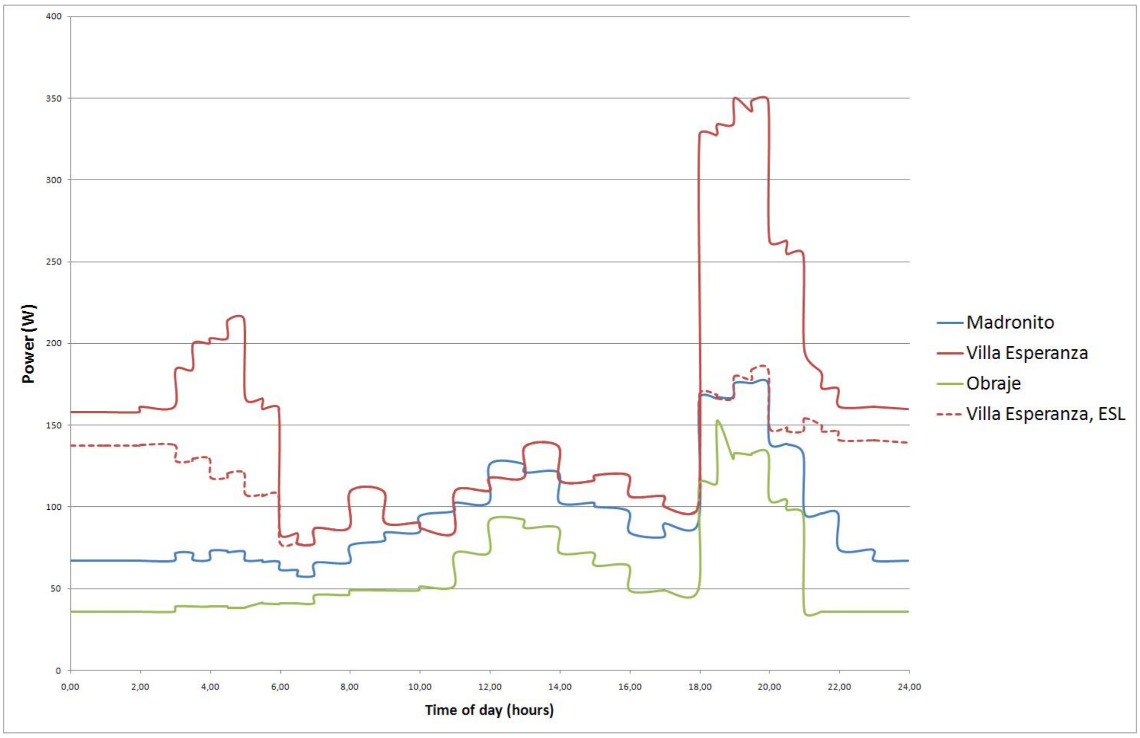

Figure 7 - Average power demand distribution over the day, including hypothetical power demand for Villa Esperanza with energy-saving lights (ESL)

Phase 1

The base load in phase 1 in El Obraje and Madroñito can mainly be attributed to the use of TVs and sound systems. In Villa Esperanza almost 50% of all households have a fridge or a freezer, resulting in that the base load here is both due to use of TVs and refrigerators. The fluctuations are due to variations in the amount of TVs in use at the same time. The two Villa Esperanza curves coincide throughout the entire phase, indicating that lights are turned off all day. The minor peak between 12AM and 2PM can be attributed to an increased number of TVs switched on during that time. From the interviews it has been found that this peak coincides with the current sending time of the news program and a famous telenovela (TV series). The time of day when this peak occurs is thereby dependent on how the current TV program is designed.

Phase 2

All curves show the same, almost instant increase in electricity demand at 6PM. However the proportion between daytime base load and peak height differs between the Villa Esperanza regular curve and the other curves. The demand in Villa Esperanza increases by more than a factor three, whereas in Madroñito and El Obraje by about a factor two. The great majority of interviewees stated that they turn on the light, mostly several light bulbs, and the TV at 6PM, because it gets dark rapidly at that time. When comparing the two curves from Villa Esperanza, it gets apparent that the disproportional high increase (compared to the other two villages) is solely due to the fact that they use 100W light bulbs. In the Villa Esperanza ESL case the increase is of similar proportion to the other villages and can hereby be attributed to an increase in amount of TVs switched on.

Phase 3

During night time the base load in El Obraje is zero for 82% of the households, but considerable (~200W) for the rest, mainly due to running fridges. The constant base load of El Obraje observed in Figure 5 results from the fact that the average demand is plotted. When analyzing the reason for the nightly base load in Madroñito one encounters the same dynamics, namely that 60% of all households have a base load of zero and the rest a rather high base load, due to running fridges. The two Villa Esperanza curves show that a large share of inhabitants keeps lights switched on during the night, a phenomena that was not observed in the other villages. Overall, 90% of the households have at least one appliance switched on overnight. The high base load of Villa Esperanza can be attributed to running fans, an appliance that is very common in that village. The comparison of the two load curves for Villa Esperanza shows that the morning peak disappears when 100W light bulbs are replaced with energy-saving lights. This indicates that the peak was due to lights. The Villa Esperanza ESL curve shows a slow decrease in power demand at around the same time that lights are started to get switched on. The explanation is that people usually turn on the light and switch off the fan when they get up. This results in a net decrease of power demanded.

In order to determine how much of the demanded energy is due to inefficient fridges, all the calculations were redone with a continuous power demand of 50W for a fridge, all other power demands equal. This corresponds to an average modern fridge of energy class A, but still used inefficiently. The resulting load curves are shown in Figure 10 in Appendix B. The change in the level of the curves indicates how sensitive the energy demand is to the power demand of the fridges. The differences in demanded energy per day as well as the highest daily power demand are presented in Table 4. It is apparent that not only the total energy demanded is less, but also the share of the total energy demanded at night decreases, which is interesting as well as important for optimizing the battery in a SHS.

Table 4 - Energy and Power demand for real and energy-saving scenarios (ESS), i.e. lower energy fridges.

	El Obraje		**Madroñito**		**Villa Esperanza**		
	normal	ESS	normal	ESS	normal	ESL	ESS
Average daily energy demand per household	1,42 kWh	1,23 kWh	2,24 kWh	1,19 kWh	3,75 kWh	2,96 kWh	1,58 kWh
Average energy demand from 5PM to 7AM per household	0,84 kWh	0,42 kWh	1,34 kWh	0,69 kWh	2,75 kWh	1,95 kWh	1,05 kWh
Highest instant power demand of one household	354 W	204 W	350 W	195 W	800 W	618 W	318 W

6 Perceptions and underlying drivers

In all three communities, the structured part of the interviews were complemented by a semi-structured part in order to give the interviewees the possibility of adding and elaborating on topics and issues that they themselves found important and that were not known beforehand. Due to the different electrification years, the focus of these questions was village-dependent. In Villa Esperanza the qualitative questions focused on the development the community had undergone since its electrification and in El Obraje on what the population had expected from the electrification.

The great majority of all interviewed households, in all communities, stated that "*obviously electricity is a great benefit*"[7]. Typical statements made were "*before we lived in darkness*"[8], "*before it was boring, now we watch telenovelas and the news, now we know what is happening in Managua*"[9], "*life is easier now*"[10], etc. Tasks perceived as easier with electricity were ironing and switching on the light. The main benefit of having electric light was stated to be its light quality and its illuminations strength, compared to the non-electric option of *candil* (oil lamps).

When asked directly about electricity costs, only a minority of the interviewees stated that these constituted a problem to the household. In Villa Esperanza, costs were not considered a problem, this probably due to the fact that the inhabitants are not paying any bills and that the mean income per household is higher compared to in the other villages. In Villa Esperanza the greatest problem or fear with electricity was the unsecure connection. There had been incidence of people getting hurt and appliances burning.

In all three villages the electrification project was done through major pressure from the communities on the municipal government. People have stated a strong desire to have access to electricity. In El Obraje and Madroñito five respectively two households had SHSs, which however were hardly used anymore since they had gained access to the main grid. A majority of the interviewed people, who did not have a SHS, expressed concerns about it being difficult to operate, whereas the interviewees owning one commented on how well it worked. Due to lack of time, reasons for this could not be investigated further.

The only observed and stated productive use of the electricity service is through selling refrigerated products. No correlation between electrification time and amount of households with productive electricity use could be found. However, the only villages in which some (three) of the interviewees stated that they were thinking of using the electricity access in a way to generate an income, other than selling refrigerated products, is Villa Esperanza, namely to set

[7] Various households, El Obraje, 2014
[8] Household 2 and Household 24, Madroñito, 2014
[9] Household 23, El Obraje, 2014
[10] Household 7, El Obraje, 2014

up a workshop. However these were just future ideas that do not have any practical implications on electricity use today.

7 Costs

Life cycle costs for the two different electricity supply options, SHSs and grid extension, are calculated according to the cost models developed in Chapter 3.4. The two options are assumed to have a life time of T =25 years.

7.1 Solar home systems

The cost model for the SHS electricity supply option

$$LCC_{PV} = d_e u^{-1}(C_{PV} + C_B) + \alpha(d_e u^{-1} C_{PV})p + d_e u^{-1} \sum_{i}^{25/\gamma} p_{i*\gamma}$$

requires estimations of the average electricity demand per household, the utilization factor, the cost of the PV system, the battery and maintenance as well as for the discount rate. The model generates the total, aggregated cost for a demand-adjusted SHS over its life time, as if it were to be paid today, i.e. the net present 25-year life cycle cost per household. An overview of the used estimates in the LCC_{PV} cost calculation is presented in Table 5.

Table 5 - Values for the calculation of LCC_{PV} for SHSs

Cost for PV system (without battery)	Battery costs	Discount rate (net present value factor)	Utility factor	Maintenance costs (share of PV system cost)
C_{PV} per W_P	**C_B** per W_P	**r (p)**	**u** per W_P	**α**
8 $	1,2 $	10% (9.08)	5 Wh	1 %

The daily electricity demand d_e is based on the current average demand of each investigated community. It is assumed to be constant over the 25-year life cycle period. The costs were calculated for all three villages for both, the investigated demand as well as the energy-saving scenarios (ESS).

The utilization factor u was set to the value provided by a SHS retailer in Managua[11], 5Wh/W_P. This value correlates well to data from Americas National Renewable energy Laboratory on solar irradiation in the Managua department, see Figure 8. It however varies considerably depending on season. The feasibility of the SHS option showed to be highly dependent on this factor together with the total daily demand, since they determine how many panels and batteries a household needs in order to produce the necessary amount of electricity.

[11] Interview with Tecnosol, Managua, 2014

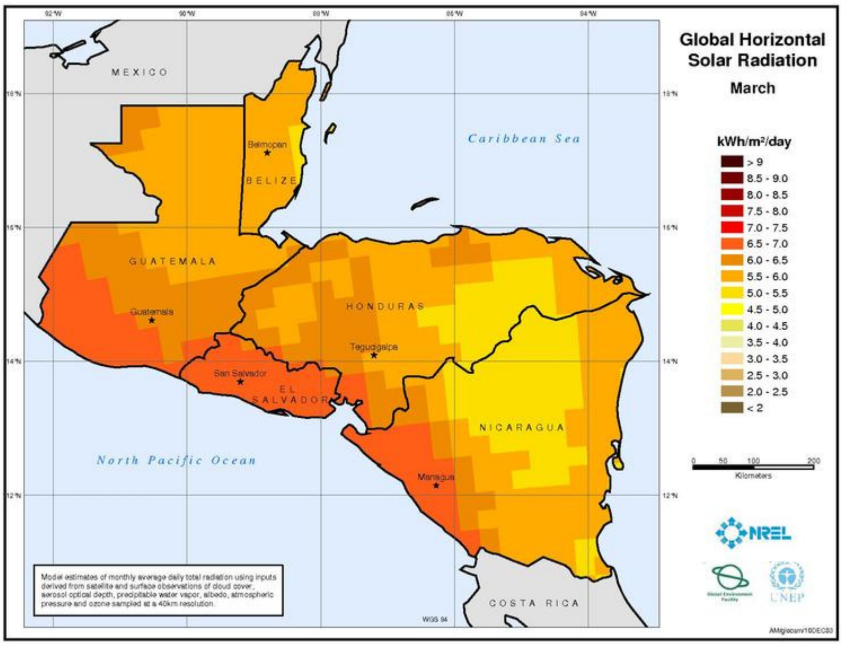

Figure 8 - Solar radiation in Nicaragua (NREL, 2003)

The costs of the solar PV system C_{PV} per W_p are based on the price that low-capacity solar home systems are sold at in Managua. By averaging over the prices of different sized systems, the cost C_{PV} has been found to be ~$8[12] per W_P. There is considerable potential in the decrease of PV system costs, since the major share of the system costs are Nicaraguan taxes. With a price of $1 per W_P (2014 retail price in Germany), solar panels become a far more attractive option, see Table 6.

When calculating the required battery capacity and hence the battery cost C_B, the obtained load curve characteristics have to be taken into account. The results on electricity demand of the different villages, presented in Table 4, show that the demand from 5PM to 7AM corresponds to around 60% of their total daily demand. It is assumed that the batter type is deep cycle, and that more than 60% of the battery capacity can be used (Northern Arizone WIND & SUN, 2014). Costs are based on the price at which batteries (65Ah, 12V) are sold in Managua and assumed to stay constant throughout the entire life cycle. Interviewees with SHSs stated that the batteries need to be changed every four years[13]. However it is assumed that the last battery would last five years. This modifies the LCCPV model to become:

$$LCC_{PV} = d_e u^{-1}(C_{PV} + C_B) + \alpha(d_e u^{-1} C_{PV})p + d_e u^{-1}(C_B p_4 + C_B p_8 + C_B p_{12} + C_B p_{16} + C_B p_{20})$$

Calculations have also been performed, assuming battery costs to decrease with 10% for every four-year period, but this has shown to only have minor influence on the final SHS cost.

12 Interview with Tecnosol, Managua, 2014
13 Interview with households 5 and 9, El Obraje, 2014

Based on former, similar case studies, the yearly maintenance costs, α, are approximated to 1% of the system investments costs (Mahapatra and Dasappa, 2012). Sensitivity analysis, see Table 6, indicates that the obtained final costs depend on α only to a minor extent. Setting maintenance costs to zero respectively three percent does not change the overall system costs notably.

All costs occurring in the future have been discounted with a discount rate of r = 10% to allow a fair comparison to other electrification options, assuming the same discount rate for different options. Life cycle costs show to be highly sensitive to the choice of the discount rate.

In Table 6, the obtained LCC_{PV} (grey) for the three communities as well as the sensitivity analysis are presented.

Table 6 - Life cycle costs for SHSs for the three investigated communities

	Average demand per household d_e	Maintenance costs $\alpha = 0$ $\alpha = 3\%$	Highest demand of household d_e	PV system cost C_{PV} = 1$ per W_P	Battery costs declining with 10% per 4 y	Discount rate r = 0 r = 0.2	Utilization factor u = 3
El Obraje							
Normal	(1421 Wh) $3449	$3242 $3861	(6476 Wh) $15716	$1277	$3317	$4888 $3037	$5744
ESS	(775 Wh) $1880	$1767 $2105	(2876 Wh) $6976	$696	$1809	$2666 $1656	$3133
Madroñito							
Normal	(2236 Wh) $5423	$5099 $6073	(7154 Wh) $17362	$2009	$5220	$7692 $4778	$9039
ESS	(1193 Wh) $2894	$2720 $3240	(3554 Wh) $8620	$1072	$2785	$4104 $2549	$4823
Villa Esperanza							
Normal	(3747 Wh) $9088	$8544 $10177	(12650Wh) $30700	$3366	$8748	$12890 $8007	$15147
opt	(2955 Wh) $7167	$6738 $8026	(11831Wh) $28212	$2655	$6899	$10165 $6314	$11946
ESS	(1578 Wh) $3827	$3598 $4286	(4631 Wh) $11232	$1418	$3684	$5428 $3372	$6379

7.2 Grid extension

Grid extension costs are calculated with the model developed in Section 3.4.2, according to

$$LCC_{grid} = \frac{C_{gen} + C_{ext}(1 + \alpha p)}{N}$$

where $C_{gen} = t_{gen} d_e N\, p\, (1 - \delta)^{-1} * 365$ and $C_{ext} = l * C_{TL} + C_T + C_c * N$. Estimations of generation costs, transmission and distribution losses, transmission line and transformer costs, maintenance costs and distance to the closest grid connection point are needed.

Values used for calculation of the life cycle grid extension costs for the three communities are presented in Table 7 and discussed below.

Table 7 - Values used for the calculation of LCC_{grid}

Electricity generation costs	Distribution and transmission losses	Net present value factor	Installation costs for transmission lines	Transformer cost	Household connection costs
t_{gen} per kWh	δ	p	c_t per km	c_T	c_C per km
$ 0.04	0.15	9,08	$10 000	$500	$70

Electricity generation costs t_{gen} depend highly on the production site and type. Neither the INE nor the MEM has information available or was willing to provide data on current electricity production costs. The closest power plant to the investigation sites is Tipitapa Power, an oil-fired thermal power plant, about 50 km away. However before 2003, the port of San Francisco Libre, where the extensions to the villages start from, was only connected to the plant in Leon. Nässén et al. (2002) assumed the electricity generation costs from an oil-fired power plant in 2002 to be 0.04$/kWh. Oil prices have risen immensely since then. Assuming that the absolute majority of the electricity generation cost can be attributed to fuel costs and setting the highly variable crude oil price to 100$ (EIA, 2014b), 0.15$/kWh has been found to constitute a representative value for the approximate, current generation costs, calculated by dividing the oil price by its energy content, 1.7MWh/barrel (EIA, 2014a) and multiplying with an approximated 40% efficiency for an oil-fired thermal power plant. Sensitivity analysis with values of t_{gen} like the one chosen by Nässén and for crude oil price of 150$ per barrel, show that life cycle cost are sensitive to fuel costs, however they are not the most determining factor.

Current distribution and transmission losses δ are hard to estimate. Estimates indicate a decrease from 24% in 2010 and to 19% in 2011 in Nicaragua (World Bank, 2014). In the calculations δ has been estimated to 15%, but sensitivity analysis showed that ± 5% does not make a notable difference in the final costs. Effects on system costs from possibly high losses in the extended, local transmission lines can be observed in the cost sensitivity analysis of transmission line costs per kilometer.

The length l of transmission lines that need to be supplied and set up has been found to be 23 kilometers for El Obraje and 12 kilometer for Madroñito and Villa Esperanza, see Section 4.

The cost for setting up the new transmission lines and the construction work C_T is the hardest to estimate; numbers in literature vary by more than one order of magnitude. Villa Esperanza's former head of community stated that the electrification project of his community (only grid extension and transformer, no connection to the individual houses) had a cost of approximately 220000 pesos (18000-19000$ with the 2002 exchange rate). This amount could however not be verified by authorities, since they refused to hand out information on project costs. The stated costs result in an extension cost per kilometer of $C_T \sim$ $1500. This is a factor ten less than the estimation of grid extension costs by Nässén et al. (2002) and about a factor five less than estimations by Mahapatra and Dasappa (2012). Muselli (1999) estimated the costs for one kilometer of grid extension to more than $50000. For this study a cost of 10000$/km has been chosen. Sensitivity analysis has shown that results are highly dependent on this value.

Connected to C_T, costs of the possibly necessary construction of a drivable road need also be considered. However, in all three investigated cases, a gravel road was in place when the electrification project was approved, therefore this has not been included as a separate factor, but has to be kept in mind as a possible, considerable cost of grid extension costs.

The average cost to connect the individual households to the new grid extension C_c is also a highly uncertain factor, since it very much depends on the quality of the connection, if it is done professionally or by the inhabitants themselves and how far away the individual households are located from the closest grid connection pole . The chosen figure of $70[14] per connection is based on estimates from the communities, and its influence on the life cycle costs have been investigated by varying it up to $2000. The total cost showed a high sensitivity to this factor.

Based on the values in Table 7, the life cycle costs of the grid extension project in the three communities were calculated. Table 8 presents the resulting LCC_{grid} per household as well as the results of the sensitivity analysis for the parameters t_{gen}, δ , p, C_{TL} and C_C.

Table 8 - Life cycle costs for grid extension per household and sensitivity analysis

El Obraje					
	Average demand d_e	Maintenance cost factor $\alpha = 0$ $\alpha = 3\%$	Generation costs t_{gen} = $ 0.04 t_{gen} = $ 0.23	Transmission line costs per km C_{TL} = $1500 C_{TL} = $30000	Connection costs per household C_C = $500 C_C = $2000
Normal	(1421 Wh) $7354	$6811 $8440	$6745 $7797	$1886 $20219	$7823 $9459
ESS	(775 Wh) $6976	$6433 $8062	$6644 $7218	$1508 $19842	$7445 $9081

[14] Interview Javier Bobadilla, Tipitapa, 2014

Madroñito					
Normal	(2236 Wh) $4843	$4548 $5431	$3884 $5540	$1915 $11732	$5312 $6948
ESS	(1193 Wh) $4233	$3939 $4821	$3721 $4605	$1305 $11122	$4702 $6338
Villa Esperanza					
Normal	(3747 Wh) $6507	$6148 $7225	$4900 $7675	$2918 $14952	$6976 $8612
Opt	(2955 Wh) $6044	$5685 $6762	$4777 $6965	$2455 $14489	$6513 $8149
ESS	(1578 Wh) $5239	$4880 $5957	$4562 $5731	$1650 $13684	$5708 $7344

7.3 Cost comparison

Based on the results of the calculation above, the electrification costs for the different communities can be compared, see Table 9.

Table 9 - Summary and comparison of the electrification costs for SHSs and grid extension for the three communities

	Average energy demand /day /hh	Peak individual power demand	Number of houses	Distance from grid connection point	Electricity costs /hh (current price)	LCC_grid /hh	LCC_PV /hh	Difference (LCC_PV - LCC_grid) /hh
Unit	kWh	W		km	US$ 1000	US$ 1000	US$ 1000	US$ 1000
Obraje	1,4	0,35	39	23	0,47	7,4	3,4	-3,9
Obraje ESS	1,2	0,20	39	23	0,26	7,0	1,9	-5,1
Madronito	2,2	0,35	38	12	0,74	4,8	5,4	0,6
Madronito ESS	1,2	0,20	38	12	0,40	4,2	2,9	-1,3
Villa E	3,7	0,80	31	12	1,2	6,5	9,1	2,6
Villa E opt	3,0	0,62	31	12	0,98	6,0	7,2	1,1
Villa E ESS	1,6	0,22	31	12	0,52	5,2	3,8	-1,4

The comparison indicates several factors that influence which electricity supply option is economically viable. For the investigated energy demand, the SHSs option is only cheaper for the community with the lowest load demands and the furthest away.

An interesting result is the break-even distance, the distance at which SHSs become the cost-efficient option when compared to conventional grid extension. This is visualized in Figure 9.

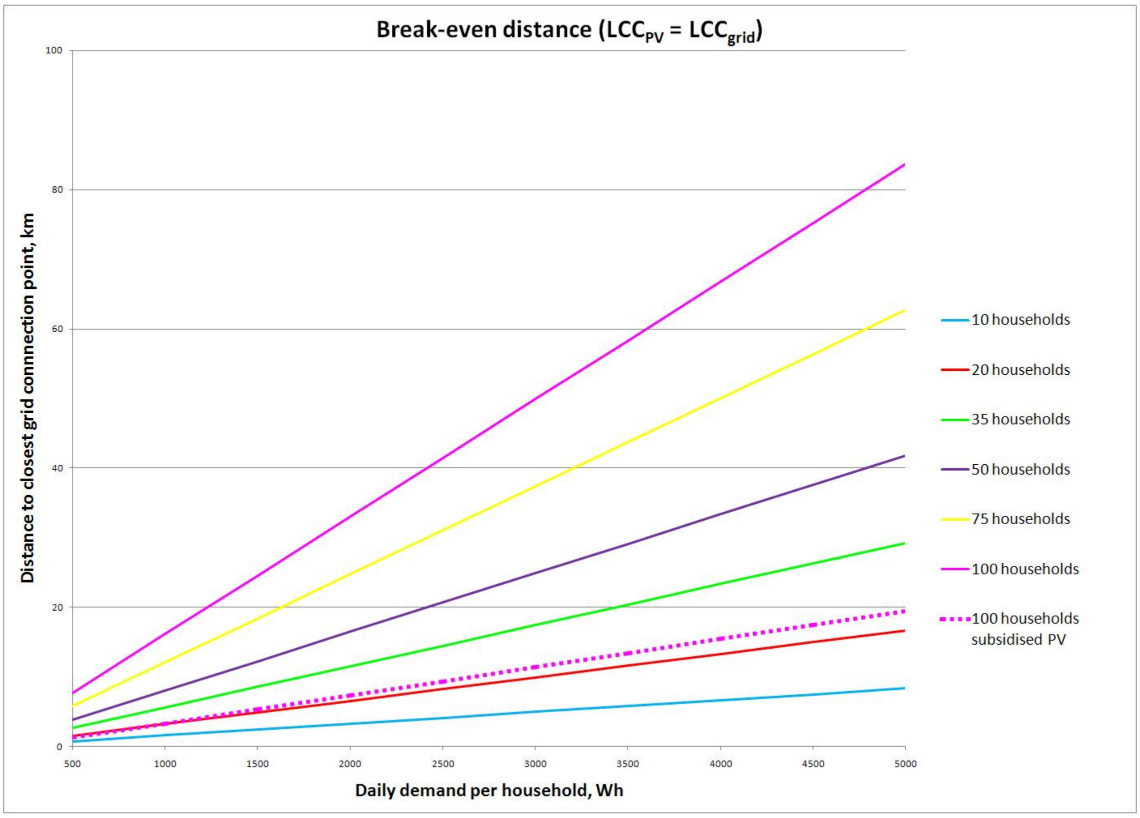

Figure 9 – Break-even distance of costs for conventional grid extension and SHSs. The figure shows the break-even distance for different amount of households in a community, depending on the average, daily electricity of a household. The dotted line shows how the break-even distance declines drastically for a lower solar PV system retail price.

The break-even distance shows to be highly dependent on the distance to the closest grid connection point and the average, daily electricity demand of the households. For a community consisting of 50 households, the break-even distance for an average daily electricity demand of 1kWh per household is 8 km. The distance increases linearly with increasing electricity demand. For communities with more households, the break-even distance for a specific household demand is higher. This is because the total amount of energy demanded per village is higher, and higher total demand favors grid extension. The break-even distance is furthermore very much dependent on the retail price of solar PV systems as indicated by the dotted, light purple line. A reduction of taxes on solar PV would thereby make electrification by SHSs far more attractive.

Figure 9 agrees with the results for the three investigated communities and with the result found by Mahapatra and Desappa (2012) for break-even distances for small communities with low electricity demand.

8 Conclusion

The results obtained in this study have to be interpreted in their context. The aim of the study is to investigate the changes of a community's electricity demand over time. This has been studied by means of comparing the load curves of three similar communities with different electrification times.

This comparison showed that the power distribution over the course of the day is similar in all three communities studied. However, it was found that the total electricity demand per household increases with electrification time, which could be attributed to a higher abundance of fridges and fans. The disproportionally high energy demand of Villa Esperanza is explained by the use of 100W light bulbs, whereas in the two other villages only energy-saving light bulbs (9W) were used.

Productive electricity use, in other forms than selling refrigerated products, was not observed; only in Villa Esperanza interviewees stated that they had plans of using the electricity for income-generating activities in the future.

Peoples' attitudes towards SHSs as an alternative to grid-provided electricity were rather skeptic, and a recurrent statement was that operating these systems seemed difficult.

Cost calculations showed that SHSs would have constituted a cost-competitive option for El Obraje. Even in Villa Esperanza and Madroñito it becomes a cost-competitive option if light bulbs were to be replaced by energy-saving ones, and fridges replaced by modern ones.

The above information indicates that communities with similar characteristics to El Obraje could be sustainably electrified by SHSs. Electricity demand is, over a period of fifteen years, not expected to grow to levels that would require grid connections nor make grid extensions the economically favorable option.

9 Discussion

A series of patterns and dynamics regarding electricity use have been discovered in this study. It is very important to understand the results in the context that they were generated in.

The data used in this study has almost exclusively been obtained through structured and semi-structured user interviews. There are certain important aspects one has to consider when referring to such data. Answers concerning quantitative statements on electricity use are estimates from the users themselves. There are several reasons for why there is no guarantee that these statements exactly reflect the real values. First, people might answer to their best knowledge and beliefs but those might not be one hundred percent accurate. Second, the interviews were conducted by a white, academic foreigner and this might result in slightly biased answers. Third, people might actually not know their exact electricity use, but are reluctant to admit it, and therefore give made-up information. Fourth, they sometimes just forget to mention information (e.g. certain electrical appliances).

Regarding the qualitative part of this study, one also needs to consider that the analysis involves observing feelings and attitudes as well as reading between the lines. This process always has certain subjectivity to it and conclusions might vary depending on the person performing the analysis.

The cost calculation part is a more straight-forward task, but even here results have to be interpreted with care since very few parameters are fixed. Several parameters are estimated (when no information on their accurate value could be found) or based on similar research by other authors. The cost models are a simplification and in order to make informed decisions the models would have to be developed further. Here their main function is indicative.

In order to be able to make more general statements on when rural electrification can be done sustainably through small-scale, decentralized electricity generation, more research is needed on load curve development, drivers for and barriers to socio-economic development related to the access to electricity as well as on models for cost comparisons of fundamentally different energy technologies.

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Appendix A – Interview guide

Name: Amount of people in household:

Address:

Age: Gender:

Position in Family: Employment:

Since when do you have electricity in the house?

What do you use the electricity for?

What appliances do you have, that use electricity? (all appliances, amount of light bulbs and where they are situated)

Which appliances did you not use/ have before you got electricity?

What is the main/most important use of electricity in the house?

What time of day do you use most electricity? Why? For what?

Have you or anyone in the house started any new income generating activities since you got electricity?

What is the main benefit you get from the electricity?

What other benefits do you get from the electricity?

Have any of your habits changed because of electricity? (cooking habits/time, homework)

Do you have problems with or because of the electricity? Which?

Is there always enough electricity?

How much does electricity cost?

How much do you pay for your electricity?

How do you pay for electricity?

At what time does the first person in the house get up?

Does he/she switch the light/tv on? Where in the house?

At what time do you switch of the light/tv?

During the day, which of your appliances do you use?

At night, at what time do you normally switch on the lights/tv/etc.? How long do the appliances stay switched on?

Do you have anything running at night? (Ventilators, TV, light)

Did you ask for to get electricity access or were you supplied by the government without being asked?

What did you think about electricity before you got access?

Has your attitude towards electricity changed since you have access? (Are you more positive/negative than you expected, why)

What did you expect/hope for from the electricity?

What do you now expect/hope for from the electricity?

Do you consider the electricity expensive, cheap, normal?

Would you use more electricity if it was cheaper? By what means?

Would you use less electricity if it was more expensive? How would you do that?

Appendix B – Potential power demand

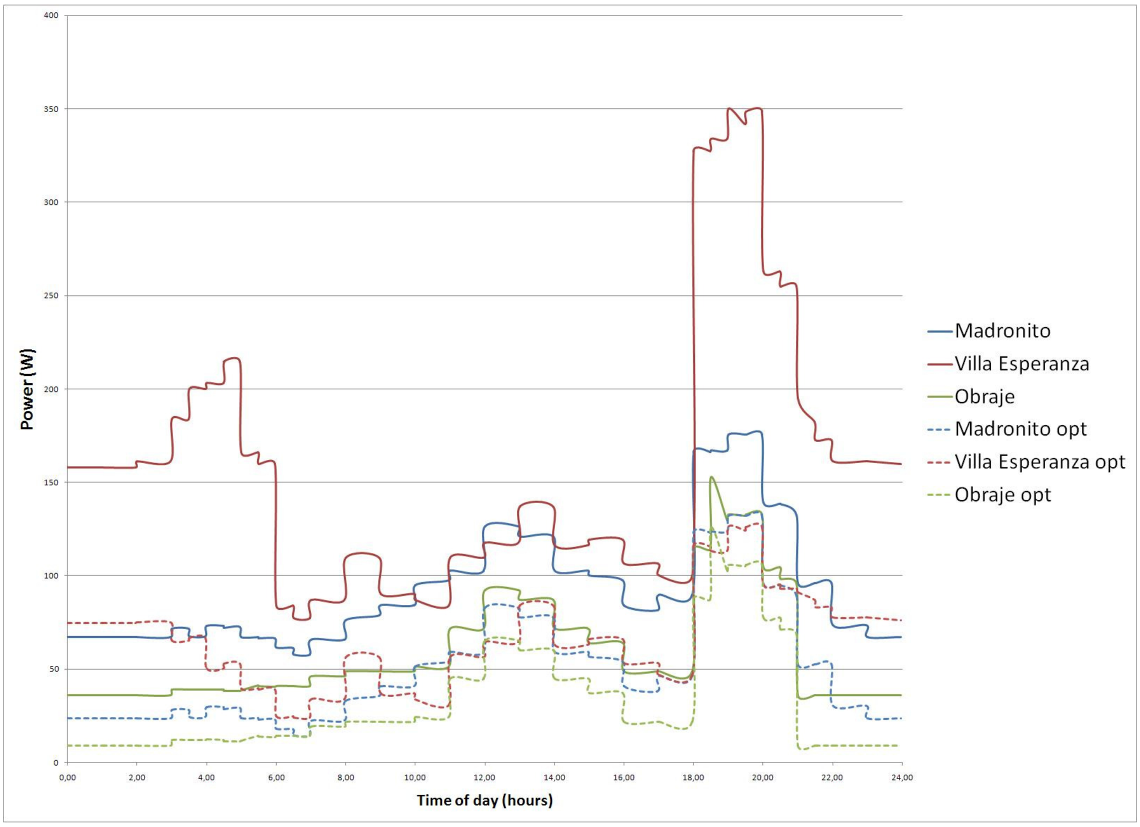

Figure 10 - Load curves of the three villages' real power demand and their potential power demand if fridges were replaces by modern one (opt), Villa Esperanza opt is based on energy saving lights