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# Sustainability of off-grid Photovoltaic Systems for Rural Electrification: Empirical Evidence from selected Andean Countries

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## Summary

Universal access to affordable, reliable and modern energy is a fundamental component for Sustainable Development. Yet, 1.2 billion people are still lacking access to electricity, especially in rural areas of Developing Countries. Tackling Climate Change under a scenario of increasing energy demand requires technologies with a low environment impact that facilitate economic development and that are socially supported. Renewable Energy solutions based on off-grid photovoltaic (PV) systems could meet these criteria in rural and remote areas where the grid extension is not practicable.

Against this background, this thesis aims to assess the sustainability of rural electrification efforts based on off-grid PV systems in three Andean countries: Chile, Ecuador, and Peru. Although deployment of this solution for rural electrification began in the early 1990s in the Andean region, most of the projects turned out to be unsustainable and did not last. Prior efforts have addressed the different issues and barriers that plagued these projects and inhibited their sustainability. However, these prior analyses were mostly quantitative; systematic qualitative evaluations have been scarce.

In this thesis, I address the following research question: *"Are the rural electrification programs (based on off-grid PV Systems) in the Andean countries sustainable?"*

In order to answer this research question, I conducted an exhaustive qualitative document analysis complemented by semi-structured expert interviews. The interviewees included experts from different ministries, project managers from leading Non-Governmental Organizations (NGOs), public and private companies' representatives, supervisors, and researchers. Although I also describe several relevant PV-based electrification efforts in the Andean countries, my research was aimed at providing an overall picture of the rural electrification efforts in these countries, rather than measuring the success or failure of specific projects.

The gathered information allowed me to assess the sustainability of rural electrification efforts in the Andean countries. This assessment was based on a set of indicators corresponding to the four dimensions of sustainability considered in this thesis: institutional, economical, environmental, and socio-cultural. These indicators were introduced after an extensive review of the theoretical framework on sustainability regarding rural electrification based on off-grid PV systems.

In addition to a generic Introduction (Chapter 1), the Theoretical Framework (Chapter 2), and additional details on the Methodology (Chapter 3), this document has three main sections: a generic literature review (Chapter 4), an empirical part (Chapter 5), and a deductive-comparative section (Chapter 6). Chapters 4-6 are based on peer-reviewed papers that this research allowed me to elaborate:

1. Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review (Chapter 4)
2. Sustainability of rural electrification programs based on off-grid photovoltaic (PV) systems in Chile (Chapter 5)
3. Are the Rural Electrification Efforts in the Ecuadorian Amazon Sustainable? (Chapter 5)
4. Sustainability of Rural Electrification Programs based on off-grid Photovoltaic Systems in Peru (Chapter 5)
5. Sustainability of rural electrification efforts based on off-grid Photovoltaic systems in the Andean Region (Chapter 6)

In Chapter 4, I provide an overview of experiences with off-grid PV systems in rural areas of DCs that have been reported worldwide (including global studies, Asia, Africa, Latin America/Caribbean, regional studies, and Oceania). It is grounded on a wide review of projects that were considered sustainable as well as cases of unsustainable experiences. The cases were purposely not restricted to research papers, but also embraced information from NGOs, energy organizations, and governments. Selecting a broad spectrum of sources intended avoiding biases concerning who implemented the off-grid systems for rural electrification. It aims to get a better understanding of whether or not

sustainability issues have been iteratively encountered across countries and among projects, and what factors have determined the sustainability of projects.

In Chapter 5, I assess the sustainability of off-grid PV projects in Chile, Ecuador, and Peru, respectively. Chapter 5 aims to address the research questions described above in the context of each country. A separate (i.e. country specific) analysis allowed me to evaluate each indicator of sustainability introduced in Chapter 2.

In Chapter 6, the findings shown in Chapter 5 were further exploited. It consists of an inter-country comparison involving Chile, Ecuador, and Peru. This analysis allowed me to contrast and to rate the efforts made in these countries for ensuring the sustainability of their rural electrification efforts based on off-grid PV systems.

Finally, in Chapter 7, I summarize some of the key points and provide a brief outlook for future research.

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**CONTENTS**

# 1 Introduction

## 1.1 Motivation

Access to modern energy is critical for development and for improved health of human beings (IEA, NA). Indeed, the use of energy is manifold, including lighting, heating, cooking, mechanical power, transport and telecommunication services (e.g. Kaygusuz, 2012). Furthermore, the access to energy is positively correlated with the Gross Domestic Product (GDP) growth as well as higher productivity, and it is indirectly associated with better health and education, and higher quality of life (Kolk and van der Buuse, 2012; IEA, NA).

The importance of energy for Sustainable Development (SD) has been recognized by the United Nations (UN) when its General Assembly declared 2012 as the "International Year of Sustainable Energy for All" (Resolution 65/151). In 2015, universal access to affordable, reliable, and modern energy for all even become a stand alone Sustainable Development Goal (SDG) (Assembly, 2015). Yet, the notions of "access" and "to all" are much discussed in literature owing to differences in the understanding of standard needs of a household as well as changing needs within the same household over time (Tomei and Gent, 2015). The International Energy Agency (IEA) for instance defines energy access as "household having access to electricity and to relatively clean, safe means of cooking" (IEA, 2015a). It fixed the minimum annual household electricity consumption at 250 Kilowatt-hours (kWh) for rural areas and 500 kWh for urban areas (IEA, 2015a). According to this definition, 1.2 billion people are still lacking access to electricity, especially in rural areas (IEA, 2015b).

The IEA (2014) estimates that the demand for energy will grow by 37% by 2040, resulting in a rise of emissions by 20%, and a temperature increase of 3.6 degrees Celsius. The major growth in demand will shift away from member countries of the Organization for Economic Co-operation and Development (OECD) to Developing Countries (DCs) (IEA, 2014). Under these circumstances, addressing sustainability in the energy sector requires a multidimensional approach that considers the protection of the environment and of natural resources, the impacts on the climate, and the social acceptance (Haselip et al., 2011, BMU, 2004). Renewable Energies (RE) may offer a solution that meets all of these requirements (BMU, 2004; Sathaye et al., 2011).

Among RE, solar technologies based on photovoltaic (PV) systems are a feasible alternative in rural areas of DCs where the extension of the grid is not practicable. In fact, according to the Universal Modern Energy Access Case (UMEAC) of the UN, whose objective is universal access to electricity by 2030, 70% of rural electrification shall be provided by systems that are not connected to the grid (of which 75% are planned for mini-grids, and 25% for off-grid solutions) (OECD/IEA, 2010).

In remote regions, off-grid (not being connected to the national grid) PV solutions have several advantages. Firstly, the technology has undergone significant price drops during the last years, as between 2007 and 2014 the prices for PV modules declined by approximately 79% (World Energy Council, 2016), whereas their material usage and their performance have considerably increased (Fraunhofer ISE, 2014). In areas of high solar irradiance (which is often the case in DCs), the technology can already compete with grid prices (so called "grid parity") (World Energy Council, 2016). Secondly, off-grid PV systems can be adapted to local consumer demands, as they range from Pico PV Systems of up to 10 Watts peak (Wp) to stand alone systems (Solar Home System, (SHS)) of between 10 and 250 Wp, up to Solar Residential Systems (SRS) of 500-4000 Wp. Even mini-grids for entire communities can be used. Thirdly, PV systems can considerably help to reduce emissions and counteract climate change (CC). This is especially important considering the sharp increase in energy demand expected from non-OECD countries that could leapfrog the contaminating fuels used in developed countries. According to the OECD/IEA (2014) (adopted from De Wild-Scholten, 2013), with a value of 20-81grams of Carbon Dioxide equilibrium per kWh (g $CO_2$-eq/kWh), the carbon footprint from PV is in the order of one magnitude below electricity from fossil fuels.

Despite these opportunities, important challenges remain. Several studies have found that a great percentage of the installed systems stopped working after some time (Nieuwenhout, 2001; IRENA, 2015). Numerous studies have already reported on the barriers that constrain the deployment of off-grid PV systems for rural electrification (see e.g. Sovacool et al., 2011; Siegel and Rahman, 2011; Karakaya and Sriwannawit, 2015; Van Norden, 2015; Sindhu et al., 2016). Given that off-grid PV systems have relatively high investment costs, while operational and maintenance (O&M) costs are low compared to alternative technologies (such as diesel generators), the advantages of PV systems can only be exploited if the systems are used over their complete lifetime. Therefore, rural electrification solutions should ensure long-term operational performance. Otherwise, neither the economic sustainability (as the systems are not paying off), nor the ecological sustainability (since the material needs to be disposed) of PV-based systems will be underwritten.

Based on this background, I will address the following general research question:

*"Are the rural electrification programs (based on off-grid PV Systems) in the Andean countries sustainable?"*

I firstly aim to get a better understanding of the concept of sustainability regarding rural electrification efforts based on off-grid PV systems. Then, I will assess the sustainability of rural electrification solutions in each country (Chile, Peru and Ecuador) separately. Finally, by making a comparison between the three countries, I intent to identify common issues and potential for improvements.

I will focus on Chile, Peru and Ecuador, because they have all deployed off-grid PV systems in the past, and plan deployments to different extents in the future. On the one hand, they are diverse in their political systems and formal/informal institutions, their energy policies, and experiences regarding off-grid PV solutions. On the other hand, they share comparable challenges and have a similar historical background. The transnational networks and convergence between indigenous people have crossed national and international boundaries among these countries, underpinned by their cultural identities (Radcliffe et al., 2002). Still, within each country, Chile, Peru and Ecuador are characterized by a tremendous cultural diversity with ethnical constitution including e.g. several heterogeneous Indigenous, Afro-descendant, Mestizo, and White populations (Means, 1918:417).

The diversity is accompanied by a complex geographical situation in the three countries that includes coastal lowlands, Andean highlands, Islands, arid deserts, tropical forests and the Amazon basin. These complex environments are highly relevant regarding the adoption of national energy policies and rural electrification programs based on off-grid PV systems.

### 1.2 Structure

The subsequent chapters are structured as follows: In chapter 2, I discuss relevant concepts for elaborating a theoretical framework that will in turn allow me to address the research question. Chapter 3 provides a brief overview of the methodology used to gather the information that in turn allowed me to address the research question. In chapter 4, I will provide an overview on the multidimensional drawbacks that constrain the sustainability of rural electrification programs and projects based on off-grid photovoltaic (PV) systems including Solar Pico Systems (SPS) and SHS in DCs. Next, in Chapter 5 I assess the sustainability of rural electrification programs in Chile, Ecuador and Peru. In Chapter 6, I highlight common and different challenges that the three Andean countries face for ensuring the sustainability of their rural electrification efforts. Chapter 7 summarizes some of the key points and provides a brief outlook for future research.

# 2 Theoretical Framework

## 2.1. Introduction

Sustainability in rural electrification is a multidisciplinary concept that comprises technological, social, environmental, and institutional issues (Brent and Rogers, 2010). Indeed, the IEA/World Bank (2015) found that traditional approaches for rural electrification tend to ignore important issues for SD, for example affordability, reliability and service quality (IEA and World Bank, 2015). Therefore several studies have recently suggested a multi-criteria sustainability analysis based on indicators for the assessment of sustainability (Bhattacharyya, 2012; Brent and Rogers, 2010; Ilskog, 2008, Mainali et al., 2014; Hong and Abe, 2012; Zalengera et al., 2014). These indicators have been clustered into three traditional dimensions of sustainability (economic, environmental, and social), plus a technological dimension, and in some cases an institutional dimension.

Sustainability indicators may be “objective” (quantitative) or “subjective” (qualitative), though both are at least partly subjective (Meadows, 1998). Depending on the research goal, indicators along the sustainability dimensions have varied considerably between rural electrification/RE studies. Wimmler et al. (2015) provide an overview of sustainability indicators used in 47 reviewed papers that applied some kind of multi-criteria decision making to RE. The most frequently used sustainability dimensions are technical, environmental, economic and social (Wimmler et al., 2015). The indicators are in general quantitative indicators (e.g. degree of local ownership; share of population with access to energy; profitability; energy tariff, emissions of kg CO2/kWh, etc.). Yet, relying solely on quantitative indicators has shown to provide only a partial view with a focus on technological achievements, while qualitative indicators are complementary and e.g. crucial to measure human experiences (Peña-López, 2008:60; Waas et al., 2014; Meadows, 1998). Furthermore, some indicators may be decisive but difficult to measure, or the availability of data may be limited: For instance, despite recognizing the importance of institutional sustainability, Mainali et al. (2014) and Mainali (2014) explicitly excluded institutional indicators from their evaluation given the difficulty of measuring them quantitatively.

Against this background, I have established a set of sustainability indicators with a qualitative connotation; they can be mapped to the four dimensions of sustainability: institutional, economic, environmental, and socio-cultural. A technical dimension has not been included, as I considered the technical indicators to be directly associated with and depending on the other 4 sustainability dimensions. Each of the dimensions will be discussed in-depth in the following sections to provide a better understanding of the concepts behind them and their contribution to SD in the context of rural electrification efforts.

## 2.2 Institutions

### 2.1.1 Background

The importance of institutions for rural electrification has been highlighted in numerous studies (e.g. AGECC, 2010; Schillebeckx et al., 2012; Steiner et al., 2006; Martinot et al., 2002; Chaurey and Kandpal, 2010). Still, what is actually understood by the term “institution” requires some clarification. North (1992:4) describes institutions as a framework of formal and informal guidelines for the interaction between human beings; institutions limit the conduction scope of individuals to set equal rules for all participants (North, 1992:4). Accordingly, institutions are distinguished from organizations, as the former refer to the ‘rules of a game’, whereas the latter make reference to the actual players (North, 1992:5). However, laws and regulations are ultimately enacted and enforced by rule-makers or legislators (Pejovich, 2012), such that these organizations are considered to be part of the institutions in this thesis.

The goal of institutions is to reduce transaction costs thanks to a common understanding of the rules, and ultimately they aim to increase efficiency by providing an incentive to the players to comply with the laws (North, 1989). This is because people need a pattern to rely on: the assumption of individuals who take rational decisions no longer holds, since people take decisions based on subjective ideas and incomplete information (North, 1992:21).

Institutions can be divided into formal and informal institutions. Formal institutions refer to laws and governmental regulations that determine the political, economic, and enforcement system, whereas informal institutions make reference to religious or moral values and traditions that have been established in a certain place and have resisted over time (Pejovich, 2012). As opposed to formal institutions, informal institutions are not communicated via official channels (Helmke and Levitsky, 2012) and therefore not fully public or transparent to outsiders (Adger et al., 2003).

Informal institutions can either be convergent or divergent to formal institutions, and depending on the effectiveness of the formal institution, this relationship is: 1) complementary (effective formal institution and convergent), 2) accommodating (effective formal institution and divergent), 3) substitutive (ineffective formal institution and convergent), or 4) competing (ineffective formal institution and divergent) (Pejovich, 2012).

As any other sector, rural electrification depends on both formal and informal institutions. In the case of rural electrification projects (based on RE), the formal institutions are determined by the Energy Ministries and Energy Supervisors, whereas Non-Governmental Organizations (NGOs)/Non-Profit Organizations (NPOs), Environmental Organizations, Energy Companies, users, and the culture of the communities may determine the informal institutional side. All of these actors may ultimately shape the institutional framework, thus they decisively influence the extent to which rural electrification is sustainable.

### 2.1.2 Stability (Durability)

Levitsky and Murillo (2009) determine that two factors account for the strength of formal institutions, namely, its stability/durability and its enforcement, and they may or may not be aligned. Formal institutions are strong if both factors are high, and weak if both factors are low (Levitsky and Murillo, 2009). In the case of high enforcement and low stability, laws are being followed, but often changed, whereas in the opposite case, although the rules persist on paper, they are ignored and substituted by informal rules (Levitsky and Murillo, 2009).

The strength of formal rules depends on two types of power: de jure and de facto power. The former is the power that is officially allocated to formal institutions, whereas de facto power is imposed by some kind of force (i.e. informal institutions) (Acemoglu and Robinson, 2005, 2006). Hence, how the (de jure and de facto) power is distributed between formal and informal institutions is important, as it determines the strength of the formal institutions. In this regard, Levitsky and Murillo (2009) identify various reasons for weak institutions: 1) the actors who implement a rule do not aim to enforce it; 2) the actors who implement a rule do not actually have the power to enact and supervise it 3) low level of societal compliance (no voluntary action, as the enforcement is purely constrained) 4) high level of inequality, and 5) the actors who implement a rule do not possess de facto power (Levitsky and Murillo, 2009).

The reasons for weak institutions clearly show that institutions depend on the context they are embedded in, meaning that not only do they influence their environment, but also vice versa are they influenced by it (Rodríguez-Pose, 2013). The fact that the relationship between authorities is determined by the cultural context (i.e., informal institutions) has important implications for the effectiveness of a law (Andersson and Ostrom, 2008). Informal institutions ultimately determine the effectiveness of formal rules, because communities decide to what extent they adopt the politics, to what extent they follow bureaucratic order, and to what extent they collaborate to tackle social dilemmas (De Soysa and Jütting, 2006).

The role of informal institutions in the regulatory landscape is unfortunately a major problem in rural electrification. According to Minogue (2013), governments often completely overlook cultural aspects (i.e. regulations being locally embedded in social, administrative, and political contexts). With regards to formal institutions, political unrest and frequent changes of rural electrification policies (triggered by changes in the government) can seriously compromise the sustainability of rural electrification projects (Urmee, 2009). Staff rotations and internal reorganization processes can also be a reflection of an unstable institutional environment, which negatively affect the sustainability of a project (World Bank, 2011; Dornan, 2011).

Given that many DCs have failed in their rural electrification efforts because of a weak institutional framework, it has become evident that the rural energy policy development and implementation demand for strengthened institutions (Haanyika, 2006). Therefore, rather than copying generalized best practices from the electricity sector of developed countries, in DCs a deep understanding of the local institutional framework including both formal and informal institutions and their interactions is indispensable (Estache and Wren-Lewis, 2009).

#### 2.1.3 Regulations and standards

The legal framework (regulations) and its planning have a substantial influence on the sustainability of projects in the energy sector (Martinot et al., 2002). Besides the strength of institutions, the second crucial element of institutional sustainability is therefore the regulatory substance, which is the content of regulations (Reiche et al., 2006). For regulations to be sustainable, they need to be coherent within and across sectors to avoid inconsistencies and negative spillover effects (OECD, 2001). Moreover, regulations and standards assure that for instance only trustworthy technologies enter a market, which reduces the risk of failure; they can also address disruptive factors like noise or visual impacts (Sawin, 2006). According to Reiche et al. (2006), standards should therefore be realistic, affordable, monitorable, and enforceable.

Unfortunately, projects of rural electrification in many DCs are conducted by institutions with a poor regulatory capacity (Bhattacharyya, 2013a), which has led to regulatory uncertainties (Bhattacharyya and Palit, 2016). Indeed, inconsistencies between the regulations of different government levels (national, regional, and local) contribute to confusion and uncertainty, which may ultimately lead to the failure of RE policies (Radzi and Droege, 2014). Establishing (technical) standards is another critical issue for rural electrification. If the regulator does not establish or enforce the compliance of quality standards, off-PV systems can become inoperative shortly after installation owing to their poor quality (Zalengera et al., 2014; World Bank, 2008a).

#### 2.1.4 Adaptability

As revealed above, the cultural context of a local environment in which institutions operate is fundamental for the effective operation of formal institutions. This is why the adaptability of the formal institutions to the culturally embedded norms is fundamental. For instance, informal institutions may be directed by veto players (e.g. the military or the church) (Levitsky and Murillo, 2012), or by international organizations or elites that do not possess de jure power (Acemoglu and Robinson, 2006). These power constitutions need to be captured and properly understood to be able to adapt to this reality.

For institutional adaptation to be appropriate for the local context and culture, previous experiences may be adopted by strongly relying on local expertise (Aron, 2002). Agrawal (2010) argues that the nature of institutional linkages as well as understanding the access that different social groups have to formal institutions ('institutional articulation') is crucial to adapt to the local context. However, adaptation requires experimenting and being flexible to allow for social and institutional learning (Agrawal, 2010). Moreover, communities should not be regarded as static objects, but instead social viewpoints differ and may change over time, such that flexibility and openness to adapt to these chances is required (High et al., 2005).

The necessity of adapting the institutional framework to the local circumstances holds particularly true for rural electrification. Indeed, off-grid PV systems in remote areas demand for different formal institutions than existing centralized institutions for on-grid connections, and the government plays a key role in adapting the institutional framework to these local needs (e.g. by creating a Rural Electrification Agency) (Gómez and Silveira, 2011). This customized structure should pay more attention to the local organizational structures of a community by treating rural electrification efforts as a local development initiative (van Els and de Souza, 2012).

### 2.1.5 Decentralization

When building institutions, the concept of decentralization has been extensively discussed. The general idea of decentralization is that, given the closeness to the local populations and their specific issues, it allows participative decision-making and ultimately enhance the authority's accountability (Machado, 2013). Moreover, according to the IPCC (Sims et al., 2007:288), decentralized RE solutions have numerous technical advantages, such as: a reduction of transmission system costs; a reduction of grid losses due to shorter transmissions; an energy recovery due to proximity of demand for heating and cooling; and an increase in use of REs (Sims et al., 2007:288).

Different concepts of decentralization can be distinguished. Literature has differentiated five organizational forms, namely privatization (shifting from public to private ownership), deregulation (the provision of private goods and services is deregulated for market liberalization), devolution (the provision of services and power for decision-making is ceded to local governments), delegation (technical and functional responsibilities are ceded to local public entities that are semi-autonomous and have obtained technical and functional know-how), and deconcentration (administrative functions are delegated to local governmental agents, but power remains in hand of central government; the approach is often used in capital intensive sectors with high strategic value) (Rondinelli et al.,1989; Shamsul Haque, 1997).

Decentralization may be preferred, since local populations may know best what they need and who they can trust, and if a project fails, costs are much lower than its implementation on a national scale (Andersson and Ostrom, 2008). However, there may be cases when (local) self management is too costly because of conflicts among community members, a general lack of interest, or high political costs (Andersson and Ostrom, 2008). In fact, despite great efforts of decentralization in many countries, the results have turned out to be mixed (e.g. Machado, 2013; Andersson and Ostrom, 2008, Grindle, 2004; Breton, 2002; Levitsky and Murillo, 2012). A major risk of decentralization may emerge when functions from different authorities are in conflict with each other (Quang, 2013; IEA, 2013). Decentralization efforts may also fall behind their expectations if local capacity and management skills are still lacking (Eakin and Lemos, 2006).

According to Andersson and Ostrom (2008), what is important is how political actors are nested in the broader system. Machado (2013) argues that the success of decentralization depends significantly on the circumstances, namely: 1) the homogeneity of the citizens' preferences and the incentives of the agents to deliver the goods; 2) the capacity of the organizations at each level of government; 3) the level of education, political participation, and inequality; and 4) the level of democracy at the local level. Moreover, the political commitment of transferring capacities, financial resources, and authority for decision making, planning, and management, to local agents is decisive for the success of decentralization (Rondinelli et al., 1989).

## 2.2 Economic Sustainability

### 2.2.1 Funding (Initial investment/ Operation &Maintenance)

Poor people are often limited in their financial resources, their know-how on sustainable practices, and are under pressure to make decisions based on their short-term needs (Oumer and Neergaard, 2011), which leaves them stuck in a poverty trap. Publicly financed interventions may become necessary to escape this poverty trap and foster economic growth, e.g. by increasing productivity (for an in depth explanation of why public funding may be inevitable, see Sachs et al., 2004).

This poverty trap has significant implications for rural electrification. As rural population in DCs tend to be even poorer on average than urban citizens (IADB, 2013), they are often not able to pay neither for the investment in PV systems, nor (fully) for its maintenance. Still, for rural electrification to be sustainable, both must be assured in the long run. Moreover, rural areas of DCs are characterized not only by low incomes per capita, but also by high dispersion of dwellings (low population density) and low energy demand. This implicates that power utilities generally focus their operations on urban areas, as providing energy to the rural areas is significantly more costly (Chaurey et al., 2004).

In these cases, the government can act as the natural regulator that provides subsidies for the purchase and installation of energy systems to correct for this market failure (The World Bank, 2008b; Bhattacharyya, 2013b; Obeng and Evers, 2009; Solis, 2015). Cross-subsidies, either within consumer categories (e.g. consumers with high energy consumptions pay a higher tariff), between consumer categories (i.e. industrial consumers pay an additional fee to cover subsidies for residential consumers), or by applying tariff policies (i.e. urban consumers pay an additional fee to cover subsidies for rural consumers) are possible options (The World Bank, 2010). Still, despite government subsidies, rural households may partially contribute to the O&M costs (Urmee et al., 2009). Therefore, Rolland (2011) proposes that the tariff should keep a balance between commercial viability and the affordability for the users.

### 2.2.2 Cost effectiveness

The economic dimension of SD requires that investment decisions are made based on an integrative approach that internalizes all hidden and external costs in the long run (Meuleman and Veld, 2009:33, Klöpffer, 2003). Tools such as cost-effectiveness analysis (CEA) or Life-Cycle Costing (LCC) can be established as a decision support system to help decision makers considering all costs and implications in the long-term (Meuleman and Veld, 2009:33).

The concept of cost-effectiveness is particularly important for rural electrification in DCs due to a rural population characterized by its scarce resources. Aiming at selecting the most appropriate on- and off-grid technology and determining the configuration of a RE system for rural electrification, the HOMER (Hybrid Optimisation Model for Electric Renewables) model (HOMER, 2011) from the National Renewable Energy Laboratory (NREL) has often been used (see e.g. Sen and Bhattacharyya, 2014; Khan and Iqbal, 2005). Comparing different technologies based on the lowest LCC approach (frequently expressed in levelized cost of electricity (LCOE) in the electricity sector) is a useful tool valid at any location to obtain the most cost-effective solution for rural electrification (Chaurey and Kandpal, 2010). Since off-grid PV systems have high investment costs but low O&M costs, they have shown to be the most cost-effective solution in many rural areas when taking LCOE as the calculation basis (see e.g. Akiki et al., 2010; Huld et al., 2014; Veldhuis, and Reinders, 2015). This is even more the case if external (environmental) costs are taken into account (Thiam, 2011; Breyer et al., 2015).

### 2.2.3 Reliability

The title of the 7th SDG Goal "*Ensure Access to Affordable, Reliable, Sustainable and Modern Energy for All*" already implies the fundamental role that reliability plays for SD in general and modern energy in particular. It assures that a product remains operational over its expected lifetime and under specific conditions of use (Misra, 2009:134).

The reliability of an energy source makes reference to the ability of a household seeking for access to modern energy to actually use it as its primary source (Rehman et al., 2012). The World Bank (2008c:6) measures the reliability of infrastructure in the electricity sector by considering the delay in obtaining an electricity connection, the days per year of electrical outages, the value of lost output due to electrical outages (as % of turnover), and the % of firms that maintain their own generation equipment.

More specifically, in rural electrification reliability can be defined by the system´s capability of working in a specific area over its expected lifetime, which implies assuring the availability of spare parts and the know-how to make replacements (Nerini et al., 2014). Measuring reliability can often be difficult (especially in rural areas), given the lack of existing data on the regularity and quality of energy supply (Pachauri, 2011). A major concern is that a failure of one apparently minor part of the PV system can have great impacts on the rest of the system (Díaz et al., 2011). Moreover, unreliable electricity services may result in significant economic losses (Kemausuor and Ackom, 2017)

### 2.2.4 Productive Use

As revealed above, SD aims to assure the satisfaction of basic human needs by increasing the material standards of living. In addition to enhancing the level of education and health care, it is fundamental for a sustainable poverty reduction to increase the productivity and profitability of the rural poor (Hayami and Godo, 2005:304).

The use of energy can substantially increase productivity. According to Cabraal et al. (2005), the term “productive use” was initially used to refer to the direct impact of the usage of energy on the GDP in a country, but it was thereinafter adapted to the Millennium Development Goals (MDG). The underlying motivation for this adaptation was that in addition to direct impacts of energy, productive use should also account for indirect goods and services such as its impact on education, health, and gender issues (Cabraal et al., 2005). Applications for productive use are extremely diverse, ranging from agricultural to commercial and industrial activities for livestock breeding (including poultry farming, milking, solar fences); food production with water pumping; milling for food processing (e.g. grain mills, hullers, shellers, polishers, oil presses); cooling for food storage; food for sale; tailoring; media and entertainment (e.g., cinemas, secretarial services); haircutting; and energy services for charging, metering, and measuring (see Olk and Mundt, 2016 for details).

Despite the positive impact that productive use can have on the development of rural communities, the vast majority of rural electrification applications remain in the residential sector, whereas the industrial development has so far been limited (World Bank 2008d). A survey conducted by Fishbein et al. (2003) revealed that due to the fact that energy is ultimately only the input to income-generating activities, stimulating demand for productive use is conditioned by: knowledge and skills on the use of electricity; technical and management capacities; facilitation of an institutional environment for decentralized business development; market access for new products; understanding of the interactions between energy and the productive use; and a minimum of infrastructure services like roads, water supply, information, and technologies (Fishbein et al., 2003). Attending these conditions, a multidimensional approach that also addresses non-energy inputs through effective institutions has been proposed for productive use to achieve sustainable energy (Garimella et al., 2015).

## 2.3 Environmental Sustainability

### 2.3.1 Environmental Awareness

The Rio Declaration on Environment and Development in 1992 highlighted the importance of the participation of all citizens for handling environmental issues, which implies raising public awareness and assumes access to information (see Principle 10 of the Declaration; UN, 1992a). Moreover, Chapter 36 of the Agenda21 proposes to the Member States to create not only awareness on the environment and on development within all sectors of society, but also to assure access to environmental education for people of any age, and to integrate environmental concepts (including the causes of environmental issues) and training in environmental programs (UN, 1992b).

High environmental awareness (e.g. on CC) is particularly important for the energy sector, as it can be decisive for people´s preferred type of energy source (Zografakis et al., 2010; Stigka et al., 2014). However, a lack of awareness on the link between the energy use and the impacts on the environment often avoids a change in behavior towards environmentally sustainable practices like efficient energy consumption (Tang and Bhamra, 2008). People also frequently lack awareness regarding the link between their energy preferences and the wide-ranging moral implications of these preferences (Sovacool and Dworkin, 2015). Considering that CC has a huge negative effect on future generations (Rendall, 2011), awareness needs to be raised on these implications to provoke a change in people’s behavior and appeal to their moral obligations (Murphy, 2012:77-78).

Yet, rather than just hoping for consumers to change their behaviors by their own striving, the national, regional, and local governments play a fundamental role in addressing environmental issues (Moloney et al., 2010). Policies that aim at decentralizing the generation of energy can help filling the gap between personal energy consumption and environmental issues such as CC (Murphy, 2012:72).

### 2.3.2 Environmental Impact

The devastating environmental impacts caused by human activities have already been recognized in the Brundtland report (1987), ranging from loss of biodiversity; ozone depletion; CC; degradation of soils, water regimes, atmosphere, and forests; acid precipitation; and droughts, just to name a few. In this context, the environmental impacts of energy usages in rural electrification constitute an important environmental sustainability indicator.

Similar to the LCC approach for economic sustainability, assessing the environmental impacts requires the Life-Cycle Assessment (LCA) comprising the construction-, operation-, and decommissioning stages (Ball and Frei, 1999). The IPCC provides a comparison of lifecycle greenhouse gas (GHG) emissions from all commercially available energy technologies, including fossil fuels and RE: Despite of large deviations between emission values (e.g, 5–217 gCO2eq/kWh in the case of PV) that are due to differences in measurement and project specific characteristics, the superiority of RE over fossil fuels cannot be denied: wind, solar, nuclear, and hydropower generate electricity with less than 5% of the lifecycle GHG emissions of coal (Bruckner et al., 2014:539-540). Other environmental benefits of Non Conventional Renewable Energies (NCRE) comprise less air pollution (less particulate matter (PM)), a reduction in water use, and impacts on the habitat/landscape and wildlife (the latter having adverse effects depending on the technology and site) (Bruckner et al., 2014:539-545).

Notwithstanding these benefits, RE for rural electrification may also have a negative impact on the environment. Particularly in DCs, environmental awareness and policies are unfortunately often still at their infancy, which can have large negative consequences for the environment (Corsair et al., 2014; McKay, 2010, Sandgren, 2001; Guerrero et al., 2013; Böni et al., 2015; Sun et al., 2015). Environmental harm of off-grid PV systems due to maloperation may concern battery misusage causing their depletions (and hence the need for frequent substitution), or lacking recycling measures for PV modules and batteries (which entail toxic materials) leading to their disposition on landfills (Balcombe et al., 2015; Aman et al., 2015). Therefore, off-grid PV systems for rural electrification can only unfold their eco-friendly potential if environmental practices (raising user awareness, providing education, and implementing recycling policies and recycling infrastructures) are established.

### 2.4 Socio-Cultural Sustainability

#### 2.4.1 Equity

The concept of equity regarding SD is closely related to the notion of distributive justice: According to Banse (2003), SD demands for intra- as well as for intergenerational redistributions of goods to achieve justice. The Bruntland report points to the bonds between SD and equity/justice:

> "[*O]ur inability to promote the common interest in sustainable development is often a product of the relative neglect of economic and social justice within and amongst nations."* (WCED, 1987:46).

What equity actually means depends on the underlying notion of justice. Utilitarians aim to maximize overall utility, i.e., the welfare of the sum of all individuals is to be maximized for a defined population (Blackorby et al., 2000). In contrast to utilitarianism, the egalitarian theory does not allow benefitting one person on costs of another to maximize the total benefit. Instead, equal opportunities for all social classes are assessed, which implies a redistribution of resources from the upper to the lower classes (Rawls, 1999:63). Sufficientarianism claims that all citizens should be secured a minimum standard, and that the maximum priority should be to provide this standard to everyone by redistribution; inequalities may persist once this minimum is passed (Rendall, 2011). Libertarians like Nozick (2003) would contrary argue that redistribution violates people's liberty, which is the greatest good of justice.

Regarding justice in rural electrification, the idea of equity makes reference to equal access to electricity for all citizens (James, 1998). When applying the theories of equity to rural energy policies, McMann et al. (2011:18-20) argue that egalitarians would impose strict obligations on governments to provide universal access of identical energy amounts to everybody, while sufficientarianists would only allow for a minimum level to everybody, though it is not clear what this minimum would be.

Utilitarians on the other hand only consider the total level of energy consumption of a country, such that the consumption of the poor in remote areas is not contemplated due to the high costs of electrification (compared to urban regions). Hence, depending on the notion of justice that a government (as well as society as a whole) has endorsed, equity in rural electrification can be understood differently. It ultimately determines the conviction of providing rural electrification to the poor despite their inability of fully paying for the energy.

### 2.4.2 Accuracy

Accurate solutions (those adapted to the local circumstances) are explicitly mentioned in the scientific and technological context of the Agenda21.

According to the UN, accurate solutions demand for local approaches. Chapter 28 of the UN Agenda21 acknowledges that its implementation should ultimately be based on local activities (i.e., the communes), since local governments are closest to the people, and

> *"[t]hrough consultation and consensus-building, local authorities would learn from citizens and from local, civic, community, business and industrial organizations and acquire the information needed for formulating the best strategies."* (UN, 1992b, Ch.28)

This local approach is indeed iteratively stressed throughout the Agenda, pointing to the importance of finding accurate solutions for SD according to the local circumstances of each commune.

Accuracy in rural electrification implies that technologies are accurate according to the social and cultural reality of a population or community. Tillmans and Schweizer-Ries (2011) define accuracy as the ability of the stakeholders of rural electrification to regard the technical solutions from the users´ perspective. The appropriate selection of a technology, and in particular the system sizing is thereby crucial to assure accuracy (Hong, 2012). If user expectations regarding the capacity of the systems are raised but not fulfilled once the systems are installed, the users may reject them, as their needs are not met (Lemaire, 2011). Energy modeling for appropriate energy supply (regarding present and future needs) therefore needs to consider realistic estimations, as the power produced by an off-grid PV system may decrease over time and the duration of use may get smaller (Mufiaty, 2014). Selecting the most eligible technology that meets the user´s needs and ability to pay, and also fits the geographical conditions can ultimately make the difference between a successful and a failed project (Sovacool, 2013).

### 2.4.3 Social Acceptance

As for accuracy, citizen participation is also fundamental for social acceptance. Given that the commitment of people and their reaction towards institutions is directly influenced by their conception of that institution (Cropanzano, et al, 2001:121), a participative approach increases the likelihood of people to accept the solution and to comply with the rules of the game (Fritsch and Newig, 2007, 2012). Acceptance can be improved by providing early and comprehensive information, since people feel involved and perceive the process to be fair (Newig, 2007).

In rural electrification, building relations of trust by involving and dialoguing with the community is a cornerstone of sustainable projects (Alvial-Palavicino et al., 2011). The underlying concept (also called "procedural sustainability"; see e.g. Subbarao and Lloyd, 2011; Del Río and Burguillo, 2008) consists of focusing on people's perception of a project, how it benefits different groups of people, and how the solution affects the acceptance of the project (Del Río and Burguillo, 2008). Projects that work best create channels of participation and communication from the very beginning (García, and Bartolomé, 2010; Urmee and Md, 2016). This can be explained by the fact that local participation can resolve conflicts, foster mutual learning, and increase the confidence in the process (Etxano Gandariasbeitia, 2012).

### 2.4.4 Cultural Justice

The importance of culture for sustainability has been highlighted by numerous studies, which has induced some authors to even propose cultural as a separate dimension of SD (see e.g. Nurse, 2006; Hawkes, 2001; Burford et al., 2013). The UN also gives special importance to culture: for instance, the Johannesburg Declaration on SD (Earth Summit 2002) and "The Future we want" (Rio +20) acknowledge the contribution of culture to SD, welcome cultural diversity, and ratify supporting indigenous people, traditional communities, and ethnic minorities.

A local version of SD called 'buen vivir' (good living) emerged in the 1990s in Latin America (Vanhulst, and Beling, 2014). It was triggered by a combination of environmental movements and indigenous movements against neoliberal policies. The concept is based on cultural justice and equality, as well as harmonic relations with nature (Houtart, 2011). In fact, Ecuador endorsed the *Buen Vivir* concept in its Constitution (Lalander, 2014).

Culture is important for SD because ethical values determine what is important for a person in life (Nurse, 2006). According to Sen (2004), culture determines the motivations of a person, his/her assessment towards risk, the way in which values are created, the degree of political participation, and a person´s environmental awareness. Pursuant to these values, differences in social structures (e.g. minorities, gender, etc.) rather than being homogenized, they ought to be recognized by- and established in political institutions to cope with diversity (Young, 1990:179).

Culture may in fact be decisive for the adoption of a technology, which makes the consideration of cultural values indispensable for rural electrification (Liu et al., 2015). Values should ultimately determine the technological design and configuration (Urmee, 2009; McKay, 2010). Therefore, sustainable rural electrification demands that cultural elements are institutionalized and integrated into a country´s policy (Garniati el al., 2014).

## 2.5 Overview Indicators of Sustainability

Based on the theoretical framework from sections 2.1-2.4, I have defined a set of indicators for the assessment of sustainability of rural electrification efforts based on off-grid PV solutions. A definition for each of these sustainability indicators is provided in Table 1. The different colors in the first column stand for different dimensions of sustainability considered in this thesis: institutional, economic, environmental, and socio-cultural.

Table 1: Sustainability Indicator considered in the thesis and definition adopted here within the scope of rural electrification

| Sustainability Dimension | Indicator | Definition |
|---|---|---|
| **Institutional** | Stability (Durability) | Stability concerns the durability of the (national and local) formal institutions of a country. This may refer to the organization itself, its legal existence, as well as the stability of personnel within the organization (staff turnover). |
| | Regulation and Standards | Regulations embrace the legal framework of a country including its consistency, coherence, and liability. Standards refer to the implementation and verification of technical standards for off-grid PV systems and their accessories including the legal bounding for quality assurance. |
| | Adaptability | Adaptability implies the formal institutions' ability to adapt to the needs of the population and its socio-cultural circumstances. The concept embraces flexible, decentralized institutional structures that have the (technical and socio-cultural) know-how and the (de facto and de jure) power to effectively steer rural electrification. |

| | | |
|---|---|---|
| | Decentralization/ Participation | Decentralization and participation refer to the degree to which formal and informal institutions work jointly together on the local projects. The participation of a local community usually requires a degree of decentralization of the agents in charge of the rural electrification project. |
| **Economic** | Funding (Initial investment/ O&M) | Funding consists of both the funds provided for the initial investment of the off-grid PV systems (including its components, installation costs, costs for user training and handbooks) as well as the funds to operate and maintain the systems over their entire lifetime (including operational costs for repairing services and substitutions (e.g., batteries), the administration of the systems (such as tariff collection), the provision and storage costs for spare parts, all kinds of travel expenses to the dwellings and back, and disposal costs). |
| | Cost effectiveness | Cost-effectiveness of a solution is defined by the degree to which monetary resources are efficiently invested by the deployment of an accurate (see indicator accuracy below) energy system for a community with the lowest costs over the system's lifetime. |
| | Reliability | Reliability requires the systems to be constantly operational. Defects are corrected in a short (and previously defined) time span. Reliability requires spare parts and know-how to be available at the local site. |
| | Productive Use | Energy systems are expected to contribute to the economic development of the users. This can be achieved by (partially) using the systems for productive uses, which generates user income (users might then even bear O&M costs) due to a higher productivity/performance associated with energy. |
| **Environmental** | Environmental awareness | Environmental awareness is defined as the consciousness of the society on the importance of the environment. It often requires an understanding of the connections between environmental, energy, and social/economic issues and its value for wellbeing. |
| | Environmental impact | Environmental impact refers to the positive as well as negative effects that a technology has on the environment. These impacts may be local or global in nature. Examples for the former are the handling of disposals (such as batteries) from the systems, noise disturbances, pollution aesthetics, etc. The latter refers to impacts on the climate system (due to greenhouse gases) or the loss of biodiversity worldwide. Positive impacts may, e.g., be the avoidance of these gases due to the adoption of "clean" renewable technologies. |
| **Socio-Cultural** | Equity | Equity (disparity) is the degree of equal (distinct) treatment for different groups of a population, e.g., rural and urban populations or different ethnic groups on the one hand, and within groups (i.e., similar rural populations from one vs. another community) on the other hand. Equity relies on the underlying concept of justice.<br><br>Equity (disparity) issues may refer to the point in time when a community is electrified (temporal equity), the provided energy quality and quantity (system size) for/within each group, and the differences between energy tariffs. |
| | Accuracy | Accuracy in sustainable rural electrification is defined as the degree to which the solutions are conforming to the lifestyle and needs of the users. Accuracy often refers to the off-grid system capacity for present and future energy demand, as well as technological specifications that consider socio-cultural factors (such as ease of use, community lifestyle, etc.). |
| | Social Acceptance | Social acceptance in sustainable rural electrification is understood as the degree to which a community agrees with a project and the |

| | | |
|---|---|---|
| | | installed technology, approves it, and ideally identifies with it. Social acceptance is often facilitated by involving and engaging the users in the project and by making them part of the solution, such that they understand its advantages and limitations and agree on the conditions (their rights and obligations). |
| | Cultural Justice | Cultural justice refers to the consideration of/and respect for the culture, and the motivations and values of the population (e.g., concerning environmental awareness). |

## 3 Methodology

The theoretical framework presented in Section 2 allowed me to define a set of indicators to systematically assess the sustainability of off-grid PV systems for rural electrification in the Andean countries and to make a meaningful comparison between the countries. These indicators comprise four dimensions of sustainability: institutional, economic, environmental, and socio-cultural.

### 3.1 Literature Review

Addressing my research question implied the assessment of the sustainability of off-grid PV systems for rural electrification not only in the Andean countries, but also in other DCs. This assessment required analyzing each sustainability indicator defined in Chapter 2.

For this purpose, I conducted a general literature review (Chapter 3) on rural electrification projects in DCs, which was not restricted to a geographical region, but included projects in Asia, Africa, Latin America/Caribbe, and Oceania. The reviewed cases were from year 2000 onwards, which left me with a total of 126 relevant documents for analysis. These documents included scientific papers, NGO reports, conference/working papers, (PhD) theses, books (chapters), and reports from governments/NGOs, and publications from energy institutions. Moreover, project databases from several international organizations as well as documentations from privately led projects were reviewed. Note that the review was purposely not restricted to scientific articles, as I was interested in a more holistic and transdisciplinary approach including different types of stakeholders.

My analysis of the sustainability indicators for each of the three Andean countries (see Chapter 5) was based on information that I gathered by conducting:

i. qualitative document analysis complemented with
ii. semi-structured interviews.

### 3.2 Qualitative document analysis

Document analysis is often used in qualitative studies to "…uncover meaning, develop understanding, and discover insights relevant to the research problem." (Merriam and Tisdell, 2015:189), as well as when the history of events or experiences is relevant, or direct inquiry cannot provide the needed information (Ritchie et al., 2013:35). Document analysis, though often used for supplementary data in research, can be fundamental for tracking changes, consistency, and development over time (Bowen, 2009).

The document analysis enabled me to gather important insights on electrification programs and cases, regulations, policies, and statistical data on rural electrification in the Andean countries. It included public documentations; electrification laws and regulations; energy-pricing models, statistic databases; publications on experiences from prior electrification projects (case studies); project auditing; and scientific papers on related topics.

It further allowed assessing the consistency and compliance of regulations and laws, as well as better understanding the progression and the changes in strategies of rural electrification policies, and the creation/reform of relevant formal institutions (including laws and regulations). Yet, assessing the enforcement of formal institutions required semi-structured interviews (see next section). For that purpose, the qualitative document analysis helped me identifying and selecting experts for the semi-structured interviews.

### 3.3 Semi-structured interviews

Semi-structured interviews are a method of qualitative social research that is used when: 1) a variety of topics must be covered that are determined by the goal of research and 2) specific information needs to be obtained from the interview (Gläser and Laudel, 2010:111). They consist of a catalogue of topics and concrete questions that are asked to each interviewee, though the order of questions is not relevant, and further inquiries (that are not mentioned in the interview guideline) can be addressed according to the course of the conversation (Gläser and Laudel, 2009:42).

Expert interviews are a common method for semi-structured interviews in social sciences, in which experts can be described as representatives of an organization or institution (Meuser, 2002). These experts refer to persons with special knowledge on the social issue to be researched (i.e., they are not analyzed as actors, but are witness of a phenomenon) to reconstruct social processes or situations (Gläser and Laudel, 2010:12-13).

Relevant interview partners were initially selected during qualitative document analysis (see above). However, additional interviewees were contacted by using the snowballing method, i.e., interview partners were suggesting to contact other experts on the field (Ritchie et al., 2013:94). This method was valid for my research, as the community on rural electrification is relatively small, and most actors usually knew some of the other actors (or at least their organization). Interviews were mostly held in Spanish, though some interview partners preferred their mother tongue, such that they were held in German and English (as I am fluent in all three languages, this did not constrain the interview in any way). Except for the banking sector (which turned out to be irrelevant for rural electrification anyways), the response rate was extremely high in all three countries. Yet, some of the interviews had to be conducted by phone, since interviewees were living in areas that were difficult to access, or they were outside the country during my research stay(s).

The interviewees for my research were experts with different background and from a broad spectrum of institution (Ministries, NGOs, universities, energy agencies), but who usually held higher hierarchical positions (directors, project managers, leading researchers, and division leaders), as I was interested in the overall institutional and organizational conditions. As pointed out above, these interviews helped me understanding and unearthing issues that could not be unveiled by the document analysis.

Before empirical research started, I defined my interview questions by systematically covering the topics that I had identified during literature research. Next, I matched the questions to the relevant literature resources and clustered them into the four dimensions of sustainability. Moreover, I contrasted the questions to those from related studies for consistency, and ultimately sent them to other researchers (including from South America) to verify their comprehension (particularly after translation into Latin-American Spanish).

Interview questions were identical not only for each researches of one country, but also among the three countries, which allowed for a systematic and unbiased approach. The questionnaire included the following questions: "What has been the role of this institution for rural electrification in the past and the present?"; "How is the rural electrification process put into practice?"; "How are the community members imbedded in the rural electrification projects?"; "Who and how is the compliance with the regulation assured?" (Institutional Sustainability); "Who is paying for the initial investment/O&M costs?"; "What has the economic impact been on the user (e.g., energy for productive uses)?"; "What are the technical minimum requirements for the systems?" (Economic Sustainability); "How is battery disposal handled in rural electrification?"; "How would you describe the awareness on environmental issues on a political and social basis?" (Environmental Sustainability); "To what extend (and how) are projects adjusted to local circumstances?"; "Have you found different behaviors related to the ethnical background?"; "Do you provide different technological solutions to different communities? If so, what are the criteria these decisions based on?"; and "Do you remember any cases where PV systems were rejected by a community?" (Socio-cultural Sustainability). These questions aimed to be sufficiently broad and neutral to provide the interviewees with the freedom to answer according to their experiences.

The information gathered by the qualitative document analysis and the semi-structured interviews needed to be structured and reduced. I used categories or concepts to organize the data (see Ritchie et al., 2013:202ff). A common method that allows structuring the data is stemming from 'grounded theory' and is based on coding: (unstructured) text, e.g. from interviews, is coded with key words (either previously selected or developed during text analysis); these keywords are then hierarchically clustered into categories that entail related topics (Gläser and Laudel, 2009:46-47). This allows for a comparative approach of similar (repetitive) texts across different document resources (Gläser and Laudel, 2009:46-47). For this purpose, I transcribed all recorded interviews of the respective country and used computer-assisted qualitative data analysis software for the coding (i.e., data was labeled with keywords). English/German texts were coded with the Spanish equivalent keyword. In the few cases where the interviewees had disapproved being recorded, I had taken notes during the interviews (and complemented them by additional notes right after the interviews). I retyped these notes and loaded them into MAXQDA® software (MAXQDA, NA), the computer software I used for the analytical support of the data management. The documents collected previous to the interviews were imported and coded in MAXQDA together with the semi-structured interviews and notes. I also added further documents after the interviews had finished, to verify documents I had not previously considered on important issues that came up during the interviews.

Following the methodology described in Ritchie et al. (2013, Chapters 8 and 9), I then assigned the coded texts to categories and sub-categories by identifying patterns of related data, which resulted in a hierarchical structure from less to more abstract levels. Based on this data structure, in a final step I searched for explanations, mainly by using the theoretical framework as well as by interpreting implicit explanations given by the interviewees, which I then abstracted. All literal quotes in the published articles were translated into English.

### 3.4 Inter-comparison

My findings on the sustainability of rural electrification efforts based on off-grid solutions of the Chile, Ecuador and Peru, were inter-compared (see Chapter 6). The comparison involved the information gathered by the qualitative document analysis and the semi-structured interviews, complemented with additional statistical data. These data were retrieved from the World Bank Indicator Database, from diverse Ministries such as the respective Ministry of Energy of each country, the Ministry of Development and Social Inclusion (Peru)/ Ministry of Social Development (Chile); Ministry of Foreign Affairs Coordinating Ministry of Strategic Sectors (MICSE by its Spanish acronyms) in Ecuador; from several public energy agencies/regulators (e.g. National Energy Commission (CNE by its Spanish acronyms) in Chile; Agency for Regulation and Electricity Control (CONELEC, by its Spanish acronyms) in Ecuador; and Organization for Investment in Energy and Mining (OSINERGMIN, by its Spanish acronyms) in Peru; and from the National Statistical Institutions of the three countries.

As shown in Chapter 6, the conjunction of the analyzed data was used to analyze and to rate the sustainability of off-grid PV systems in rural areas of the three countries. Although a global assessment is also provided, following the theoretical framework described in section 2, my analysis was initially clustered and discussed according to the four dimensions of sustainability (institutional, economic, environmental and socio-cultural).

## 4 Review on off-Grid PV (Paper 1: Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review)

The first paper is a review, which provides a global overview of the sustainability of rural electrification programs based on off-grid PV systems in DCs. It allows me to identify and to highlight the factors that have contributed to ensuring the sustainability of the systems on the one hand, and flaws that have inhibited their sustainability on the other hand. Following the theoretical framework described in section 2 of this thesis, these factors were clustered and discussed according to the four dimensions of sustainability (institutional, economic, environmental and socio-cultural).

I included scientific papers, NGO reports, conference/working papers, (PhD) theses, books (chapters), and scientific reports from governments/NGOs and publications from energy institutions regarding projects of rural electrification conducted in Asia, Africa, Latin America/Caribbe, and Oceania in the review.

The reviewed projects have shown that an integrative and multidimensional rural electrification approach is needed to ensure sustainability in the rural electrification sector. Yet, although attention needs to be paid to each sustainability dimensions, the institutional dimension emerged as significantly important. Indeed, I found that the absence of strengthened and empowered formal institutions (that also assure the enforcement of laws) has been a major constrain to rural electrification in DCs, and ultimately also compromised the environmental and socio-cultural sustainability of the off-grid PV systems.

*Review*

# Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review

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**Abstract:** A review on rural electrification programs and projects based on off-grid Photovoltaic (PV) systems, including Solar Pico Systems (SPS) and Solar Home Systems (SHS) in Developing Countries (DCs) was conducted. The goal was to highlight the main multidimensional drawbacks that may constrain the sustainability of these systems. Four dimensions of sustainability (institutional, economic, environmental and socio-cultural) were considered in this review. It was found that institutional flaws (such as the scarcity of durability/stability and enforcement of formal institutions, weak regulations or standards, incomplete decentralization/participation and the lack of institutional adaptability) seriously compromise the sustainability of rural electrification efforts in DCs. While the lack of an effective focalized subsidy scheme (e.g., cross-tariff scheme) for the electricity tariffs of the poor population often made projects economically unsustainable, the scarcity of environmental awareness, regulations or incentives has often turned presumably clean energy technologies into environmentally unsustainable projects. Progress regarding social acceptance, accuracy and cultural justice is urgently needed for ensuring the socio-cultural sustainability of rural electrification efforts in DCs. This review may help stakeholders to identify and (based on prior experiences) address the most severe drawbacks affecting the sustainability of rural electrification efforts in DCs.

**Keywords:** off-grid PV systems; rural electrification; developing countries; sustainable energy

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## 1. Introduction

Access to energy offers great benefits to development through the provision of reliable and efficient lighting, heating, cooking, mechanical power, transport and telecommunication services [1,2]. Additionally, access to power has proven economic welfare, as productivity increases with businesses, substituting manual work by automated processes and finally leading to a positive virtuous growth cycle [3]. According to the United Nations (UN), Sustainable Development (SD) is not possible without sustainable energy, such that the issue has been prioritized by devoting a stand-alone SD goal (No. 7) to sustainable energy, which implies universal access to affordable, reliable and modern energy [4].

Although there is no universal definition of energy access and data are often scarce, the International Energy Agency (IEA) defines energy access as "household having access to electricity and to a relatively clean, safe means of cooking" [5]. For electricity, the methodology used by the IEA is fixing a minimum annual household consumption of 250 Kilowatt-hours (kWh) in rural areas and 500 kWh in urban areas [5]. According to this definition, 1.2 billion people worldwide are still lacking access to electricity, especially those from rural areas [6].

Though it is not the only alternative (see Figure 1), a viable solution for meeting the Seventh SD goal of the UN in vast rural areas still not served by the power grid is the deployment of renewable off-grid technology. One of these off-grid technologies is photovoltaic (PV) systems, which have been installed in many Developing Countries (DCs) aiming to provide people with electricity who would otherwise have to wait for years to get connected to the national power grid.

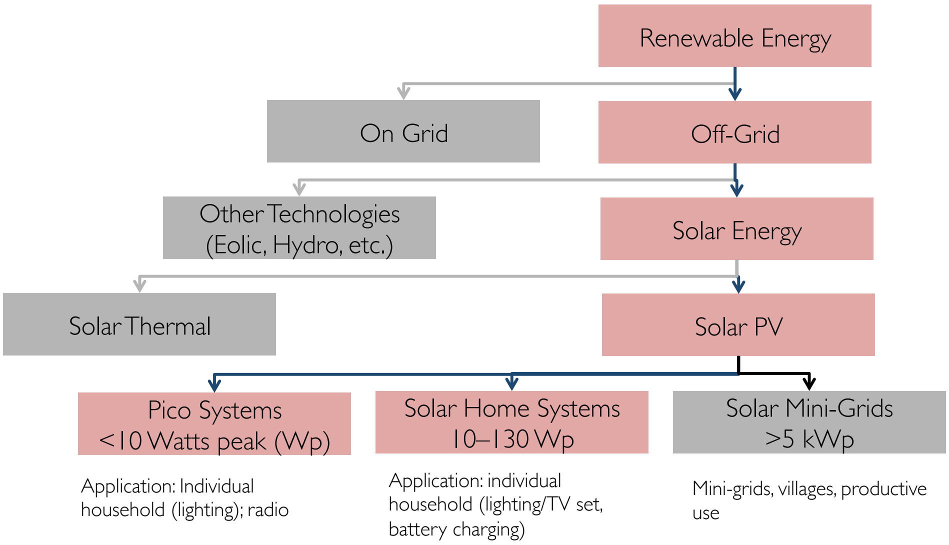


**Figure 1.** Types of solar PV systems. In this paper, the sustainability of off-grid PV systems is addressed.

PV systems may be used in different ways: technological solutions range from very small applications such as Solar Pico Systems (SPS) (i.e., one to 10 watts, e.g., used for lightning to replace kerosene lamps) to mid-scale solutions like Solar Home Systems (SHS); the latter usually have a capacity of a 10–130 watts peak (up to a 250 watts peak has been installed in some households) [7–9]. For SHS, more artifacts, such as several lamps, a radio and TV, can be supplied with energy; yet, in addition to the PV cells, other accessories, including batteries, an inverter (to convert DC into AC) and a charge controller (to regulate the charge from a solar panel into a deep cycle battery bank), are necessary, making the system more expensive. It has been estimated that worldwide, there are about six million SHS installed today (as compared to 1.3 million systems in 2002), although significant data gaps only allow for indicative numbers [10].

PV systems have also been installed in large-scale projects, such as hospitals or whole communities. For that purpose, hybrid solutions (including, e.g., diesel generators or eolic systems) are combined and fed into a local mini-grid, which can provide energy to a whole community [9]. Yet, mini-grids will not be considered in this paper, since prior relevant efforts have already addressed mini-grids [11,12], and their uses may differ from SPS and SHS [13]. For instance, mini-grids require a combination of diverse local generators with a very high technological complexity and are used when the dispersion within the community is low [12,14].

Barriers that constrain the deployment of off-grid PV systems for rural electrification have been described in numerous studies [15–19]. Yet, apart from entry barriers for these solutions, a high failure rate of already deployed systems (i.e., feeble sustainability) has also been detected: e.g., in Guatemala, 45% of the systems were not operational [20]; in Laos, it was 65% [21].

In this paper, the main multidimensional drawbacks that constrain the sustainability of off-grid PV systems are highlighted. Accordingly, an exhaustive electronic literature and project review was performed. Although several relevant PV-based electrification efforts are referred to below, the review was aimed at gathering an overall picture of the rural electrification efforts in DCs, rather than addressing the success or failure of specific projects.

As explained below, the gathered information was allocated according to a set of indicators associated with the sustainability dimensions considered in this paper: institutional, economic, environmental and socio-cultural; see, e.g., [22–24].

## 2. Materials and Methods

### 2.1. Theoretical Framework

Institutional sustainability demands for stability/durability [25–30], technical and service standards, as well as coherence between laws and regulations [24–27]. Failures in rural electrification have often been attributed to the lack of coherence in the legal frame (laws, regulations and standards) [25,27,29] or the absence of proper standards [31,32]. White et al. [33] have also shown how unexpected policy changes can have negative impacts on investments and cause uncertainty. Furthermore, numerous studies have underscored the fact that sustainable institutions should have the ability to adapt to future needs of the population (e.g., [25,26,34–36]).

Sustainable institutions not only need to preserve themselves over time, but they should also be open to the society and its interests, be accountable and transparent in their decision making, while equally considering the other sustainability dimensions [24]. Therefore, decentralization and participation have often been mentioned as indicators for sustainable institutions (e.g., [23,25,28,36–39]). Wüstenhagen et al. [40] argue that a top-down approach at the central government level may inhibit the acceptance of a technology at the local level. Despite the advantages of decentralization, Rondinelli et al. [41] have pointed out the fact that decentralization may be problematic if local institutions in a decentralized administration lack the expertise, know-how and management capacity to administrate the services. Indeed, numerous studies have shown that the scarcity of expert know-how on Renewable Energies (RE) can affect the sustainability of off-grid PV systems [35,42,43].

The economic sustainability of electrification solutions requires ensuring the funding or affordability of the systems (i.e., the initial investments and the Operation and Maintenance (O&M) over its lifetime) [24,26,29,35,38,44–47]. In the energy sector, other important indicators for the economic sustainability of electrification solutions are the cost-effectiveness [25,26,46,48] and the reliability of supply (see, e.g., [25–27,34,49,50]). Moreover, since energy consumption is correlated with income, efforts on rural electrification are expected to contribute to the income of its users [25,46,51–53]. However, if energy projects aim at a higher productive outcome of rural communities, electrification programs need to be coupled with complementary infrastructure, including training and education [53].

Ensuring environmental sustainability for rural electrification requires civil society's awareness of environmental issues, as their support is needed to enforce environmental policies and regulations [54]. Environmental sustainability also requires minimizing the negative impacts of energy solutions on the environment. These impacts may concern the amount of greenhouse gases, such as $CO_2$, $SO_2$ or NO (see, e.g., [26,35,36,46,49,50,52,54,55]); a loss of biodiversity due to deforestation [26,46,50,56] or local impacts, such as air quality caused by pollution in households, noise or aesthetic disturbances [26,50,52,57].

Socio-cultural sustainability requires considering equity/disparity criteria between different communities. In rural electrification, decisions have to be made regarding who will have access to energy (first) and how much energy is provided to each household [35,37,46,56,58]. Furthermore, attention must be paid to the accuracy of a technology for the specific environmental/socio-cultural conditions where it will be implemented [26,59], as well as to the social acceptance, which implies a participatory and inclusive approach in which the local community is engaged to increase accountability [40,49,60]. It is therefore vital for ensuring socio-cultural sustainability to embrace the notion of cultural justice, which in this context refers to justice through participation and recognition [61]. The cultural justice in rural electrification depends on the ability shown to integrate the technology into the existing social structures [26,35,50,54]. Indeed, as argued elsewhere (e.g., [34,62]), the socio-cultural context determines to what extent a technology is adopted.

The set of indicators used in Table 1 were adapted from Feron et al. [63] to qualitatively evaluate the sustainability of the analyzed rural electrification efforts.

**Table 1.** Indicators for the sustainability of off-grid PV systems (adapted from Feron et al. [63]).

| Institutional | Economic | Environmental | Socio-Cultural |
|---|---|---|---|
| Stability (durability) and long-term vision | Cost effectiveness | Environmental awareness | Accessibility (disparity, equity) |
| Regulation, standards and enforcement | Reliability | Environmental impact | Social acceptance |
| Decentralization and openness to participation | Funding (initial investment; operation and maintenance) | - | Accuracy |
| Expert know-how | Contribution to the income of users | - | Cultural justice |
| Adaptability (ability to meet future needs | | | |

**2.2. Methodology**

An extensive review of recent experiences since 2000 in the off-grid PV sector in DCs has been conducted. The review included: scientific papers (63), NGO reports (32), conference/working papers (12), (PhD) theses (11), books (chapters) (5) and scientific reports (3) from governments/NGOs and publications from energy institutions, such as the International Renewable Energy Agency (IRENA) or the International Energy Agency (IEA). Project databases from the World Bank, UN and the Global Environment Facility (GEF), as well as documentation from privately led projects were also reviewed.

The keyword search compiled “sustainability”/”sustainable development” and “rural electrification”/”off-grid”/“solar energy”/“solar home systems”/”SHS”/“pico PV”/“SPS”. This step intended getting an overview of sustainability issues in the analyzed projects. Only experiences from DCs were analyzed; thus, any studies on developed countries were filtered out. Based on the results from Step 1, the search was further refined in a second step by successively adding either “institutional”, “economic”, “ecological” or “socio-cultural” to the search terms “sustainability”/“sustainable development”, such that the information could be clustered according to the sustainability dimensions considered in this paper: institutional, economic, environmental and socio-cultural.

Further analysis allowed allocating the finding to the set of indicators associated with the sustainability dimensions considered in this paper. It should be noted that, albeit that sustainability has traditionally been considered to be three-dimensional (either in the form of a pillar model, concentric circles or overlapping circles; [64]), a fourth dimension (institutional) was added to the analysis due to the high relevance of institutions for the sustainability of off-grid PV systems identified in Step 1.

The search was purposely not restricted to a geographical region (within DCs), as patterns of flaws beyond country and cultural boundaries were of interest. Therefore, the review embraces different continents and countries, aiming to identify common flaws that may affect the sustainability of off-grid PV solutions. The geographic distribution of the analyzed documentation is as follows: worldwide (42); Asia (29); Africa (28); Latin America/Caribbean (16); several countries (7); and Oceania (4).

The findings are presented below.

## 3. Results

### 3.1. Institutional Sustainability

Numerous studies have highlighted the importance of institutions for sustainable rural electrification [56,65,66–69]. Institutions can be understood as a framework of guidelines that set the rules of the game for interactions between human beings [70]; while formal institutions refer to laws and regulations that have been legally enacted by actors and that determine the political, economic and enforcement system, informal institutions can be understood as religious or moral values and traditions that have been established in a certain place, though they have not been legally enacted [71].

Institutional flaws have been found to constrain the sustainability of off-grid PV systems in DCs [28,72–75]. The scarcity of durability/stability and enforcement, weak regulations or standards, incomplete decentralization/participation and the lack of adaptability are among those institutional flaws.

#### 3.1.1. Durability (Stability) and Enforcement

Prior efforts have shown that sustainable off-grid PV systems require strengthened formal institutions [15,44,74–81]. Strengthened formal institutional are characterized by their stability (durability) and their enforcement [82]. In DCs, these two factors tend to be low, which is problematic for the sustainability of off-grid PV systems.

Concerning stability, in Ecuador for example, disruptive changes of institutions (conveyed by frequent changes in the constitution, elimination/creation of ministries and changing regulations) have been shown to compromise the sustainability of off-grid PV systems adopted for the electrification of rural indigenous communities in the Ecuadorian Amazon basin [63]. In Ghana, the weak (instable) institutional framework has been pointed out as the main reason for the lacking dissemination of SHS [83]; although incentives on RE were announced in this country, they were later rejected by lawmakers [72]. In Nigeria, political instability was revealed to be a major challenge for off-grid systems, since the electrification programs were often abandoned after a change in the government [84]. These cases show the importance of ensuring stable formal institutions for the PV system's sustainability.

Regarding enforcement, in Pakistan for example, early burnout of bulbs and failures of solar controllers were not addressed due to the lack of enforcement of warranties [85]. In South Africa, weak control and enforcement resulted in previous agreements with providers in bids for tenders [76]. In Bangladesh, on the contrary, the government-owned financial intermediary not only set technical quality standards for SHS (e.g., establishing a testing laboratory for SHS), but also enforced them, resulting in high user satisfaction [32]. Indeed, the state-owned Infrastructure Development Company Limited (IDCOL) established a Technical Standard Committee that determines the compliance with quality standards for the SHS, and their inspectors carry out physical verifications of the installed systems to enforce their regulations and standards [86,87].

The enforcement of formal institutions strongly depends on informal institutions [88]. For instance, although prohibited by law, corruption can be broadly accepted, given that the interpretation of its actual meaning is tied to norms and attitudes [88]. Informal corruptive behavior is a substantial issue for the sustainability of rural electrification efforts in DCs. In Nigeria for example, corruption was a major reason for off-grid PV failures and ultimately led to the closure of the Rural Electrification Agency [84]. In the Philippines, the selection of contracting partners for PV system installations appeared to be based on personal preferences rather than on a bidding system for the most competent partner [89]. In Pakistan, although laws and regulations for RE had been implemented, in reality, the promised incentives for companies to invest in RE only existed on paper: the conditions were actually set via negotiations between authorities and companies [75]. In Kenya, relationships and access to high-ranking governmental officials appeared to be much more important than rules and compliance with regulations [90]. Therefore, although corruption appears to have avoided the introduction of a fee for service approach (where a company/the government is the owner and sells electricity as a service) in Kenya, that approach was shown to be successful in Zambia, where stronger institutions exists [91].

### 3.1.2. Regulations and Standards

Prior experiences have shown that the adoption of a regulatory frame favors the sustainability of rural electrification efforts based on off-grid PV systems [75,76,92]. The existence of a regulatory agency has also been shown to have a positive effect (e.g., [93–96]).

Flaws in the institutional framework often determine the regulatory landscape in DCs [97–99]. These institutional flaws frequently refer to an incoherent legal frame (e.g., between the constitution, laws and regulations) [100]. In Ecuador for example, inconsistencies between the constitution and the regulations have been observed: though energy was declared a basic right within the Ecuadorian Constitution, it was not anchored in the law, nor put into practice [63]. Similarly, the Chinese Renewable Energy Law showed inconsistencies and even contradictions between its different versions that were frequently changed [101]. Incoherent regulations were also a major issue for off-grid PV systems in Papua New Guinea, given the inconsistent political incentives from different government bodies [15].

Directly linked to the regulatory issues are lacking technical standards. Several studies (e.g., in South Africa, Ghana or Bangladesh) have revealed that a lack of technical standards for PV systems led to dissatisfaction caused by poor system performance and ultimately to a negative promotion of these systems [15,18,42,85,102]. The lack of technical standards can reduce the quality of the systems and may also inflate costs. The Alliance for Rural Electrification (an international NGO) has therefore published a list of recommended quality standards for small standalone systems, but their application needs to be assured by strengthened institutions [9].

### 3.1.3. Centralization/Decentralization

Centralized formal institutions may lead to inappropriate rural electrification solutions that are not adapted to the users' needs. In Mozambique for instance, local government agents defined household lights as a priority in their preferences, but when the project was implemented, the central government installed solar streetlights instead [28]. This lack of local participation in decision-making has been frequently observed in Latin America; Canessa et al. [103] concluded in their evaluation of the Eurosolar Program in Latin America that the low participation of communities and municipalities in the project design phase (turnkey solutions "designed from above") led to substantial adaptation issues, making at risk the sustainability of the PV kits.

Decentralization is meant to facilitate participative decision-making, thus enhancing the chances of a technology to meet the needs of the population [28,36,44,58,81,104]. Decentralized institutions may be preferred for rural electrification since local users know best what they need and who they can trust [105]. However, in some cases, decentralization based on (local) self-management is too costly because of: conflicts among users; high political costs; or a lack of expertise, know-how and management capacity of local institutions for the administration of the services [41,73,105,106]. Indeed, issues for off-grid systems related to decentralization often arose as qualified specialists with the required (cultural and technical) expert know-how are not available in remote areas [75,79,107–110]. For example, decentralizing the administrative resources to local authorities had been a major constraint to the PV implementation in Mexico: management tasks (including finance and control) of rural electrification were reassigned to the municipalities without creating the needed capacities [73]. This lack of local agents' capacities on planning and decision-making substantially lowered the efficiency of the systems [73].

Decentralization may also increase the risk of misalignments among institutions. If responsibilities between local and central government bodies are not agreed upon by all of the involved parties, power games between central and local agents or a lacking coordination between them can lead to unsustainable PV systems. In Nepal for instance, competition and power games between the different government agents have been the result of overlaps in their tasks [72]. In Sri Lanka, the central government decided to connect a region to the grid; this decision made the off-grid systems that were previously deployed by the local government redundant, because they were not needed any more [111]. These organizational issues are examples of how the sustainability of the systems can be constrained by a lack of coordination between local and national governments.

According to Machado [104], the decision for or against a decentralization/centralization ultimately depends on the particular circumstances of each country. Nevertheless, polycentricity has been proposed as an alternative solution. Polycentricity is based on different authorities with overlapping jurisdictions [105] and on sharing the power between multiples actors and mechanisms [112]. The logic behind polycentricity is tackling problems of energy at several levels, such that the advantage of local initiatives (e.g., exchange of knowledge, control measures by locals who know the area, identification with a project, etc.) can be exploited in parallel with national initiatives [113]. Empirical results of decentralized small-scale electricity projects in seven countries have already shown that polycentricity may in fact improve energy governance [114]. Still, in many DCs (e.g., China, Brazil, Thailand), top-down decision-making has been preferred over a polycentric approach [115].

### 3.1.4. Expert Know-How

Several studies have shown that the scarcity of expert know-how on RE can affect the sustainability of off-grid PV systems [35,42,43]. The lack of technicians has led to poor implementations (e.g., causing shadowing or the wrong size of cables), the use of uncertified materials and to under-sizing (due to erroneous power capacity estimations) [75,79,107–110]. Therefore, sustainable off-grid PV systems require generating critical expert know-how. The latter is often a challenge because of significant gaps in the educational system of DCs. Tailored PV solutions for local needs would require innovation and development from local universities, but they often do not have the capacities to generate this knowledge. For example, in Bolivian universities, it was found that poor infrastructure, low wages and missing research programs hampered innovations [80]. Pansera [81] found that the institutionalization of strategic knowledge, which is fundamental to educate experts in solar energy, is still lacking in Bolivia. In Peru, the major constraint concerning human resources has been assigned to the lack of instruction on solar energy; therefore, the country has significant deficiencies in competent technicians [116]. A prioritization of capacity building as a long-term goal is therefore critical for enhancing the sustainability of off-grid PV systems.

### 3.1.5. Adaptability of Institutions

Prior experiences have shown that the sustainability of rural electrification efforts based on off-grid PV systems can be seriously compromised by the lack of adaptability of formal institutions (i.e., the ability to meet the changing needs of the rural population) [25,34,36,117]. Due to the lack of adaptability, the capacity of the off-grid systems tends to be too small for income-generating activities. Indeed, PV systems are typically installed without considering the population's requirements on current and future energy demand, location, technology or the energy potential for future uses [118]. For example, in Bangladesh, less than 9% of the households used the energy from SHS to generate income [119]. Accordingly, users tend to consider the off-grid PV systems a backup solution (with limited energy capacity), being afraid of not receiving the promised grid.

### 3.1.6. Key Points

Sustainable off-grid PV systems require strengthened formal institutions, which are characterized by their stability (durability) and their enforcement. Prior rural electrification efforts have shown that weak formal institutions hinder the compliance with rules due to peoples' expectations of sudden changes or a lack of enforcement.

The adoption of a regulatory frame and standards favors the sustainability of rural electrification efforts based on off-grid PV systems. The existence of an agency aimed at rural electrification has been shown to have a positive effect. A decentralized agency may also facilitate adaptability and participative decision-making, thus enhancing the chances of a technology to meet the needs of the population.

### 3.2. Economic Sustainability

#### 3.2.1. Cost-Effectiveness

For an electrification solution to be sustainable, it needs to be cost-effective given that financial resources are scarce, especially in DCs [26,46,120]. Off-grid PV systems can be a cost-effective solution in the case of dispersed populations with low per capita energy consumptions [121,122].

However, governments often favor costly conventional energy sources over RE: indeed, in 2015, global energy post-tax subsidies on coal, petroleum, natural gas and electricity totaled US $5.3 trillion (i.e., 6.5% of the global GDP), with the greatest share given to coal (3.9% of global GDP) [123]. In Malaysia for instance, Petroliam Nasional Berhad (PETRONAS by its acronyms; the oil and gas state company) gave a 60% subsidy on natural gas to the utilities, such that RE had to compete with extremely low prices [124]. In Nigeria, total kerosene subsidies were higher than social programs for security, critical infrastructure, human capital development and land and food security combined [125]. These subsidies are particularly high in some DCs, including the Middle East, North Africa, Afghanistan and Pakistan, the Commonwealth of Independent States and Emerging and Developing Asia, where they amounted to 13–18 percent of the respective national GDPs [123]. In Vanuatu for instance, the local electricity utility was exempted from tax duties for diesel acquisitions, thus giving them a substantial competitive advantage over RE providers for rural electrification [79]. Contrarily, duties on PV cells and modules were found to be up to 50% in Pakistan [75]. These policies favor unsuitable energy sources, neglecting the internalization of external costs caused by environmental damages and, in turn, blocking cost-effective solutions [126].

Not only governments exhibit problems for adopting cost-effective solutions for rural electrification. PV systems have a higher initial investment, while lower Operation and Maintenance (O&M) costs relative to other off-grid solutions (e.g., diesel generators). Therefore, low-income households avoid buying these off-grid PV systems, although over the lifetime, they would pay off [9]. Rolland [9] explains this behavior with the unavailability of financial products (e.g., microcredits) in rural areas, as well as with the near future focus of the poor population. The lack of tailored financial products can often be attributed to the deficient know-how on alternatives for financial tools that are valid for rural off-grid PV systems. In Lesotho, for instance, neither the users nor the financial institutions were properly trained to make use of financial solutions, and no lending schemes tailored for renewable systems were offered [127]. As a result, costly (and therefore, unsustainable) solutions are oftentimes chosen.

#### 3.2.2. Reliability

Ensuring the sustainability of off-grid PV systems entails making the energy supply reliable [25,27,34,50]. For rural areas, energy reliability demands for the availability of spare parts, as well as user know-how to understand the functionalities, use the systems appropriately and exert simple maintenance [34].

The availability of spare parts has been one of the critical success factors of the SHS in Bangladesh, where spare parts were held in offices that were at most a few kilometers away from the project area [128]. However, in the case of many other rural electrification projects, spare parts are often not available due to a distribution network focused on highly populated areas [81,129,130]. The scarcity of spare parts makes off-grid PV systems unreliable, thus compromising their sustainability.

Moreover, user training has been proven to enhance the reliability of the systems. In Bangladesh for instance, training programs have been undertaken by IDCOL for creating awareness not only among the installation companies, but also among the customers [88]. Nonetheless, many off-grid PV projects worldwide became unsustainable as they ignored the importance of user know-how (e.g., [15,31,69,79,102,107,108,111,131–133]). For example, in Uganda, Tillmans and Schweizer-Ries [107] reported a substantial knowledge drop in the chain of information (manufacturer-local supervisor and NGO-local solar company and user) towards the user. This experience has shown that an organizational structure that assures transmitting the know-how for proper handling is indispensable for the systems' reliability.

### 3.2.3. Initial Investment

The sustainability of off-grid PV systems further involves ensuring the affordability of the systems. Electrification programs aimed at rural communities are usually unprofitable in DCs (due to high dispersion, low energy demand; difficult access, etc.). For instance, Best [98] found that in Argentina, logistic costs, on the one hand, and low consumption of rural populations, on the other hand, made the rural electrification market unattractive for investors.

Moreover, numerous studies have shown that the relatively high initial investment costs make off-grid PV systems unattainable for rural households in DCs [9,79,118,124,134,135], except for the rural elite [136]. In India for instance, given the unequal income distribution, SHS could only be afforded by around 10% of households [135]. Part of the problem is that rural households are mainly socially deprived and not in a strong bargaining position to negotiate conditions for the acquisition of a system [111]. Even if a loan for off-grid PV systems is provided to rural families, this does not imply that the users can meet the repayment rates. In addition to the irregular income of rural families and despite being aware of their installment rates, these families often have no clear view of their earnings [111].

Due to these conditions, the sustainability of off-grid PV systems aimed at the rural population in DCs may require policy intervention, which means allocating public funds for covering both the initial investment and the O&M of the systems or subsidizing private investment in rural electrification. In Ecuador for example, the high rate of rural electrification can be partially explained by the existence of "Fund for Rural and Urban-marginal Electrification" (FERUM by its Spanish acronym). Since 1998 until 2008, the FERUM received resources from a 10% tax charged to the tariff paid by on-grid commercial and industrial consumers around the country, funding initial investments associated with rural electrification efforts [63]. In Bangladesh, the state-owned IDCOL provides soft loans to so-called Partner Organizations, companies that install the PV systems and operate them afterwards; IDCOL itself receives funds from international donors, such as the World Bank, to foster private investments [87,88]. Bangladesh also applies indirect subsidies (soft loans and slow repayment terms) [137]. In Kenya, favorable loans to users and suppliers have also contributed to the wide diffusion of SHS [138].

### 3.2.4. Operation and Maintenance

Ensuring the sustainability of off-grid PV systems requires covering O&M over their lifetime ([29], p. 28, and [44]). However, numerous project failures can be related to the lack of funds for covering O&M [7,38,81]. For example, in the case of projects funded by private donors, several studies have found that they tend to prefer only paying for the initial costs of the PV systems, avoiding the long-term commitment associated with O&M; (e.g., [108,111]).

Part of the problem is that the O&M costs of the off-grid PV systems can be hardly estimated, as outlay may vary considerably depending on factors, such as the availability of trained maintenance providers, community dynamics or the possibility of training local users [122]. As a consequence, O&M costs have been frequently underestimated. For example, Carrasco et al. [139] found that in Morocco, where more than 13,000 off-grid PV systems were installed, the user fee (a fee for service approach was used) covered only 14.9% of the global costs over the system's lifetime; this fee did not cover O&M, which led to an unsustainable economic situation. Indeed, a fee for service approach for off-grid PV systems will unlikely succeed when the rural population in DCs can hardly afford the O&M costs for items, such as battery replacement or maintenance devices.

Assuring the sustainability to the off-grid PV systems may therefore involve subsidizing the electricity tariffs of poor population (such that all O&M are covered). According to Eberhard et al. [140], widespread subsidies for electricity never reach the poor; instead, the authors registered highly regressive effects from subsidies for power provision in Sub-Saharan Africa.

Therefore, an effective focalized subsidy scheme (e.g., cross-tariff scheme) that reaches the poor and assures covering the O&M is advisable [111,127,141].

### 3.2.5. Contribution to User Income (Productive Use)

Electrification not only provides greater comfort to households, but it can also contribute to a higher income of the users [46,142–144]. In fact, high potentials of productive uses have been revealed in various studies (e.g., [145–149]). For instance, Glemarec [150] resumes numerous studies, which coincide that an additional household income of around US $900 can be obtained from productive use thanks to access to electricity. This has also been observed for off-grid PV systems: for instance, in Ghana, an additional income of US $5–$12/day could be attained in grocery stores thanks to solar PV lighting [151].

In fact, a great variety of applications of off-grid PV systems for productive use can be found. Fishbein et al. [147] and Board [152] name among others e-commerce of digital local culture and handicrafts, artisan, rural industry, agricultural uses (e.g., pumping water for livestock, micro-irrigation, ice production for fishermen, fish farming, and milk cooling tanks), solar water heaters and ovens, shops, cinemas, tourism, stations for battery charging, food processing, drinking water pumps, grinding and refrigeration. For instance, PV-powered water pumps for irrigation have been shown to have a significant potential. For example, in Chile, the Agency for Agrarian Development (with the support of the Ministry of Energy) replaced about 1400 pumps powered by fossil fuels by PV-powered water pumps (subsidizing 90% of the initial investment), which allowed the farmers to irrigate with very low O&M costs [153].

Although the PV systems are in many cases even simpler than the fossil fuel solutions [147] and despite its productive potential, a study from the World Bank [154] found that still the vast majority of rural electrification is for residential use, whereas industrial development has been very limited. For example, in Bangladesh, less than 9% of the households used the energy from SHS to generate income [119].

The limited use for income generation can be mostly explained by a lack of user know-how and proper training on the different uses of electricity [108,119]. On this note, the provision of electricity does not automatically lead to productive uses [149], but requires complementary government programs [108,147,155]. Interdisciplinary projects involving cross-sectorial collaboration would be needed (for example with the ministry of education or similar institutions of the respective country), but the missing cooperation between the countries' ministries or organizations makes this collaboration difficult. The Renewable Energy Project in Rural Markets (PERMER by its Spanish acronym) in Argentina for example set up about 6000 SHS and 1449 school systems with lights [98]; yet, since the program had not been aligned with other programs (such as the telecommunications or in a productive sector, like agriculture) on a province level, its impact on poverty reduction was low [98].

Similarly, in the Eurosolar Project in Latin America (which embraced Bolivia, Ecuador, El Salvador, Guatemala, Honduras, Paraguay and Peru), the different ministries (e.g., Ministry for Health, Education, with the Energy Ministry) had to work together to build an infocenter on REs; the main objective was to set up an integral program including access to the Internet, printers, computers, phones, water purification, fridges and lightning. Thus, the program required cooperation between these ministries, but the coordination became very challenging, as each of the ministries had its own budget, organization and plans [80]. As summarized by Kapadia [156], sectorial boundaries (especially with the health and the educational sector) are extremely hard to overcome and demand for considerable knowledge transfer from experts of both (several) sectors.

### 3.2.6. Key Points

The economic sustainability of off-grid PV systems aimed at poor rural population in DCs requires policy intervention, which means allocating public funds for directly covering both the initial investment and the O&M of the systems or for subsidizing private investment in rural electrification.

Off-grid PV systems can also decisively promote local economic development since rural electrification has the potential to contribute to the user income. However, prior experiences have shown that productive uses of off-grid PV systems require additional government programs, offering cooperation and training. Indeed, user training has been proven to enhance the reliability of the systems, ensuring in turn their sustainability.

### 3.3. Environmental Sustainability

#### 3.3.1. Environmental Awareness

Environmental sustainability demands that civil society to be aware of environmental issues, such as environmental norms and regulations [86]. Kollmuss and Agyeman [157] define environmental awareness as "knowing of the impact of human behavior on the environment" (p. 253). Education is vital for creating environmental awareness, as shown, e.g., in Brazil, where the level of education was found to be a strong predictor of the awareness on environmental issues [158]. However, especially rural and remote areas in DCs often have a weak education system. For example, Yu [159] revealed in a comparative study in China that environmental awareness was much lower in rural areas than in urban areas.

Nonetheless, education is not enough for ensuring environmental sustainability, since human behavior may also be affected by external factors (such as institutional and economic factors) [157]. These external factors demand economic and institutional policies that provide regulations and incentives (e.g., subsidies on RE), as well as an appropriate infrastructure (such as recycling bins) to foster a pro-environmental behavior [157]. Often, the lack of proper education, regulations and incentives may lead to environmental issues. For example, in Ghana and in the Ecuadorian Amazon basin, the lack of policies for ensuring recycling and proper disposal of PV modules and batteries after the end of their service life resulted in the batteries being simply buried, releasing acid substances into nearby lakes and rivers [63,160].

#### 3.3.2. Positive Environmental Impacts

Due to their relatively low environmental impact, PV technologies for rural electrification yield long-term benefits in terms of pollution abatement and climate change mitigation. In contrast, fossil fuels can lead to important negative co-impacts as they contribute to climate change, emitting not only Greenhouse Gases (GHG), but also producing about 1/4 of Short-Lived Climate Pollutants (SLCP) like black carbon (BC) [161]. BC is not only produced in households from cooking and heating, but also from lightning; Mills [162] estimates that worldwide, approximately 500 million households consume 77 billion liters of kerosene and other liquid fuels for lightning. According to Lam et al. [162], the environmental impact is significant, as 7%–9% of fuel from kerosene lamps converts to almost pure BC. Indeed, 270,000 tons of BC are currently emitted by these lamps, which is roughly equivalent to the forcing that 230 million tons of $CO_2$ exerts over 100 years after its emission [163].

#### 3.3.3. Negative Environmental Impacts

Although RE including off-grid PV systems are an alternative for reducing negative environmental impacts from lightning in remote areas [120], they may also do environmental harm if not properly used. As mentioned above, one major potential source of environmental co-impacts is inappropriate battery disposal. For instance, in Guatemala, Corsair [164] found that almost all users threw their lead-acid battery from off-grid PV systems away as regular waste; in one case, the battery was even given to a child as a toy. Likewise, in Nepal, the users dropped the batteries on the ground, which led to damages caused by acid spoiling [165]. Analogously, in Uganda, acids diluted with lead compounds were poured outside the users' houses [166]. These cases show that even presumably clean technologies may become environmentally unsustainable in the context of a scarcity of environmental awareness and regulations, weak enforcement and lacking incentives.

However, the potential negative environmental impacts of off-grid system can be overcome if regulation are adopted and enforced. In Bangladesh for example, a battery-recycling policy was introduced in 2013 when the government forced the battery retailers to recycle batteries [167].

#### 3.3.4. Key Points

Although PV technologies for rural electrification yield long-term benefits in terms of pollution abatement and climate change mitigation, the lack of environmental awareness and policies (for example on ensuring recycling and proper disposal of PV modules and batteries) may also lead to negative environmental co-impacts.

### 3.4. Socio-Cultural Sustainability

#### 3.4.1. Accessibility (Disparity, Equity)

The access to energy (i.e., the accessibility) is driven by the notion of social justice, which determines the equity/disparity between different groups of people (such as gender or race). Accessibility aims at equal opportunities to receive clean and reliable energy [37,46,56,58,168]. Off-grid PV systems offer an alternative for greater equity, as they may provide energy access to the vulnerable population (e.g., women or indigenous people) where a grid connection would not be viable [169].

As discussed elsewhere [170], energy has been key for equity from a gender perspective and was therefore included in the UN Millennium Development Goals. Household electrification is important not only because women are the main users of residential electricity, but also because they have to carry the burden of collecting biofuels (leading to physical exhaustiveness and a significant loss of their time that could be used for productive uses); girls cannot attend school because they have to help their mothers collect biofuels; without electricity, women do not have access to information through telecommunication on modern family planning, their rights and empowerment; and women are mainly exposed to indoor air pollution [170].

Nonetheless, significant inequalities in the energy sector remain between genders, especially in DC [112]. Off-grid PV systems have been no exception: for instance, in Bangladesh, between 2005 and 2010, 2797 women from low-income households received a 15-day technological training sponsored by the U.S. government agency USAID to repair and operate SHS; it aimed to integrate women into the value chain of Grameen Shakti (a subsidiary of the Grameen Bank), the fastest growing rural-based RE company of Bangladesh, and to ultimately enhance women's employment and income situation [171]. Yet, despite a huge boom of SHS installations (more than one million) in Bangladesh, none of these women got a job as an entrepreneur in the RE sector, which was partly due to male domination in the company [171]. Furthermore, in India, Sundarban women had limited control over financial assets, which left them without any decision-making power concerning electrification projects; men paid for the solar systems and were also the owners, as electricity was considered to fit into the scope of male responsibilities [172]. In addition, it was found that when women saved time thanks to a newly-introduced technology (e.g., solar cookers), men tended to become suspicious, which was explained by the fact that men felt bypassed, as they were no longer the providers of technology [173].

Energy disparity between urban and rural areas also remains in many countries and is becoming greater instead of smaller. For instance, according to Nathan [174], the gap between urban and rural electricity consumption in India has tripled in 25 years. The situation is often aggravated due to higher electricity tariffs in rural areas; e.g., in urban parts of Cambodia, tariffs amounted to US $0.15/kWh as compared to US $1.00/kWh in rural regions [175].

#### 3.4.2. Accuracy

Accuracy implies designing energy solutions according to the socio-cultural reality, which implies meeting the needs of the local community rather than implementing a plug and play solution (without further knowledge of the local context) [26,59]. Estimating an accurate capacity of a PV system for the rural population of DC is challenging, since standardized econometric energy models used in developed countries (which estimate the demand based on a representative consumer) are not suitable for rural areas of DC [176]. While new models suitable for DCs could be developed, the lack of input data for accurately modeling the energy demand is challenging [177]. In Cambodia for example, the unavailability of statistical data on electricity demand was a main barrier for project development in rural areas [178]. This problem has been confirmed iteratively in studies focusing on DCs, e.g., by Sarkar and Singh [77], Bhattacharyya and Timilsina [179] and Mundaca and Neij [180].

Inaccurate systems often lead to unsatisfied users and in turn unsustainable solutions. For instance, in Indonesia, users were dissatisfied with the SHS, because they expected them to run applications, such as TVs or radios, refrigerators or rice cookers, as they had been used to from diesel generators [181]. As illustrated in that study, a higher energy demand from users was not met by the inaccurate solutions installed.

Moreover, adapting the off-grid PV systems to the local needs can be challenging, as engineers and designers (typically from developed countries) do not know who their users are and how their products are used. Hence, they often fail to adapt the systems to the local conditions [7]. For example, in Ethiopia, lamps were perceived to be of low quality, although they received a high quality rating in Germany; as revealed by Müggenburg et al. [60], this was due to different quality criteria from Ethiopian users, who appreciated attributes like the cone of light, handling for multi-purpose usage, a non-glaring lamp, robustness and the duration of the light.

Difficulties are further aggravated as users may give statements about their preferences they know the project managers want to hear, first to avoid disappointed expectations and second to continue receiving donations or subsidies. For instance, in Papua New Guinea, the motivation of the users (for receiving electricity) does not necessarily concur with the ideals of a donor: although the end-users stated that they used the electricity for expanded study hours, they actually preferred to rest at nights [15]. This can be explained by the fact that, e.g., farmers in rural areas may live in a different rhythm than urban electricity users. Similarly, although electricity from off-grid PV systems may extend working hours, which is generally advocated to increase people's income (see, e.g., [42,119,131]), women were found to refuse electricity given the additional work burden [173].

Women's necessities are indeed often ignored in the design of the project/technology despite their substantial importance for accurate solutions as principle energy users [182–185]. In a review of projects for sustainable energy solutions based on small-scale projects that were implemented worldwide between 2007 and 2012, Terrapon-Pfaff et al. [186] revealed that almost half of the projects poorly considered gender-related issues, if at all. In the Eurosolar Project for instance, gender was not contemplated in any way in the project design [103]. One reason for this may be that in some countries it is particularly difficult to ask for women's opinions, as they need prior permission from their husbands to reason [42]. The consequences may be devastating, as, e.g., exposed by Clancy [187]: SHS did not provide sufficient energy for family meals, and cooking with solar cooking stoves did not match with the eating time of many cultures. These issues occurred because the energy systems were designed according to men's prospects, although women were the principal energy users, resulting in inaccurate solutions for the users and ultimately in the system's abandonment. Therefore, understanding rural lifestyle is needed to tailor a technology and improve the accuracy, reducing in turn rejection and disappointments [15].

#### 3.4.3. Social Acceptance

Many authors consider that ensuring the sustainability of PV systems in DC's rural areas stands for socio-cultural, rather than technological challenges [9,31,107,108,111,188]. For an energy system to be sustainable, it needs to be socially accepted, which implies the active participation and engagement of the community aimed at enhancing the accountability of the project [40,47,50,56,60,189,190]. Off-grid PV systems can be a great opportunity to assure social acceptance; Burton and Hubacek [191] found that, compared to large-scale solutions, small-scale energy approaches may have a higher social acceptance.

Nonetheless, lack of communication concerning the applications and limitations of off-grid PV systems can lead to false expectations and negative perceptions, thus constraining their acceptance [107,108,192,193]. In French Guiana for instance, users complained about a lack of relationship and insufficient contact with the installing company; the negative attitude towards the company was the principal factor for rejecting the PV systems [194]. The Renewable Energy Policy Network for the 21st Century (REN21) [195] confirm that the lack of the commitment of a community leads to a detachment of actual local requirements and the deception of rural users. As argued by Campbell et al. [196], levels and types of participation need to be mapped to all interest groups of the community that are characterized as "complex, self-organizing, self-imagining, and conceptually productive" actors.

Poor participation has been found to lead to social issues. For example, according to the UN [127], the lack of involvement of the community resulted in theft of off-grid PV components in South Africa. Indeed, vandalism took place in several countries (e.g., Papua New Guinea, Tunis, China; several African countries), and systems were broken (e.g., [3,69,85,103]). In Ethiopia, users took the systems with them instead of charging them at home due to envy issues within the community [60]. This behavior is also believed to be due to the lack of mutual social control [85]. Therefore, Frame et al. [47] propose that the community should own the systems (SHS, as well as PV solutions for community facilities like schools and health centers), which implies getting organized in a committee to administrate and maintain them to generate a sense of responsibility. Still, McKay [165] compared two models of ownership to set up off-grid PV systems in Nepal and found that social issues emerged in both cases. The first model was based on a cluster solution (i.e., community ownership), which connected several houses to a battery bank that was stored in one of the houses; despite significant cost savings of this solution, it had numerous drawbacks. Not only the users complained about the free-rider problem of their neighbors (connecting more devices than initially agreed upon), but they could not even protest about it owing to the cast system prevailing in Nepal. Additionally, when the user who held the batteries in his/her house moved during seasons, the other users did not have access to it. In the case of the individual SHS (second model) by contrast, it was observed that individual owners had sold donated components, since the community as a whole was not the owner, and thus, it did not oppose any pressure [165].

A case study conducted in Mozambique [25] provides a positive example of how the participation of the local community can contribute to the social acceptance (and in turn, to the sustainability) of energy solutions: a management committee consisting of different user groups who represented the users' interest was set up for managing and enforcing the agreed terms; it assured direct collaboration with the local government, which in turn communicated with higher government officials. The committee contributed to the engagement and commitment of the users, which made it a key success factor of the project [25].

#### 3.4.4. Cultural Justice

Some authors have suggested that culture should be a sustainability dimension, e.g., in terms of cultural integrity for indigenous people [19]. Culture determines the responsible conduct and motivations of a person, risk assessment, degree of political participation, value formation and environmental awareness [197]. Cultural justice for energy concerns the respect for cultural habits and values when designing an energy solution [65]. Unfortunately, the culture of small rural communities is often not considered in the execution of public policies. For example, in Ecuador, the government has been building micro-grids for semi-nomadic communities (who regarded nomadism as a cultural value), who were then expected to adapt their culture to this new reality [63]. Similarly, de Swart ([198], p.12) cautions about social enterprises that implement RE in indigenous communities and unconsciously impose their values and beliefs on the people. Urmee [199] therefore argues that it is indispensable to understand the community, i.e., how decisions are made, their culture, interests and habits, which allows for a more sustainable solution. Hirmer and Cruickshank [59] argue that creating value (cultural, social, emotional, functional, etc.) for the users of an off-grid system is particularly important for its sustainability.

### 3.4.5. Key Points

Off-grid PV systems offer an alternative for greater equity, as they may provide energy access to the vulnerable population (e.g., women or indigenous people) where a grid connection would not be viable.

For an energy system to be sustainable it must be accurate (which means meeting the needs of the community respecting its particularities and culture); and it must be socially accepted (which requires the active participation and engagement of the community in the design, implementation and operation of the project).

## 4. Discussion and Conclusions

A review of rural electrification programs and projects based on off-grid PV systems (including SPS and SHS in DCs) was conducted. The gathered information was allocated according to a set of indicators associated with the sustainability dimensions considered in this paper: institutional, economic, environmental and socio-cultural. The goal of this review is to highlight the main multidimensional challenges that may constrain the sustainability of off-grid PV systems in DCs.

Prior efforts have shown that sustainable off-grid PV systems require strengthened formal institutions, which are characterized by their stability (durability) and their enforcement. In DCs, these two factors tend to be low, which is problematic for the sustainability of off-grid PV systems. The adoption of a regulatory frame (including technical standards) and the existence of a regulatory agency tend to favor the sustainability of rural electrification efforts based on off-grid PV systems. However, prior experiences have shown that the enforcement of these formal institutions strongly depends on informal institutions. For instance, informal corruptive behavior is a substantial issue for the sustainability of rural electrification efforts in DCs. The international experience suggests that ensuring the PV system's sustainability requires paying attention to forming or adopting formal institutions, as well as ensuring their enforcement.

Centralized formal institutions may lead to inappropriate rural electrification solutions that are not adapted to the users' needs. Decentralization is meant to facilitate adaptability and a participative decision-making, thus enhancing the chances of a technology to meet the needs of the population. However, decentralization may also increase the risk of weak coordination between local and national governments and the lack of expert know-how (often not available in remote areas).

The lack of expert know-how is related to significant gaps in the educational system of DCs since local universities often do not have proper capacities to generate this knowledge. The lack of technicians has led to poor implementations (e.g., causing shadowing or the wrong size of cables), the use of uncertified materials and to under-sizing (due to erroneous power capacity estimations). A prioritization of capacity building as a long-term goal is therefore critical for enhancing the sustainability of off-grid PV systems.

Not only expert know-how is required. Many off-grid PV projects worldwide became unreliable (and in turn, unsustainable) as they ignored the importance of the user know-how. An organizational structure that assures transmitting the know-how for proper handling is indispensable for the systems' sustainability.

For an electrification solution to be sustainable, it also needs to be affordable and cost effective. Although off-grid PV systems are a cost-effective electrification solution in the case of disperse populations with low per capita energy consumption, governments often favor costly conventional energy sources over RE. Not only governments exhibit problems for adopting cost-effective solutions for rural electrification. The unavailability of financial products (e.g., microcredits) and the higher initial investment of PV systems make off-grid PV systems unattainable for rural households in DCs and often force the poor population in rural areas to choose costly (and therefore, unsustainable) solutions.

The economic sustainability of off-grid PV systems aimed at poor rural populations in DCs may require policy intervention, which means allocating public funds for covering both the initial investment and the O&M of the systems. Numerous project failures can be related to the lack of funds for covering O&M or their underestimation. Therefore, assuring the sustainability of the off-grid PV systems requires an effective focalized subsidy scheme (e.g., cross-tariff scheme) for the electricity tariffs of poor population (such that all O&M are covered).

Although electrification is expected to contribute to a higher income of the users, several cases worldwide show that the provision of electricity does not automatically lead to productive uses. Part of the problem arises from the lack of user know-how and proper training on the different uses of electricity, which demands for interdisciplinary projects involving cross-sectorial collaboration (for example, with the ministry of education or a similar institution).

Due to their relatively low environmental impact, PV technologies for rural electrification yield long-term benefits in terms of pollution abatement and climate change mitigation. However, the lack of environmental awareness and policies (for example, on ensuring recycling and proper disposal of PV modules and batteries) has led to environmental co-impacts in several DCs. These lessons shows that even presumably clean technologies may become environmentally unsustainable in the context of the scarcity of environmental awareness and regulations, weak enforcement of regulations and the lack of incentives.

Off-grid PV systems offer an alternative for greater equity as they may provide energy access to the vulnerable population (e.g., women or indigenous people) where a grid connection would not be viable. However, energy solutions should be designed accurately (i.e., according to the socio-cultural reality of the users). Inaccurate systems (unable to meet the actual energy demand) often lead to unsatisfied users and, in turn, unsustainable solutions. Several cases worldwide show that understanding the rural lifestyle is needed to tailor a technology and improving the accuracy, reducing in turn rejection and deception.

For an energy system to be sustainable, it needs to be socially accepted, which implies the active participation and engagement of the community aimed at enhancing the accountability of the project. Compared to large-scale solutions, small-scale energy approaches may have a higher social acceptance. However, a lack of communication concerning the applications and limitations of off-grid PV systems can lead to false expectations and negative perceptions, thus constraining their social acceptance. Prior experiences show that in order to avoid social issues (envy, stealing, etc.), participation needs to include all interest groups of the community.

Sustainable energy solutions should be designed respecting the cultural habits and values of local population. Unfortunately, the culture of small rural communities is often not considered in the execution of public policies in DCs. Sustainable energy solutions for small rural communities require better understanding the community, i.e., how decisions are made, their culture, interests and habits. Progress regarding social acceptance, accuracy and cultural justice is urgently needed for ensuring the socio-cultural sustainability of rural electrification efforts in DCs.

The reviewed efforts on rural electrification have shown that ensuring sustainability requires an integrated and multidimensional approach. Although the dimensions of sustainability (institutional, economic, environmental and socio-cultural) are strongly interwoven and are deeply interdependent, prior experiences have underlined the importance of paying special attention to the institutional dimension. Indeed, the absence of strengthened and sustainable formal institutions appears to be a major drawback in DCs that, by inhibiting law enforcement, compromises the environmental and socio-cultural sustainability of rural electrification efforts, particularly in rural areas.

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**Abbreviations**

| | |
|---|---|
| BC | Black Carbon |
| $CO_2$ | Carbon dioxide |
| CC | Climate Change |
| CTF | Clean Technology Fund |
| DCs | Developing Countries |
| FERUM | Fund for Rural and Urban-marginal Electrification |
| FDI | Foreign Direct Investments |
| GEF | Global Environmental Facility |
| GHG | Greenhouse Gases |
| IDCOL | Infrastructure Development Company Limited |
| IEA | International Energy Agency |
| IRENA | International Renewable Energy Agency |
| kWh | Kilo Watt hours |
| NGO | Non-Governmental Organization |
| O&M | Operation and Management |
| PERMER | Renewable Energy Project in Rural Markets |
| PETRONAS | Petroliam Nasional Berhad |
| PV | Photovoltaic |
| RE | Renewable Energy |
| REN21 | Renewable Energy Policy Network for the 21st Century |
| SD | Sustainable Development |
| SHS | Solar Home Systems |
| SLCP | Short-Lived Climate Pollutant |
| SPS | Solar Pico Systems |
| UN | United Nations |
| UNDP | United Nations Development Programme |
| WHO | World Health Organization |
| Wp | Watts peak |

**References**


1. Kaygusuz, K. Energy for sustainable development: A case of developing countries. *Renew. Sustain. Energy Rev.* **2012**, *16*, 1116–1126.
2. Kirubi, C.; Jacobson, A.; Kammen, D.M.; Mills, A. Community-based electric micro-grids can contribute to rural development: Evidence from Kenya. *World Dev.* **2009**, *37*, 1208–1221.
3. International Energy Agency (IEA). *Comparative Study on Rural Electrification Policies in Emerging Economies*; International Energy Agency: Paris, France, 2010.
4. Assembly, U.G. *Transforming Our World: The 2030 Agenda for Sustainable Development*; Resolution Adopted by the General Assembly on 25 September 2015; United Nations: New York, NY, USA, 2015.
5. International Energy Agency (IEA). World Energy Outlook 2015—Methodology for Energy Access Analysis. 2015. Available online: http://www.worldenergyoutlook.org/media/weowebsite/2015/EnergyAccess_Methodology_2015.pdf (accessed on 25 June 2016).
6. International Energy Agency (IEA). World Energy Outlook. Electricity Access Database. 2015. Available online: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/ (accessed on 16 December 2015).
7. Lysen, E.H. *Pico Solar PV Systems for Remote Homes: A New Generation of Small PV Systems for Lighting and Communication*; Photovoltaic Power Systems Programme, IEA PVPS Task; International Energy Agency: St. Ursen, Switzerland, 2013.
8. Pachauri, S.; Scott, A.; Scott, L.; Shepherd, A. *Energy for All: Harnessing the Power of Energy Access for Chronic Poverty Reduction*; Energy Policy Guide No. 3; The Chronic Poverty Advisory Network: London, UK, 2013.
9. Rolland, S. *Rural Electrification with Renewable Energy: Technologies, Quality Standards and Business Models*; Alliance for Rural Electrification: Brussells, Belgium, 2011.
10. International Renewable Energy Agency (IRENA). *Off-Grid Renewable Energy Systems: Status and Methodological Issues*; Working Paper; IRENA: Abu Dhabi, UAE, 2015.
11. Deshmukh, R. *Sustainable Development of Renewable Energy Mini-Grids for Energy Access: A Framework for Policy Design*; The University of California: Berkeley, CA, USA, 2014.
12. Dutt, P.K.; MacGill, I. Addressing some issues relating to hybrid mini grid failures in Fiji. In Proceedings of the 2013 IEEE Global Humanitarian Technology Conference: South Asia Satellite (GHTC-SAS), Trivandrum, India, 23–24 August 2013; pp. 106–111.
13. Nygaard, I. The compatibility of rural electrification and promotion of low-carbon technologies in developing countries-the case of Solar PV for Sub-Saharan Africa. *Eur. Rev. Energy Mark.* **2009**, *3*, 125–158.
14. Palit, D.; Chaurey, A. Off-grid rural electrification experiences from South Asia: Status and best practices. *Energy Sustain. Dev.* **2011**, *15*, 266–276.
15. Sovacool, B.K.; D'Agostino, A.L.; Jain Bambawale, M. The socio-technical barriers to Solar Home Systems (SHS) in Papua New Guinea: Choosing pigs, prostitutes, and poker chips over panels. *Energy Policy* **2011**, *39*, 1532–1542.
16. Siegel, J.R.; Rahman, A. *The Diffusion of Off-Grid Solar Photovoltaic Technology in Rural Bangladesh*; Energy, Climate, and Innovation Program Report; Tufts University: Medford, MA, USA, 2011.
17. Karakaya, E.; Sriwannawit, P. Barriers to the adoption of photovoltaic systems: The state of the art. *Renew. Sustain. Energy Rev.* **2015**, *49*, 60–66.
18. Van Norden, S. Investigation of the Barriers for the Diffusion of Photovoltaic Systems in Cape Town. Master's Thesis, KTH School of Industrial Engineering and Management (ITM), Stockholm, Sweden, 2015.
19. Sindhu, S.; Nehra, V.; Luthra, S. Identification and analysis of barriers in implementation of solar energy in Indian rural sector using integrated ISM and fuzzy MICMAC approach. *Renew. Sustain. Energy Rev.* **2016**, *62*, 70–88.
20. Nieuwenhout, F.D.J.; van Dijk, A.; Lasschuit, P.E.; van Roekel, G.; van Dijk, V.A.P.; Hirsch, D.; Wade, H. Experience with solar home systems in developing countries: A review. *Prog. Photovolt. Res. Appl.* **2001**, *9*, 455–474.

21. International Renewable Energy Agency (IRENA). Accelerating Off-Grid Renewable Energy. Second International Off-Grid Renewable Energy Conference (IOREC 2014) Key Findings and Recommendations. 2014. Available online: http://www.irena.org/DocumentDownloads/Publications/IRENA_2nd_IOREC_2015.pdf (accessed on 12 October 2016).
22. Burford, G.; Hoover, E.; Velasco, I.; Janoušková, S.; Jimenez, A.; Piggot, G.; Podger, D.; Harder, M.K. Bringing the "missing pillar" into sustainable development goals: Towards intersubjective values-based indicators. *Sustainability* **2013**, *5*, 3035–3059.
23. Derakhshan, F. *On Sustainability in Local Energy Planning*; Lund University: Lund, Sweden, 2011.
24. Pfahl, S. Institutional sustainability. *Int. J. Sustain. Dev.* **2005**, *8*, 80–96.
25. Sharma, T.; Balachandra, P. Benchmarking sustainability of Indian electricity system: An indicator approach. *Appl. Energy* **2015**, *142*, 206–220.
26. Wimmler, C.; Hejazi, G.; de Oliveira Fernandes, E.; Moreira, C.; Connors, S. Multi-criteria decision support methods for renewable energy systems on Islands. *J. Clean Energy Technol.* **2015**, *3*, 185–195.
27. Reddy, B.S. *Measuring and Evaluating Energy Security and Sustainability: A Case Study of India*; Working Paper 2015-008; Indira Gandhi Institute of Development Research: Mumbai, India, 2015.
28. Lyndrup, M.; Jensen, T.Y.H.W. Illuminating the Potential for a Rural Energy Service Company-Meeting the Off-Grid Electrification Challenge in Mozambique. Master's Thesis, Roskilde University, Roskilde, Denmark, 2012.
29. Ilskog, E.; Kjellström, B. And then they lived sustainably ever after?—Assessment of rural electrification cases by means of indicators. *Energy Policy* **2008**, *36*, 2674–2684.
30. Bazilian, M.; Nakhooda, S.; van de Graaf, T. Energy governance and poverty. *Energy Res. Soc. Sci.* **2014**, *1*, 217–225.
31. García, V.G.; Bartolomé, M.M. Rural electrification systems based on renewable energy: The social dimensions of an innovative technology. *Technol. Soc.* **2010**, *32*, 303–311.
32. World Bank. Implementation Completion and Results Report (IDA-36790 IDA-46430 IDA-50130 TF-51301) Sustainable Development Department. 2014. Available online: http://www.thegef.org/gef/sites/thegef.org/files/gef_prj_docs/GEFProjectDocuments/MandE/EO_TEs_FY13/WorldBank_TEs_APR2013/1209_WB_TE_ICR.pdf (accessed on 14 August 2016).
33. White, W.; Lunnan, A.; Nybakk, E.; Kulisic, B. The role of governments in renewable energy: The importance of policy consistency. *Biomass Bioenergy* **2013**, *57*, 97–105.
34. Dunmade, I. Indicators of sustainability: assessing the suitability of a foreign technology for a developing economy. *Technol. Soc.* **2002**, *24*, 461–471.
35. Ilskog, E. *Rural Electrification Sustainability Indicators: Manual for Field Workers*; Royal Institute of Technology: Stockholm, Sweden, 2008.
36. Retnanestri, M. The I3A Framework—Enhancing the Sustainability of Off-Grid Photovoltaic Energy Service Delivery in Indonesia. Ph.D. Thesis, University of New South Wales (UNSW), Sydney, Australia, 2007.
37. Ribeiro, F.; Ferreira, P.; Araújo, M. The inclusion of social aspects in power planning. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4361–4369.
38. Winkler, H.; Simões, A.F.; Rovere, E.L.L.; Alam, M.; Rahman, A.; Mwakasonda, S. Access and affordability of electricity in developing countries. *World Dev.* **2011**, *39*, 1037–1050.
39. Holland, R.; Perera, L.; Sanchez, T.; Wilkinson, R. Decentralised rural electrification: The critical success factors. Experience of ITDG (Intermediate Technology Developmental Group). *Refocus* **2006**, *2*, 28–31.
40. Wüstenhagen, R.; Wolsink, M.; Bürer, M.J. Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy* **2007**, *35*, 2683–2691.
41. Rondinelli, D.A.; Mccullough, J.S.; Johnson, R.W. Analysing decentralization policies in developing countries: A political-economy framework. *Dev. Chang.* **1989**, *20*, 57–87.
42. Bawakyillenuo, S. Rural Electrification in Ghana: Issues of Photovoltaic Energy Technology Utilization. Ph.D. Thesis, University of Hull, Kingston upon Hull, UK, 2007.

43. International Energy Agency (IEA). Technology Perspectives. scenarios & strategies to 2050. Available online: https://www.iea.org/publications/freepublications/publication/etp2010.pdf (accessed on 28 March 2014).
44. Breyer, C.; Werner, C.; Rolland, S.; Adelmann, P. Off-grid photovoltaic applications in regions of low electrification: High demand, fast financial amortization and large market potential. In Proceedings of the 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 5–9 September 2011.
45. Rosen, M.A. Energy sustainability: A pragmatic approach and illustrations. *Sustainability* **2009**, *1*, 55–80.
46. Bhattacharyya, S.C. Energy access programmes and sustainable development: A critical review and analysis. *Energy Sustain. Dev.* **2012**, *16*, 260–271.
47. Frame, D.; Tembo, K.; Dolan, M.J.; Strachan, S.M.; Ault, G.W. A community based approach for sustainable off-grid PV systems in developing countries. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–29 July 2011; pp. 1–7.
48. Kolshus, H.H.; Vevatne, J.; Torvanger, A.; Aunan, K. *Can the Clean Development Mechanism Attain Both Cost-Effectiveness and Sustainable Development Objectives*; Working Paper/CICERO-Senter for klimaforskning; Universitetet i Oslo: Oslo, Norway, 2001.
49. International Atomic Energy Agency (IAEA). *Energy Indicators for Sustainable Development: Guidelines and Methodologies*; IAEA: Vienna, Austria, 2005.
50. Prandecki, K. Theoretical aspects of sustainable energy. *Energy Environ. Eng.* **2014**, *2*, 83–90.
51. Pereira, M.G.; Freitas, M.A.V.; da Silva, N.F. Rural electrification and energy poverty: Empirical evidences from Brazil. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1229–1240.
52. Vera, I.A.; Langlois, L.M.; Rogner, H.H.; Jalal, A.I.; Toth, F.L. Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency. In *Natural Resources Forum*; Blackwell Publishing Ltd.: Hoboken, NJ, USA, 2005; Volume 29, pp. 274–283.
53. Cook, P. Infrastructure, rural electrification and development. *Energy Sustain. Dev.* **2011**, *15*, 304–313.
54. Demirtas, O. Evaluating the best renewable energy technology for sustainable energy planning. *Int. J. Energy Econ. Policy* **2013**, *3*, 23–33.
55. Mainali, B.; Pachauri, S.; Rao, N.D.; Silveira, S. Assessing rural energy sustainability in developing countries. *Energy Sustain. Dev.* **2014**, *19*, 15–28.
56. Mainali, B. Sustainability of Rural Energy Access in Developing Countries. Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2014.
57. United Nations. The Energy Challenge for Achieving the Millennium Development Goals. 2005. Available online: http://www.undp.org/content/undp/en/home/librarypage/environment-energy/sustainable_energy/ the_energy_challengeforachievingthemillenniumdevelopmentgoals.html (accessed on 1 September 2016).
58. Axelsson, R.; Angelstam, P.; Degerman, E.; Teitelbaum, S.; Andersson, K.; Elbakidze, M.; Drotz, M.K. Social and cultural sustainability: Criteria, indicators, verifier variables for measurement and maps for visualization to support planning. *Ambio* **2013**, *42*, 215–228.
59. Hirmer, S.; Cruickshank, H. The user-value of rural electrification: An analysis and adoption of existing models and theories. *Renew. Sustain. Energy Rev.* **2014**, *34*, 145–154.
60. Müggenburg, H.; Tillmans, A.; Schweizer-Ries, P.; Raabe, T.; Adelmann, P. Social acceptance of PicoPV systems as a means of rural electrification—A socio-technical case study in Ethiopia. *Energy Sustain. Dev.* **2012**, *16*, 90–97.
61. Fenner, R.A.; Ainger, C.M.; Cruickshank, H.J.; Guthrie, P.M. Widening engineering horizons: Addressing the complexity of sustainable development. *Proc. ICE Eng. Sustain.* **2006**, *159*, 145–154.
62. Jordan, A.; O'Riordan, T. *Social Institutions and Climate Change: Applying Cultural Theory to Practice*; CSERGE Working Paper GEC 97-15; Centre for Social and Economic Research on the Global Environment: London, UK, 1997; p. 56.
63. Feron, S.; Heinrichs, H.; Cordero, R.R. Are the rural electrification efforts in the Ecuadorian Amazon Sustainable? *Sustainability* **2016**, *8*, 443.

64. Adams, W.M. The future of sustainability: Re-thinking environment and development in the twenty-first century. In Proceedings of the IUCN Renowned Thinkers Meeting, Zurich, Switzerland, 29–31 January 2006; Volume 29, p. 31.
65. Schillebeeckx, S.J.; Parikh, P.; Bansal, R.; George, G. An integrated framework for rural electrification: Adopting a user-centric approach to business model development. *Energy Policy* **2012**, *48*, 687–697.
66. The Secretary-General's Advisory Group on Energy and Climate Change (AGECC). *Energy for a Sustainable Future*; The Secretary-General's Advisory Group on Energy and Climate Change: New York, NY, USA, 2010.
67. Steiner, A.; Wilde, T.; Bradbrook, A.J.; Schutyser, F. International institutional arrangements in support of renewable energy. In *Renewable Energy*: *A Global Review of Technologies, Policies and Markets*; Earthscan: London, UK, 2006; pp. 152–162.
68. Martinot, E.; Chaurey, A.; Lew, D.; Moreira, J.R.; Wamukonya, N. Renewable energy markets in developing countries. *Annu. Rev. Energy Environ.* **2002**, *27*, 309–348.
69. Chaurey, A.; Kandpal, T.C. Assessment and evaluation of PV based decentralized rural electrification: An overview. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2266–2278.
70. North, D.C. *Institutionen, Institutioneller Wandel und Wirtschaftsleistung*; Mohr Siebeck: Heidelberg, Germany, 1992; Volume 76.
71. Pejovich, S. The effects of the interaction of formal and informal institutions on social stability and economic development. *J. Mark. Moral.* **2012**, *2*, 164–181.
72. Brew-Hammond, A. *Terminal Evaluation of UNEP GEF Project Solar and Wind Energy Resource Assessment—SWERA*; United Nations Environment Programme: Nairobi, Kenya, 2011.
73. World Bank. Mexico (CRL) Rural Electrification Project Report No. AB2919. 2007. Available online:http://documents.worldbank.org/curated/en/2007/03/7450052/mexico-crl-rural-electrification-project (accessed on 7 November 2013).
74. Bhatia, M.; Banerjee, S.G.; Raghunathan, K.; Soni, R. *Unleashing the Potential of Renewable Energy in India*; World Bank Publications: Washington, DC, USA, 2011.
75. Mani, M. *Assessing the Investment Climate for Climate Investments*; Policy Research Paper 6211; World Bank: Washington, DC, USA, 2012.
76. Wlokas, H.L. *A Review of the Solar Home System Concession Programme in South Africa*; University of Cape Town: Cape Town, South Africa, 2011.
77. Sarkar, A.; Singh, J. Financing energy efficiency in developing countries—Lessons learned and remaining challenges. *Energy Policy* **2010**, *38*, 5560–5571.
78. World Bank. *Energy Efficient Lighting Options for Afghanistan*; World Bank: Washington, DC, USA, 2009.
79. Polack, A. Drivers and Barriers of Renewable Energy in the Electrification of Vanuatu. Ph.D. Thesis, Murdoch University, Perth, Australia, 2010.
80. Käppler, R.; Avila, O.; Castro, M. *Evaluación de Programa EUROSOLAR*; Framework Contract Request No. 2010/244306/1; European Comission: Brussels, Belgium, 2010. (In Spanish)
81. Pansera, M. Renewable energy for rural areas of Bolivia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6694–6704.
82. Levitsky, S.; Murillo, M.V. Variation in Institutional Strength. *Annu. Rev. Political Sci.* **2009**, *12*, 115–133.
83. Bawakyillenuo, S. Policy and institutional failures: photovoltaic solar household system (PV/SHS) dissemination in Ghana. *Energy Environ.* **2009**, *20*, 927–947.
84. Elusakin Julius, E.; Olufemi, A.O.; Chuks, D.J. Challenges of sustaining off-grid power generation in Nigeria rural communities. *Afr. J. Eng. Res.* **2014**, *2*, 51–57.
85. World Bank. *Policy and Governance Framework for Off-Grid Rural Electrification with Renewable Energy Sources*; World Bank: Washington, DC, USA, 2008.
86. De Soysa, I.; Jütting, J. *Informal Institutions and Development—What Do We Know and What Can We Do*; International Seminar; OECD Development Center: Paris, France, 2006.
87. Schwan, S. Overcoming Barriers to Rural Electrification. Master's Thesis, Aarhus University, Aarhus, Denmark, 2011.
88. World Bank. *Implementation Completion and Results Report (IDA-36790 IDA-46430 IDA-50130 TF-51301)*; World Bank: Washington, DC, USA, 2013.

89. World Bank; Sustainable Development Department—Philippines Country Management Unit. *Implementation Completion and Results Report (IBRD-72040, IBRD-76730 and TF-52188)*; World Bank: Washington, DC, USA, 2013.
90. Ndegwah, D.; Vanheule, L.; Kroesen, O.; Kamp, L. *Knowledge Transfer, Policy, Innovation Systems and Civil Society in the Energy Market*; African Technology Policy Studies Network (ATPS): Nairobi, Kenya, 2011.
91. Kovic, M. Investigating technology transfer projects and institutional development in developing countries. *Manag. Environ. Qual. Int. J.* **2010**, *21*, 761–772.
92. Fevrier, C. The Caribbean Renewable Energy Development Programme (CREDP). 2011. Available online: http://insula.org/eurocaribbean/CREDP.pdf (assessed on 14 August 2013).
93. Gutiérrez, L.H. The effect of endogenous regulation on telecommunications expansion and efficiency in Latin America. *J. Regul. Econ.* **2003**, *23*, 257–286.
94. Wallsten, S.J. *Does Sequencing Matter: Regulation and Privatization in Telecommunications Reforms*; Development Research Group, Macroeconomics and Growth; World Bank: Washington, DC, USA, 2002.
95. Navajas, F.H. Hydrocarbon policy, shocks, and the collective imagination: What went wrong in Bolivia? In *The Natural Resources Trap: Private Investment without Public Commitment*; MIT Press: Cambridge, MA, USA, 2010; p. 331.
96. Stern, J.; Cubbin, J. *Regulatory Effectiveness: The Impact of Regulation and Regulatory Governance Arrangements on Electricity Industry Outcomes*; World Bank-Free PDF; World Bank: Washington, DC, USA, 2005; Volume 3536.
97. Estache, A.; Wren-Lewis, L. Toward a theory of regulation for developing countries: Following jean-jacques laffont's lead. *J. Econ. Lit.* **2009**, *47*, 729–770.
98. Best, S. *Remote Access Expanding Energy Provision in Rural Argentina through Public-Private Partnerships and Renewable Energy*; A Case Study of the PERMER Program; International Institute for Environment and Development: London, UK, 2011.
99. Sarraf, M.; Rismanchi, B.; Saidur, R.; Ping, H.W.; Rahim, N.A. Renewable energy policies for sustainable development in Cambodia. *Renew. Sustain. Energy Rev.* **2013**, *22*, 223–229.
100. Mutimba, S.; Wanyoike, R. *Towards a Coherent and Cost-Effective Policy Response to Climate Change in Kenya: Country Report*; Heinrich Bðll Stiftung: Nairobi, Kenya, 2013.
101. Xinlei, L.I. Cognitive learning and policy change: Analyzing renewable energy policy evolution in China. In Proceedings of the 22nd World Congress of Political Science, Madrid, Spain, 8–12 July 2012.
102. Rahman, M.Z. Multitude of progress and unmediated problems of solar PV in Bangladesh. *Renew. Sustain. Energy Rev.* **2012**, *16*, 466–473.
103. Canessa, R.; Santome, J.M.; Buss, I.N. Evaluación ex Post del Programa Euro-Solar. Informe Final Contrato Específico No. 2013/332211. 2014. Available online: https://ec.europa.eu/europeaid/sites/devco/files/eurosolar-informe-final_es.pdf (accessed on 3 July 2016). (In Spanish)
104. Machado, F.V. *Decentralization and Accountability: The Curse of Local Underdevelopment*; IDB Working Paper Series 397; Inter-American Development Bank: Washington, DC, USA, 2013.
105. Andersson, K.P.; Ostrom, E. Analyzing decentralized resource regimes from a polycentric perspective. *Policy Sci.* **2008**, *41*, 71–93.
106. Medard, M. A Social Analysis of Contested Fishing Practices in Lake Victoria, Tanzania. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 2015.
107. Tillmans, A.; Schweizer-Ries, P. Knowledge communication regarding solar home systems in Uganda: The consumers' perspective. *Energy Sustain. Dev.* **2011**, *15*, 337–346.
108. Schäfer, M.; Kebir, N.; Neumann, K. Research needs for meeting the challenge of decentralized energy supply in developing countries. *Energy Sustain. Dev.* **2011**, *15*, 324–329.
109. Bello, C.; Sánchez, R.; Cossoli, P.; Vera, L.; Busso, A.; Cadena, C. Evaluación del Desempeño de Sistemas Fotovoltaicos Autónomos en Zonas Rurales de la Provincia de Corrientes, Argentina. In Proceedings of the 4th Congresso Brasileiro de Energia Solar e V Conferencia Latino-Americana da ISES, São Paulo, Brazil, 18–21 September 2012.
110. Tamir, K.; Urmee, T.; Pryor, T. Issues of small scale renewable energy systems installed in rural Soum centres in Mongolia. *Energy Sustain. Dev.* **2015**, *27*, 1–9.

111. Laufer, D.; Schäfer, M. The implementation of Solar Home Systems as a poverty reduction strategy—A case study in Sri Lanka. *Energy Sustain. Dev.* **2011**, *15*, 330–336.
112. Sovacool, B.K. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Res. Soc. Sci.* **2014**, *1*, 1–29.
113. Ostrom, E. *A Polycentric Approach for Coping with Climate Change*; World Bank: Washington, DC, USA, 2009.
114. Sovacool, B.K. An international comparison of four polycentric approaches to climate and energy governance. *Energy Policy* **2011**, *39*, 3832–3844.
115. Koster, A.M. An Institutional Approach to Understanding Energy Transitions. Ph.D. Thesis, Arizona State University, Lake Havasu City, AZ, USA, 2013.
116. Van den Akker, J. Electrificación Rural a Base de Energía Fotovoltaica en el Perú—Proyecto PER/98/G31. Gobierno de Peru, 2008. Available online: https://www.climate-eval.org/sites/default/files/ evaluations/513%20Photovoltaic%20Based%20Rural%20Electrification.pdf (accessed on 5 October 2013) (In Spanish)
117. Brent, A.C.; Rogers, D.E. Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context. *Renew. Energy* **2010**, *35*, 257–265.
118. Escobar, R.; Vilar, D.; Velo, E.; Ferrer-Martí, L.; Domenech, B. Promoting and improving renewable energy projects through local capacity development. In *Modelling and Optimization of Renewable Energy Systems*; In Tech: Rijeka, Croatia, 2012; pp. 146–147.
119. Harun, M. The Role of Solar Home System (SHS) in Socio-Economic Development of Rural Bangladesh. Ph.D. Thesis, BRAC University, Dhaka, Bangladesh, 2015.
120. Panwar, N.L.; Kaushik, S.C.; Kothari, S. Role of renewable energy sources in environmental protection: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1513–1524.
121. Krithika, P.R.; Palit, D. Participatory Business models for off-grid electrification. In *Rural Electrification through Decentralised Off-Grid Systems in Developing Countries*; Springer: London, UK, 2013; pp. 187–225.
122. Ranaboldo, M.; Domenech, B.; Reyes, G.A.; Ferrer-Martí, L.; Moreno, R.P.; García-Villoria, A. Off-grid community electrification projects based on wind and solar energies: A case study in Nicaragua. *Sol. Energy* **2015**, *117*, 268–281.
123. Coady, D.P.; Parry, I.; Sears, L.; Shang, B. *How Large Are Global Energy Subsidies*; International Monetary Fund Working Paper; International Monetary Fund (IMF): Washington, DC, USA, 2015.
124. Oh, T.H.; Pang, S.Y.; Chua, S.C. Energy policy and alternative energy in Malaysia: Issues and challenges for sustainable growth. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1241–1252.
125. Mills, E. *Lifting the Darkness on the Price of Light: Assessing the Effect of Subsidies for Fuels in the Off-Grid Lighting Market in West Africa*; United Nations Environmental Program: Geneva, Switzerland, 2014.
126. Whitley, S.; van der Burg, L. *Fossil Fuel Subsidy Reform in Sub-Saharan Africa: From Rhetoric to Reality*; Working Paper; The New Climate Economy: Washington, DC, USA, 2015.
127. United Nations (UN). Renewable Energy-Based Rural Electrification in Lesotho. Electronic Document. 2006. Available online: http://www.undp.org.ls/energy/renewable_energy.php (accessed on 14 December 2013).
128. Urmee, T.; Harries, D. Determinants of the success and sustainability of Bangladesh's SHS program. *Renew. Energy* **2011**, *36*, 2822–2830.
129. Van der Vleuten, F.; Stam, N.; van der Plas, R. Putting solar home system programmes into perspective: What lessons are relevant? *Energy Policy* **2007**, *35*, 1439–1451.
130. Mondal, M.A.H.; Kamp, L.M.; Pachova, N.I. Drivers, barriers, and strategies for implementation of renewable energy technologies in rural areas in Bangladesh—An innovation system analysis. *Energy Policy* **2010**, *38*, 4626–4634.
131. Das, D. Is solar electrification a sustainable solution for rural electrification? Learning from field experience. *Indian J. Energy* **2013**, *2*, 121–128.
132. Wahi, R.R.H.; Ahsan, N.U. Feasibility study of solar home system in rural areas of Bangladesh: Prospect, progress and challenges. In Proceedings of the Global Engineering, Science and Technology Conference 2012, Dhaka, Bangladesh, 28–29 December 2012.

133. Brent, A.C.; Kruger, W.J. Systems analyses and the sustainable transfer of renewable energy technologies: A focus on remote areas of Africa. *Renew. Energy* **2009**, *34*, 1774–1781.
134. Kumar, A.; Mohanty, P.; Palit, D.; Chaurey, A. Approach for standardization of off-grid electrification projects. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1946–1956.
135. Kamalapur, G.D.; Udaykumar, R.Y. Rural electrification in India and feasibility of photovoltaic solar home systems. *Int. J. Electr. Power Energy Syst.* **2011**, *33*, 594–599.
136. Karekezi, S.; Kithyoma, W. Renewable energy strategies for rural Africa: Is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa? *Energy Policy* **2002**, *30*, 1071–1086.
137. Rahman, M.M.; Paatero, J.V.; Poudyal, A.; Lahdelma, R. Driving and hindering factors for rural electrification in developing countries: Lessons from Bangladesh. *Energy Policy* **2013**, *61*, 840–851.
138. Hansen, U.E.; Pedersen, M.B.; Nygaard, I. *Review of Solar PV Market Development in East Africa*; UNEP Risø Centre, Technical University of Denmark: Kongens Lyngby, Denmark, 2014.
139. Carrasco, L.M.; Narvarte, L.; Lorenzo, E. Operational costs of A 13,000 solar home systems rural electrification programme. *Renew. Sustain. Energy Rev.* **2013**, *20*, 1–7.
140. Eberhard, A.; Foster, V.; Briceño-Garmendia, C.; Ouedraogo, F.; Camos, D.; Shkaratan, M. *Underpowered: The State of the Power Sector in Sub-Saharan Africa*; Background Paper 6; World Bank: Washington, DC, USA, 2008.
141. Moss, J.; McMann, M.; Zipprich, A.; Macer, D.R.; Nyambati, A.R.; Ngo, D.; Wolbring, G. *Energy Equity and Environmental Security*; Regional Unit for Social and Human Sciences in Asia and the Pacific; United Nations Educational, Scientific and Cultural Organization (UNESCO): Bangkok, Thailand, 2011.
142. Economic Consulting Associates. *Correlation and Causation between Energy Development and Economic Growth*; Evidence on Demand; Economic Consulting Associates: London, UK, 2014; p. 32.
143. Van Campen, B.; Guidi, D.; Best, G. Solar photovoltaics for sustainable agriculture and rural development. In *Rural Development*; Environment and Natural Resources Working Paper No. 2; Food and Agriculture Organization (FAO) Publication: Rome, Italy, 2000.
144. Renewable Energy Policy Network for the 21st Century (REN21). *Renewables 2014—Global Status Report REN21 Secretariat*; REN21: Paris, France, 2014. Available online: http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_KeyFindings_low%20res.pdf (accessed on 14 January 2016).
145. Vyas, Y. Terminal Evaluation of the Renewable Energy-Based Rural Electrification Programme for Botswana. 2011. Available online: https://info.undp.org/docs/pdc/Documents/BWA/00036350_Inception%20Report%20-%20RE-Botswana%20Terminal%20Evaluation%20_Final_.pdf (accessed on 5 July 2016).
146. Ahlborg, H.; Hammar, L. *Drivers and Barriers to Rural Electrification in Tanzania and Mozambique–Grid Extension, Off-Grid and Renewable Energy Sources*; World Renewable Energy Congress: Linköping, Sweden, 2011.
147. Fishbein, R.E.; Sanghvi, A.P.; Unit, A.E. *Survey of Productive Uses of Electricity in Rural Areas*; World Bank: Washington, DC, USA, 2003.
148. Finucane, J.; Bogach S.; Garcia, L.E. *Promoción de Los usos Productivos de la Electricidad en las Áreas Rurales de Perú: Experiencia y Lecciones Aprendidas*; The World Bank Group: Washington, DC, USA, 2012. (In Spanish)
149. Pool, F. Pacific Islands Greenhouse Gas Abatement through Renewable Energy Project (PIGGAREP). UNDP, SPREP, and GEF. 2010. Available online: https://erc.undp.org/evaluation/documents/download/4478 (accessed on 26 June 2016).
150. Glemarec, Y. Financing off-grid sustainable energy access for the poor. *Energy Policy* **2012**, *47*, 87–93.
151. Obeng, G.Y.; Evers, H.D. Impacts of public solar PV electrification on rural micro-enterprises: The case of Ghana. *Energy Sustain. Dev.* **2010**, *14*, 223–231.
152. Board, M.S. *Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices*; World Bank: Washington, DC, USA, 2008.
153. Feron, S.; Heinrichs, H.; Cordero, R.R. Sustainability of rural electrification programs based on off-grid photovoltaic (PV) systems in Chile. *Energy Sustain. Soc.* **2016**, *6*, 32.

154. World Bank. *The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits*; An IEG Impact Evaluation; World Bank: Washington, DC, USA, 2008.
155. Obeng, G.Y.; Evers, H.D. *Solar PV Rural Electrification and Energy-Poverty: A Review and Conceptual Framework with Reference to Ghana*; ZEF Working Paper Series No. 36; The Center for Development Research (ZEF): Bonn, Germany, 2009; pp. 1–18.
156. Kapadia, K. *Productive Uses of Renewable Energy: A Review of Four Bank-GEF Projects*; Consultant Report to World Bank; World Bank: Washington, DC, USA, 2004.
157. Kollmuss, A.; Agyeman, J. Mind the gap: Why do people act environmentally and what are the barriers to pro-environmental behavior? *Environ. Educ. Res.* **2002**, *8*, 239–260.
158. Aklin, M.; Bayer, P.; Harish, S.P.; Urpelainen, J. Understanding environmental policy preferences: New evidence from Brazil. *Ecol. Econ.* **2013**, *94*, 28–36.
159. Yu, X. Is environment ‘a city thing’ in China? Rural–urban differences in environmental attitudes. *J. Environ. Psychol.* **2014**, *38*, 39–48.
160. Boateng, E. The potential socio-economic and environmental impacts of solar PV mini-grid deployment on local communities: A case study of rural island communities on the Volta Lake, Ghana. Master’s Thesis, University of Jyväskylä, Jyväskylä, Finland 2016.
161. World Health Organization (WHO). *Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children*; WHO: Geneva, Switzerland, 2016.
162. Mills, E. The specter of fuel-based lighting. *Science* **2005**, *308*, 1263–1264.
163. Lam, N.L.; Chen, Y.; Weyant, C.; Venkataraman, C.; Sadavarte, P.; Johnson, M.A.; Bond, T.C. Household light makes global heat: High black carbon emissions from kerosene wick lamps. *Environ. Sci. Technol.* **2012**, *46*, 13531–13538.
164. Corsair, H.J. Causes of Success and Failure of Stand-alone Solar Electric Systems in Rural Guatemala. Ph.D. Thesis, Johns Hopkins University, Baltimore, MD, USA, 2014.
165. McKay, K.H. Socio-cultural dimensions of cluster vs. single home photovoltaic solar energy systems in Rural Nepal. *Sustainability* **2010**, *2*, 494–504.
166. Sandgren, A. *Batteries Used within Solar Electric Systems in Rural Uganda*; Lund University: Lund, Sweden, 2001.
167. Batteiger, A. *Off-Grid Electrification and Its Impacts on the Waste Management System—The Case of Bangladesh*; International Renewable Energy Agency: Abu Dhabi, UAE, 2015; pp. 279–282.
168. Murphy, K. The social pillar of sustainable development: A literature review and framework for policy analysis. *Sustain. Sci. Pract. Policy* **2012**, *8*, 15–29.
169. Thiam, D.R. Renewable energy, poverty alleviation and developing nations: Evidence from Senegal. *J. Energy S. Afr.* **2011**, *22*, 23–34.
170. Cecelski, E. *From the Millennium Development Goals towards a Gender-Sensitive Energy Policy Research and Practice: Empirical Evidence and Case Studies*; Draft Synthesis Report to DFID KaR on Research Project 2005. Available online: https://assets.publishing.service.gov.uk/media/57a08c28e5274a31e0001030/R8346-dfid_ synthesis.pdf (accessed on 3 August 2016).
171. Hemson, D.; Peek, N. *Integrating Women into Grameen Shakti’s Renewable Energy Value Chain in Bangladesh: A Study of the Project and Lessons Learned*; Development and Training Services (dTS) Inc.: Arlington, VA, USA, 2014; Bangladesh Institute for Development Studies: Dhaka, Bangladesh, 2014.
172. Nielsen, K.B.; Waldrop, A. (Eds.) *Women, Gender and Everyday Social Transformation in India*; Anthem Press: London, UK, 2014.
173. Clancy, J.; Winther, T.; Matinga, M.; Oparaocha, S. *Gender Equity in Access to and Benefits from Modern Energy and Improved Energy Technologies: World Development Report Background Paper*; University of Twente: Enschede, The Netherlands, 2012.
174. Nathan, H.S.K. Solar energy for rural electricity in India: A misplaced emphasis. *Econ. Political Wkly.* **2014**, *49*, 60–67.
175. Phoumin, H. *Renewable Energy Policies and the Solar Home System in Cambodia*; ERIA Discussion Paper No. DP-2015-64; Economic Research Institute for ASEAN and East Asia: Jakarta Pusat, Indonesia, 2015.

176. Bhattacharyya, S.C.; Timilsina, G.R. Modelling energy demand of developing countries: Are the specific features adequately captured? *Energy Policy* **2010**, *38*, 1979–1990.
177. Sathaye, J.; Lucon, O.; Rahman, A.; Christensen, J.; Denton, F.; Fujino, J.; Heath, G.; Kadner, S.; Mirza, M.; Rudnick, H.; et al. Renewable energy in the context of sustainable development. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2011.
178. Javadi, F.S.; Rismanchi, B.; Sarraf, M.; Afshar, O.; Saidur, R.; Ping, H.W.; Rahim, N.A. Global policy of rural electrification. *Renew. Sustain. Energy Rev.* **2013**, *19*, 402–416.
179. Bhattacharyya, S.C.; Timilsina, G.R. A review of energy system models. *Int. J. Energy Sect. Manag.* **2010**, *4*, 494–518.
180. Mundaca, L.; Neij, L. *Energy-Economy Models and Energy Efficiency Policy Evaluation for the Household Sector*; IIIEE Reports; The International Institute for Industrial Environmental Economics: Lund, Sweden, 2009; Volume 2.
181. Mufiaty, H. Solar home systems performance in rural area in aceh case study: Deah mamplam village, aceh besar. *Energy Procedia* **2014**, *47*, 133–142.
182. Terrapon-Pfaff, J.; Dienst, C.; König, J.; Ortiz, W. How effective are small-scale energy interventions in developing countries? Results from a post-evaluation on project-level. *Appl. Energy* **2014**, *135*, 809–814.
183. Glemarec, Y.; Bayat-Renoux, F.; Waissbein, O. Removing barriers to women entrepreneurs' engagement in decentralized sustainable energy solutions for the poor. *AIMS Energy* **2016**, *4*, 136–172.
184. Köhlin, G.; Sills, E.O.; Pattanayak, S.K.; Wilfong, C. *Energy, Gender and Development: What are the Linkages? Where Is the Evidence*; Policy Research Working Paper Series No. 5800; World Bank: Washington, DC, USA, 2011.
185. Khamati-Njenga, B.; Clancy, J. *Concepts and Issues in Gender and Energy*; University of Twente: Enschede, The Netherlands, 2003.
186. Terrapon-Pfaff, J.; Dienst, C.; Ortiz, W. The role of gender concerns in the planning of small-scale energy projects in developing countries. In *Decentralized Solutions for Developing Economies;* Springer International Publishing: New York, NY, USA, 2015; pp. 285–294.
187. Clancy, J. *Policies, Projects and the Market Empowering Women? Some Initial Reactions to Developments in the Energy Sector*; Working Paper; University of Twente: Enschede, The Netherlands, 2000.
188. Friebe, C.A.; von Flotow, P.; Täube, F.A. Exploring the link between products and services in low-income markets—Evidence from solar home systems. *Energy Policy* **2013**, *52*, 760–769.
189. Belguedj, M.; Chantelot, E. *The Role of Liquefied Petroleum (LP) Gas in Meeting the Goals of sustainable Development*; World Bank: Washington, DC, USA, 2013.
190. Urmee, T.; Md, A. Social, cultural and political dimensions of off-grid renewable energy programs in developing countries. *Renew. Energy* **2016**, *93*, 159–167.
191. Burton, J.; Hubacek, K. Is small beautiful? A multicriteria assessment of small-scale energy technology applications in local governments. *Energy Policy* **2007**, *59*, 200–205.
192. Anuta, O.; Crossland, A.; Mcneil, B.; Wade, N. *Energy Procedia Assessing the Impact of Society and Energy Storage on the Success of Solar Photovoltaic Systems Utilized for Healthcare in Rural Rwanda*; Proceeding Paper; Durham University: Durham, UK, 2013.
193. Martinot, E.; Reiche, K. *Regulatory Approaches to Rural Electrification and Renewable Energy: Case Studies from Six Developing Countries*; Working Paper; World Bank: Washington, DC, USA, 2000.
194. Linguet, L.; Hidair, I. A detailed analysis of the productivity of solar home system in an Amazonian environment. *Renew. Sustain. Energy Rev.* **2010**, *14*, 745–753.
195. Renewable Energy Policy Network for the 21st Century (REN21). *Renewables 2013—Global Status Report REN21 Secretariat*; REN21: Paris, France, 2013. Available online: http://www.ren21.net/Portals/0/documents/Resources/GSR/2013/GSR2013_lowres.pdf (accessed on 21 July 2015).
196. Campbell, B.; Cloke, J.; Brown, E. Communities of energy. *Econ. Anthropol.* **2016**, *3*, 133–144.

197. Sen, A. How does culture matter? In *Culture and Public Action*; Rao, V., Walton, M., Eds.; Stanford University Press: Stanford, CA, USA, 2004; pp. 37–58.
198. De Swart, B. Indigenous Power: Renewable Electricity and Local Sustainability in Mexico and South America. Master's Thesis, University of London, London, UK, 2012.
199. Urmee, T. Social, cultural and policy issues of the application of remote area off-grid photovoltaic. In Proceedings of the 52nd Annual Conference Australian Solar Energy Society, Melbourne, Australia, 8–9 May 2014; p. 11.

# 5 Sustainability of off-grid PV systems in selected Andean countries (Paper 2-4)

## 5.1 Paper 2: Sustainability of rural electrification programs based on off-grid photovoltaic (PV) systems in Chile

In this paper, I assess the sustainability of rural electrification efforts in Chile. Following the theoretical framework described in Chapter 2, my assessment considers four dimensions of sustainability (institutional, economic, environmental, and socio-cultural), while according to the methodology described in Chapter 3, my findings are based on an exhaustive qualitative document analysis, complemented by semi-structured expert interviews.

I found that programs aimed at supporting agricultural activities have had widespread success. Also, systems from big scale rural electrification projects conducted by the Ministry of Energy are still operational. However, great differences in the operational sustainability of different projects persist. Particularly small-scale projects have struggled with maintenance issues. A national energy agency aimed at the operation of off-grid systems is needed for technological support and supervision. Moreover, a cross subsidy fund could contribute to the economic sustainability of the systems, since there is currently no funding assured for O&M. Despite of an augmenting awareness of environmental issues in Chilean society, a stronger public role in the country's energy policy is indispensable to tackle environmental as well as socio-cultural issues.

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# Sustainability of rural electrification programs based on off-grid photovoltaic (PV) systems in Chile

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## Abstract

### Background

Mainly based on expanding the grid, Chile has reached an impressive electrification rate. However, due to unviable grid expansion to islands and remote areas of the country, the government started implementing off-grid Electrification Programs. In this paper, we assess the sustainability of rural electrification efforts in Chile paying special attention to off-grid photovoltaic (PV) programs.

### Methods

Our assessment of the rural electrification efforts in Chile takes into account four dimensions of sustainability (institutional, economic, environmental, and socio-cultural). It is based on an extensive qualitative document analysis, complemented by semi-structured interviews to key stakeholders.

### Results

We found that, despite several successful pilot off-grid PV projects, the deployment of off-grid PV solutions for rural electrification lagged behind the enormous solar potential of the country. Part of the problem is that decisions favoring other technologies have been made without considering costs over the lifetime and environmental co-impacts. Moreover, the social-acceptance of off-grid PV solutions has been seriously compromised due to problems regarding the accuracy (systems were unable to meet the user's needs) and reliability (systems often failed due to lack of mandatory standards and the uncertain maintenance).

### Conclusions

Although Chile has conducted remarkable efforts on electrification during the last 20 years, the indigenous communities still have less access to electricity. This disparity is major drawback that underscores the need for adjusting the electrification approach (which means that the communities or the local authorities have to request electrification at first place) adopted by the Ministry of Energy in rural electrification. Indeed, this approach favors better organized communities leaving behind others - normally the poorest indigenous communities. Moreover, major progress on cultural justice, equity and environmental awareness is needed for ensuring the sustainability of rural electrification efforts in Chile.

**Keywords**: Off-grid PV, Rural Electrification; Sustainable Energy

## 1. Background

### 1.1. Introduction

The United Nations established the Sustainable Energy for All (SE4All) initiative in 2011 [1]. According to this initiative, Sustainable Energy not only seeks access to modern and clean energy, but it must also embrace energy efficiency and the use of Renewable Energies (RE) [1]. Indeed, developing countries (DC) still have the chance to provide cleaner and more efficient energy to their citizens that do not have access yet, thus omitting the process of technological development undergone by the developed countries [1]. This is an important opportunity, since by 2013 1.2 billion people worldwide were still lacking access to electricity [2]. Great differences remain concerning the access to electrification between the urban and the rural sector. From a global perspective, while 94% of the urban population is electrified, its number is much lower in the rural case, with a rate of only 68% [2].

Chile has reached an impressive rural electrification rate of 97.3% (whereas in 1992 it was only 53%) [3,4]. This achievement has been mainly based on expanding the grid. Yet, despite this attainment, there are still about 20,000 people - almost exclusively in rural areas – that do not have access to electricity [5]. Due to unviable grid expansion to islands and remote areas of the country, the government started looking for alternatives. In 2001, the "Removal of barriers for rural electrification with Non Conventional Renewable Energies" program was launched to further improve the rural electrification rate by deploying Non Conventional Renewable Energies (NCRE).

While prior efforts have pointed out that northern Chile is the place where the highest surface irradiance is likely to occur [6,7], most of the Chilean territory has a significant solar potential [8]. However, the deployment of solar technologies in Chile has historically lagged behind that potential. Only in recent years, the solar energy in Chile has experienced high growth rates: e.g., while in 2012 the installed PV capacity was insignificant, in December 2015 the power capacity of grid-connected utility-scale PV plants peaked at 0.75 GWp [9]. However, despite some successful pilot programs, little attention has been paid to off-grid PV systems in Chile as a tool for rural electrification.

In this paper, we assess the sustainability of rural electrification efforts in Chile, addressing the following research question: Are the Chilean rural electrification efforts based on off-grid PV systems sustainable?

In order to answer our research question, we conducted an exhaustive qualitative document analysis for social sciences [10, p.29], complemented by semi-structured interviews with key stakeholders. According to the approach broadly used for the assessment of sustainability (see for example [11-15]), the interviewed stakeholders included representatives from different Ministries (Energy, Social Development, Agriculture), non-profit-organizations (NPOs), private companies, and universities. Although below we describe several relevant PV-based electrification efforts in Chile, our research was aimed at gathering an overall picture of the rural electrification efforts in the country, rather than measuring the success or failure of a specific project.

The gathered information allowed us to assess the sustainability of rural electrification efforts in Chile. Our assessment was based on a set of indicators (see Table 1) corresponding to the four dimensions of sustainability considered in this paper: institutional, economical, environmental, and socio-cultural; see e.g.[16-18].

### 1.2 Theoretical Framework

Institutional sustainability demands for stability/durability (e.g. [19-23], technical and service standards, as well as coherence between laws and regulations ([17, 19, 22- 24]. Failures in rural electrification have often been attributed to the lack of coherence in the legal frame (laws, regulations, and standards) [19,22,23], or the absence of proper standards (e.g. [25, 26]). White et al. [27] have also shown how unexpected policy changes can have negative impacts on investments and cause uncertainty. Furthermore, numerous studies have underscored the fact that sustainable institutions should have the ability to adapt to future needs of the population (e.g. [19,22,28-31]).

Sustainable institutions not only need to preserve themselves over time, but they should also be open to the society and its interests, be accountable and transparent in their decision makings, while equally considering the other sustainability dimensions [17]. Therefore, decentralization and participation has often been mentioned as an indicator for sustainable institutions (e.g. [16,19,24,31-34]). Wüstenhagen et al. [35] argue that a top-down approach at central government level may inhibit the acceptance of a technology at the local level. Despite the advantages of decentralization, Rondinelli et al. [36] have pointed out the fact that decentralization may be problematic if local institutions in a decentralized administration lack the expertise, know-how, and management capacity to administrate the services.

Economic sustainability of electrification solutions requires ensuring the funding or affordability of the systems (i.e. the initial investments and the operation and maintenance (O&M) over its lifetime) (e.g. [20, 22, 30,33,37-40]). In the energy sector, other import indicators for economic sustainability of electrification solutions are the cost-effectiveness (e.g. [19,22,39]) and the reliability of supply (see e.g. [19,22,23,28,41,42]). Moreover, since energy consumption is correlated with income, efforts on rural electrification are expected to contribute to the income of its users, (e.g. [19,39,43-45]). However, if energy projects aim at a higher productive outcome of rural communities, electrification programs need to be coupled with complementary infrastructure, including training and education [45].

Ensuring the environmental sustainability for rural electrification requires civil society's awareness on environmental issues, as their support is needed to enforce environmental policies and regulations [46]. Environmental sustainability also requires minimizing negative impacts of energy solutions on the environment. These impacts may concern the amount of greenhouse gases (GHG) such as C02, S02, or NO (see e.g. [22,30,31,39,41,42,44,47,48]); a loss of biodiversity due to deforestation [22,39,42,48], or local impacts such as air quality caused by pollution in households, noise, or aesthetical disturbances [22,42,44,48-50].

Socio-cultural sustainability requires considering equity/disparity criteria between different communities. In rural electrification, decisions have to be made regarding who will have access to energy (first), and how much energy is provided to each household [30,32,39,48,51]. Furthermore, attention must be paid to the accuracy of a technology for the specific environmental/socio-cultural conditions where it will be implemented [22,52], as well as to the social acceptance, which implies a participatory and inclusive approach in which the local community is engaged to increase accountability [35,42,53]. It is therefore vital for ensuring socio-cultural sustainability, embracing the notion of cultural justice, which in this context refers to justice through participation and recognition [54]. The cultural justice in rural electrification depends on the ability shown to integrate the technology into the existing social structures [22,30,42,47]. Indeed, as argued elsewhere (e.g. [28,55]), the socio-cultural context determines to what extend a technology is adopted.

Based on this theoretical framework we built up a set of indicators (see Table1). These indicators were qualitatively evaluated and allowed us to assess the sustainability of the rural electrification efforts in Chile based on off-grid PV systems.

Table 1: Indicators for Sustainability of off-grid PV Systems in Chile (adapted from [15])

| Institutional | Economic | Environmental | Social /Cultural |
|---|---|---|---|
| **Stability (Durability) and long-term vision** | Cost effectiveness | Environmental awareness | Accessibility (disparity, equity) |
| **Regulation , Standards and Enforcement** | Reliability | Environmental impact | Social Acceptance |
| **Decentralization and Openness to participation** | Funding (initial investment; operation and maintenance) | | Accuracy |
| **Adaptability (ability to meet future needs)** | Contribution to income of users | | Cultural Justice |

## 1.3 Chile

### 1.3.1 General Background on Chile

Chile is a South-American country of about 756,950km2 with a coastline of 6,435 kilometers and borders with Argentina, Peru, and Bolivia. The geography of Chile is extremely diverse as the country extends from latitude 17° South to 56° South and from the Pacific Ocean on the west to the Andes on the east. Considerable climate differences can be found: from the extremely arid desert in the North (the Atacama desert), through the semiarid central Chile with Mediterranean climate, to the cooler and rainy Southern Chile. The extreme geography of the country is one of the reasons for the isolation of communities in northern and southern Chile [56].

Chile's population was about 17.6 million in 2013, of which 10.6% was rural. The latter has been declining during the last 10 years by an annual average of approximately 1.3% [57]. In 2014, Chile's gross domestic product per capita amounted to US$ 21,800 [57]. The Chilean economy is highly dependent on the mining industry, which represents 54.2% of its exports [58]. Due to its stable economic framework, Foreign Direct Investments (FDI) have increased considerably, reaching a record of US$11,9 billon in 2014, of which electricity, gas and water have a stake of 17.7% [58]. The country could halve its poverty rate from 29.1% (extreme poverty of 12.6%) in 2006 to 14.4% (extreme poverty of 4.5%) in 2013 [59]. Nevertheless, inequality is still a major issue: with a GINI Index (see [60] for details) of 50.5, Chile is the country with the most unequal income distribution in the Organization for Economic Cooperation and Development (OECD) [57,61]. This is especially true for minorities [56]; e.g., extreme poverty is higher for indigenous populations (4.3%) than for non-indigenous populations (2.7%) [62].

Chile is a democratic presidential republic that accounts for 15 "regions" or territories, 54 provinces, and 346 boroughs (municipalities). The regional governments (GOREs by its Spanish acronym) are constituted by a regional ministerial representative (appointed by the President of the Republic) and a regional council (CORE by its Spanish acronym) whose members are elected by the citizens. The main function of the GORE is to advocate for the territorial development. The GORE initiatives are funded by the National Development Fund (FNDR by its Spanish acronym) [63] that depends on annual national budget. The GORE of each region can distribute its funds according to the needs in different sectors including electrification, education, health, drinking water, routes, and others [5].

Each province is headed by a governor (also appointed by the President of the Republic), whose main role consists of assuring internal security [64]. The boroughs or groups of several boroughs rely on municipalities governed by a mayor elected by the citizens, whose functions include planning and regulations, development of infrastructure and services, as well as environmental protection [63].

Regarding this research, there are two additional relevant institutions in the country. First, the Subsecretary of Regional Development and Administration (SUBDERE by its Spanish acronym) that is in charge of the coordination and promotion of the regional development by means of the regional and municipal governance; it strengthens technical and institutional capacities of these administrations and administrates funds [65]. Second, the Regional Secretaries of the Ministries (SEREMIs by its Spanish acronym) that though operating in the regions, are controlled by Ministries of the central governmental [63].

Despite prior attempts of decentralization (e.g. in 2000, 2004, 2008, and 2011), the central government remains highly concentrated [66,67]. [63], This is due to two factors: the lack of financial autonomy (regional/local governments financially depend on the central administration), and the lack of administrative autonomy (due to a rigid organization) [63].

### 1.3.2 Electrification in Chile

Chile's electricity sector was publically held until the National Energy Commission (CNE by its Spanish acronyms; founded in 1978) enacted the Electricity Act in 1982, which drove privatization and allowed for competition in generation and distribution [68,69]. The Electricity Act was reformed in 2004 and 2005 by Laws 19.940 and 20.018 ("Ley Corta" I and II) that aimed to foster further competition. The electricity distribution companies (EDCs) operating in Chile (currently 33) are hence privately held. The EDCs are obliged by law to provide the service in the area where they own a concession even if it results in a loss for them.

In 2010, a new law (No. 20.402) created the Ministry of Energy, which took over part of the tasks from the CNE, and is in charge of the energy policy and planning. The role of the CNE changed thereinafter, making it responsible for setting prices, tariffs and technical norms [70]. Moreover, the Electricity and Fuel Authority (SEC by its Spanish acronym), is responsible in Chile for monitoring the compliance with laws, regulations and technical standards for a proper operation of the energy sector (including pricing, energy quality, and security) [71]. The Center for Renewable Energies (CER by its Spanish acronym) is another important institution of the energy sector; it was renamed in 2014 to Center for Sustainable Energy Innovation and Promotion (CIFES by its Spanish acronym). The CIFES aims to promote the design, implementation, and evaluation of strategic sustainable energy projects [9].

Regarding electricity generation, about 30% of the installed capacity in 2015 was hydropower; 18% diesel; 20.5% carbon, and 13% NCRE, including 4.26% stemming from solar energy [72]. In 2008, Chile adopted a renewable energy target that, although subsequently modified, nowadays states that by 2025 electricity companies that inject energy into the two major electricity systems, the Northern Interconnected System (SING by its Spanish acronym) and the Central Interconnected System (SIC by its Spanish acronym), must ensure that 20% of the annual energy consumption is met by non-conventional renewable generators [75].

In recent years, RE in Chile has experienced high growth rates: e.g., while in 2012 only 2 MWp of PV had been installed, in December 2015 the installed power capacity of NCRE had increased to 2.6 GWp (thereof solar PV: 0.75 GWp), and another 2.7 GWp is currently under construction [9]. This boom has been driven by the high energy prices in Chile combined with ideal conditions for the generation of solar energy, which motivated mainly foreign companies to invest in utility-scale power plants, especially in northern Chile. In the case of the small-scale NCRE plants (up to 100 kWp), further progress is expected due to the new Law No. 20.571 "Net Metering" that allows feeding-in electric energy surpluses into the grid for a reward [76].

### 1.3.3 Rural Electrification in Chile

In 1992, the urban Chilean electrification rate reached 97%, although in rural areas only 53% of the population had access to electricity [69]. Attending this deficit, in 1994 the CNE launched the National Program for Rural Electrification (PER by its Spanish acronym), which was funded by the FNDR. PER allowed gradually increasing the rural electrification rate to 75% in 1999 and 97.3% in 2013 [3,4]. Yet, this remarkable achievement was mainly based on grid expansions. In 2001 the central government looked for an alternative for electrification in the case of highly dispersed inhabitants of remote areas. That year, the "Removal of barriers for rural electrification with NCRE" program was launched to further improve the rural electrification rate.

In 2009 the CNE created a program called The National Program on Rural and Social Energy (PERYS by its Spanish acronym). The PERYS program focuses on 1) the electrification of rural schools and small health centers; 2) the incorporation of solar thermal systems in public buildings; and 3) the implementation of NCRE systems for small-scale productive uses. The PERYS program depends on the Ministry of Energy, and its Department of Energy Access and Equity (DAEE by its Spanish acronym). This Department is embedded with the SEREMIs and it took over the Rural Electrification Area from the CNE. The DAEE also developed the rural electrification strategy for the upcoming years (2015-2018), which is supposed to favor NCRE solutions [5].

Rather than a top down approach, the DAEE favors a bottom-up approach, which means that the communities have to request electrification at first place. The request is normally directed to the mayor of the municipality on which the community depends. Whether or not a municipality conducts a project on its own account depends on the project size (i.e., the budget): Projects with a budget of up to 70 million Chilean pesos (approx. US$ 120,000) can be directly executed by the municipality without further formal requirements. However, projects that exceed this amount need a formal request to the GORE to apply for funds from the FNDR. This formal process comprises a feasibility study of the project to select the appropriate technological and administrative design for the particular circumstances in a community; it concerns the price and capacity of the energy supply, the quality of the service, and the O&M model. Additionally, the study requires approval from the DAEE (at the respective SEREMI).

The projects selected by the GORE are carried out by private company selected by a call for bid. Whether or not the tender cover only the initial installation or also the O&M of the systems depends on the project's selected O&M model. The latter is project-specific, the systems can either be operated by the community via cooperative, or by a private company against a compensation fee [77].

In the case of off-grid systems, there are no regulations on the power capacity of the projects (i.e., neither a minimum nor a maximal power capacity per household). The O&M costs of the off-grid PV systems are not regulated either and therefore they are determined based on project-specific agreements between the municipality and the partner in charge of the O&M (either a private company or a cooperative). However, the funds are expected to cover all O&M costs [78,79].

The projects selected by the GORE (funded by the FNDR) are centrally registered in an Integrated Project Database (BIP by its Spanish acronym), which is administrated by the Ministry of Development. The BIP not only assures traceability of all projects (thus avoiding duplications), but it also allows the GORE to prioritize and select the projects that will receive funds from the FNDR.

Although the tariff for off-grid is not regulated, in the case of off-grid PV projects, the tariff from the closest community connected to the grid is normally adopted. Hence, the monthly tariff is set per unit price of energy from the neighboring community and multiplied by the energy that will approximately be generated by the installed PV system [80]. Since this tariff can hardly cover the O&M costs, subsidies can be requested to the GORE (although they must be evaluated and approved each year by the respective SUBDERE).

Table 2 provides an overview of the rural electrification programs in Chile (including those aimed at productive uses) that have been considered in this paper. In addition to the PER and the PERyS programs, we also considered a micro-grid project (implemented in Huataconbo by a Chilean University and a NPO) and two successful off-grid PV initiatives, the so-called "Coquimbo Project", and a program of PV-powered water pumps. Due to their importance, the two latter projects are described in detail below.

Table 2: Rural electrification projects considered in this paper.

| | National Program for Rural Electrification (PER) (PV projects only) | The National Program on Rural and Social Energy (PERyS) (PV projects only) | Huataconbo micro-grid project | Coquimbo Project (PV only) | PV-powered Water Pumps program |
|---|---|---|---|---|---|
| **Reports for ex-post evaluations** | Covarrubias et al [82]; Navarro et al. [83]; Deuman,[84]; DIPRES [80]; Comunidades Energéticas [85] ; Ministero de Desarrollo Social [86]; Gobierno Regional de Aysén [87] | IEA [88]; Ministerio de Energía [89] | Jiménez-Estévez et al. [90]; Núñez et al. [91] | Rodriguez [81] ; Estay [92] | GreenLab [93] |
| **Program sponsored by** | CNE/Ministry of Energy (GOREs) | Ministry of Energy | University of Chile/NPO | CNE/Ministry of Energy, GEF, UN | Agency for Agrarian Development (INDAP) |
| **Location** | Curepto/ Pencahue (Maule region); Cochrane (Aysén Region; Regions of Tarapacá, Coquimbo, and Maule) | Nationwide | Huataconbo (Region of Tarapacá; northern Chile) | Coquimbo | Nationwide |
| **Energy use** | Residential rural electrification; electrification of schools/health centers/social buildings | Electrification of schools/health centers/social buildings/public lightning | Residential rural electrification and Productive use | Residential rural electrification | Productive use |
| **Capacity/ Sizing** | Between 50 and 600 Wp per dwelling | Between 380Wp and 4 kWh per project | 22.68kW PV plant + 120 [kVA] diesel group for a community | 125 Wp per dwelling | Three different kits available: 230/ 690 /1380 Wp per farmer |
| **Year of installations** | Since 1997 | Since 2009 | 2009 | 2001-2012 | 2012-2013 |
| **Number of installations/households electrified** | Solar Home Systems (SHS): 12,565; Schools: 87; Health Centers: 14; Productive Use: 6 | 83 | About 100 people | 3,064 SHS (new); 1,500 (improvements); 55 schools and health centers | 1876 |

Sources: Own elaboration based on information from [81,86,89,94,95]

***The "Coquimbo Project" (Northern Chile)***

From 2001 to 2012 the CNE (and later the DAEE) led the program "Removal of barriers for rural electrification with NCRE". The program was partially funded by the Global Environmental Facility (GEF) and supported by the United Nations Developing Program (UNDP). The program aimed to remove institutional, financial, regulative, technological, and knowledge barriers that inhibited the adoption of NCRE in rural areas of the country. The total project costs amounted to about US$ 32 million, of which the Chilean government contributed around US$ 26 million, and the GEF contributed the remaining US$ 6 million [92].

Seven of the nine action lines of this program were related to PV. Action line 1 included the comprehensive information gathering across the country, which entailed land registries and a survey of 12,400 households in rural areas concerning their needs, current energy sources used, as well as the available infrastructure. Based on this information, 33 NCRE projects (mainly PV) were implemented [81,92].

As a part of the program, the CNE/UNDP team also elaborated 15 technical regulations for PV (44 in total) based on international norms (IEC/ISO) and a certification process for PV systems (action lines 2 and 3). The Chilean norms (e.g. NCh2903 for PV systems and NCh2978 for batteries; see [96]) were developed by personnel from CNE, the National Institute of Normalization (INN, by its Spanish acronym), Universities, private consultants, and others, and thereinafter adopted by the INN. Though these norms are voluntary, supervision as well as the certification is responsibility of the SEC [92].

The promotional campaign (action line 4) of the program aimed to increase the demand for NCRE. The budget for this line amounted to about US$ 500,000, which was financed by the GEF and the Chilean Government. A training program was also developed (action line 5) with a budget of U.S. $ 536,875 (mainly funded by the GEF). The program was aimed at central and regional politicians, regulatory agencies, engineers, technicians, and users. Up to 2009, workshops and seminars had been given to about 3,500 people, and further efforts for improving capacities were made in government bodies, education centers, and universities, aiming to foster the access to knowledge on NCRE in these organizations [92].

Action line 6 implied the installation of 3,064 PV systems for rural households in 15 municipalities in the Coquimbo region. The systems were funded by the FNDR (US$ 5 million). The National Electrical Force Company (CONAFE**,** by its Spanish acronyms)**,** a private EDC that operates in the regions of Coquimbo and Valparaíso (serving almost 500,000 clients) installed the PV systems from 2005 to 2006, and has furthermore been in charge of the O&M of the systems for a period of 10 years (with an option for renewal) [92]. The action line 7 aimed to promote productive uses (e.g. for farming) based on NCRE. This action line was funded (US$ 25 millions) by the Chilean government and until 2010, led to several demonstration-scale PV-powered water pump projects for irrigation [92].

The success of the program ultimately sought to pave the way for the implementation of further projects based on NCRE in remote areas across the country.

***PV-powered water pumps***

The CNE/UNEP program also favored projects for productive uses implementing five demonstration systems for PV-powered water pumps. These pilots helped to raise the interest of the PV technology in the Ministry of Agriculture. Indeed, some of the (10) sub-divisions and agencies of the Ministry of Agriculture have successfully adopted and transferred these systems to farmers after the end of the CNE/UNEP program in 2010.

The Chilean Agency for Agrarian Development (INDAP by its Spanish acronym) was the agency that promoted to replace with PV-powered water pumps, existing systems powered by diesel generators. The systems consist of a PV panel, a pump, and a controller, and they were designed with no critical parts like batteries or inverters (pumps are directly connected to the PV modules). These decisions were meant to ensure high durability and low maintenance. The Agency participated in the design of the systems, and set particular value on quality standards. Currently, three different kits (230 Wp, 690 Wp, and 1380 Wp) are available, which provide solutions according to the flux and vertical height needed at each farm to pump up the water.

The pumps are acquired by INDAP in relatively great numbers by issuing a call for bids, which facilitates economy of scale. The company that won the bid is in charge of the deployment in rural areas across the country. Between 2012 and 2013, about 1,400 PV pumps were installed with a total cost of 3,767,723,586 Chilean Pesos (about US$ 7.5 million) and an installed capacity of 743 kilowatts (kW). INDAP subsidizes 90% of the investment sum and provides credits to the farmers for the remaining 10%; amortization is reached within about four years (depending on the type of kit and on the energy fuel used before) [97].

INDAP is a decentralized agency (depending on the Ministry of Agriculture) whose personnel are in close and permanent contact with the farmers and with the GOREs. Therefore, they use to assist farmers to solve simple technical problems at no cost including those related to PV-powered pumps. Only major technical issues are diverted to the pump vender whose contract includes a system checking in the second year of operation [95] and an extended guarantee (three years for the pump and five years for the PV systems; [95]. Indeed, the maintenance of current systems is based on the extended guarantee that includes covering the cost of replacing spare parts.

Although according to an INDAP representative the vast majority of the systems are operative, one challenge may lie in the maintenance once the systems run out of their guarantee as the farmers would have to pay themselves for repairing services and spare parts (so far no concept has been presented for this case).

**2. Methods**

In order to assess the sustainability of off-grid PV projects in Chilean rural areas, a qualitative document analysis for social sciences was applied (e.g. [10, p.29]). The off-grid PV solutions reviewed in this study included Solar Home Systems (SHS) for residential use, PV-powered water pumps for productive uses, off-grid PV systems for communitarian facilities (health centers and schools), and a micro-grid aimed at both residential and productive uses. These PV-based solutions were compared with previously deployed conventional energy solutions (such as candles/matches, batteries, and diesel generators).

Multiple data sources were assessed for the analysis including regulations, energy policies, ex-post evaluation reports on electrification programs and projects, as well as the National Energy Agenda (prior and current versions), statistics from the National Energy Commission, the Center for Sustainable Energy Innovation and Promotion and the National Statistics Institute, and scientific papers on related topics. We collected information on the different initiatives, on their evolution, and on their stakeholders. The document analysis also allowed us to identify and select a set of key stakeholders that were interviewed.

Indeed, in addition to the document analysis, we conducted semi-structured interviews with key stakeholders. According to the approach broadly used for the assessment of sustainability (see, for example, [11-15]), the interviewed stakeholders included experts from different Ministries (Energy, Social Development, Agriculture), NPO activists and project managers, companies´ representatives, solar energy lobbyists, and researchers. The method of theoretical sampling was used, i.e., additional interview partners were selected based on the information obtained from the interviewees who we had initially identified [10, p.80]. Interviews were finished after saturation (when no additional information could be obtained from further interviews; [98, p. 168]. The interviewed stakeholders (see Table 3 for details) were used to validate the qualitative document analysis and allowed us to fill information gaps.

Interview questions were clustered into four dimensions (institutional, economic, environmental, and socio-cultural) considered in this paper and addressed each of the indicators from Table 1. Questions on the institutional dimension comprised e.g.: “What has been the role of this institution for rural electrification in the past and the present?”; “How is the rural electrification process put into practice?”; “How are the community members imbedded in the rural electrification projects?”; “Who and how is the compliance with the regulation assured?” The economic dimension was addressed by questions like: “Who is paying for the initial investment/ O&M costs?”; “What has the economic impact been on the user (e.g., energy for productive uses)?”; “What are the technical minimum requirements for the systems?” The interview covered questions on the environmental dimension such as “How is battery disposal handled in rural electrification?”; “How would you describe the awareness on environmental issues on a political and social basis?”. Finally, we asked about socio-cultural issues: “To what extend (and how) are projects adjusted to local circumstances?”; “Have you found different behaviors related to the ethnical background?”; “Do you provide different technological solutions to different communities? If so, what are the criteria these decisions are based on?”; “Do you remember any cases where PV systems were rejected by a community?”. As the interviews were semi-structured, in addition to these questions previously defined, we dived much deeper into specific topics by addressing additional topics depending on the background and expertise of the interviewees.

The interviews lasted from 41 to 92 minutes, and all of them were recorded. Interviews were mostly held in Spanish with the exception of two interviews held in German. The interviewees were of higher hierarchical positions (directors, project managers, leading researchers, and division leaders), as we were interested in the institutional and organizational strategy and the stakeholders’ experiences over time.

The assessment of the information gathered by the document analysis and the semi-structured interviews was based on coding. We used the MAXQDA11® software [99], which allowed us to analyze the information and cluster it according to the to the four dimensions of sustainability considered in this paper.

Table 3: Interview Partners.

| Area | Sub-Area | Division (if applicable) |
|---|---|---|
| Government Institutions Energy Sector | Ministry of Energy | Division of Renewable Energy |
| | | Division of Energy Access and Equity |
| | Center for Sustainable Energy Innovation and Promotion (CIFES) | |
| Government Institutions Non-Energy Sector | Ministry of Social Development | Division of Project Revision and Approval |
| | Ministry of Agriculture | FIA |
| | | INDAP |
| Academics & Research Institutes | Universities | Sociologist |
| | | Politician |
| | | RE Project Manager |
| | Solar Energy Research Center | Project Manager |
| NPOs | Solar Energy Association | Lobbyist |
| | Chilean Non Profit Organization | RE Project Management |
| Foreign Institutions | German-Chilean Chamber of Commerce | |
| | German Society for International Cooperation | RE Department |
| Energy Companies | Solar Energy Companies (2) | Project Managers |

## 3. Results and Discussion

### 3.1 Institutional Sustainability

***Stability***

The stability (durability) of formal institutions requires a long-term vision. Although institutional stability appears to be less problematic than in its South American neighbors, in Chile as in many DC, short-term thinking is prevalent. This problem does not apply to public employees and formal institutions only, but was considered by several interviewees as typical for the Chilean society (i.e.

informal institutions). E.g., talking about self-consumption PV systems, a manager from a German PV company stated:

> *"here in Chile, I have to say, the time horizon is extremely short. In Chile, PV systems will never have the success that they are having for instance in Germany (...), because people are willing to accept three, four years of amortization only (...). Anything above that is completely out!"*

A sociologist from a Chilean university argued that short-term thinking could be a consequence of frequent political and economic crises on the continent, which inhibits people to make long-term plans or investments. He argued that Chile's economy has been stable with high growth rates during the last 25 years, but that people's approach of pure survival has nowadays transformed into access to consumption on credit combined with a 'here and now' philosophy.

Numerous interviewees also highlighted the widespread neoliberal vision embedded in the state and ultimately in the Chilean society. For example, in our interviews with representatives of the government, they repetitively underlined the importance of technology neutrality, since in their view any form of facilitation or promotion of RE may lead to a market distortion. This neoliberal vision constrains not only the planning role of formal institutions, but also restricts the development and enforcement of regulations and standards.

***Regulations and Standards***

The regulatory framework of the electricity sector in Chile has been considered weak and accounts for a very limited role of the government [100]. In the case of PV systems, the regulatory framework (certification standards and technical regulations) was developed through the GEF/UNDP program "Removal of Barriers for Rural Electrification with RE" (see above). However, this regulatory framework is not mandatory in the case of small-scale off-grid projects.

Indeed, we found that local implementations seem particularly vulnerable when the SEREMI of the Ministry of Energy is not involved in the projects, and their technical approval is not required. This may be the case when the investment cost of the rural project does not exceed 70 million Chilean Pesos (approx. US$ 120,000). For example, the representative of a private firm that recently won three local public bids for off-grid PV systems stated *"(...) there are relatively many municipalities with little idea about what they need, but they know that there are funds or state subsidies for certain PV projects"*. This may become a great issue, since

> *"there are insufficient minimum standards in the bids, so that you often lead an unwinnable battle, well, that you have a futile situation if you own a good product and of course you want to offer it, but at the same time you have competitors that evidently offer low quality products. Yet, if the person that ultimately takes the decision lacks technical know-how or the background or experience with the products, it will be hard for him to decide."*

***Adaptability***

The regulatory framework of projects with a budget greater than 70 million Chilean Pesos (approx. US$ 120,000) is notoriously more robust; these projects have formal requirements that even include defining an O&M model. However, O&M ultimately depends on either the commitment/organization of the community (operating the systems via cooperative), or the availability of a private company (operating the systems against a compensation fee). Still, finding a private company interested in the operation of small-scale electrification projects is a challenge in remote areas of the country. Local governments can hardly assume these tasks either. According to a representative of the Ministry of Social Development:

> *"(...) since local governments, since they have many functions, they don't have the technical capacity to operate and maintain (...), at a national scale, this can be solved, but at the scale*

*of small communities, it's not that easy (...). We clash with the issue of not having an agency to operate and maintain [small-scale electrification projects]."*

The lack of an agency with the responsibility of overseeing off-grid PV systems seems to be a major drawback, which compromises the ability of Chilean institutions to meet O&M needs and in turn to ensure the sustainability of off-grid PV systems. This weakness in the Chilean institutions is well known in local academic circles. For example, according to a researcher from a Chilean university: *"here in Chile there should be a central agency - I even named it "Monitoring Microgrid Unit". This office should indeed focus on doing this kind of management."* Yet, the Ministry of Energy has not considered such an agency in the case of the off-grid PV systems.

The successful program for PV-powered water pumps aimed at supporting small and isolated farms (see above) may be an example of the benefits of having a public decentralized agency overseeing off-grid PV systems. Indeed, as described above, INDAP not only sponsored the deployment of the systems, but also offers support on their O&M, solving small technical problems that the poor farmers could hardly overcome by their own.

***Decentralization and Openness to Participation***

In the case of off-grid systems, the participation of the community has helped to successfully implement some early projects. For example, in the "Coquimbo Project" (see above), according to a representative of the Ministry of Energy, people were involved in the project from the beginning. Indeed, the Ministry of Energy believes that a close collaboration between the community and the project implementer is indispensable for these projects to be sustainable over time. As declared by a DAEE representative "*the most striking success factor for the PV systems is an empowered community who wants the project, accepts it, and understands it."*

Unfortunately, a participative approach has not been applied in all off-grid projects. For example, in 2010, several off-grid PV projects were implemented in rural areas in southern Chile; in particular in the Aysén region, one of the 15 Chilean "regions" or territories. When in 2012 an ex-post evaluation was conducted on these projects, it showed that though the off-grid PV systems were appropriately deployed, harming system interventions from users occurred in 18% of the cases because of a lack of user training (only 44% of the beneficiaries of a PV system received written instructions for use, and 47% received some kind of briefing) [84]. A lack of user training and technical know-how was similarly observed in a small town called Curepto in the Maule region (about 300 km south from Santiago) [82].

**3.2 Economic Sustainability**

***Cost Effectiveness***

In order to be sustainable, a solution for electrification must be cost-effective. Rural electrification costs depend on various factors including population density, local energy resources, the distance from the closest grid, and the level and quality of the energy access [101]. Off-grid PV systems are indeed a cost-effective solution at Chilean locations where the grid expansion is not viable due to geographical conditions, or at locations with a high degree of dispersion of the local population [92]. However, according to Chilean officials, fossil fuel solutions such as those based on diesel generators are often deployed at these remote locations.

The problem is that in the past, the chosen technology had often been selected based on the initial costs only (PV systems have high initial costs compared to diesel), without considering for example environmental impacts or O&M costs. Regarding small off-grid systems based on diesel generators deployed in small islands in southern Chile, a project manager explained:

*"(...) all these projects that have been implemented they are all diesel, which is ultimately more expensive. So, you are travelling two hours to an island where there are 100 families and you have to*

*bring diesel."*

Due to the low O&M cost of PV-based solutions, the total costs of a diesel generator normally exceed those of a RE system over its lifetime. For instance, in the Aysén region, different technologies were compared in order to electrify 49 families with an energy consumption of around 15kwh per month [87]. Although the initial investment of a 1200Wp PV system (including logistics, batteries, inverters, user training, etc.) was quite high (236,499,000 Chilean pesos per system; i.e. about US$ 380,000) as compared to a diesel generator (61,025,000 Chilean pesos; i.e. about US$ 98,000), the present value of capital costs was actually lower (at a 6% discount rate for a 20 years term) for the off-grid PV systems with a value of 473,594,000 Chilean pesos (about US$ 764.000), than for a diesel generator with 783,498,000 Chilean pesos (about US$ 1,263,000) [87].

In recent years, it appears that Chilean officials have recognized that off-grid PV systems are a cost-effective solution at remote locations [102]. Indeed, previously deployed diesel generators have recently been substituted by off-grid RE systems in many projects [81]. Moreover, the new Energy Agenda issued by the Ministry of Energy in 2014 [103] vows to further substitute diesel generators by RE systems and, even more importantly, to consider all costs over the lifetime in the evaluation of rural electrification projects.

***Reliability***

The ex Ex-post evaluations of rural electrification projects shown in Table 2 have revealed significant differences in their operational reliability. Whereas in the evaluation reports for the Coquimbo project and some communities from the Maule region all systems from the analyzed projects were found operational [81,84], Covarrubias et al. [82] and Navarro et al. [83] reported deficiencies and a poor performance of the systems in the inspected projects (Maule, Aysén, Tarapacá, Coquimbo region). In fact, even where systems were found operational, Deuman [84] warned that the reliability of the systems was jeopardized, as O&M ultimately relied on voluntary efforts from the users.

Indeed, the reliability of the off-grid PV systems strongly depends on ensuring O&M. This explains the high reliability of the micro-grid project in Huataconbo (only one failure between 2010 and 2014), where a very well organized and trained community facilitated and ensured O&M [90]

Another factor that jeopardizes the reliability of the systems is that although Chile has a legal system significantly more developed than its South American neighbors, enforcement of contracts with private companies in charge of the operation of small electrification programs has often been problematic. For instance, in Curepto (located in the Maule region) the contract between the company that installed the systems (42 households were electrified with off-grid PV systems) and the local municipality stipulated that the company was in charge of O&M (including the battery replacement); yet, the company never complied with its duties, such that the system reliability was extremely poor [82]. Moreover, Navarro et al. [83] found that despite the fact that the contracts between the CNE and the EDCs have a clause that requires the EDC to register all off-grid system defects, the projects had not been followed up upon, which substantiates the lack of enforcement.

In cases where a private company is not available to operate the systems, the technical know-how and skills have to be locally available or transferred to the community in advance. Otherwise, the reliability of the system can be seriously comprised. For example, in the "Aysén" region (in southern Chile), the ex-post evaluation of the projects (90 off-grid PV systems) that were supposed to be operated by the community via cooperative, showed that: the systems were not administered by anyone [84]; spare parts (i.e. bulbs) were not available, such that the users replaced them by poor quality products; and that funding for O&M was not available [84]. Although the CNE requested to the local municipalities to take care of the operation of the systems, this did not occur [104]; the mayors of the municipalities explained that despite their willingness, they neither had the funds, nor the technicians to do so [84].

***Initial Investment***

In the Chilean residential sector, according to a representative of a Solar Energy Association, investments in self-consumption PV systems (that are connected to the grid) have an estimated payback period of 10-12 years. However, the required investment may still not be affordable for most Chilean households. A researcher from a Solar Energy Research Center pointed out that: *"…this case [*self-consumption PV system*] is not for Juanita [name that stands for a mid-income citizen], this is for the Miss who is living in the upper class neighborhood"*. The unaffordability of self-consumption PV systems is aggravated, by the lack of funding instruments (such as leasing) for private consumers in Chile.

In contrast, the affordability of the initial investment of off-grid PV systems for rural users is not an issue if the project is selected and given preference by the GORE, since it is fully covered by the FNDR or by the sponsoring public agency [3]. In the case of the PV-powered water-pumps sponsored by INDAP, the agency subsidizes 90% of the initial investment, while the beneficiary pays the remaining 10% as a long-term loan.

***O&M costs***

In the case of off-grid projects funded by the FNDR/GORE, the O&M costs are included in the contracts between the municipalities (that normally sponsor the projects) and the private companies in charge of the O&M [78,79]. Although the users pay for energy consumption, the tariff is hardly enough to cover the O&M of the systems. Since the tariff for off-grid PV systems is unregulated, normally the tariff per kWh from the closest community with a grid connection is adopted [78].

For instance, within the "Coquimbo" project (northern Chile), the monthly charge for the running costs of a 225 Wp PV system is 12,326 Chilean Pesos (about USD 20), of which the user pays 3,000 Chilean Pesos (around US$ 5); the regional government pays for the difference of 9,326 Chilean Pesos (about US$ 15) per user [81]. Although since 2009 the subsidies needed to cover these differences can also be requested to the respective GORE (see Resolution No. 137), they must be evaluated and approved each year by the respective SUBDERE. The need of annual approval causes uncertainty, since the subsidy is not guaranteed for the entire lifetime of the project. According to a representative of the Ministry of Social Development, O&M costs are not considered as relevant as the initial investment in the case of off-grid projects:

> *"In Chile, the public sector (...) is very concerned about taking care of the investment processes, investment in capital. But this process, which is O&M, isn't so, so important. (...) So, good evaluation and investment analysis are made, but after that, there isn't much interest for this to have a permanent expenditure."*

A researcher from the Solar Energy Research Center confirmed that the budget allocation focused mainly on the initial investment is also common in the case of projects funded by donations from the private sector:

> *"(...) they [private companies and the government] can give great support to the initial investment. They will fund the system. But those who support the development are not very interested afterwards to be in charge of the maintenance and all that, because it is a headache, and they say 'I don't want to continue with all these things. I support you with the construction, but I don't want to get involved in this infinite thing'.*"

Although the low O&M cost of PV technologies should favor the deployment of PV solutions, decisions have often been made only considering the cost of the initial investment (which tends to favor fossil fuels technologies such as those based on diesel generators). As further discussed in section 3.1, this behavior may be related to the short-term thinking prevalent in the Chilean society and the governmental agencies).

***Contributions to income of users***

The program of PV-powered water pumps promoted by INDAP showed that in Chile off-grid PV project for productive uses can succeed. Indeed, an ex-post study conducted by GreenLab (2012) estimates that the substitution of the diesel pumps by off-grid PV water pumps generates a net benefit of between 57 and 68 million Chilean pesos (US$ 92,000 to US$ 110,000) per project. As explained by a representative of the Foundation for Agrarian Innovation (FIA by its Spanish acronym):

> *"In the case of the farmers, who are business people after all, because agriculture is a business. If you present to them, 'look, pumping with grid electricity will cost you this, and pumping with a PV panel will cost you that', they will take it.*"

According to an INDAP representative, considering the short payback period (of about four years), farmers with higher spending capacities than those who received PV-powered water pumps from INDAP, bought the PV pumps on their own account. Contrary to the residential electrification project, farmers made this investment decision as they could decide on the technology, thus taking the entire costs (initial investment plus O&M) in their technology choice into consideration.

Beyond the water pump program, several other RE projects for productive uses have been implemented in Chile. For instance, the FIA funded demonstration systems of PV-powered purification and desalinization of water; PV-powered greenhouses; PV-powered irrigation; and a joint program with Information and Communication Technology (TIC by its Spanish acronym) using PV-powered antennas that allowed Internet connections in rural areas. However, all of these solutions are only pilot projects so far.

### 3.3 Environmental Sustainability

***Environmental Awareness***

In 2010, the creation of the Chilean Ministry of Environment and the Service for Environmental Evaluation (SEA, by its Spanish acronyms) showed the country's increased environmental awareness. Environmental policies like the carbon tax of US$5 per ton of Carbon dioxide (C02) (starting from 2018) have thereinafter been approved (law 20.780). Moreover, in its Intended Nationally Determined Contribution (INDC) declaration for the COP21 in Paris, Chile committed to reduce its CO2 per GDP unit by 30% by 2030 compared to 2007. However, this reduction may be insufficient, as due to the expected GDP growth, GHG emissions would be 222% above 1990 and 75% above 2010 levels (calculations were based on the medium case GDP projections of the Chilean government) [105]. The Ministry of Environment had presented two more ambitious proposals (Option A: 40-45% and Option B: 35-40% reduction of GHG by 2030; [106]) but they were ultimately not considered by the central administration. Indeed, several interviewees pointed to the limited role of this Ministry of Environment in the national policy, which is also reflected in the small budget allocated to this Ministry (about 0.13% of total national budget in 2014 [107]).

The Ministry of Energy in turn has so far maintained its (previously mentioned) policy of technological neutrality in the energy sector, which is also reflected in the energy matrix: In the case of the SING systems carbon and gas currently account for 48.9% and 36.5% of the total electricity generation respectively, whereas fuel oil and diesel contribute about 4% each [108]. In case of the SIC system, hydro energy makes up almost 40% of the energy share, followed by diesel (21.2%), Natural Gas (11.5%), Carbon (10.4%), and carbon petroleum coke (3.6%) [108].

Several interviewees confirmed a higher awareness on environmental issues, especially of the younger population. This has recently led to social movements, which successfully stopped several energy generation projects (e.g. HidroAysén, Alto Maipo, Castilla, Punta Acalde) [109-112]. However, according to a social scientist, these movements seem to be mainly motivated by concerns about potential negative effects on the local communities (for example, direct pollution), and often they also tend to embrace a form of "technology neutrality". This means that communities can reject any form of the energy generation regardless of the type of technology (fossil fuel or renewable), if they are directly affected. A representative of the German-Chilean Chamber of Commerce explained *that: "(...) if somewhere far away, 500 km towards the sea there is a coal-fired power plant, they don't care. But if there is a little power plant in their backyard, although renewable, then they might now get bothered."* From the Chilean perspective, concerns on global problems such as climate change seem to be distant.

***Environmental Impacts***

In the case of off-grid rural electrification projects funded by the FNDR/GORE, the selection criteria for a technology are exclusively based on direct costs, such that environmental impacts due to direct pollution or GHG emissions are not considered in the project evaluation process. Furthermore, although rural off-grid PV systems have a much lower environmental impact than e.g. diesel generators, the battery disposal may become a major issue in rural communities. However, we were unable to find any functionary involved in off-grid PV projects funded either by the FNDR/GORE or by municipalities, aware of the battery disposal norms established during the CNE/UNDP program.

**3.4 Socio-Cultural Sustainability**

***Accessibility (Disparity/Equity)***

In Chile, major efforts on electrification during the last 20 years have led to a remarkable electrification rate (about 99% of urban and 97.3% of rural households are electrified [3]). These sustained efforts have shown the broad political consensus on the necessity of providing electricity to all. However, figures show significant differences in the electrification rate between different groups. For example, 1.62% of the extreme poor have no access to electricity, as opposed to 0.35 of the non-poor [63]. Moreover, as shown in Figure 1, there is also a discrimination against indigenous people.

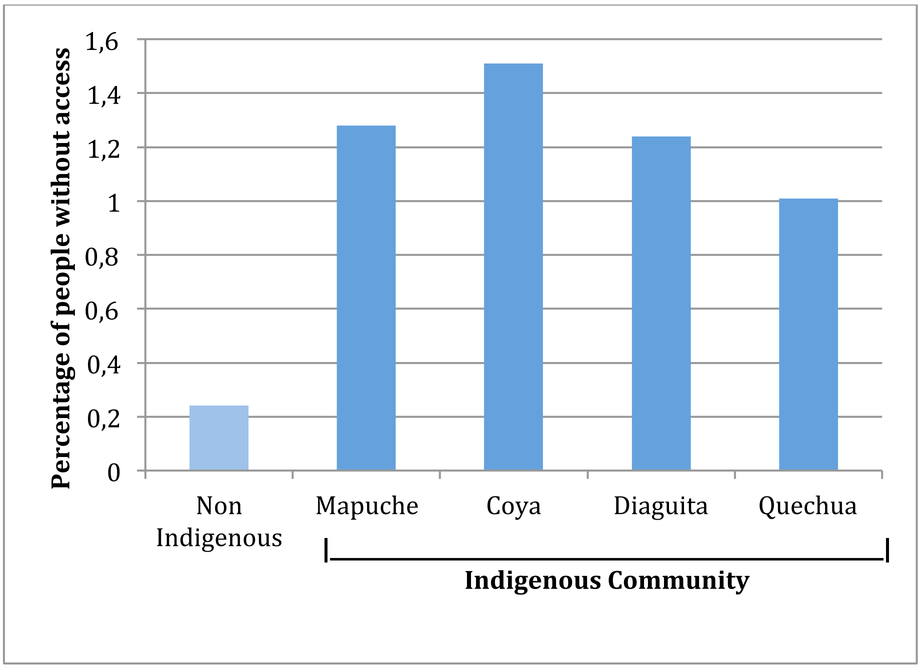


Figure 1: Percentage of people in 2011 without access to electricity according to their ethnical background. Source: Own elaboration based on data from [62].

Moreover, for those who do have access, there is a high divergence of electricity prices between regions. This is due to the fact that in Chile electricity tariffs for regulated consumers (including residential users) reflect the real costs of energy generation, transmission, and distribution. Differences in tariffs may diverge by a factor of 2.3 between one community and another [113]. As a consequence, whereas the poorest quintile (often from rural areas where distribution costs are higher and electricity is therefore more expensive) spent about 8.25% of their income on electricity (though consuming much less), the portion of the richest quintile accounted for 3.47% only [114]. Recently (June 2016), the National Congress approved a law on "tariff equity", a sort of cross-subsidy mechanism that will be funded by customers with a monthly consumption above 200 kWh; the law stipulates that residential electricity tariffs may not diverge by more than 10% between regions [115].

In addition to differences in tariffs, the amount of energy supplied by the off-grid systems may also differ between projects and regions. No protocols have been defined regarding the capacity or the amount of energy supplied by the off-grid systems. Part of the problem is that there is no updated information on the energy consumption per household in rural areas. This has led to complains of some users, as a low energy supply was provided to some communities, while a somewhat higher supply was provided to others (e.g. sufficient capacity for a fridge). For instance, in Aysén (southern Chile), a community insisted in a higher PV system capacity than initially planned. According to a representative of the Ministry of Energy, these complains led to a discussion on Disparity/Equity: "*we [the Ministry of Energy] had a conflict, we said, gosh, how are we going to fund [electricity for] a fridge if we didn't do it before [in other projects]?"*

As opposed to the grid, off-grid PV systems cannot provide more energy in response to a changing demand, as they are limited to the initially installed capacity. A DAEE representative acknowledged that although households count as electrified in the statistics, basic needs such as a refrigerator are usually not met with the current PV systems, as projects were designed based on budget constraints. For instance, Covarrubias et al. [82] found that the system on average only provided electricity for 1-1.5 hours (never more than 4 hours) per day.

Being aware of this issue, the DAEE is currently working on a new definition of electrification, and *"based on this definition that we are working on, we are trying to convince the Minister [of Energy], we say that certain systems were pre-electrification, and now we will do a second phase, which is electrification."* Therefore, the currently installed energy system will either need to be substituted, or upgraded to meet an increasing energy demand.

The Ministry of Energy is also currently switching its strategy from an electrification approach to an integral '*energization'* approach, which goes beyond basic household electrifications and aims to cover all energy needs of the communities. The DAEE was created precisely to tackle this problem, as explained by its representative: *"…[t]he concept of equity for us is a concept that … if the State provides different services, we should all have the same service quality everywhere."* According to the energy roadmap from the Ministry, one of the first steps in the application of the *energization'* approach is to assess the necessities of vulnerable groups, which is expected to occur from 2016 to 2018.

***Social Acceptance***

The civil society has recently played a significant role in the Chilean energy sector. In response to disagreements and discontent with several energy projects (mainly hydroelectric- and coal-fired power plants), social movements have emerged [100]. Protesters claim to be consulted and involved in the projects, otherwise they have shown to have the power to stop them. As revealed by a representative of the German Chamber of Commerce, this was for instance the case with a German firm that had been working on a PV project for three years. Since the firm did not engage the local community and their elected local authorities, residents of the community with the support of their mayor sued the company. According to the representative of the German Chamber of Commerce, they managed to stop the project despite the fact that the company had complied with all formal and legal requirements. As discussed elsewhere [100, 109], efforts for engaging the community have not been addressed properly in Chile, as participation is still understood as the provision of information, rather than the engagement of the community from cradle to grave.

According to several interviewees, the off-grid PV systems have also experienced rejection from communities in rural areas. These cases mainly involved indigenous communities in southern Chile. A DAEE representative recalls:

> *"They [the community] prefer to wait two years to obtain the resources, such that they put them the grid. It was like that; we already had the project ready. The party leader came here to the Ministry, and said 'listen, sweetheart, your study is really great, but my people don't want this. […] We will talk to the distribution company. It's either grid or grid.'"*

According to the Ministry of Social Development, the negative experience with off-grid PV systems (including the limited capacity installed) that inhabitants of rural areas observed in neighboring villages in the past, may have aggravated the premature rejection of the systems. An NPO member has proposed identifying important social actors within a community to rely on, who also have the status, the skills, and the motivation to engage and involve the community.

Nevertheless, there are successful experiences in gaining social acceptance of off-grid PV project. In the Huancano project for example, the community was previously characterized by a multidisciplinary team of specialist including anthropologists, sociologists, and legal scholars, who defined social interactions of the community and their use of the resources, they identified key participants, and analyzed the disposition of the users to participate in the project and define their roles [91]. As a consequence, most users accepted and advocated the project, as 73% considered that the project had a positive effect on their everyday life [90].

***Accuracy***

In order for a project to be accurate, it has to meet the specific local needs and consider the socio-cultural reality of each community. The Ministry of Energy seems to be aware of the need of accuracy. Accordingly the staff from DAEE is trained on the bottom-up energy model "HOMER", an optimization model aimed at remote areas that evaluates micro power on-grid and off-grid systems to determine the configuration of the most appropriate solution for a particular community [116]. Yet, when the Ministry of Energy is not involved in the selection process (in the case of projects of less than approx. US$ 120,000), the municipality is entitled to decide which technology will be deployed (usually without having the required know-how on energy models nor on technological options). This lack of know-how can become problematic, since the municipality may have to trust in a provider whose opinion maybe biased. A representative of the Ministry of Energy recalled a conversation with a local energy provider of PV systems who was trying to sell his product to the Municipality:

> *"'Listen, I [the provider] can put PV panels for 100 houses.' And it turns out that all these houses are contiguous, and you have a river with a waterfall and you say 'no, no, no, wait. Let's see. Here it's better to build a mini hydro station, you have much more energy, it's cheaper, and more sustainable over time, etc.'"*

Inaccurate systems tend to underestimate the required capacity: For instance, as the system capacity of 150Wp was too small in Curepto (providing on average 1.5-2hours of electricity), people had to continue using their alternative energy sources such as candles, batteries for lanterns and radios, and paraffin. Hence, on average they spend an additional US$6.3 per month [82]. This deficiency has been explained by the fact that the PER program exclusively focused on reaching the target electrification rate instead of assuring the quality of the service/technology [83]. A review of the BIP database shows that some recent projects have corrected this flaw by upgrading the capacity of SHS e.g. to 480Wp in Curanilahue (Maule region); 600Wp in Los Torreones, Lago Zenteno, and Litoral (in the Aysén region); and 500Wp in Tortel, O´Higgins, and Cochrane (also in the Aysén region) [86]. In other projects however the capacity remains low until today (e.g. SHS of 100Wp and 130Wp in Coquimbo region in 2012, and 85Wp in the Arica and Parinacota region in 2009) [86].

***Socio-Cultural Justice***

Interviewees from Universities, NPOs, and the Ministry of Energy all agreed on the importance of engaging small communities and respecting their culture. However, they also pointed out the fact that there is no universal solution (i.e. an engagement model) for all communities, mainly because of the diversity of small communities inhabiting rural areas in Chile. As summarized by a researcher from a Chilean University:

> *"It strongly depends e.g. how the community is organized, if it is a united social structure, how decisions are taken within a community, the vision they have about the systems. Many things. How organized they are. […] and based on all that, one can propose -as we are doing as a university- the management scheme that best adapts to this reality."*

Therefore, the major issue is not necessarily the lack of awareness on the cultural particularities of small communities, but the lack of an engagement model. This has been particularly problematic in the case of large-scale energy projects (such as hydropower plants), (see [100]).

Regarding each sustainability indicator considered in this paper, Table 4 provides a summary of the strengths and weaknesses of rural electrification efforts in Chile based on off-grid PV solutions.

Table 4: Strengths and weaknesses of rural electrification efforts in Chile based on off-grid PV solutions.

| Indicator | Strengths | Weaknesses |
|---|---|---|
| **Stability** | Formal Institutions are stable in Chile compared to its Latin American neighbors. | |
| **Regulation and Standards** | Technical standards and regulations for PV systems have been defined (GEF/UNDP program). | Standards not mandatory and not necessarily used in tenders. |
| **Decentralization and Openness to participation** | Engagement of communities, in some projects, for example, in the case of the Coquimbo and Huatacondo projects. | Lack of (technical) know-how in rural areas (which has affected some PER projects).<br><br>Participation is still understood as the provision of information, rather than the engagement of the community from cradle to grave. |
| **Adaptability** | | Chile lacks a decentralized agency for overseeing off-grid electrification projects. |
| **Affordability** | Initial investment is covered by FNDR. | No cross subsidies aimed at covering off-grid costs (from users connected to the grid for example). |
| **Cost effectiveness** | New Energy Agenda considers the substitution of projects based on diesel generators for cost-effective solutions based on PV. | Decisions have been made based on the initial costs only, not considering O&M costs or environmental impacts (life-cycle costs). |
| **Consideration of O&M costs** | | The costs for O&M of PER-sponsored projects have to be annually approved by the SUBDERE (thus causing uncertainties). |
| **Contribution to income of users** | PV programs for productive use (such as those sponsored by INDAP) widespread. | |
| **Reliability of supply** | Ex-post project evaluations found that most of the systems of the PER program were operational. | Reliability depends on the engagement/proactivity and technical skills of the community, which may threaten the sustainability of these projects. . |
| **Environmental awareness** | The younger population exhibits higher awareness on environmental issues. | Selection criteria for a technology are still exclusively based on direct costs without considering the environmental impacts. |
| **Environmental impact** | GEF/UNDP environmental standards for disposal have been established. | As environmental standards are not mandatory, battery disposal is often not considered in the projects. |
| **Accessibility (Disparity, equity)** | High electrification rate in Chile (99% national; 97% rural). | Indigenous communities still have less access to electricity, since communities have to request electrification at first place. This approach favors better organized communities leaving behind others -normally the poorest indigenous communities. |

| | | |
|---|---|---|
| **Social acceptance (Accuracy)** | System size has been upgraded in many local projects.. Training on the energy model HOMER for staff of the Ministry of Energy. | As no minimum capacity is defined, inaccurate solutions often lead the rejection of off-grid PV systems |
| **Cultural Justice** | Chilean officials are aware of the importance of local participation. Indeed, cultural factors (gender, ethnical background, roles within a community) are considered in the programs. | |

## 4. Conclusions

This paper analyzes the sustainability of rural electrification efforts in Chile paying special attention to off-grid PV programs. Our assessment was based on a set of indicators (Table 1) corresponding to the four dimensions of sustainability considered in this paper: institutional, economic, environmental, and socio-cultural.

Institutional sustainability demands for stability/durability. Although institutional stability appears to be less problematic that in its South American neighbors, the widespread neoliberal vision embedded to the Chilean society appears to be constraining the role of formal institutions and restricting the development and enforcement of regulations and standards. In fact, although a regulatory framework for Rural Electrification with RE exists, it is not mandatory.

The lack of a mandatory set of regulations and standards makes the implementations of small-scale off-grid projects unreliable. This is the case of projects whose investment cost does not exceed 70 million Chilean Pesos (approx. US$ 120,000) that can be funded by Municipalities or local authorities without the prior technical approval of the Ministry of Energy. Greater projects with public funding require the revision of the Ministry of Energy, which even includes defining an O&M model. However, O&M has shown to be a challenge in remote areas of the country due to the fact that private companies are not interested in the operation of small-scale electrification projects. Having a public decentralized agency overseeing off-grid PV systems in the country may address this drawback, but the Ministry of Energy has not yet considered such a solution.

Economic sustainability of electrification solutions requires ensuring the funding of the systems. The affordability of the initial investment in the case of off-grid PV systems for rural users is not an issue in Chile, since it is fully covered by the FNDR or by the sponsoring public agency. However, the cost of the O&M, which can hardly be afforded by the largely poor inhabitants of remote areas of the country, is neither funded by the FNDR, nor by the private sponsors. Although O&M costs can also be requested to the respective GORE, they must be evaluated and approved every year. The need of annual approval causes uncertainty and leads to unreliable systems, since the subsidy is not guaranteed for the entire lifetime of the project.

Economic sustainability also requires providing a cost-effective solution for electrification. Though the Ministry of Energy favors cost-effective solutions for rural electrification, they have been making decisions based on the initial costs only, without considering for example O&M costs or environmental impacts. This situation has recently improved, and the new Energy Agenda vows to consider all costs over the lifetime in the evaluation of rural electrification projects.

Some programs, such as the PV-powered water pumps promoted by INDAP (an agency that depends on the Ministry of Agriculture), have successfully contributed to the income of users. Although most of these programs were only pilot projects, they have showed the potential of off-grid PV project for productive uses in Chile. Indeed, favored by the unique conditions of its northern and central territory, the adoption of solar energy technologies would yield substantial benefits for the poor inhabitants of rural areas of the country. However, exploiting the solar potential of the country will require a better coordination between different ministries (such as Energy, Agriculture, and Economy, Promotion, and Tourism).

Environmental sustainability entails the prevention of negative environmental impacts, which in turn requires a widespread environmental awareness. Although especially the younger population exhibits a higher awareness on environmental issues, these movements seem to be mainly motivated by concerns on potential negative effects on the local communities (for example, direct pollution). From the Chilean perspective, concerns on global problems such as climate change seem to be distant. Moreover, the selection criteria for a technology in off-grid rural electrification projects funded by the FNDR/GORE are still exclusively based on economical factors. Environmental impacts due to direct pollution or GHG emissions are not considered in the project evaluation process. Improvements regarding the impact assessment, but also in environmental awareness and understanding, are required for ensuring the environmental sustainability of rural electrification efforts.

Although Chile has conducted remarkable efforts on electrification during the last 20 years, current figures show that the poor and indigenous communities have less access to electricity than non-poor and non-indigenous communities. This disparity is a major drawback that underscores the need for adjusting the bottom-up approach (which means that the communities or the local authorities have to request electrification at first place) adopted by the Ministry of Energy in rural electrification. Indeed, this approach favors better organized communities leaving behind others -normally the poorest. The bottom-up approach in rural electrification fails to meet equity criteria, significantly compromising the socio-cultural sustainability of rural electrification efforts in Chile.

In the case of projects targeting indigenous communities, social acceptance of some off-grid PV solutions has been problematic. The rejection of some communities to off-grid PV solutions has often been due to their lack of accuracy (as the provided solution was unable to meet the specific local needs). Ultimately, the rejection may be linked with the lack of an engagement model. Indeed, in Chile participation is still understood as the provision of information, rather than the engagement of the community from cradle to grave. Progress regarding accuracy is needed for ensuring the socio-cultural sustainability of rural electrification efforts in Chile.

Yet, the formal institutions in Chile (in particular, the Ministry of Energy) are making progress and have learnt important lessons from flaws in previous rural electrification programs. Indeed, the new policy of the Ministry of Energy includes considering the life-cycle costs in the valuation of projects; shifting from a pre-electrification approach with low PV system capacities to an *energization* approach; fostering the productive use of energy; and adopting cross subsidies aimed at improving equity in energy prices.

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**Authors' Contributions**
The first author conceptualized and structured the paper. The first author was solely responsible for data collection (interviews) and analysis. The whole paper was jointly drafted and developed by the authors to bring to the current state.

**Competing Interests**
The authors declare no competing interests.

**Abbreviations**
BIP: Integrated Project Database
CO2: Carbon dioxide
CC: Climate Change
CER: Center for Renewable Energies
CIFES: Center for Innovation and Promotion of Renewable Energies
CONAFE: National Electrical Force Company
CNE: National Energy Commission

CORE: Regional Council
DAEE: Department of Energy Access and Equity
DC: Developing Countries
EDC:  Electricity Distribution Companies
FDI: Foreign Direct Investments
FIA Foundation for Agrarian Innovation
FNDR: National Development Fund
GEF: Global Environmental Facility
GHG: Greenhouse Gases
GORE: Regional Government
INDAP: Agency for Agrarian Development
INDC: Intended Nationally Determined Contribution
INN: National Institute of Normalization
kWh: kilo Watts hours
kWp: kilowatts peak
MW: Mega watts
NCRE: Non Conventional Renewable Energy
NPO: Non Profit Organization
NPV: Net Present Value
OECD: Organization for Economic Co-operation and Development
O&M: Operation and Management
PER: National Program for Rural Electrification
PERYS: The National Program on Rural and Social Energy
PPA: Power Purchase Agreement
PV: Photovoltaic
RE: Renewable Energy
SD: Sustainable Development
SEA: Service for Environmental Evaluation
SEC: Electricity and Combustible Authority
SIC: Central Interconnected System
SING: Northern Interconnected System
SUBDERE: Subsecretary of Regional Development and Administration
SEREMI: Regional Secretaries of the Ministries
TIC: Information and Communication Technology
UNDP: United Nations Development Program
Wp: Watts peak

**References**


1. United Nations (UN)(2012). Sustainable Energy for All. A Framework for Action. The Secretary-General's High-level Group on Sustainable Energy for All.
2. International Energy Agency (IEA)(2015). "World Energy Outlook. Electricity access database." Available at: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/ Accessed on 16 December 2015.
3. Argomedo, R. (2015)."Financiamiento Estatal en Chile. Programa Electrificación Rural (PER)" Workshop on Energy Storage for Sustainable Development April 16-17 2015, Rio de Janeiro. (in Spanish)
4. Ministerio de Energia (2010) Cobertura de Electrificación Rural a Diciembre de 2010. Available at: http://antiguo.minenergia.cl/minwww/opencms/04_Programas/PER/estadisticas.html Accessed on 25 July 2014. (in Spanish)
5. Estay, C. (2014). Electrificación Rural: Objetivos e Instrumentos para su Desarrollo (Chile). IV Seminario Latinoamericano y del Caribe de Electricidad. (in Spanish)
6. Cordero R.R., Damiani A., Seckmeyer G., Jorquera J., Caballero M., Rowe P., Ferrer J., Mubarak R., Carrasco J., Rondanelli R., Matus M., Laroze D., The Solar Spectrum in the Atacama Desert, Sci. Rep. (2016), 6, 22457
7. Rondanelli, R., Molina, A. & Falvey, M. e Atacama Surface Solar Maximum. *Bull. Am. Meteorol. Soc*. **96,** 405–418 (2015).
8. Escobar, Rodrigo A., et al. "Solar energy resource assessment in Chile: Satellite estimation and ground station measurements." Renewable Energy 71 (2014): 324-332.
9. Centro para la Inovacion y Fomento de las Anergias Sustentables (CIFES) (NA). Reportes CIFES. Available at: http://cifes.gob.cl/ Accessed on 29 January 2016. (in Spanish)
10. Ritchie, J., Lewis, J., Nicholls, C. M., & Ormston, R. (Eds.). (2013). Qualitative research practice: A guide for social science students and researchers. Sage.
11. Bernhardt, J. The Effectiveness of Science-Policy Interactions: Case Studies on Climate Change Mitigation and Sustainable Development in Pan-European Forest Research and Politics. 2015. Doctoral Thesis, Univerity of Hamburg, Hamburg, Germany. Available online: http://ediss.sub.uni-hamburg.de/volltexte/2015/7160/ Accessed on 24 March 2015.
12. Heinrichs, H.; Laws, N. "Sustainability State" in the Making? Institutionalization of Sustainability in German Federal Policy Making. Sustainability 2014, 6, 2623–2641.
13. Nguyen-Trinh, H.A.; Ha-Duong, M. Perspective of CO2 capture & storage (CCS) development in Vietnam: Results from expert interviews. Int. J. Greenh. Gas Control 2015, 37, 220–227.
14. Hugé, J.; Mukherjee, N.; Fertel, C.; Waaub, J.P.; Block, T.; Waas, T.; Dahdouh-Guebas, F. Conceptualizing the effectiveness of sustainability assessment in development cooperation. Sustainability 2015, 7, 5735–5751.
15. Feron, S., Heinrichs, H., & Cordero, R. R. (2016). Are the Rural Electrification Efforts in the Ecuadorian Amazon Sustainable?. Sustainability, 8(5), 443.
16. Derakhshan, F. (2011). On Sustainability in Local Energy Planning. Lund University.
17. Pfahl, S. (2005). Institutional sustainability. International journal of sustainable development, 8(1-2), 80-96.
18. Burford, G., Hoover, E., Velasco, I., Janoušková, S., Jimenez, A., Piggot, G., ... & Harder, M. K. (2013). Bringing the "missing pillar" into sustainable development goals: Towards intersubjective values-based indicators. Sustainability, 5(7), 3035-3059.
19. Sharma, T., & Balachandra, P. (2015). Benchmarking sustainability of Indian electricity system: An indicator approach. Applied Energy, 142, 206-220.
20. Ilskog, E., & Kjellström, B. (2008). And then they lived sustainably ever after?—Assessment of rural electrification cases by means of indicators. Energy Policy, 36(7), 2674-2684.
21. Bazilian, M., Nakhooda, S., & Van de Graaf, T. (2014). Energy governance and poverty. Energy Research & Social Science, 1, 217-225.
22. Wimmler, C., Hejazi, G., de Oliveira Fernandes, E., Moreira, C., & Connors, S. (2015). Multi-Criteria Decision Support Methods for Renewable Energy Systems on Islands. Journal of Clean Energy Technologies, 3(3).
23. Reddy, B. S. (2015). Measuring and Evaluating Energy Security and Sustainability: A Case Study

of India.
24. Lyndrup, M., & Jensen, T. Y. H. W. (2012). Illuminating the Potential for a Rural Energy Service Company-Meeting the off-grid electrification challenge in Mozambique (Doctoral dissertation).
25. García, V.G.; Bartolomé, M.M. (2010). Rural electrification systems based on renewable energy: The social dimensions of an innovative technology. Technol. Soc. 2010, 32, 303–311.
26. Worldbank. Policy and Governance Framework for Off-grid Rural Electrification with Renewable Energy Sources (TF090884) (2008). Available online: https://openknowledge.worldbank.org/bitstream/handle/10986/7954/683390ESW0WHIT0lectrification0Final.txt?sequence=2/ Accessed on 24 August 2015).
27. White, W., Lunnan, A., Nybakk, E., & Kulisic, B. (2013). The role of governments in renewable energy: The importance of policy consistency. Biomass and bioenergy, 57, 97-105.
28. Dunmade, I. (2002). Indicators of sustainability: assessing the suitability of a foreign technology for a developing economy. *Technology in Society*, *24*(4), 461-471.
29. Brent, A. C., & Rogers, D. E. (2010). Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context. Renewable Energy, 35(1), 257-265.
30. Ilskog, E. (2008). Rural electrification sustainability indicators:-Manual for field workers.
31. Retnanestri, M. (2007). The I3A framework–Enhancing the sustainability of off-grid photovoltaic energy service delivery in Indonesia. University of New South Wales (UNSW): PhD thesis. OpenURL.
32. Ribeiro, F., Ferreira, P., & Araújo, M. (2011). The inclusion of social aspects in power planning. Renewable and Sustainable Energy Reviews, 15(9), 4361-4369.
33. Winkler, H., Simões, A. F., La Rovere, E. L., Alam, M., Rahman, A., & Mwakasonda, S. (2011). Access and affordability of electricity in developing countries. World Development, 39(6), 1037-1050.
34. Holland, R., Perera, L., Sanchez, T., & Wilkinson, R. (2006). Decentralised rural electrification: the critical success factors. Experience of ITDG (Intermediate Technology Developmental Group).
35. Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy policy*, *35*(5), 2683-2691.
36. Rondinelli, Dennis A.; Mc Cullough, James S.; Johnson, Ronald W. Analysing decentralization policies in developing countries: a political‐economy framework. Development and change, 1989, 20. Jg., Nr. 1, S. 57-87.
37. Breyer, C., Werner, C., Rolland, S., & Adelmann, P. (2011). Off-grid photovoltaic applications in regions of low electrification: High demand, fast financial amortization and large market potential. Proc. 26th EU PVSEC, 5-9.
38. Rosen, M.A. Energy sustainability: A pragmatic approach and illustrations. Sustainability 2009, 1, 55–80.
39. Bhattacharyya, S. C. (2012). Energy access programmes and sustainable development: A critical review and analysis. Energy for sustainable development, 16(3), 260-271.
40. Frame, D., Tembo, K., Dolan, M. J., Strachan, S. M., & Ault, G. W. (2011, July). A community based approach for sustainable off-grid PV systems in developing countries. In Power and Energy Society General Meeting, 2011 IEEE (pp. 1-7). IEEE.
41. International Atomic Energy Agency (IAEA), United Nations Department of Economic and Social Affairs (UNDESA), International Energy Agency (IEA), Eurostat, European Environment Agency (EEA), 2005. Energy Indicators for Sustainable Development: Methodologies and Guidelines, International Atomic Energy Agency (IAEA), Vienna.
42. Prandecki, K. (2014c). Theoretical Aspects of Sustainable Energy. Energy and Environmental Engineering, 2(4), 83– 90. doi:10.13189/eee.2014.020401
43. Pereira, M. G., Freitas, M. A. V., & da Silva, N. F. (2010). Rural electrification and energy poverty: empirical evidences from Brazil. Renewable and Sustainable Energy Reviews, 14(4), 1229-1240.
44. Vera, I. A., Langlois, L. M., Rogner, H. H., Jalal, A. I., & Toth, F. L. (2005). Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency. In Natural Resources Forum (Vol. 29, No. 4, pp. 274-283). Blackwell Publishing Ltd.

45. Cook, P. (2011). Infrastructure, rural electrification and development. Energy for Sustainable Development, 15(3), 304-313.
46. De Soysa, I., & Jütting, J. (2006). Informal Institutions and Development–What do we know and what can we do?. OECD Development Center, International Seminar.
47. Demirtas, O., "Evaluating the best renewable energy technology for sustainable energy planning," International Journal of Energy Economics and Policy, Vol. 3, 2013, pp. 23–33.
48. Mainali, B., Pachauri, S., Rao, N. D., & Silveira, S. (2014). Assessing rural energy sustainability in developing countries. Energy for Sustainable Development, 19, 15-28.
49. Jacquin, P., Ortiz, B., & Vallve, X. (2011). Social, economic and organizational framework for sustainable operation of PV hybrid systems within mini-grids. Report IEA-PVPS T11-05, 2011.
50. United Nations (2005). The Energy Challenge for Achieving the Millennium Development Goals. Available at: http://www.undp.org/content/undp/en/home/librarypage/environment-energy/sustainable_energy/the_energy_challengeforachievingthemillenniumdevelopmentgoals.html Accessed on 16 August 2015.
51. Axelsson, R., Angelstam, P., Degerman, E., Teitelbaum, S., Andersson, K., Elbakidze, M., & Drotz, M. K. (2013). Social and cultural sustainability: Criteria, indicators, verifier variables for measurement and maps for visualization to support planning. Ambio, 42(2), 215-228.
52. Hirmer, S., & Cruickshank, H. (2014). The user-value of rural electrification: An analysis and adoption of existing models and theories. Renewable and Sustainable Energy Reviews, 34, 145-154.
53. Müggenburg, H., Tillmans, A., Schweizer-Ries, P., Raabe, T., & Adelmann, P. (2012). Social acceptance of PicoPV systems as a means of rural electrification—A socio-technical case study in Ethiopia. Energy for Sustainable Development, 16(1), 90-97.
54. Fenner, R.A.; Ainger, C.M.; Cruickshank, H.J.; Guthrie, P.M. Widening engineering horizons: addressing the complexity of sustainable development. Proc. ICE Eng. Sustain. 2006, 159, 145–154.
55. Jordan, A., & O'Riordan, T. (1997). Social institutions and climate change: applying cultural theory to practice (p. 56). Centre for Social and Economic Research on the Global Environment.
56. Bertelsmann Stiftung, BTI 2014 — Chile Country Report. Gütersloh: Bertelsmann Stiftung, 2014.
57. Worldbank (NA). Development Research Group. Available at: http://databank.worldbank.org. Accessed on 13 January 2016.
58. Ministerio de Relaciones Exteriores (2015). Informe Anual Comercio Exterior de Chile 2014-2015. Departamento de Estudios Dirección General de Relaciones Económicas Internacionales. Available at: https://www.direcon.gob.cl/wp-content/uploads/2015/07/Informe-anual-de-Comercio-Exterior-de-Chile-2014-2015.pdf Accessed on 20 October 2015. (in Spanish)
59. Ministerio de Desarrollo Social (2014).CASEN. Situación de la pobreza en Chile Presentación de la nueva metodología de medición de la pobreza y síntesis de los principales resultados. (in Spanish). Available online at: http://observatorio.ministeriodesarrollosocial.gob.cl/documentos/Casen2013_Situacion_Pobreza_Chile.pdf Accessed on 4 October 2015 (in Spanish).
60. Yitzhaki, S. (1979). Relative deprivation and the Gini coefficient. The quarterly journal of economics, 321-324.
61. OECD (2015). Todos Juntos.¿Por qué reducir la desigualdad nos beneficia?...en Chile. Available at: http://www.oecd.org/chile/OECD2015-In-It-Together-Highlights-Chile.pdf Accessed on 23 January 2016. (in Spanish).
62. Ministerio de Desarrollo Social (2012). Encuestra Casen. Available at: http://www.redatam.org/redchl/mds/casen/casen2011/Index.html Accessed on 28 January 2016. (in Spanish)
63. Etcheverry, C. A. L. (2009). Descentralización: La experiencia chilena, un estudio sobre los gobiernos regionales. *Tékhne-Revista de Estudos Politécnicos*, (11), 145-171.
64. Ministero del Interior (2005). «DFL 1-19175: Fija el texto refundido, coordinado, sistematizado y actualizado de la Ley Nº 19.175, orgánica constitucional sobre gobierno y administración regional», Biblioteca del Congreso Nacional de Chile. (in Spanish)

65. Subsecretaría de Desarrollo Regional y Administrativo (SUBDERE) (2011). Misión, visión y ejes estratégicos de la SUBDERE. Available at: http://www.subdere.gov.cl/documentacion/misión-visión-y-ejes-estratégicos-de-la-subdere-0 Accessed on 21 January 2016. (in Spanish)
66. Pressacco, C. F., & Rivera, S. (2015). Democracia, participación y espacio local en Chile. Papel Político, 20(1), 65-89. (in Spanish).
67. Monje-Reyes, P. A. (2015). La Teoría Crítica como perspectiva de análisis de las relaciones de dominación y los procesos de descentralización en Chile. Cadernos EBAPE. BR, 13(2), 402-409. (in Spanish).
68. Pollitt, M.G. (2004). "Electricity Reform in Chile: Lessons for Developing Countries." CMI Electricity Project Working Paper, No.51, Department of Applied Economics, University of Cambridge.
69. Jadresic, A. (2000). Promoting Private Investment in Rural Electrification: The Case of Chile.
70. Comision Nacional de Energia (CNE) (NA). Available at: http://www.cne.cl/quienes-somos/ Accessed on 22 September 2015. (in Spanish)
71. Central de Energia (NA). Autoridad – coordinación. Available at: http://www.centralenergia.cl/actores/autoridad-energia-chile/ Accessed on 30 April 2016 (in Spanish)
72. Comision Nacional de Energia (CNE) (NAb). Balance nacional de energía. Available at: http://energiaabierta.cne.cl/visualizaciones/balance-de-energia/ Accessed on September 19 2015. (in Spanish)
73. Comision Nacional de Energia (CNE) (2009), Non-Conventional Renewable Energy in the Chilean Electricity Market, Comision Nacional de Energia (CNE) and Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ) GmbH, Santiago, 2009
74. Generadores de Chile AG (2015). Boletín del Mercado Eléctrico. Sector Generacion. (in Spanish)
75. Congreso Nacional de Chile (2013). Introduce Modificaciones A La Ley General De Servicios Eléctricos Respecto De La Generación De Energía Eléctrica Con Fuentes De Energías Renovables No Convencionales (in Spanish)
76. Senado de Chile, 2012. Available at: http://www.senado.cl/appsenado/templates/tramitacion/index.php?boletin_ini=6041-08. Accessed on 14 June 2014 (in Spanish)
77. Ministerio de Desarrollo Social (2013). Proyectos de electrificacion rural sistemas de autogeneración (in Spanish)
78. Ministerio de Desarrollo Social (2015). Metodología De Formulación Y Evaluación De Proyectos de Electrificación Rural. Available online: http://sni.ministeriodesarrollosocial.gob.cl/fotos/11%20Metodolog%C3%ADa%20de%20Electrificación%20Rural%202015.pdf Accessed on November 11 2015 (in Spanish)
79. Barnes, D. (2005)." Meeting the Challenge of Rural Electrification in Developing Nations: The Experience of Successful Programs". Energy Sector Management Assistance Program
80. Ministero del Interior y Seguridad Publica (DIPRES) (2012). Informe De Cumplimientos De Compromisos al 30-06-2012. Programa Electrificación Rural (PER). (in Spanish)
81. Rodriguez, Humbero (2012). H. Rodriguez, "Programa Remoción de Barreras para la Electrificación Rural," UNDP-GEF Project (Project CHI/00/G32 (11799) (in Spanish)
82. Covarrubias, F., Irarrázaval, I. & Galáz, R. (2005). Programa de Asistencia a la Gestión del Sector de la Energía: Desafíos de la Electrificación Rural en Chile. Washington, D.C.: Banco Internacional de Reconstrucción y Fomento.
83. Navarro , P., Titelman E., Twyman C. (2005). Informe Final Programa De Electrificación Rural. Ministerio Del Interior Comisión Nacional De Energía Subsecretaria De Desarrollo Regional Y Administrativo. Available at: http://www.dipres.gob.cl/595/articles-141050_informe_final.pdf Accessed on 18 September 2016. (in Spanish)
84. Deuman (2012). "Evaluación Ex-Post del Primer Proyecto de Electrificación Mediante Sistemas Fotovoltaicos en las Comunas de Tortel, Villa O´Higgins y Cochrane de la Provincia de Capitán Prat, Región de Aysén del General Carlos Ibáñez del Campo". (in Spanish)
85. Comunidades Energeticas (NA). Luces y sombras para las comunidades energéticas aisladas en Patagonia. Documento de Trabajo. REDES- Conicyt. N° 14001. Available at: http://www.comunidadesenergeticas.com/wp-content/uploads/2016/04/Luces-y-sombras-para-las-comunidades-energéticas-aisladas-en-Patagonia.23-marzo.pdf Accessed on 24 April 2016.

86. Ministerio de Desarrollo Social (NA). Banco Integrado de Proyectos (BIP). Available at: http://bip.ministeriodesarrollosocial.gob.cl/bip-consulta/BusquedaProyectoAction.do Accessed on 14 September 2016 (in Spanish).
87. Gobierno Regional de Aysén (NA). SISTEMAS DE GENERACION FOTOVOLTAICOS VARIOS SECTORES COMUNA DE AYSEN CODIGO BIP: 30125568 – 0. Available at: https://www.mercadopublico.cl/Procurement/Modules/Attachment/ViewAttachment.aspx?enc=POxTpc8k5kEehmdX82SavZIQCfSKkB5w%2fMuND7DysolmQMtod18DSfVAjxSA77MOtaEelk6qsw6Y804hSA6nr45%2b8ndDK%2b3WmB23KeufdQIbaBcUcpmlF9E9Z5TiT00pEgAvs1lvZFCICIDRphX58IpxZyTMBIE5zvsj1il2HWizs4gLOxZyAfrovwOwyuFqPN6TJw%2bUKvPU0x08o6ZStxBbIsfOB9ibwT8rQoSADfPOjWko4sZCKexwXnIlpzGoaBPHPa3ci527OsAIP7qYdcSAcRApjPp3lhdwjfqQieKylQ%2fSUyz6IEGSYceVDRfs Accessed on 22 September 2016
88. International Energy Agency (IEA) (2009). Chile: ENERGY POLICY REVIEW. ISBN 978-92-64-07314-2. Available at: https://www.iea.org/publications/freepublications/publication/chile2009.pdf accessed on 14 May 2014.
89. Ministerio de Energía (NA). Proyectos DAEE. Available at: http://proyectosdaee.minenergia.cl Accessed on 15 September 2016 (in Spanish).
90. Jiménez-Estévez, G. A., Palma-Behnke, R., Ortiz-Villalba, D., Mata, O. N., & Montes, C. S. (2014). It Takes a Village: Social SCADA and Approaches to Community Engagement in Isolated Microgrids. IEEE Power and Energy Magazine, 12(4), 60-69.
91. Nuñez, O., Villalba, D. O., & Palma-Behnke, R. (2013). Microrredes en la red eléctrica del futuro-caso Huatacondo. Ciencia y Tecnología: Revista de la Universidad de Costa Rica, 29(2), 1-16. (in Spanish)
92. Estay, C.(2006). Remocion de Barreras para la electrificacion rural con energias renovables. Informe Catastro de Campo XI Region. (in Spanish)
93. GreenLab UC and Ingenergia DICTUC (2012). Estimación de Parámetros para Cuantificación de Beneficios Sociales y Externalidades en Proyectos de Energización. Santiago de Chile. (in Spanish).
94. Centro de Energía (NA). http://centroenergia.cl/en/proyectos/proyectos-destacados/micro-red-huatacondo/ Accessed on 15 September 2016 (in Spanish).
95. Doberti, G (2013). ERNC en la Agricultura familiar campesina y Programa Nacional de Bombeo Fotovoltaico INDAP. (in Spanish)
96. Instituto Nacinoal de Normalizacion (INN) (2006). Listado de Normas Chilenas Por CIN. (in Spanish)
97. IEnergia (NA). Adquisición e Instalación de Sistemas de Bombeo Fotovoltaico Licitación Pública No. 609-177-LP11. Available at: http://www.mercadopublico.cl/Procurement/Modules/RFB/DetailsAcquisition.aspx?qs=dza7kbJKxHYLcrpUT5HvHQ== Accessed on 4 May 2016. (in Spanish)
98. Flick, U., von Kardoff, E., & Steinke, I. (Eds.). (2004). A companion to qualitative research. Sage.
99. MAXQDA, software for qualitative data analysis, 1989-2016, VERBI Software – Consult – Sozialforschung GmbH, Berlin, Germany
100. Susskind, L., Kausel, T., Aylwin, J., & Fierman, E. (2014). The Future of Hydropower in Chile. Journal of Energy & Natural Resources Law, 32(4).
101. Nerini, F. F., Broad, O., Mentis, D., Welsch, M., Bazilian, M., & Howells, M. (2016). A cost comparison of technology approaches for improving access to electricity services. Energy, 95, 255-265.
102. Comision Nacional de Energia (CNE) (2002). Proyecto CHI/00/G32."Remocion de barreras para la electrificacion rural con Energias Renovables." Proyecto Fotovoltaico IVa Region de Coquimbo.Analisis y Evaluacion de posibles esquemas de gestion. (in Spanish)
103. Ministerio de Energia (2014). Agenda de Energía. Un Desafío País, Progreso Para Todos. Available at: http://www.cumplimiento.gob.cl/wp-content/uploads/2014/03/AgendaEnergiaMAYO2014_FINAL.pdf Accessed on 1 June 2016. (in Spanish)
104. Ministero del Interior y Seguridad Publica DIPRES (2014b). Informe De Cumplimientos De Compromisos al 30-06-2014. Programa Electrificación Rural (PER). Available at:

http://www.dipres.gob.cl/574/articles-94552_doc_pdf.pdf Accessed on 5 September 2015 (in Spanish)
105. Climate Analytics, Ecofys and Potsdam Institute for Climate Impact Research (2016). Are countries on track for 2°C or 1.5°C goals? Available at: http://climateactiontracker.org/countries/chile.html Accessed on 1 March 2016.
106. Ministerio de Medio Ambiente (2014). Anteproyecto De Contribución Nacional Tentativa (Indc) En El Contexto Del Tratado Climático 2015 A Ser Finalizado En La Vigesimo Primera Conferencia De Las Partes (Cop21) De La Convencion Marco De Naciones Unidas Sobre Cambio Climático. Available at: http://portal.mma.gob.cl/consultacontribucion/ Accessed on: 21 January 2016 (in Spanish)
107. Ministero del Interior y Seguridad Publica (DIPRES) (2014b). Presupuesto por partida 2014. Proyecto de Ley de Presupuestos 2014 Available at http://www.dipres.gob.cl/594/articles-109104_Gasto_por_Partida_2014.pdf Accessed on 27 March 2015 (in Spanish)
108. Comision Nacional de Energia (CNE) (2015). Capacidad Instalada por Sistema Electrico Nacional" December 2015. Available at: http://www.cne.cl/en/estadisticas/electricidad/ Accessed on 15 February 2016.
109. Hernando, A. (2014). El sector energético en Chile y la Agenda de Energía 2014: Algunos elementos para la discusión. Centro de Estudios Publicos. (in Spanish)
110. Comisión Ciudadana-Técnico-Parlamentaria para la Política y la Matriz Eléctrica (CCTP) (2011). Chile Necesita una Gran Reforma Energética. Available at: http://www.patagoniasinrepresas.cl/final/dinamicos/chile_necesita_una%20gran_reforma_energetica.pdf Accessed on 17 June 2016. (in Spanish)
111. Barton, J. R. (2013). Climate change adaptive capacity in Santiago de Chile: creating a governance regime for sustainability planning. International Journal of Urban and Regional Research, 37(6), 1916-1933.
112. Newbold, J. (2004). Balancing economic considerations and the rights of indigenous people. The Mapuche people of Chile. Sustainable Development, 12(3), 175-182.
113. Almonacid Barría, A. (2014). Autoconsumo Fotovoltaico en Chile. Potencial y Barreras Energía Solar para la Generación de Electricidad y Calor. GIZ, Santiago de Chile, Chile. (in Spanish)
114. Instituto Nacional de Estadistica (INE), (NA). VII encuesta de presupuestos familiares. (in Spanish). Available at: http://www.ine.cl/epf/base-de-datos.php Accessed on 14 January 2016.
115. Ministerio de Energia (2016). Congreso Nacional aprueba proyecto de Equidad Tarifaria. Available at: http://www.energia.gob.cl/tema-de-interes/congreso-nacional-aprueba-proyecto. Accessed on 1 June 2016. (in Spanish)
116. HOMER (2011). Getting Started Guide for HOMER Legacy (Version 2.68). Available at: http://www.homerenergy.com/HOMER-getting-started-guide.html Accessed on July 2014

### 5.2 Paper 3: Are the rural electrification efforts in the Ecuadorian Amazon sustainable?

In this paper, I assess the sustainability of rural electrification programs in Ecuador, paying special attention to programs targeting small indigenous communities in the Amazon basin. Following the theoretical framework described in Chapter 2, my assessment considers four dimensions of sustainability (institutional, economic, environmental, and socio-cultural), while according to the methodology described in Chapter 3, my findings are based on an exhaustive qualitative document analysis, complemented by semi-structured expert interviews.

I found that Ecuador has not been able to establish strengthened formal institutions in the energy sector due to a variety of issues including disruptive changes in electrification policies, a poor enforcement of constitutional rights, a lack of technical standards, and legal incoherence. In spite of these major flaws, national efforts to fund rural electrification have been persistent throughout different administrations, which is due to a broad consensus on granting access to energy for all. Unfortunately, despite of these efforts, substantial reliability issues of the off-grid PV systems emerged, since the projects have completely neglected the allocation of funds for O&M. Moreover, neither constitutional claims for environmental protection, nor socio-cultural rights for indigenous communities have played a major role in rural electrification projects based on off-grid PV systems. Ensuring sustainability in the Ecuadorian rural electrification sector therefore demands for strengthened institutions that make progress towards environmental awareness, social acceptance, and cultural justice.

*Article*
# Are the rural electrification efforts in the Ecuadorian Amazon sustainable?

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**Abstract:** In this paper, we assess the sustainability of rural electrification programs in Ecuador, paying special attention to programs targeting small indigenous communities in the Amazon basin. Our assessment considers four dimensions of sustainability (institutional, economic, environmental, and socio-cultural) and is based on an exhaustive qualitative document analysis, complemented by semi-structured expert interviews. We found that disruptive changes have affected the electrification policies in Ecuador during decades avoiding the development of strengthened institutions. Despite this major drawback, we found that there is a consensus on granting access to energy for all. This partially explains the national efforts, persistent through different administrations to fund rural electrification. However, in the case of off-grid photovoltaic solutions, these efforts have consistently neglected allocating funds for operation and maintenance, which has seriously compromised the sustainability. Moreover, although Ecuadorian officials declared to favor stand-alone photovoltaic systems in the case of indigenous communities in the Amazon, we found that environmental or socio-cultural aspects have a minor role in the selection of these systems. Progress regarding environmental awareness, social acceptance, and cultural justice, is still needed for ensuring the sustainability of rural electrification efforts in the Ecuadorian Amazon.

## 1. Introduction

In 2013, about 1.2 billion people (i.e. 17% of the global population) did not have access to electricity (IEA, 2015). The lack of access to energy is mainly a rural issue: e.g., while in 2012 the global urban electrification rate reached 94%, the rural electrification rate constituted only 68% [1].

Although it was not explicitly declared a goal, the access to energy was already considered a key factor for achieving the eight Millennium goals [2]. This is why, in 2015, affordable and clean energy was explicitly named as one (goal number seven) of the 17 new Sustainable Development goals, which are to be achieved by 2030 [3]. Furthermore, in 2011 the United Nations (UN) initiated the "Sustainable Energy for all" initiative, which focuses on three targets to be reached by 2030: 1) the provision of universal access to modern energy; 2) doubling the energy efficiency rate; and 3) doubling the share of Renewable Energy (RE) globally [4]. The emphasis given to RE can be tracked back to the Agenda 21 in Rio in 1992, that highlighted not only the need of reliable and affordable access to clean energy, but also the environmental soundness to be accomplished [5].

As compared to its Latin-American neighbors, the electrification rate in Ecuador is high, having increased from 89% of the total population (79% of the rural population) in 2001, to 94,82% (89,03% of the rural population) in 2010, and up to 96.77 % (no rural figures available) in December 2013 [6,7]. These notable achievements regarding electrification have been based on the extension of the grid, which was favored by the size of Ecuador (the smallest among the Andean countries). However, the focus on on-grid expansion has begun to change in recent years as it becomes unviable in isolated remote areas. For example, in the northern Ecuadorian Amazon, the electrification rate ranges from 81.6% in the province of Pastaza to 88.2% in the province of Napo [7]. In addition to the major geographical challenges for the extension of the grid, the main challenge in the Ecuadorian Amazon basin (that stands for nearly 40% of the territory of the country) is that the small indigenous communities in these areas are dispersed and isolated [8], which makes the grid expansion too costly.

Although off-grid systems based on RE may have been an alternative to the national Ecuadorian grid in prior rural electrification efforts, little attention has been paid to non-conventional renewable energy (NCRE) in Ecuador. Indeed, the NCRE share in the country accounts for less than 2% of the total power generation, with photovoltaic (PV) (0.07%) and Eolic (0.32%) still playing a minor role [9]. Since 1998, the few efforts focused on small indigenous communities in the Ecuadorian Amazon basin have been based on stand-alone PV solutions. However, more recently the Ministry of Electricity and Renewable Energy (MEER) began to promote PV-powered microgrids in remote areas [10].

In this paper, we critically analyze the current status and challenges of electrification programs in Ecuador aimed at the rural population of remote areas. Paying especial attention to programs targeting small indigenous communities in the Amazon basin, we addressed the following research question: Are the rural electrification efforts in Ecuador sustainable?

In order to answer our research question, we conducted an exhaustive document analysis [11] complemented by a qualitative research based on semi-structured interviews [12]. The interviewees included experts from different ministries, national and international agencies, energy companies (public and private), non-profit-organizations (NPOs), consultants, and researchers. Although below we describe several relevant PV-based electrification efforts in Ecuador, our research was aimed at gathering an overall picture of the rural electrification efforts in the country, rather than measure the success or failure of specific projects.

The gathered information allowed us to assess the sustainability of the rural electrification efforts in Ecuador. As detailed below, our assessment is based on a set of indicators (see our theoretical framework) corresponding to the four dimensions of sustainability considered in this paper: institutional, economic, environmental, and socio-cultural (see e.g. [13-15]).

## 2. Materials and Methods

### 2.1 Theoretical Framework

The importance of institutional sustainability is well established (see e.g. [15-17]. Institutions are a framework of formal and informal guidelines that set the rules of interaction between individuals [18]. While informal institutions include religious or moral values and traditions [19], formal institutions comprise laws, regulations, and standards meant to correct market failures and protect individual rights [20]. Failures in rural electrification have often been attributed to the lack of coherence in the legal frame (laws, regulations, and standards) [21-23], or the absence of proper standards (e.g. [24-25]). Therefore, strengthened formal institutions are considered to be essential for rural electrification [21-23,26,27]. According to Levitsky and Murillo [28], two factors determine the strength of formal institutions: their enforcement and their stability (durability).

Numerous studies have revealed project failures in rural electrification due to a lack of collaboration between local and central government entities on the one hand (see e.g. [29-31]), and a lack of collaboration between different stakeholders from the energy sector (e.g. public agencies, NPOs, and private companies) on the other hand (see e.g. [32,33]). These studies underline the importance of openness to participation in the decision-making process by considering the role of informal institutions [22,26]. Decentralization has also been stressed for facilitating participative decision-making, improving in turn the accountability of authorities [34] as well as the adaptability (i.e. the ability to meet the changing needs of the population in remote areas) [30,35-38].

Ensuring the funding or affordability of energy solutions is a major issue since rural households of developing countries like Ecuador are generally significantly poorer than urban households. The economic sustainability of rural electrification solutions requires ensuring the funding or affordability of the systems (i.e. the initial investments and the operation and maintenance (O&M)) (see e.g. [23, 38-40]). In this context, it is important to provide a cost-effective solution for electrification [23,38].

The security of supply (or reliability) of the provided solution also needs to be addressed. Although RE may help to increase the reliability of supply (due to the diversification of energy matrix; [23,39,41]), reliability in rural areas demands for local access to spare parts, which entails the know-how to exert maintenance [42]. Moreover, as a higher access to energy is usually correlated with higher income [38], these solutions are expected to contribute to the income generating opportunities for inhabitants of remote areas [43-45]. In this case, electrification programs need to be coupled with complementary infrastructure including training and education [46].

Empowered individuals have strong influence on policy makers [47]. Therefore, ensuring environmental sustainability depends to a significant extent on people supporting the adoption and enforcement of policies aimed at environmental protection. The support is linked with understanding and awareness [48].

Environmental sustainability also entails the prevention of negative environmental impacts [49]. RE can generate electricity with low or very low net CO2 emissions over their lifecycle [48]. In addition to this positive long-term effect, the adoption of RE technologies in the Amazon may have direct short-term environmental impacts in terms of reducing deforestation, which may also result in a loss of biodiversity [23,38,39,50]. Although the positive impact of PV-based solutions is appealing, ensuring recycling and proper disposal of PV modules and batteries after the end of their service life needs to be ensured in order to avoid indirect environmental impacts [33].

Socio-cultural sustainability embraces notions of social justice, since ensuring the accessibility (i.e. the access to electricity) may improve the life conditions of rural population in term of more education (longer study hours due to the availability of electric light) and higher productivity (use of machines) [23,35,37,51,52]. These notions of social justice drive the principle of equity/disparity used to distribute the limited available resources as well as to decide who is provided with electricity [38,39] and the amount of energy to be provided to each person [35,39, 53].

Socio-cultural sustainability also requires social acceptance (which implies a participatory and inclusive approach in which the local community is engaged to increase their accountability for a technology; [37,54,55]); as well as the accuracy (which comprises the selection of the technology appropriate to the local consumer demands; [23,42]).

The importance of culture (traditions, values, identities, and cultural diversity) for sustainability has been stressed elsewhere (e.g. [26,35,53,56]). In this regard, cultural justice refers to justice through participation as well as mutual learning and knowledge sharing [57]. The cultural justice in rural electrification can be evaluated according to the ability shown to integrate the technology into the existing social structures [23,50,51,58].

Based on this review, we have defined a set of indicators (see Table 1) that were in turn used to qualitatively evaluate the sustainability of the rural electrification efforts in Ecuador.

**Table 1**: Indicators of sustainability used in this study

| Institutional | Economic | Environmental | Social /Cultural |
|---|---|---|---|
| **Stability (Durability)**<br><br>**Regulation and Standards**<br><br>**Decentralization and Openness to participation**<br><br>**Adaptability (ability to meet future needs)** | Cost effectiveness<br><br>Reliability<br><br>Funding (initial investment; operation and maintenance)<br><br>Contribution to income of users | Environmental awareness<br><br>Environmental impact | Accessibility (disparity, equity)<br><br>Social Acceptance<br><br>Accuracy<br><br>Cultural Justice |

**2. 2 Methodology**

A qualitative document analysis was conducted; document analysis is used when the history of events is relevant to the research question [11]. It included public documentations such as the current constitution; the "National Plan for Good Living (PNBV by its Spanish acronym); electrification laws and regulations published by the energy regulator; energy roadmaps (prior and current versions); academic publications on rural electrification projects; online newspaper articles on the social effects of energy projects; rural electrification project descriptions and their outcomes from international organizations; and scientific papers on topics related to the PNBV as well the fields of study such as decentralization, government relations with indigenous communities, and political institutions. Special attention was paid to prior efforts that tackled rural electrification programs in Ecuador from the perspective of the indigenous communities (see for example references [59-62].

In addition to the document analysis, we conducted semi-structured interviews with stakeholders. According to the approach broadly used for the assessment of sustainability (see for example [63-66]), the stakeholders included experts from different ministries, national and international agencies, energy companies (public and private), non-profit-organizations (NPOs), consultants, and researchers (see Table 2 for details). The selection of initial interview partners was grounded on literature review that we conducted before empirical research started. After receiving information from the initially identified interviewees, we selected new relevant interview partners according to both the theoretical sampling methodology [11] and the snowball principle [11,67]. Once we had reached data saturation, as no additional information could be obtained from further interviews, the empirical interview process was closed (for details on this methodology, see [11,67].

A total of 22 interviews were conducted in three series: the first interview series (12 interviews) was held in December 2014 in Quito (Ecuador). Based on the recommendations from the first group of interviewees, we interviewed further experts (5) in April 2015 (also in Quito). Finally, for completion of data collection, we conducted five additional interviews via Skype® in May 2015, mainly with international partners. Most of the interviews were held in Spanish except one interview that was held in English and one in German.

While interviews with officials of the central government gave insights into the legal framework as well as into strategic plans, interviews with representatives of Electricity Distribution Companies (EDCs) provided information on specific rural electrification projects. Interviews with academics allowed us a better understanding of the political and social circumstances, while interviews with international and local NPOs gave important insights into the consequences on the local population of policies and specific rural electrification programs. Indeed, representatives of NPOs, closely working with the communities, exposed several complaints from indigenous communities regarding the electrification policy of the central government.

Interview questions were clustered into four dimensions (institutional, economic, environmental, and socio-cultural) considered in this paper and addressed each of the indicators in Table 1. Questions on the institutional dimension (e.g. "What has been the role of this institution for rural electrification in the past and the present?" "How is the rural electrification process put into practice?" "How are the community members imbedded in the rural electrification projects?" "Who and how is the compliance with the regulation assured?") were focused on the regulatory framework and its compliance, as well as the interaction between key stakeholders. Questions on the economic dimension (e.g. "Who is paying for the initial investment/O&M costs?" "What has the economic impact been on the user (e.g. energy for productive uses)?" "What are the technical minimum requirements for the systems?") addressed the funding of the systems over their lifetime, their reliability as well as the economic potential of energy for rural areas. Questions on the environmental dimension ("How is battery disposal handled in rural electrification?" "How would you describe the awareness on environmental issues on a political and social basis?") focused on the environmental awareness (formal and informal). Finally, questions on the socio-cultural dimension ("To what extend (and how) are projects adjusted to local circumstances?" "Have you found different behaviors related to the ethnical background?" "Do you provide different technological solutions to different communities? If so, what are the criteria these decisions are based on?" "Do you remember any cases where PV systems were rejected by a community?) aimed to address socio-cultural aspects of policies and electrification programs as well as their social acceptance and accuracy. Although the questions were previously defined, the semi-structured interviews allowed us dive much deeper into specific topics by asking additional questions according to the background and expertise of the interview partners.

The interviews lasted between 28 and 108 minutes, and all of them but one (as one interviewee asked to stop the recorder fearing political retaliations) were fully recorded. Two additional statements were given by email. A representative from a German Bank for Development refused the interview fearing to fuel diplomatic turbulences between Germany and Ecuador at that time.

The information gathered by the document analysis and the semi-structured interviews allowed us to assess the sustainability of the rural electrification efforts in Ecuador. The assessment of the information was based on coding. By using the MAXQDA11® software, the codes were clustered according to a set of indicators (see Table 1) corresponding to the four dimensions of sustainability considered in this paper: institutional, economic, environmental, and socio-cultural. Our assessments are presented below.

**Table 2**: Interview Partners

| Area | Sub-Area | Division (if applicable) |
|---|---|---|
| Government Institutions Energy Sector | Ministry of Electricity and RE (MEER) | Division of Renewable Energy |
| | | Division of Energy Distribution |
| | Agency for Regulation and Electricity Control (ARCONEL, by its Spanish acronym) | Division of Planning |
| | | Division of Technical Regulation |
| | | Division of Environmental Management |
| | National Institute for Renewable Energy and Energy Efficiency | Research Line on Solar Energy |

| | | |
|---|---|---|
| Government Institutions<br><br>Non- Energy Sector | Coordinating Ministry of Strategic Sectors (MICSE) | Sub-secretary Coordinating Ministry |
| | National Planning and Development Secretary (SENPLADES by its Spanish acronyms) | General Sub-secretary for Planning of Good Living |
| | Ministry of Environment | Third Communication on Climate Change Mitigation |
| Academics & Research Institutes | Universities/Research Centers | Public Policies |
| | | Sociologist |
| | | Electric Engineer |
| International Agencies | United Nations Development Program (UNDP) | Energy Division |
| | Inter-American Institute for the Cooperation in Agriculture (IICA by its Spanish acronyms) | Division of renewable energies |
| NPOs | Ecuadorian Foundation for the Proper Technology (FEDETA) | |
| | Rural Development Organization (naming undesired) | Local solar energy initiative |
| | Cooperation for the Investigation on Energy | |
| Energy Companies | Electricity Distribution Companies (EDCs) | RE Unit |
| | Private RE Companies | RE Companies |
| Independent Energy Consultant (previously hired at EDCs) | Energy | Rural Energy |

## 3. Ecuador

### 3.1. General Background

Ecuador is a former Spanish colony of about 283,500 km$^2$ bordered by Colombia on the north, Peru on the east and south, and the Pacific Ocean to the west. The Andes act as a transect from north to south dividing the country into three geographic regions: the coastal lowlands (located between the Andes and the Pacific coastline and characterized by its tropical climate), the Andean highlands (mostly temperate and relatively dry), and the Amazon basin (on the eastern side of the Andes and characterized by a rainforest climate).

Most of the inhabitants of the country (nowadays about 15,8 millions) traditionally lived in the coastal lowlands and the Andean highland. In 2015, 63.7% of the total population of the country was urban [68]. By the mid-sixties, the Amazon basin of about 120,000 $km^2$ was basically disconnected from the rest of the country, which favored the conservation of the Amazon rainforest. This area was traditionally inhabited by small and dispersed indigenous communities. However, during the last decades the central government favored the colonization of the region, which was further accelerated by the discovering of oil in the early seventies. To date, still less than 5% of the total population of the country inhabits this area that stands for nearly 40% of the total territory of the country.

Although Ecuador's economy was traditionally based on agriculture, during the last decades the country has been highly dependent on oil revenues that in 2013 accounted for 56.5% of its incomes from exports [69]. Mostly driven by oil revenues, between 2007 and 2014, on average the GDP grew by 4.3% per year, while the poverty ratio declined from 38% to 23% during that period [70].

The government of the country is organized at different levels: municipalities or cantons (often including towns, small cities and also rural areas), provinces (that includes several cantons), and more recently political regions (that include several provinces). Ecuador is a presidential republic and representative democracy. Officials are elected by popular vote also at different levels: majors in municipalities or cantons, prefects in provinces, and the president of the country (that controls the national government and designates officials in charge of the political regions [71]. Despite this formal decentralization, oil revenues are controlled by the national government, and there is a partial redistribution of these funds to municipal and provincial governments. The representatives (congress men) are elected by popular vote to the National Assembly (unicameral Congress) that acts as the legislative branch. The current President, Rafael Correa, was elected in January 2007 for the first time, and reelected in 2013. Since 2008, the national government has been reorganized, currently accounting for 21 Ministries, 6 Coordinating Ministries, and 11 State Secretaries [72]. In 2013, Ecuador ranked 79th on the Democracy Index (compiled by the Economist Intelligence Unit, EIU).

### 3.2 Electrification in Ecuador

Generation and distribution of electricity began in Ecuador during the first half of the XX century as private initiatives, later supported by local governments (municipalities) of major cities in the country. This is why municipalities still hold some shares of EDCs serving major cities in the country (see e.g. [73-75]). These early initiatives were focused on major urban nucleus and only in the early sixties the national government assumed a regulation role by creating the Ecuadorian Institute of Electrification (INECEL, by its Spanish acronym). Since 1961 to 1999, INECEL centralized the sector's planning, regulation, tariffs, construction, and operation processes, leading to high electrification growth rates [76]. INECEL bought most of the shares of existing EDCs, and created new public companies on generation (including important hydroelectric projects), transmission, and distribution (aimed at areas beyond major cities) [77,78].

In the nineties, a liberal administration tried to open the electric sector to private investors [79]. Aimed at the privatization of the public EDCs, this administration decreed the substitution of INECEL by the Agency for Regulation and Electricity Control (CONELEC, by its Spanish acronyms). CONELEC assumed the role of strategic planning, control and supervision of the EDCs, as well as the tariff regulator [80], while INECEL's assets were transferred to the "Solidarity Fund" ("Fondo de Solidaridad"). The latter was an agency created in 1993 and controlled by the National Modernization Council (CONAM, by its Spanish acronym) that led the privatization processes in Ecuador [81]. The "Solidarity Fund" became the majority shareholder of six generation companies, one transmission company, and 20 EDCs [10]. Yet, the planned privatization of the EDCs was never accomplished.

In 2009, the Correa Administration eliminated the "Solidarity Fund" transferring the assets of the six generation companies to a new public consortium: the Ecuadorian Electric Corporation (CELEC E.P. by its Spanish acronym). Assess of the EDCs were transferred to a new ministry: the Ministry of Electricity and Renewable Energy (MEER by its Spanish acronym) that assumed the role of designing policies on generation, transmission, and distribution [76].

In 2015, the Correa Administration ordered the merge of the existing EDCs to form a single company, and reorganized the functions of the MEER and CONELEC (which slightly changed its name and its Spanish acronym to ARCONEL), giving more power to the MEER. The MEER assumed the role of strategic planning, while ARCONEL kept the role of control and supervision of the EDCs, as well as a tariff regulator [80].

Currently, the share of NCRE in Ecuador accounts for less than 2% of the total power generation, with PV (0.07%) and Eolic (0.32%) playing still a minor role [82]. The country mainly relies on hydro and thermal power plants that account for 46% and 49% of the total power generation respectively [82]. The relative importance of hydropower plants will sharply increase in the upcoming years, as the government commissioned the constructing of several major power plants accounting for a total power capacity of about 2.5 GW, which stands for an increment of nearly 50% of the current power capacity (5.3 GW) [83].

Tariffs in the on-grid sector are highly regulated; all of grid-connected residential users in Ecuador are subjected to the same electricity tariff (US$ 1.4 fixed costs plus US$ 0.08 per kwh consumed), which is adjusted annually by ARCONEL [84]. However, households that consume less than 130kwh/month (in the Amazon basin and the Coastal lowlands) and 110kwh/month (in the Andean highlands) are subjected to the so-called "dignity tariff" (enacted by Constitutional Mandate No.15 in 2008), which is half of the regular tariff. On the other hand, the off-grid sector is still mostly unregulated and there is neither a tariff regulation nor are there service standards.

**3.3 Rural Electrification**

As compared to its Latin-American neighbors, the electrification rate in Ecuador is high, having increased from 89% of the total population (79% of the rural population) in 2001, to 94,82% (89,03% of the rural population) in 2010, and up to 96.77 % (no rural data available) in December 2013 [6,7].

These notable achievements in rural electrification were fueled by the "Fund for Rural and Urban-marginal Electrification" (FERUM by its Spanish acronym). Since 1998 until 2008, the FERUM received resources from a 10% tax charged to the tariff paid by on-grid commercial and industrial consumers around the country [85].

In 2008, the Correa administration cancelled this tax, and funds for FERUM have thereinafter directly been disbursed from the national budget. Although the funds for FERUM increased in the first years (from US$ 46 millions in 2007 to US$ 126 millions, in 2008), promises of funding the FERUM by US$120 millions were not fulfilled in 2009 and in 2011 [6]. More recently, in 2012/2013, FERUM received about US$ 55 millions (US$ 40 millions by the Inter American Development Bank (IADB) and about USD 15 million by the national government). A new contract (known as FERUM II) was signed with the IADB in 2014 for a credit of US$ 30 millions [86].

So far, most of the FERUM investments have been focused on the expansion of the grid to rural areas. From 1998 to 2009, only 1.86% of the FERUM was invested in off-grid RE solutions including stand-alone PV systems [87]. However, the focus on the grid expansion has begun to change in recent years as it becomes unviable in remote areas. Especially the provinces of Pastaza and Napo in the northern Ecuadorian Amazon and the province of Esmeraldas in the northern Ecuadorian coastal lowlands present major geographical challenges for the extension of the grid. Moreover, some communities in these areas are dispersed and isolated [8], which makes the grid expansion too costly.

Until 2009, few efforts targeted these remote and isolated areas by providing stand-alone PV solutions. Before disappearing, the CONAM and the "Solidarity Fund" installed off-grid PV systems in the Ecuadorian Amazon basin [88]. International initiatives in collaboration with the MEER, such as the Euro-Solar program (EUROSOLAR, NA), and the PROMEC program [88] were also relevant efforts, targeting communities in the Amazon basin and the northern coastal lowlands [89]. Yet, estimations indicate that only about 10% of the off-grid PV systems installed until 2009 are still in use [90].

In 2009, ARCONEL proposed to the EDCs to form special units focused on rural electrification based on off-grid RE solutions. Some companies, following this proposal, thereinafter deployed stand-alone PV systems funded by FERUM. For example, the EDC "Empresa Electrica Quito (EEQ)" formed a RE Unit and has installed 370 stand-alone PV systems (funded by the FERUM) in rural areas surrounding Quito (the capital of the country of nearly two millions inhabitants). EEQ has the responsibility of providing electricity to Quito, but also to the surrounding rural population (that includes non-indigenous farmers separated from the grid by dozen of kilometers). EEQ has installed systems of 390 Watts peak (Wp), which translates into approximately 45.81kwh per month (roughly twice those provided by the EDC CentroSur) [91]. EEQ set a monthly fix price of US$5. The company subsidies the remaining US$14.4 to cover the total O&M costs of US$ 19.4 per month [91].

Another EDC, "CentroSur", also formed a RE Unit and installed since 2010 approximately 2900 stand-alone PV systems of 150 Wp in about 70 communities in the Amazon basin. CentroSur is the EDC in charge of providing electricity to Cuenca (the third most populated city in Ecuador with nearly half a million inhabitants), but also to a significant part of the southern Ecuadorian Amazon basin (inhabited by small indigenous communities –each with a population of less than 60- often highly dispersed). CentroSur estimates that the minimum energy generated by their PV solutions is 19kwh per month, which is charged by applying the "dignity tariff" [88]. Montero and Cajamarca [92] estimate that this tariff only covers about 15% of the related operational costs of the EDC. The rest of the operational costs are normally absorbed by the EDC, which is facilitated by the size of the company and the incomes from providing the service to a significant urban population.

Nowadays, rather than stand-alone solutions, the MEER is promoting PV-powered microgrids of up to 10 Mega Watts peak (MWp) in remote areas. These microgrids should be funded by the FERUM (through the FERUM II contract) and are meant to generate energy not only for households, but also for schools, public lightning, and small health centers.

## 4 Results

### 4.1 Institutional Sustainability

#### *Stability*

Institutional sustainability requires strengthened formal institutions, whose strength is determined by their enforcement and their stability (durability). Both have always been problematic in Ecuador.

As described above, the Correa administration has introduced profound reforms that included the energy sector [93]. However, institutional changes did not begin with the Correa administration. In fact, Ecuador has undergone frequent institutional changes in its short history as a free nation. Since 1938, the country has adopted seven different constitutions: in 1938, 1945, 1946, 1967, 1978, 1998, and 2008. The last of these constitutions was promoted by President Rafael Correa after his election in 2006.

Disruptive changes can also be observed in RE policies. For example, in 2011, ARCONEL introduced a very high Feed-In-Tariff (FIT) of 40 cents per kWh to foster on-grid NCRE; an even higher tariff of 44 cents per kWh was introduced in Galapagos Islands (which are also Ecuadorian territory). Despite the fact that it did not reach the goal of 300 MWp, the FIT program was abandoned.

Rural electrification efforts by off-grid PV systems have been affected by these frequent institutional changes as well. In 2004, the CONAM, decided to run a program to install 620 stand-alone PV systems. The systems were acquired and installed by the "Solidarity Fund" in remote areas in the Ecuadorian Amazon basin. In order to ensure the maintenance of the systems, they were supposed to be transferred to the EDCs. However, the transfer of the system to the EDCs did not occur and the "Solidarity Fund" was eliminated in 2009. According to an EDC representative, due to the lack of a legal transfer, the PV systems did not have an owner and were eventually abandoned, as they were not maintained by anyone.

Several interviewees considered the continuing changes in the institutional framework and the changes in authorities to be a significant issue in Ecuador. According to a representative of the UNDP *"one of the big issues of any project is the rotation of authorities in the different Ministries. [...] So, often the planning of the projects is affected by these authority changes. And this really affects the projects a lot, and especially, it affects the transmission of all the generated information*."

***Regulations and Standards***

The National Planning and Development Secretary (SENPLADES, by its Spanish acronym) was found in 2004 as a planning entity that originated from a merger of the CONAM with the National Secretary of Development of Millennium Goals [94]. It is a branch of the Presidency and is the ultimate to decide on the project approvals of all sectors. SENPLADES generated the "National Plan for Good Living PNBV 2009-2013", and more recently, the PNBV 2013-2017 [94].

Allegedly based on the 2008 Constitution, the PNBV aims to provide a roadmap for developing the country. However, several interviewees have questioned if the PNBV was conceived according to the reality of the country's situation and if its effective execution is possible. According to a social science researcher

*" ... they [SENPLADES] are writing what is the policy or the dream of Good Living. [….] So you got persons [….] who are directly from the middle upper class, especially middle class, who have a wonderful vision, full stop. From there on it is disconnected from reality."* Furthermore, according to a political science researcher, objectives in the PNBV are expressed as mere intentions without any quantifiable indicators.

A professor of electric engineering argued that another reason why PNBV objectives are hardly achievable is that *"many of these things are in the constitution, but from the constitution it needs to be passed on to laws, and from there to regulations*". However, at different government levels, some public agencies have not produced the regulations needed to deliver the vision expressed in the PNBV. Reasons are manifold but some interviewees pointed to the lack of consensus on some of the PNBV objectives. According to a social science researcher, there is a gap *"[b]etween the political decision and the technical criteria, and hence the applicability of the policy*."

The lack of coherence between the constitution and the regulations has affected the rural electrification in Ecuador. According to a representative of ARCONEL, although the 2008 constitution declares that energy is a basic right, it is not anchored in the law, such that the lack of provision of service is not penalized. An energy consultant added: *"in fact, one of the managers [of an EDC] who is a very good friend of mine, said 'Listen, I already have enough with the grids. Don't put me any more activities, because I don't even get along with what I have. It is irresponsible to compromise to attend more people when I can't attend the current ones well'."*

Constitutional rights regarding energy have also lacked enforcement in Ecuador. This lack of enforcement has inhibited the development of strengthened and sustainable formal institutions, which in turn may avoid further efforts on improving regulations or setting new standards.

***Decentralization and Openness to Participation***

In addition to a decentralization process (understood as redistribution of the funds to elected local governments), the Correa administration adopted a "deconcentration" approach (understood as the delocalization of the central government aimed at the efficient provision of services). Indeed, several services have undergone delocalization/deconcentration in recent years. However, the energy sector, in particular the distribution of electricity, takes the reverse strategy, being subject to a process of recentralization.

Law 418 issued in 2015 stipulates that the 11 EDCs in the country will be merged to one single company, whose ownership will be transferred to the central government by the end of 2016. This decision was mainly motivated by the prospect of economies of scale. The interviewees partly welcomed the initiative, since it may facilitate the compensation of eventual losses of one EDC by other EDCs. Indeed, losses are frequent in the case of EDCs serving rural areas, while they are less frequent in the case of companies serving urban populations. Moreover, EDCs show considerable differences in their efficiency, and pay different attention to rural electrification. One single EDC could phase out these differences. The same is true for technical and quality standards, as there are currently differences between the standards adopted by different EDCs.

Recentralization may lead to short-term benefits to the Ecuadorian energy sector (by facilitating the adoption of coherent technical and quality standards of service). However, some interviewees pointed to the loss of adaptability (i.e. the ability to meet the changing needs of the rural population in remote areas of the country). The central government planning may further restrict local participation, while empowering its own position. According to a representative of a NPO: *"On top is the Ministry of Electricity. In theory, with the new electricity law, the [...] national energy operator, the one which would basically be the generation, transmission, and distribution, would all be below this organism. So, basically this is a very high concentration of power in the electricity sector."* and *"the EDC, in this case [referring to an example] the CentroSur, does not have the independence from the MEER to take decisions in the area, in the local sector."*

### 4.2 Economic Sustainability

***Cost Effectiveness and Reliability***

In the case of the remote areas (inhabited by small communities –each with a population less than 60 and often very dispersed), Ecuadorian officials appear to recognize that off-grid RE systems are a cost-effective solution (since grid expansion is too costly in the northern Ecuadorian Amazon as well as in the province of Esmeraldas, in the northern Ecuadorian coastal lowlands). This may explain why in 2009 ARCONEL proposed to the EDCs to form RE Units focused on rural electrification based on off-grid RE solutions. As described above, following ARCONEL's advice, some companies (such EEQ and Centro Sur) established RE units and have deployed stand-alone PV systems funded by FERUM in rural areas of the country.

The cost-effectiveness of off-grid PV solutions in remote areas is also favored by the geographical location of Ecuador. Indeed, the adoption of solar energy technologies has the potential to yield long-term benefits for the country in terms of reliability (through reliance on an inexhaustible and import-independent resource). However, assuring a reliable energy supply further demands for local access to spare parts, which entails not only the know-how, but also funding for O&M. Yet, missing spare parts and a lack of know-how of the communities on how to do small maintenance repairs has been one of the reasons for the damage of PV systems from the FERUM 2008-2010 program [95]; in the case of CentroSur on the other hand, despite the fact that costs are not covered by the government, the communities all have a stock of spare parts and receive training (all users get trained on basic maintenance, and a technical operator is trained in-depth) on how to maintain the systems [88]. As explained below, O&M funding is still an open issue in Ecuador, which may compromise the reliability of off-grid PV solutions in remote areas.

***Initial Investment***

Economic sustainability of rural electrification efforts requires ensuring the affordability of the systems and their O&M. In Ecuador, policy intervention is inevitable because rural populations are poor and cannot afford the initial investment by themselves.

The initial investment (either for grid extension or for off-grid PV solutions) is provided by the FERUM. The high rate of rural electrification reached in Ecuador in recent decades is a consequence of the FERUM that funded initial investments associated with rural electrification efforts. Although the FERUM is still the main source of resources for initial investments aimed at rural electrification, it is no longer funded by on-grid commercial and industrial consumers, but by the central government.

In other words, the budget of FERUM depends on political priorities of the central government. The change in the funding mechanism for FERUM has resulted in great variability of funds aimed at rural electrification.

These changes in the funding system of the FERUM were sharply criticized by interviewees who were also skeptical on the perspectives of the FERUM. According to a NPO representative, as *"[l]ean periods that may come next year because of a lack of oil revenues, what are you going to do? Cut the budget."*

***Operation and Maintenance***

There are no public funds specifically allocated to O&M of rural electrification programs. In the case of grid-connected users, the costs of O&M are covered by the tariff (also in rural areas). However, in the case of off-grid PV solutions, these costs are significantly greater than what poor inhabitants in remote areas can afford. Although in the latter case the IADB has suggested the MEER to allocate funds for O&M, the interviewees from MEER and from ARCONEL confirmed that up to now it is not clear how to fund the O&M of the off-grid rural electrification programs. The costs of O&M of rural solutions could be included in the tariff of urban users or be covered by the FERUM. However, no solution has been implemented yet.

As FERUM only funds the initial investments, the O&M of off-grid systems must currently be assumed by EDCs. However, according to the interviewees, companies are reluctant to assume these costs (especially in the case of remote areas), since it generates a financial gap for EDCs. Although this gap is supposed to be covered by the Ministry of Finance, according to an interviewed consultant (and confirmed by a representative of an EDC), the reimbursement to EDCs for O&M expenses is not met in practice.

The need of allocating funds aimed at O&M is well known by the Ecuadorian officials. However, a representative of the MEER declared that the country is still searching for a model to ensure the economic sustainability of rural off-grid electrification.

***Contribution to income of users***

As a higher access to energy is usually correlated with higher income, for energy solutions to be sustainable they are expected to contribute to income generating opportunities for inhabitants of remote areas. This idea seems to drive the new policy adopted by MEER that promotes PV-powered microgrids of up to 10 (MWp) for remote areas. A pilot project based on microgrids at Zancudococha (Orellana Province) has benefitted 29 families [10]; the new microgrids will be funded by the FERUM (through the FERUM II contract) and are meant to generate energy not only for households, but also for schools, public lightning, and small health centers. However, for the user's productive outcome to be increased, the electrification programs need to be coupled with complementary infrastructure including training and education, which according to the interviewees is currently not the case.

Moreover, several projects based on productive uses have been implemented in Ecuador by NPOs. These projects range from handcrafts, to corn dryers powered by PV energy, solar boats for transportation, and energy for milk collection centers. All of these solutions are only pilot projects so far. A representative of a NPO involved in the development and implementation of these solutions stressed that *"in order to be sustainable, it needs to originate right there. From the profitability of the proper system, which need to be sufficiently profitable to be attractive."* Similarly, another NPO representative agreed on the importance of *"...not creating a project from outside and imposing it on the community so much, but rather talk about what is solar energy capable of, and what would be helpful to them."*

### 4.3 Environmental Sustainability

***Environmental awareness***

Interviewees considered especially the middle and upper class in Ecuador to be aware of the need for environmental protection. Indeed, the country was one of the first Latin-American countries in creating a Ministry of Environment (in 1996) [96]. Moreover, the concept of environmental protection was included in the 2008 Constitution. The 2008 Constitution also states the need of consulting the communities affected by any major economic activity (such as oil drilling or mining). However, these rules are usually not complied in practice, which may indicate that environmental awareness is not widespread in Ecuador.

A representative of a NPO explained that communities in the Amazon basin, where most of the oil drillings take place, are mostly opposed to these activities since "*they know that their lives economically, as well as socially, but economically, that they depend on the health of the forests."* Despite the opposition of some communities, drilling in the Amazon basin and major mining in the Andean highlands are currently flourishing in the country. Indeed, recently the Correa administration authorized oil drilling in the Yasuni National Park, located in the Amazon basin and considered to be one of the most biologically diverse forests in the world [97]. This authorization was issued despite the fact that the area was a protected National Park hosting uncontacted indigenous communities [98].

The high dependence of the country on oil revenues that accounted for 56.5% of its incomes from exports in 2013 [69] appears to be driving decisions of the central government. Notwithstanding what is written in the constitution, environmental issues seem to be having a minor role in policy making.

***Environmental impacts***

In general terms, the adoption of solar energy technologies yields long-term benefits in terms of pollution abatement and climate change mitigation. In the Amazon basin that hosts the greatest biodiversity on earth, the benefits are particularly clear in the short term; the adoption of solar energy technologies for electrification in these areas may contribute to protect the biodiversity, reduce deforestation, moderate land degradation, and avoid noise (that may disturb uncontacted indigenous communities inhabiting some areas in the Amazon basin; [99,100]. Despite these benefits, rural electrification policies in Ecuador continue to favor the grid expansion. Off-grid solutions have been adopted only in areas that present major geographical challenges for the extension of the grid, or that are inhabited by dispersed and isolated communities.

Regarding the prevention of negative environmental impacts, environmental considerations seem to rank behind economic or political motivations of electrification efforts. One example has been in San Lorenzo (a town in the province of Esmeraldas, in the northern Ecuadorian coastal lowlands), where the grid extension was only possible by clearing part of the mangrove forest. The alternative would have been a minigrid, but as stated by an NPO manager, *"...because on Saturday I [the president during his TV-aired weekly "report of activities"] say 'they will put it [the grid] in this part [in San Lorenzo].' So everybody [the public agencies] ran and in two months they cleared the mangrove forest and put the things."*

Even in those cases within which off-grid solutions have been adopted, potential negative environmental impacts have not been taken into account. In the particular case of stand-alone PV systems, the major issue is the battery disposal. Although some EDCs collect the batteries after replacement, there is no regulation on what to do with the old batteries. According to a senior official of the MEER, *"the whole amount of batteries is extremely heavy. So it sums up. So, the battery is sometimes buried, or they are really taken out to be processed here in the urban regions. There are companies that take care of that, but the costs are not yet made transparent. So, we are still in the discussions."* Although, in the main cities of the country there are companies that buy the old batteries and thus in theory facilitate a cleaner disposal, it is not clear what is currently occurring with the batteries of stand-alone PV systems after replacement.

### 4.4 Socio-cultural Sustainability

***Accessibility (disparity/equity)***

Based on the interviews, we found especially the middle and upper class in Ecuador to have a notion of social justice concerning distribution of economic resources (which includes the access to electricity). This may partially explain the notable achievements in rural electrification of the country as compared to its Latin-American neighbors. The rural electrification rate in Ecuador reached 89,03% in 2010 [6,7] and the 2008 constitution states that electricity is a basic right.

Despite the apparent consensus regarding the accessibility (access to electricity) for everybody, different redistribution approaches coexist in the country. These approaches are relevant when deciding who is provided with electricity, and the amount of energy to be provided to each person. The most recent approach adopted by the current administration is nowadays promoting PV-powered microgrids of up to 10 MWp for remote areas, rather than the stand-alone solutions. A microgrid can have a positive socio-economic impact in terms of productivity by delivering significantly more energy per inhabitant than stand-alone solutions.

However, several interviewees criticized this microgrid policy because it leads to a disparity of resources, which may be unfair. According to a representative of a private company, the microgrid is *"…a project which they have and want to take out quickly, because it is a good image for them, because it is a big system and it will look very nicely on the picture […]. We are providing the solution to 20 families, and that's fine, but what happens to the rest?"* Regardless of the motivation of the MEER, the issue is that microgrids are significantly more expensive, such that few communities receive a complete solution, while others have to wait until new funds are available.

These critics favor policies based on the principle of equity that claims that all citizens should be secured a minimum standard. Hence, the EDCs should provide a minimum level of energy for everybody (including rural areas). Although it is not clear what this minimum would be, the interviewees have some suggestions. For example, according to a representative of a private company, *"they [the government] should put a real goal, and say 'I can eliminate the darkness', right? I won't give them a TV, nor a fridge […] But I do take them out of the darkness, I will give them light. And that could be done. They could do so very rapidly. In six years we could leave the country completely free from matches."*

***Social Acceptance and Accuracy***

Social acceptance requires a participatory and inclusive approach in which the local community is engaged. Efforts to promote social acceptance are necessary, because often political differences between indigenous leaders and the government have led to the rejection of electrification programs in Ecuador [88]. Although social acceptance of electricity appears to be still an issue in remote areas of the country, some EDCs have addressed the topic. For example, CentroSur has carried out significant efforts aimed at getting its consumers involved in the Amazon basin (often small and isolates communities). The RE Unit of this EDC reaches the community and gets them involved by creating an Electrification Committee (formed by the heads of each beneficiary household) and a Steering Committee (formed by member of the community that act as the local representative of the EDC). Another elected local official is in charge of collecting the monthly payments and presents the monthly reports and accounting to the EDC. This engagement strategy is actually aimed at gaining the social acceptance of the technology, and at least in the case of CentroSur, has proven to be appropriate. Indeed, this engagement strategy may explain the success of CentroSur; according to Urdiales [88], more the 95% of the stand-alone systems installed by this EDC are still operating.

Although they argue that it was determined according to the consumption habits of the local population, CentroSur provides to its consumers in the Amazon basin stand-alone PV systems of 150 Watts peak (Wp). The lack of accuracy (the capability of meeting local consumer demand) of this flat solution has been criticized since it was not defined according to gender-specific or community-specific requirements [95]. The same type of criticism applies for the microgrids promoted by MEER since, for example, in Esmeraldas, Leid [62] reported that they were oversized for the electricity consumption of the area. The sophistication of microgrids may also be inaccurate for rural population if the system is expected to be locally managed [62].

***Cultural Justice***

The 2008 Constitution in Ecuador as well as the PNBV emphasize that Ecuador is a Plurinational and Intercultural State, with all ethnic groups having rights. Yet, the culture of small indigenous communities is often not considered in the execution of public policies. Referring to the situation of small isolated indigenous communities in the Amazon basin, a representative of a NPO provided an example: "*they [government] are building them [indigenous] a house of 40 meters, of 50 meters, with bricks, with cement, with these, and stairs. [But] they don't live with stairs […] they start to close down the lower part, because they don't want to live downstairs. Or they put the animals downstairs.*"

The microgrid policy from MEER has also been mentioned as an example of the disengagement between public policies and culture of indigenous communities. For instance, although in the Amazon basin an EDC discarded microgrids for semi-nomad indigenous communities, this technology was ultimately imposed by the MEER. According to a NPO representative, "*the argument of the MEER is that […] you couldn't say that you don't like pizza, if you haven't been given pizza. So I will give you pizza, and let's see if you like it.' "*

The major issue is not necessary the lack of awareness of the cultural particularities of small indigenous communities, but the lack of respect for them. According to a representative of a NPO, *"[s]o I told them [the MEER] 'this [nomadism] is part of their culture as an identification term of their behavior.' So they said 'change their culture'."*

## 5. Discussion

Institutional sustainability requires durable and strengthened formal institutions. We found that disruptive changes have affected the electrification policies in Ecuador during decades avoiding the development of strengthened institutions. New ministries, regulators, and EDCs have been created and later disappeared, often after changes in the central government administration. This lack of stability or durability in formal institutions has in turn prevented further efforts on enforcing regulations, ensuring the coherence of the legal frame and setting better standards. The absence of strengthened and sustainable formal institutions is a major drawback in Ecuador that, by inhibiting law enforcement, also compromises the environmental and socio-cultural sustainability of rural electrification efforts, particularly in the Ecuadorian Amazon.

Despite the frequent changes in policies and in the institutional framework, we found that in Ecuador there is an apparent consensus on granting access to energy for all. This partially explains the steady national efforts aimed at funding rural electrification. Favored by its size, the notable achievements of the country regarding electrification have been based on the extension of the grid. Since 1998, efforts targeting small indigenous communities in the Ecuadorian Amazon basin also included off-grid PV systems. Although this type of solution may be particularly suitable for semi-nomad indigenous communities in the Amazon Basin (that hosts the greatest biodiversity on Earth), we found that environmental and socio-cultural aspects appear to have a minor role in explaining the choice for RE solutions. Indeed, rural electrification policies in Ecuador continue to favor the grid expansion. Off-grid solutions have been adopted only in areas within which the grid expansion is too costly. Although throughout different administrations, Ecuadorian officials declared to favor off-grid PV systems for rural populations, they have consistently avoided allocating funds aimed at the O&M of the systems compromising the sustainability of the systems. Granting funds specifically to O&M is required for ensuring the economic sustainability of off-grid PV solutions in Ecuador.

Environmental sustainability entails the prevention of negative environmental impacts. Although Ecuador was one of the first Latin-American countries in creating a Ministry of Environment (in

1996), the environmental regulation are usually not complied in practice, which may be a consequence of the lack of strengthened and sustainable institutions, but also of the absence of widespread environmental awareness of civil society. We found that environmental impact seems to rank behind the economic and political motivation in Ecuador, such that environmental issues seem to still play a minor role in the policymaking. Even in those cases within which stand-alone PV systems have been adopted, potential negative environmental impacts (for example, the battery disposal) are not taken into account. Improvements regarding the impact assessment, but also in environmental awareness and understanding, are required for ensuring the environmental sustainability of rural electrification efforts.

The whole legal framework emphasizes that Ecuador is a Plurinational and Intercultural State, with all ethnic groups having full rights. Yet, the culture and opinion of small indigenous communities are often not considered in public policies. The proposal aimed at providing energy to semi-nomad indigenous communities in the Amazon deploying microgrids is a clear example. Although their rights are explicitly recognized by the constitution, once again, the lack of strengthened and sustainable formal institutions frustrates the enforcement of rights, laws, and regulations. The lack of inclusive approaches in the policy making also indicates that, despite the awareness of their cultural particularities, there is not a widespread respect for small indigenous communities in the country. Progress regarding social acceptance, accuracy, and cultural justice is urgently needed for ensuring the socio-cultural sustainability of rural electrification efforts in the Ecuadorian Amazon.

## 6. Conclusions and Recommendations

In this paper, we assess the sustainability of rural electrification programs in Ecuador, paying special attention to programs targeting small indigenous communities in the Amazon basin. Our assessment was based on a set of indicators (Table 1) corresponding to the four dimensions of sustainability considered in this paper: institutional, economic, environmental, and socio-cultural.

Disruptive changes in electrification policies in Ecuador are too frequent. This lack of stability in the institutional framework needs to be addressed if the country aims to build up strengthened and sustainable formal institutions. Since these frequent disruptive changes have often occurred after political changes, it is advisable for the central administration to promote a broader political compromise aimed at building up strengthened and sustainable formal institutions.

Furthermore, the enforcement of the constitutional rights regarding energy is still weak in Ecuador and the coherence of the legal frame regarding rural electrification is currently feeble. Since the off-grid sector remains mostly unregulated, the MEER should consider reviewing the current legal frame (including regulations and standards), paying particular attention to the consistency with the constitutional rights. Moreover, ARCONEL should set technical and service standards that are binding for all EDCs. Sponsored by ARCONEL, it is advisable for the EDCs to also define billing models, which may differ from one community to the other.

Ecuador exhibits an incomplete decentralization, since decision-making rests on the central government, not only regarding policies, but also concerning specific solutions (minigrids, stand-alone systems, etc.). Therefore, ARCONEL should study the possibility of granting the faculties to the existing RE Units to decide on specific solution among the possible alternatives (minigrids, stand-alone systems, etc.) and the power capacity of the systems. Granting these faculties to RE Units (which are normally in closer contact with the communities) will also address the likely loss of adaptability (i.e. the ability to meet the changing needs) expected as a consequence of the ongoing administrative recentralization process (all EDCs are merging on a single EDC). In order to address the alleged weak openness to participation of locally elected authorities or community representatives, it is advisable for ARCONEL to enforce a consulting mechanism between the existing RE Units, locally elected authorities, and native community representatives.

Although off-grid RE systems appear to be a cost-effective solution in rural areas of Ecuador, few EDCs have conducted detailed cost analyses of off-grid solutions. Therefore, sponsored by

ARCONEL, the EDCs ought to carry out such detailed cost analyses for installation cost (per Wp) of off-grid RE solutions, the cost of O&M, recycling and proper disposal, as well as the spending capacity of the inhabitants of remote areas. These analyses are also useful for defining billing models.

Moreover, the FERUM funds the initial investment, but its annual budget depends on political priorities. O&M costs are covered neither by users, nor the existing funding mechanism (i.e. FERUM). Currently, these costs are borne by EDCs, which makes them reluctant to deploy off-grid RE systems. Thus, it is recommendable for the central administration to restore the prior model based on cross subsidies (from users connected to the grid). A scheme based on cross subsidies would also address the uncertainty related to the funds allocated to the FERUM, whose annual budget would no longer depend on political priorities. The MEER should thereby ensure that this cross subsidy will cover O&M costs of off-grid systems used to power low-income inhabitants of rural communities.

Several NPOs have installed PV-powered prototypes of productive systems (e.g. handcraft, corn dryers, solar boats, milk collection centers). A government-sponsored program including micrgrids (for households, schools, and health centers) has also been initiated recently, aiming to contribute to the income of users. However, no program exists for complementary infrastructure (training and education, telecommunication, and transport). The MEER should therefore consider strengthening transdisciplinary relations with other sectors, as well as identifying and replicating successful pilot projects (in collaboration with NPOs).

Environmental protection is anchored in the Ecuadorian constitution, but rules are often not complied in practice, which may indicate that environmental awareness is not widespread. In this regard, the MEER and the EDCs ought to include environmental experts in the design and implementation of programs in sensitive zones such as the Amazon. Moreover, environmental impacts (positive or negative) are currently not included in the evaluation of small-scale electrification projects. Therefore, the MEER and ARCONEL may want to consider including environmental impacts (positive or negative) in the evaluation of small-scale electrification projects. In case of off-grid PV projects, it is also recommendable for the RE Units to ensure recycling and proper disposal of PV modules and batteries after the end of their service life. ARCONEL should therefore explicitly regulate the battery disposal.

In Ecuador there is consensus regarding accessibility to electricity for everybody, but disagreements persist on who is provided with electricity first, and the amount of energy to be provided to each person. Recent programs based on microgrids provide sufficient power to households, but will favor a limited number of people leaving thousands waiting for solutions. In this context, the MEER may want to consider promoting a policy aimed at getting rid of dangerous energy sources like matches/candles by granting access to electricity with a minimum capacity to all citizens first. In this regard, pre-electrification via pico solar PV systems could be an option.

Also, few EDCs, through their RE Units, apply a participatory and inclusive approach aimed at gaining social acceptance of the technology. Following the example of the successful program applied by CentroSur, it is advisable for ARCONEL to enforce a participatory and inclusive approach, particularly important in the case of indigenous communities.

As far as the EDCs are concerned, they apply one-size PV solutions that do not necessarily fit all needs and that have not been determined based on gender-specific and community specific requirements. In order to improve the accuracy of their solutions, they should take gender-and community- specific requirements in their project designs into account.

In general terms, cultural justice criteria and the opinion of small indigenous communities are not considered in public policies (e.g. microgrids for semi-nomad indigenous communities in the Amazon). In this regard, the MEER may want to consider including sociologists or social experts in the design of programs for indigenous communities.

Even if not comprehensive or sufficient, these recommendations may be the first step in further improving the sustainability of rural electrification programs in Ecuador. As the qualitative approach can do justice to the complexity of such energy policies in the national context, additional qualitative approaches to evaluate the sustainability of off-grid PV systems in different countries would be insightful; these studies could then be used for an intercomparison between countries.

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**Abbreviations**

The following abbreviations are used in this manuscript:

ARCONEL: Agency for Regulation and Electricity Control
CELEC: Ecuadorian Electric Corporation
CONELEC: Agency for Regulation and Electricity Control
CONAM: National Modernization Council
EDC: Electricity Distribution Company
EIU: Economist Intelligence Unit
EEQ: Electric Compnay Quito
FEDETA: Ecuadorian Foundation of Appropriate Technology
FERUM: Fund for Rural and Urban-marginal Electrification
IADB: Inter American Development Bank
IICA: Inter-American Institute for the Cooperation in Agriculture
INECEL: Ecuadorian Institute of Electrification
MEER: Ministry of Electricity and Renewable Energy
MICSE: Coordinating Ministry of Strategic Sectors
MWp: Mega Watts peak
NCRE: Non-conventional renewable energy
NPO: Non-profit-organization
O&M: Operation and maintenance
PNBV: National Plan for Good Living
PV: Photovoltaic
RE: Renewable Energy
SENPLADES: National Planning and Development Secretary
UN: United Nations
UNDP: United Nations Development Program
Wp: Watts peak

## References


1. International Energy Agency (IEA)(2015). "World Energy Outlook. Electricity access database."
2. Organisation for Economic Co-operation and Development (OECD) and International Energy Agency IEA (2010). ENERGY POVERTY. "How to make modern energy access universal? Special early excerpt of the World Energy Outlook 2010 for the UN General Assembly on the Millennium Development Goals." Available at: http://www.se4all.org/wp-content/uploads/2013/09/Special_Excerpt_of_WEO_2010.pdf. Accessed on 13 December 2015.
3. United Nations (2015). TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT. Available at: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf Accessed on 7 April 2016.
4. United Nations (2012), Sustainable Energy for All. A Framework for Action, The Secretary-General's High-Level Group on Sustainable Energy for All. Available at: www.un.org/wcm/webdav/site/sustainableenergyforall/shared/Documents/SE%20for%20All%20-%20Framework%20for%20Action%20FINAL.pdf. Accessed on 23 August 2015
5. Agenda, E. S. (1992). 21: the United Nations Programme of Action from Rio. Agenda, 21. , Chapter 4, 7, and 9
6. CONELEC (2012). Plan Maestro de Electrificación 2012-2021.
7. CONELEC (2013). Cobertura De Servicio Eléctrico A Diciembre De 2013. Available at http://www.conelec.gob.ec/contenido.php?cd=10275&l=1 Accessed on 18 June 2015
8. Ten, Maria (2013). Revisión de los resultados de la operación 2608/OC-EC: Electrificación Rural y Urbano-Marginal del Ecuador. Programa de Electrificación Rural y Urbano-Marginal (FERUM)
9. CONELEC. Centrales Renovables No Convencionales (NA). Available at: http://www.conelec.gob.ec/images/documentos/doc_10238_CENTRALES_RENOVABLES_NO_CONVENCIONAL.pdf Accessed on 18 June 2015
10. Ministerio de Electricidad y Energias Renovables (MEER) (2014a).Informe – Rendición de Cuentas.
11. Ritchie, J., Lewis, J., Nicholls, C. M., & Ormston, R. (Eds.). (2013). Qualitative research practice: A guide for social science students and researchers. Sage.
12. Gläser, J., & Laudel, G. (2010). Experteninterviews und qualitative Inhaltsanalyse. Springer.
13. Burford, G., Hoover, E., Velasco, I., Janoušková, S., Jimenez, A., Piggot, G., ... & Harder, M. K. (2013). Bringing the "missing pillar" into sustainable development goals: Towards intersubjective values-based indicators. Sustainability, 5(7), 3035-3059.
14. Derakhshan, F. (2011). On Sustainability in Local Energy Planning. Lund University.17. Pfahl, S. (2005). Institutional sustainability. International journal of sustainable development, 8(1-2), 80-96.
15. Spangenberg, J. H., Pfahl, S., & Deller, K. (2002). Towards indicators for institutional sustainability: lessons from an analysis of Agenda 21. Ecological indicators, 2(1), 61-77.
16. Ciegis, R., Ramanauskiene, J., & Martinkus, B. (2015). The concept of sustainable development and its use for sustainability scenarios. Engineering Economics, 62(2).
17. Platje, J. (2011). The level of institutional capital and challenges in sustainable development. Economic and Environmental Studies, 11 (1), 99-116.
18. North, D. C. (1992). Institutionen, institutioneller Wandel und Wirtschaftsleistung (Vol. 76). Mohr siebeck, p.4
19. Pejovich, S. (2012). The effects of the interaction of formal and informal institutions on social stability and economic development. Journal of Markets & Morality, 2(2).
20. Reiche, K., Tenenbaum, B., & de Mästle, C. T. (2006). Electrification and regulation: principles and a model law. Energy and Mining Sector Board, The World Bank.
21. Reddy, B. S. (2015). Measuring and Evaluating Energy Security and Sustainability: A Case Study of India.
22. Sharma, T., & Balachandra, P. (2015). Benchmarking sustainability of Indian electricity system: An indicator approach. Applied Energy, 142, 206-220.

23. Wimmler, C., Hejazi, G., de Oliveira Fernandes, E., Moreira, C., & Connors, S. (2015). Multi-Criteria Decision Support Methods for Renewable Energy Systems on Islands. Journal of Clean Energy Technologies, 3(3).
24. García, V. G., & Bartolomé, M. M. (2010). Rural electrification systems based on renewable energy: The social dimensions of an innovative technology. Technology in society, 32(4), 303-311.
25. The World Bank (2008). Policy and Governance Framework for Off-grid Rural Electrification with Renewable Energy Sources (TF090884). Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/7954/683390ESW0WHIT0lectrification0Final.txt?sequence=2 Accessed on: 24 August 2015.
26. Ilskog, E., & Kjellström, B. (2008). And then they lived sustainably ever after?—Assessment of rural electrification cases by means of indicators. Energy Policy, 36(7), 2674-2684.
27. Vera, I. A., Langlois, L. M., Rogner, H. H., Jalal, A. I., & Toth, F. L. (2005). Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency. In Natural Resources Forum (Vol. 29, No. 4, pp. 274-283). Blackwell Publishing Ltd.
28. Levitsky, S., & Murillo, M. V. (2009). Variation in Institutional Strength. Annu. Rev. Polit. Sci, 12, 115-33.
29. Laufer, D., & Schäfer, M. (2011). The implementation of Solar Home Systems as a poverty reduction strategy—A case study in Sri Lanka. Energy for sustainable Development, 15(3), 330-336.
30. Lyndrup, M., & Jensen, T. Y. H. W. (2012). Illuminating the Potential for a Rural Energy Service Company-Meeting the off-grid electrification challenge in Mozambique (Doctoral dissertation).
31. Wlokas, H. L. (2011). A review of the solar home system concession programme in South Africa. Cape Town: Energy Research Centre, University of Cape Town.
32. Friebe, C. A., von Flotow, P., & Täube, F. A. (2013). Exploring the link between products and services in low-income markets—Evidence from solar home systems. Energy Policy, 52, 760-769.
33. Polack, A. (2010). Drivers and barriers of renewable energy in the electrification of Vanuatu (Doctoral dissertation, Murdoch University).
34. Machado, F. V. (2013). Decentralization and Accountability: The Curse of Local Underdevelopment.
35. Axelsson, R., Angelstam, P., Degerman, E., Teitelbaum, S., Andersson, K., Elbakidze, M., & Drotz, M. K. (2013). Social and cultural sustainability: Criteria, indicators, verifier variables for measurement and maps for visualization to support planning. Ambio, 42(2), 215-228.
36. Pansera, M. (2012). Renewable energy for rural areas of Bolivia. Renewable and Sustainable Energy Reviews, 16(9), 6694-6704.
37. Retnanestri, M. (2007). The I3A framework–Enhancing the sustainability of off-grid photovoltaic energy service delivery in Indonesia. University of New South Wales (UNSW): PhD thesis. OpenURL.
38. Bhattacharyya, S. C. (2012). Energy access programmes and sustainable development: A critical review and analysis. Energy for sustainable development, 16(3), 260-271.
39. Mainali, B., Pachauri, S., Rao, N. D., & Silveira, S. (2014). Assessing rural energy sustainability in developing countries. Energy for Sustainable Development, 19, 15-28.
40. Rosen, M. A. (2009). Energy sustainability: A pragmatic approach and illustrations. sustainability, 1(1), 55-80.
41. International Atomic Energy Agency (IAEA), United Nations Dfrtment of Economic and Social Affairs (UNDESA), International Energy Agency (IEA), Eurostat, European Environment Agency (EEA), 2005. Energy Indicators for Sustainable Development: Methodologies and Guidelines, International Atomic Energy Agency (IAEA), Vienna.
42. Dunmade, I. (2002). Indicators of sustainability: assessing the suitability of a foreign technology for a developing economy. Technology in Society, 24(4), 461-471.
43. Van Campen, B., Guidi, D., & Best, G. (2000). Solar photovoltaics for sustainable agriculture and rural development. In RURAL DEVELOPMENT", FAO PUBLICATION.
44. Khandker, S. R., Barnes, D. F., & Samad, H. A. (2013). Welfare impacts of rural electrification: a panel data analysis from Vietnam. Economic Development and Cultural Change, 61(3), 659-692.

45. Kirubi, C., Jacobson, A., Kammen, D. M., & Mills, A. (2009). Community-based electric micro-grids can contribute to rural development: evidence from Kenya. World development, 37(7), 1208-1221.
46. Cook, P. (2011). Infrastructure, rural electrification and development. Energy for Sustainable Development, 15(3), 304-313.
47. O'Faircheallaigh C, Public participation and environmental impact assessment: Purposes, implications, and lessons for public policy making, Environmental Impact Assessment Review, 30(1), 2010, 19–27
48. International Energy Agency (IEA) (2010). Energy Technology Perspectives, Paris, France
49. Pope, J., Annandale, D., & Morrison-Saunders, A. (2004). Conceptualising sustainability assessment. Environmental impact assessment review, 24(6), 595-616.
50. Prandecki, K. (2014). Theoretical Aspects of Sustainable Energy. Energy and Environmental Engineering, 2(4), 83-90.
51. Ilskog, E. (2008). Rural electrification sustainability indicators: Manual for field workers.
52. Kolk, A., & van den Buuse, D. (2012). In search of viable business models for development: sustainable energy in developing countries. Corporate Governance: The international journal of business in society, 12(4), 551-567.
53. Ribeiro, F., Ferreira, P., & Araújo, M. (2011). The inclusion of social aspects in power planning. Renewable and Sustainable Energy Reviews, 15(9), 4361-4369.
54. Chaurey, A., & Kandpal, T. C. (2010). Assessment and evaluation of PV based decentralized rural electrification: An overview. Renewable and Sustainable Energy Reviews, 14(8), 2266-2278.
55. Frame, D., Tembo, K., Dolan, M. J., Strachan, S. M., & Ault, G. W. (2011, July). A community based approach for sustainable off-grid PV systems in developing countries. In Power and Energy Society General Meeting, 2011 IEEE (pp. 1-7). IEEE.
56. Nurse, K. (2006). Culture as the fourth pillar of sustainable development. Small states: economic review and basic statistics, 11, 28-40.
57. Fenner, R. A., Ainger, C. M., Cruickshank, H. J., & Guthrie, P. M. (2006). Widening engineering horizons: addressing the complexity of sustainable development. Proceedings of the ICE-Engineering Sustainability, 159(4), 145-154.
58. Demirtas, O. (2013). Evaluating the best renewable energy technology for sustainable energy planning. International Journal of Energy Economics and Policy, 3(S), 23-33.
59. Mendieta Vicuña, D. and Escribano Pizarro, J. (2015). Electricidad, Desarrollo Rural y Buen Vivir, III Simposio Internacional Historia de la electrificación. Estrategias y cambios en el territorio y la sociedad.
60. Montero Banegas, M., & Cajamarca Huayllazaca, E. (2012). Análisis socio-económico de las comunidades aisladas en la provincia de Morona Santiago beneficiadas del servicio eléctrico mediante la instalación de sistemas fotovoltaicos, en el período 2009-2011.
61. Zhumi, M., & Gerardo, L. (2012). Diagnóstico de la implementación de los sistemas fotovoltaicos correspondientes a la primera etapa del proyecto Yantsa ii Etsari.
62. Leid, L. H. (2014). Llegó La Luz: a case study of the impacts of solar photovoltaic electricity in Las Balsas, Ecuador (Doctoral dissertation).
63. Bernhardt, J. (2015). The Effectiveness of Science-Policy Interactions: Case Studies on Climate Change Mitigation and Sustainable Development in Pan-European Forest Research and Politics.
64. Heinrichs, H., & Laws, N. (2014). "Sustainability State" in the Making? Institutionalization of Sustainability in German Federal Policy Making. Sustainability, 6(5), 2623-2641.
65. Nguyen-Trinh, H. A., & Ha-Duong, M. (2015). Perspective of CO 2 capture & storage (CCS) development in Vietnam: Results from expert interviews. International Journal of Greenhouse Gas Control, 37, 220-227.
66. Hugé, J., Mukherjee, N., Fertel, C., Waaub, J. P., Block, T., Waas, T., ... & Dahdouh-Guebas, F. (2015). Conceptualizing the effectiveness of sustainability assessment in development cooperation. Sustainability, 7(5), 5735-5751.
67. Flick, U., von Kardoff, E., & Steinke, I. (Eds.). (2004). A companion to qualitative research. Sage., p. 168

68. Instituto Nacional de Estadística y Censos (INEC) (NA). MUJERES Y HOMBRES del Ecuador en Cifras III. Editorial Ecuador. ISBN: 978-9942-07-390-7
69. Ministerio Coordinador de Sectores Estrategicos (MICSE) (2014). Políticas Energéticas en Ecuador. Available at: http://www.nist.gov/iaao/upload/3-_Presentacion_Politica_Energia__v2-pptx_DARWIN_COSTA.pdf accessed on 24 August 2015.
70. The World Bank (NA). World Development Indicators. Available at: http://databank.worldbank.org/data//reports.aspx?source=2&country=ECU&series=&period=
71. Secretaría Nacional de Planificación y Desarrollo (SENPLADES) (2013). Plan Nacional para el Buen Vivir 2013-2017)
72. Presidencia de Ecuador (NA). Gabinete de la Revolución Ciudadana Available at: http://www.presidencia.gob.ec/gabinete-de-la-revolucion-ciudadana/ Accessed on 03 July 2015
73. Empresa Eléctrica Ambato EEASE (NA). 55 Años En La Historia De Empresa Eléctrica Ambato Regional Centro Norte S. A. Accessed on 11 December 2015
74. CENTROSUR (NA). Trayectoria de la Centrosur Al Servicio de la RegiónAvailable at: http://www.centrosur.com.ec/?q=node/10 Accessed on 11 December 2015
75. Azogues (NA). Reseña Histórica. Available at: http://www.elepcosa.com/eec/index.php/la-empresa/2014-11-08-14-13-09 Accessed on 12 December 2015.
76. Ministerio de Electricidad y Energias Renovables (MEER) (2014b). Plan Estratégico Institucional 2014 – 2017
77. Mena Pachano, A. (NA). La investigación y desarrollo de energías renovables en el Ecuador. Análisis crítico.
78. Congreso Nacional (2011). Ley De Regimen Del Sector Electrico. Registro Oficial Suplemento 43 de 10-oct-1996.
79. Haanyika, C. M. (2005). Rural Electrification Policy and Institutions in a Reforming Power Sector. Energy Policy Journal, Elsevier Ltd.
80. Asamblea Nacional (2015). Ley Orgánica del Servicio Público de Energía Eléctrica
81. Congreso Nacional (1993). Ley de Modernizacion del estado. Ley 50, Registro Oficial 349 de 31 de Diciembre de 1993.
82. Agencia de Regulación y Control de Electricidad (ARCONEL) (2014). Estadística del sector eléctrico ecuatoriano 2014.
83. Ministerio de Electricidad y Energias Renovables (MEER). (NA) http://www.energia.gob.ec/coca-codo-sinclair/# Accessed on 28 August 2015.
84. CONELEC (2014). Cargos Tarifarios. Available at: http://www.conelec.gob.ec/documentos.php?cd=3073&l=1 Accessed on: 14 August 2015
85. Asamblea Constituyente (2008). Mandato Constituyente No. 15.Montecristi, Ecuador.
86. Inter American Development Bank (IADB) (2014). CONTRATO DE PRÉSTAMO No. 3087/OC-EC. Programa de Electrificación Rural y Urbano-Marginal del Ecuador II. Available at http://idbdocs.iadb.org/wsdocs/getdocument.aspx?docnum=38805074 Accessed on 16August 2015
87. CONELEC (2009). Plan Maestro de Electrificación 2009-2020.p 417
88. Urdiales Flores, L. E. (2015). Procedimiento para la electrificación en zonas aisladas: caso cantón Taisha, Morona Santiago.
89. Ten, María; Neira Marcelo; Navarro, Gabriela; Cordero, Miguel (2015). Experiencias De Modelos De Gestión Off-Grid, En Ecuador e Internacionalmente.
90. Inter American Development Bank (IADB) (2013). Soluciones Sostenibles De Energias Renovables Fuera De Red Para Comunidades Aisladas En Ecuador. Available at: http://idbdocs.org/wsdocs/getdocument.aspx?docnum=37911288 Accessed on 07 June 2015.
91. Balseca, Milton (2015). Programa De Energizacion Rural "Luz Para El Sumak Kawsay". Xxx Seminario Nacional Del Sector Eléctrico, Riobamba
92. Pino, B. A., & Dolcetti, M. (2014). Revolución ciudadana, buen vivir y cooperación en Ecuador (2007-2013). Relaciones Internacionales, 23(46).
93. Secretaría Nacional de Planificación y Desarrollo (SENPLADES) (NA). Reseña Histórica. Available at: http://www.planificacion.gob.ec/resena-historica/ Accessed on 04 June 2015

94. Fundación Ecuatoriana De TecnologíA Apropiada (FEDETA) (2014). Modelo de Gestión para Sistemas Energéticos Aislados - Articulación Energética Territorial para Poblaciones Indígenas de la Región Amazónica Ecuatoriana
95. Ambiente (NA). Subsecretarías y Direcciones http://www.ambiente.gob.ec/subsecretarias-y-direcciones-2/ Accessed on 23 June 2015
96. Bass, M. S., Finer, M., Jenkins, C. N., Kreft, H., Cisneros-Heredia, D. F., McCracken, S. F., ... & Di Fiore, A. (2010). Global conservation significance of Ecuador's Yasuní National Park. PloS one, 5(1), e8767.
97. Fileccia, C. M., Caravaggio, N., & Conte, E. Buen Vivir: Sumak Kawsay and reality.
98. Finer, M., Jenkins, C. N., Pimm, S. L., Keane, B., & Ross, C. (2008). Oil and gas projects in the western Amazon: threats to wilderness, biodiversity, and indigenous peoples.
99. Orta-Martínez, M., & Finer, M. (2010). Oil frontiers and indigenous resistance in the Peruvian Amazon. Ecological Economics, 70(2), 207-218.

### 5.3 Paper 4: Sustainability of Rural Electrification Programs based on off-grid Photovoltaic Systems in Peru

In this paper, I assess the sustainability of rural electrification efforts in Peru based on off-grid PV solutions, paying special attention to the ongoing deployment of 150,000 off-grid PV systems in remote areas. Following the theoretical framework described in Chapter 2, my assessment considers four dimensions of sustainability (institutional, economic, environmental, and socio-cultural), while according to the methodology described in Chapter 3, my findings are based on an exhaustive qualitative document analysis, complemented by semi-structured expert interviews.

The article shows that the rivalry between two rural electrification agencies with overlapping competences and constant staff rotations made Peru's' institutions instable, and impeded that the rural electrification strategy could be followed through, while a weak supervision has negatively affected the reliability of the systems. On the positive side, a cross subsidy mechanism has assured the affordability of the systems as well as the covery of O&M costs. Notably, I found that Peruvian officials appear to be unaware of the importance of local participation, and there is a significant mistrust between the government and the rural population (especially in areas where mining is extensive). As a consequence, the lacking participation and engagement of the community has not only significantly impaired seizing opportunities regarding productive uses of off-grid PV systems, but it has also frequently caused payment defaults and ultimately accounted for project failures.

**Sustainability of Rural Electrification Programs based on off-grid Photovoltaic Systems in Peru**

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**Abstract:** We assess the sustainability of rural electrification programs in Peru based on off-grid photovoltaic (PV) solutions, paying special attention to the ongoing deployment of 150,000 off-grid PV systems in remote areas. Our assessment considers four dimensions of sustainability (institutional, economic, environmental, and socio-cultural) and is based on an exhaustive qualitative document analysis complemented by semi-structured expert interviews. We found that staff rotation and overlapping competences have caused disturbing changes and inhibited following a strategic line, while weak controls have often affected the reliability of the deployed systems. Although cross subsidies have made off-grid PV systems affordable for users, systems often fell short of energy demand. We also found that most of the projects are still being designed without the participation and engagement of the communities, which has frequently led to project failures, payment defaults, and inhibited seizing opportunities regarding productive uses of off-grid PV systems.

**Keywords**: Rural Electrification; Off-grid PV; Sustainability; Sustainable Energy; Developing Countries; Renewable Energy; Social Justice; Sustainable Institutions

## 1. Introduction

Although Peru has managed to considerably increase its rural electrification rate from 8% in 1993 to 29.5% in 2007 and 78% in 2015 (MEM, 2015), it is still among the countries in Latin America with a low rural electrification rate. Though this increase was primarily due to grid expansions, the government has recently prioritized the deployment of off-grid photovoltaic (PV) systems, especially in the remote areas where the grid expansion is unviable. Communities of these areas are characterized by low energy demand, low income, high dispersion, and difficult accessibility (MEM, 2011).

In this paper, we critically analyse the current status and challenges of rural electrification programs (based on off-grid PV systems) in Peru. We aim to better understand drivers of success and highlight flaws that have compromised the sustainability of these efforts. Paying special attention to the ongoing deployment of 150,000 off-grid PV systems, we addressed the following research question: Are the Peruvian rural electrification programs based on off-grid PV systems sustainable?

In order to answer our research question, we conducted an exhaustive qualitative document analysis complemented by semi-structured expert interviews. This approach has been broadly used for the assessment of sustainability (see for example, Bernhardt, 2015; Heinrichs and Laws, 2014; Nguyen-Trinh and Ha-Duong, 2015; Hugé et al., 2015; Feron et al., 2016). The interviewees included experts from different ministries, project managers from leading Non-Governmental Organizations (NGOs), public and private companies' representatives, supervisors, and researchers. Although below we describe several relevant PV-based electrification efforts in Peru, our research was aimed at gathering an overall picture of the rural electrification efforts in the country, rather than measuring the success or failure of a specific project.

The gathered information allowed us to assess the sustainability of rural electrification efforts in Peru. Our assessment was based on a set of indicators (adopted from Feron et al., 2016) corresponding to the four dimensions of sustainability considered in this paper: institutional, economical, environmental, and socio-cultural. Additional methodological details are provided below.

## 2. Theoretical Framework

Institutional sustainability has been acknowledged as an important factor for the sustainability of rural electrification initiatives (see e.g. Ilskog, 2008; Derakhshan, 2011). For institutions to be sustainable, they need to be stable and durable (e.g. Sharma and Balachandra, 2015; Wimmler et al., 2015; Reddy, 2015). In that context, Gollwitzer (2014) highlights the importance of the organizational set-up, which includes adopting and enforcing norms and regulations. Authors further agree that for an effective sustainable energy development, the openness to participation of all stakeholders is imperative (Frame et al., 2011; Retnanestri et al., 2007; Holland et al., 2006). The participation is important for decentralization, which makes sense not only because of numerous technical advantages of decentralized renewable energy (RE) solutions (Sims et al., 2007:288; Fischedick, Borbonus and Scheck, 2011), but also because it favours the adaptability of the institutions. Indeed, sustainable institutions must have the ability to adapt to the needs of the country over time (e.g. Brent and Rogers, 2009; Ilskog, 2008; Retnanestri et al.; Wimmler et al., 2015).

Economic sustainability of electrification solutions requires ensuring the affordability of the systems (Mainali et al., 2014; Brent and Rogers, 2009), which implies adopting cost-effective solutions and procuring funding for both the initial investment and the operation and maintenance (O&M) of the systems (Mainali, 2014; Dincer and Acara, 2015; Wimmler et al.,2015; Dunmade, 2002). Access to electricity is also expected to contribute to an increase in household income of users (Cook, 2011; Khandker, Barnes, and Samad, 2013). However, contributing to the income of users also requires ensuring the reliability of the energy systems (Garniati et al., 2014). Dunmade (2002) and Chaurey and Kandpal (2010) therefore stress the importance of local availability of spare parts for adequate maintenance and a reduction of its downtime.

The lack of awareness and citizen participation in environmental decision-making may thwart the progress towards environmental sustainability (Stringer and Paavola, 2013). Awareness should hence be assessed in evaluations of energy choices; for instance, it has been found that RE could contribute to greater environmental awareness of citizens in remote areas, and even motivate them to participate in environmental initiatives of other fields (Rickerson et al., 2012). Yet, not only the awareness of environmental concerns is appraised in environmental sustainability, but also the prevention of negative environmental impacts (e.g. Wimmler et al., 2015; Mainali et al., 2014; Retnanestri et. al., 2007); these impacts may be of global or of local nature (Mainali et al., 2014; Ilskog, 2008). Besides the mitigation of greenhouse gases, environmental impacts also concern the conservation of a stable resource base, the safeguard of biodiversity, the prevention of deforestation, avoidance of noise, and waste management (Retnanestri et. al., 2007; Vera et al., 2005; Dunmade, 2002). For off-grid PV systems and particularly their batteries, this implies that the waste disposal requires a proper treatment, as the impact evaluation must consider the whole lifecycle of a technology (Polack, 2010; Rosen, 2009).

Socio-cultural sustainability is closely related to the notion of social justice, as access to modern energy can contribute to better living conditions due to a healthier environment, access to information (e.g. radio or TV), higher security (through public lightning), and better education (e.g. Wimmler et al., 2015; Reddy, 2015; Mainali et al., 2014; Ilskog, 2008). The equity in the amount of energy consumption per capita as well as the disparity of energy use between different groups of people (e.g. according to gender, ethnical background, etc.) determines the accessibility (Mainali et al., 2014; Derakhshan, 2011; Sharma and Balachandra, 2015; Bhattacharyya, 2012). Moreover, an energy solution can be considered to be sustainable if it is accepted by the society, which will depend on multiples factors, including the consideration of culture and traditions in the energy planning (Dunmade, 2007; Ribeiro et al., 2011); the participation of the local community (Retnanestri et al., 2007; Derakhshan, 2011; Lähtinen et al., 2014); and the exchange of information aimed at learning experiences and knowledge-sharing (Fenner et al., 2006).

Based on this theoretical framework, we have built up a set of indicators (see Table 1; see also Feron et al. (2016)) clustered into the four dimensions (institutional, economic, environmental, and socio-cultural) of sustainability considered in this paper. These indicators were used to qualitatively evaluate to what extend Peru's rural electrification efforts based on off-grid PV systems are sustainable.

**Table 1:** Indicators of sustainability used in this study (adapted from Feron et al., 2016).

| Institutional | Economic | Environmental | Social /Cultural |
|---|---|---|---|
| **Stability (Durability)** | Cost effectiveness | Environmental awareness | Accessibility (disparity, equity) |
| **Regulation and Standards** | Reliability | Environmental impact | Social Acceptance |
| **Decentralization and Openness to participation** | Funding (initial investment; operation and maintenance) | | Accuracy |
| **Adaptability (ability to meet future needs)** | Contribution to income of users | | Culural Justice |

## 3. Methodology

In order to assess the sustainability of off-grid PV projects in Peruvian rural areas, we conducted a qualitative document analysis (Ritchie et al., 2013) complemented with semi-structured interviews (Bernhardt, 2015).

The document analysis enabled us to gather important insights on electrification programs and cases, regulations, policies, and statistical data on rural electrification in Peru. It included public documentations such as the National Plan of Rural Electrification (PNER by its Spanish acronyms); electrification laws and regulations; energy–pricing models; statistic databases; publications on experiences from Peruvian electrification projects (case studies); project auditing; and scientific papers on related topics. This qualitative document analysis helped us identifying and selecting experts for the semi-structured interviews.

The interviews allowed us to understand and to unearth issues that could not be unveiled by the document analysis; expert interviews have indeed been broadly used for the assessment of sustainability (see, for example, Bernhardt, 2015; Heinrichs and Laws, 2014; Nguyen-Trinh and Ha-Duong, 2015; Hugé et al., 2015; Feron et al., 2016). The interviewees were of higher hierarchical positions (directors, project managers, leading researchers, and division leaders; see Table 2), as we were interested in the overall institutional and organizational conditions.

According to the four dimensions of sustainability, coding schemes were defined for the gathered information using MAXQDA® software (MAXQDA, NA) (see Hall and Rist, 1999).

**Table 2:** Interview Partners

| Area | Sub-Area | Division (if applicable) |
|---|---|---|
| **Government Institutions Energy Sector** | Ministry of Energy - General Direction of Rural Electrification (MEM-DGER) | Direction of Grant Funds (DFC) |
| | | Project Management Direction (DPR) |

| | | |
|---|---|---|
| | Supervisory Organization for Investment in Energy and Mining (OSINERGMIN) | Tariffs, Regulation and Tenders |
| | | Generation Off-Grid System |
| | Consultant | High ranking administrative officer and consultant |
| **Government Institutions Non-Energy Sector** | Ministry of Development and Social Inclusion (MIDIS) | Technical Project Coordination |
| **Academics & Research Institutes** | Universities | Sociologist |
| | | Technological Transition and Renewable Energies (RE) |
| | | RE Research Centre |
| **NGOs** | ACCIONA | ACCIONA Microenergia Perú (AMP) |
| | Soluciones Prácticas | Renewable Energy (RE) Department |
| **Foreign Institutions** | International Cooperation Agency (ICA) | Renewable Energy (RE) Department |
| **Energy Companies** | Public Companies | Electrical Infrastructure Administration Enterprise (ADINELSA) |
| | | Electronoroeste (ENOSA) |
| | | Electro Oriente S.A. (ELOR) |
| | Private Companies | Servicios Especializados y Logística En General (SELEGSA) |
| | | Green Energy |
| | | Ergon S.A. |

Source: Own elaboration.

## 4. Peru

### 4.1 General Background

Peru's total population counted about 31 million in 2015 (INEI, 2015), of which the rural population represented 21% in 2014, though its share is declining (e.g., in 1990, it still accounted for 31%)

(Worldbank, NA). Moreover, although total poverty has dropped from 58.7% in 2004 to 23.9% in 2013, rural poverty (48%) remained significantly higher than urban poverty (16%) (INEI, NA).

Peru reformed its Constitution (law N° 27680) in 2002 to foster decentralization. The administrative division in Peru now comprises 24 departments that are governed by 26 regional governments; these departments consist of 196 provinces and 1,854 districts (INEI, 2015; IDEA, 2008). In addition to restructuring its administrative division in 2002, the decentralization also entailed budget allocation to regional and local governments. However, budget allocation has neither come along with capacity building nor with the establishment of control and evaluation mechanism (Damonte, Fuller and Valcárcel, 2009). Furthermore, national and regional goals lacked any form of coordination (e.g. Damonte, Fuller and Valcárcel, 2009; Contraloría General de la República, 2014).

This has led to poor results in decentralization, such that the country is recently showing trends of recentralization: e.g. whereas the annual budget of the central government accounted for 67% of the total budget in 2013 (16% regional, 17% local government), it increased to 75% in 2016 at the expense of the regional/local government budget (14% regional, 11% local) (MEF, NA).

### 4.2 The Peruvian Energy Sector

The Ministry of Energy and Mining (MEM by its Spanish acronyms) was founded in 1968 (Decree No. 17271; substituted by Decree 25962 in 1992). In 1972, the government passed the Normative Electricity Law (Decree Law No. 19521), which induced the nationalization of the electricity companies. It was exerted by the company ELECTROPERU, which was created the same year for that purpose. Ten years later (1982), the General Electricity Law was enacted, stipulating that energy distribution was passed on from ELECTROPERU to regional companies, while ELECTROPERU was converted to a public-private company (Torero and Pasco-Font, 2001a).

In 1992, the enactment of the Electric Concession Law (No. 25844) privatized the electricity market (including parts of ELECTROPERU). The role of the state focused on the regulation of the sector. Privatization was not fully accomplished, as only 14 companies were privatized between 1994 and 1997 (Torero and Pasco Font, 2001b). As revealed by Torero and Pasco Font (2001b), privatization led to an increase in the electrification tariff of 6 cents/kWh in 1996 to 10 cents/kWh in 1998, but the electrification rate did not progress as expected in urban areas (Ruiz-Caro, 2002). Electrification rate in rural areas by contrast did increase due to higher investments in rural electrification, which remained in public hands and was therefore conducted by the MEM with public funds (Ruiz-Caro, 2002).

In the context of privatization in the 90s, and in order to regulate the electricity, hydrocarbon and mining industries, the Organization for Investment in Energy and Mining was founded in 1996 with the name of OSINER (since 2007, the name changed to OSINERGMIN). In addition to its role as a supervisor, OSINERGMIN also sets electricity tariffs based on the policies defined by the MEM (OSINERGMIN, NA).

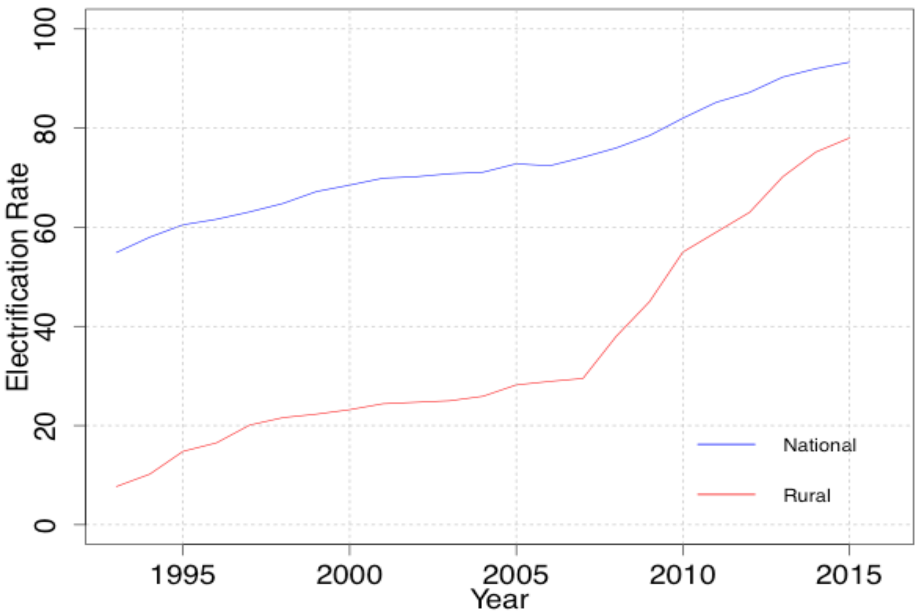
There are currently 43 electricity generation, 9 transmission, and 23 distribution companies operating in Peru, which can be both public or private (MEM, NA). The electricity distribution companies (EDCs) are usually operating in small areas around urban centres; they have the obligation of providing electricity to clients that claim for energy and that are located within 100 meters of the EDC's existing network (MEM, 2014).

### 4.3 Rural electrification

As in 1993 the rural electrification rate was about 8% (see Figure 1) and the private sector was not interested in electrifying remote areas, the MEM established a new division called Executive Project Management (DEP by its Spanish acronyms; Decree No. 021-93) to promote rural energy projects with special funds. Moreover, one year later, a new public EDC ('Electrical Infrastructure Administration Enterprise' (ADINELSA by its Spanish acronyms)) was founded to deal and manage rural electrification projects from local institutions (e.g. from municipalities). ADINELSAs' clients are located outside the operation areas of others EDCs.

In 2007, the DEP was merged with a project for rural electrification improvement, and renamed as General Direction of Rural Electrification (DGER by its Spanish acronyms). Later that year, the Direction of Grant Funds (DFC by its Spanish acronyms) and the Project Management Direction (DPR by its Spanish acronyms) were created to operate under the DGER (MEM, 2015). While the DFC has been in charge of conducting electrification projects supported and funded by international organizations (e.g. Worldbank), the DPR acts by using national funds.

**Figure 1:** Electrification rate in Peru




Source: Own elaboration, based on data from Ministerio de Energía y Minas (2015)

Rural electrification is regulated under the Law of Rural Electrification (Law 28749) enacted in 2006. It stipulates that the state is in charge of planning the rural electrification by means of the DGER. Owing to the alleged financial unattractiveness of this sector, the law allocates state subsidies to rural electrification (Congreso de la Republica, 2006). The law further specifies that the DGER is responsible for elaborating the PNER, an annually published strategy paper on rural electrification with a time horizon of 10 years.

In the case of centralized projects aimed at rural electrification based on off-grid solutions (i.e. stand alone PV systems), although the regional or local governments request the electrification, the projects need approval from the MEM and from the Ministry of Economics and Finance (MEF by its Spanish acronyms). Projects are registered in a database, the National System of Public Investment (SNIP by its Spanish acronyms) to avoid project duplications (MEF, NAb). If approval is given from both the MEM and the MEF, the EDC (or ADINELSA) of the region where the project is located will issue a request for tenders. The private company that wins the tender conducts the installation of the off-grid systems, but the EDC (or ADINELSA) will be in charge of O&M (MEM and Banco Mundial, 2005; MEM, 2015).

Regional and local governments can also promote rural electrification projects with off-grid solutions, either in collaboration with the MEM, or on their own account (and financed from own resources); in the latter case, the approval from MEF/MEM is not necessary. When these energy systems become operative, the local/regional governments may lease or transfer the assets to the EDC of the region (Defensoría del Pueblo, 2010).

Among the rural electrification initiatives based on off-grid solutions, several projects are deploying stand-alone PV systems. Some of them are worth to mention. Between 2006 and 2013, the DFC conducted the Rural Electrification Improvement Project I (FONER I by its Spanish acronyms) in collaboration with the Worldbank that triggered rural electrification initiatives based on PV (MEM, 2012). The DFC is currently running a follow-up project (FONER II), which will deploy a total of 11,000 off-grid PV systems (MEM, 2012).

Moreover, OSINERGMIN conducted a request for tenders (commissioned by the MEM) in 2014 to install between 150,000 and 500,000 stand-alone PV systems all around the country in the so-called 'massive program'. The contract was signed with the MEM/DPR in a public-private partnership; the installation started in August 2015 and completion was planned for mid 2016 (MEM, 2015). The contract stipulates that the private company that won the tender, Ergon S.A., is in charge of the identification of potential users (by a survey), the installation, and the O&M of the systems for 15 years; the administration (e.g. tariff collection) on the other hand will be carried out by the EDCs of the covered regions (OSINERGMIN, 2014).

Table 3 provides an overview of the rural electrification programs in Peru that have been analysed in this paper. The list includes public project as well as projects sponsored by NGOs.

**Table 3:** Rural Electrification Programs based on off-grid PV systems considered in this paper

| | **Rural Electrification Improvement Project (FONER I & II)** | **RE Programs from the General Direction of Rural Electrification (DGER)** | **Massive Program** | **Municipalities** | **Non-Governmental Organizations (NGOs)** |
|---|---|---|---|---|---|
| **Reports for ex-post evaluations** | Jané La Torre and Palacios, 2015; van den Akker, 2008; | Jané La Torre and Palacios, 2015; JICA, 2008; UNDP/GEF, 2006 | NA | Jané La Torre and Palacios, 2011; Jané La Torre and Palacios, 2015 | Canessa et al., 2014; Jané La Torre and Palacios, 2015, Fernandez, 2015; Verástegui Gubler el al., NA; Prialé Ugás, 2012; Horn ,2003; Egido et al., 2004; Arráiz and Calero, 2015; Magill and Valdes, NA |
| **Program sponsored by** | Direction of Grant Funds (DFC) and,Worldbank | Project Management Direction (DPR) | Ministry of Energy (DGER) | Municipalities | ACCIONA Microenergía Perú (AMP); German Society for International Cooperation (GIZ);<br><br>Soluciones Prácticas<br><br>Universities<br><br>Eurosolar |
| **Location** | Nationwide | Nationwide, among others: Cajamarca, Ucayali, Loreto, Junin,Cusco, Pasco, Ayachucho | Nationwide (divided into northern, central, and southern Peru). | Nationwide, among others: Loreto, Puno, Cajamarca, Ucayali, Amazonas, Piura, Pasco, Madre De Dios | Cajamarca. Puno, San Martin, Amazon, Cusco<br><br>Lambayeque, Piura, Ayacucho, Huancavelica: Ica, Junin, Tacna |

| | | | | | |
|---|---|---|---|---|---|
| **Energy use** | Residential rural electrification; electrification of schools/health centres/social buildings | Residential rural electrification | Residential rural electrification; electrification of schools, health centres and social buildings | Residential rural electrification | Residential rural electrification (Solar Home Systems (SHS) and Solar Pico Systems (SPS); Schools and Churches, Health Centres, Community Centres |
| **Capacity/ Sizing** | FONERI: 60 Wp<br>FONERII: 60Wp, 80Wp were proposed for future installations | PER/96/028: 50Wp<br>PER/98/G31: 35-51Wp | 120Wp | 50Wp | Renewable Energy Center (CER-UNI): 45-50 Wp<br>AMP: 60-80Wp<br>Eurosolar: 1400Wp (hybrid solar-wind systems) |
| **Year of installations** | FONER I: 2006-2011<br>FONER II: Since 2012 | Since 1996 | Since 2015 | Various, e.g.:<br>Regional Government of Tacna: 2007 – 2008<br>Regional Government of Cajamarca and Loreto: 2011 | CER-UNI: 1986 – 1987, 1995/1996, 1999<br>AMP: Since 2009<br>Eurosolar: 2011<br>Soluciones Practicas: 2006/07 |
| **Number of installations/households electrified** | FONER I: 9,115<br>FONER II: 20,000 | PER/96/028:<br>1,523<br>PER/98/G31: 4,200 | 150,000-500,000 | Estimation of total users: 6197 | CER-UNI: 100, 451, 781 (different projects)<br>AMP: ~3,900<br>Eurosolar: 130 communities (902 panels) |

Sources: Own elaboration based on MEM (2016); AMP(NA); Horn (2003); Jané La Torre and Palacios (2015 & 2011); FISE (2016); UNDP/GEF (2006)

## 5. Results

### 5.1 Institutional Sustainability

***Stability (durability)***

Although the PNER includes a long-term perspective on rural electrification aiming to assure planning security to the electrification policy, reality has diverged from this objective. Abrupt political changes in the energy sector have inhibited following a clear and strategic policy line. According to a representative of OSINERGMIN, these political changes have been an issue for Non-Conventional RE (NCRE) policies as the RE quota has been fixed depending on who is in the government, thus leading to high uncertainty. Moreover, the staff rotation in the MEM caused by political changes has led to a loss of know-how.

Furthermore, mistrust towards formal institutions is widespread in Peru. The red tape in the public sector was an often-named problem, which has led to animosity towards the governments and the public institution in general. The lack of trust in the government may have also contributed to widespread outsourcing. In rural electrification the installation of off-grid PV systems and their O&M is outsourced; the regulatory agency (OSINERGMIN) has even outsourced the supervision of these outsourced activities.

***Regulation and Standards***

Technical standards for off-grid PV systems in Peru are not up to date (e.g. technology for light bulbs has improved considerably in the meantime) (MEM, NAb). Additionally, the quality of the mostly imported components of off-grid PV systems is not controlled, which has resulted e.g. in premature battery failures. Due to the lack of quality standards, rural electrification projects (particularly those implemented by local governments) are compromised by the use of very poor qualitative parts.

OSINERGMIN's supervision of the EDCs has indeed been weak regarding off-grid PV systems for rural electrification. In fact, up to now only two punctual revisions were conducted by OSINERGMIN in 2011 and 2013, where a total of 1,110 off-grid PV systems from different public and private projects were inspected. Out of these 1,110 revised systems, 34% were found inoperative (Jané La Torre and Palacios, 2015). Part of the problem is that in Peru regulations are not clear regarding what actions to take and who is hold responsible if the systems are not operative.

Some interviewees have also described the lack of technical standards as a problem affecting the "massive program". A representative of OSINERGMIN admitted that many technical details were not included in the request for tenders of the "massive program". As a consequence, disagreements between the MEM and Ergon concerning the technical standards of the systems delayed their implementation in 2015.

***Decentralization and Openness to participation***

Article 3 of the law of Rural Electrification specifies that the MEM shall develop projects for rural electrification in collaboration with regional and local governments. Yet, the MEM is centrally designing the projects, without the participation of those who are closest to the community (i.e. the EDCs). Moreover, the role of the rural communities is limited and they are not involved at all in the design and implementation of projects.

Decentralization (understood as redistribution of the funds to elected local governments) has allowed local or regional governments to implement electrification projects by themselves. However, as mentioned above, these projects have been rarely successful. Indeed, though the number may not be representative, the two supervisions conducted by OSINERGMIN (2011/2013) found that only one out of 29 supervised PV systems implemented by municipalities was operative (Jané La Torre and Palacios, 2015). A representative of the Ministry of Development and Social Inclusion (MIDIS by its Spanish acronyms) explained these flaws by the fact that although funds were remitted from the national to local and regional governments, they were not accompanied by development programs and technical assistance to the local governments.

Decentralization in Peru has also been plagued by a lack of coordination. Although projects implemented by local or regional governments should be registered in the SNIP to avoid duplications, this is often not occurring. Furthermore, the data the government holds on rural electrification are not up to date. In fact, electrification rate published by the MEM diverged considerably from other databases (such as census data) (Defensoría del Pueblo, 2010).

The lack of reliable data also became evident in the case of the "massive program". The MEM gave Ergon a tentative database of the communities that lack electricity access but many of the communities from the MEM's database were already electrified. In fact, in the request for tenders of the "massive program", the number of installations under contract was not set partially due to the fact that the actual number of households without electricity is still unknown.

***Adaptability***

The sustainability of rural electrification programs demands for institutions that have the capacity to adapt to the situation of a country and its needs. This normally implies having strong formal institutions with a flexible and decentralized structure (Pyhala, 2002; Thoenig, 2008:294). However, regarding rural electrification, the organization of the MEM/DGER hardly meets these criteria.

Currently two agencies (DFC and DPR) both under the MEM/DGER, conduct off-grid PV projects for rural electrification. The need of having two agencies both focused on rural electrification is not clear. Although project proposals for rural electrification from across the country are presented to the DGER and thereinafter assigned to either one of the agencies, there are no written criteria that determine to which one a project is assigned. Competences of both agencies appear to be overlapping, which has caused rivalry between them.

Several interviewees argued that projects from the DFC were technically superior to those from the DPR. The difference may be due to the fact that the DFC has vast experience in off-grid PV system installations, whereas until very recently the DPR had no interest in PV. Still, the "massive program" is being coordinated by the DPR, leaving the DFC completely out.

The lack of a single agency with the responsibility of promoting and overseeing all rural electrification programs in the country seems to be a major drawback, which compromises the ability of Peruvian institutions to ensure the sustainability of off-grid PV projects (including the "massive program"). Also, the current regulations may not be flexible enough for allowing EDCs to adapt to the particularities of the communities. For example, aiming to meet the needs of isolated communities in remote areas, several interviewees mentioned a variety of applications such as Solar Pico Systems (SPS) (i.e., small-scale solutions of 0.3 Watts peak (Wp) up to 10 Wp such as solar lanterns; see IEA, 2013 for details). SPS may be useful in remote regions that EDCs technicians cannot reach regularly as well as for nomad communities (who change their dwelling several times per year). However, SPS solutions have not yet been considered in government projects and recently, the MEM rejected a proposal of the GIZ to consider SPS for remote areas. This example shows that Peruvian institutions have still problems to adapt to the needs of different communities, which inhibit seizing opportunities.

### 5.2 Economic Sustainability

#### *Cost effectiveness and reliability*

In order to be sustainable, a solution for electrification must be cost-effective. In remote areas of Peru, conventional grid expansions have shown to be too difficult and expensive (Jané La Torre and Palacios, 2015). In these cases, off-grid PV systems are a cost-effective alternative and therefore, several EDCs and NGOs have been deploying off-grid solutions in these areas for years.

Aimed at cost-effectiveness, basically all EDCs (and NGOs) have outsourced both installations and O&M services to local firms. Moreover, some of the EDCs have recognized the advantage of economies of scale. According to a representative of ADINELSA, they attained lowering the monthly O&M costs from about S/.60 to S/.50 (US$20 to US$17) per user by increasing the number of off-grid PV clients across the country. Indeed, the "massive program" was designed following the approach of economies of scale.

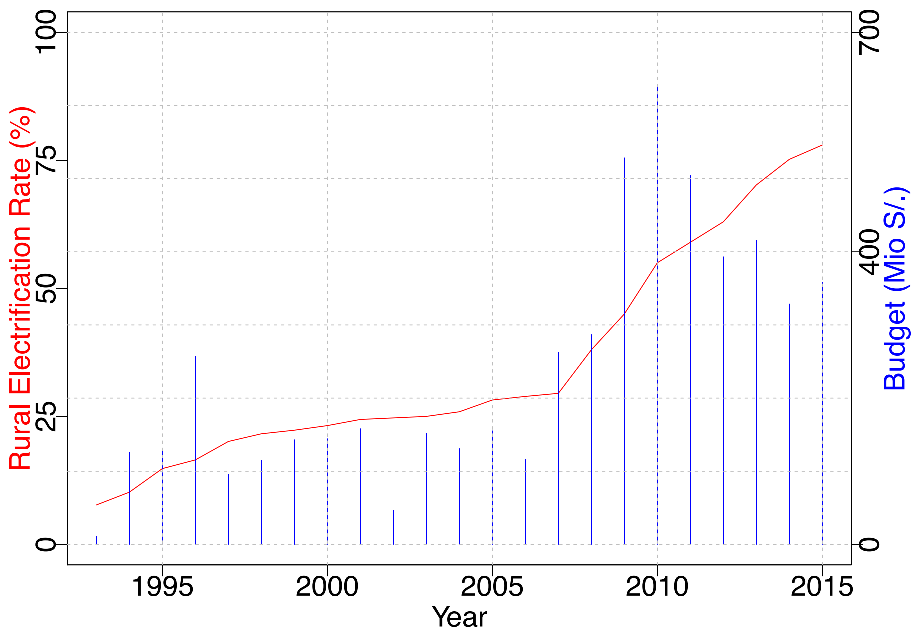
In the case of the "massive program", the tender bid winner (Ergon) expects the program's costs per user to be very low, even below the current subsidy paid to the public EDCs in the southern region: Ergon will receive US$8,370,054 per year (for 15 years) for 50,000 users (i.e., about US$167 per system per year) (Ramos Rivas, 2014). This is nearly half of the price offered by the second bidder in the same area (that had bidden US$16,703,235) (Ramos Rivas, 2014). This difference has been highlighted by several interviewees that were quite sceptical about the reliability of the service offered by Ergon. Indeed, although the contract of the "massive program" stipulates that Ergon must execute all maintenance tasks, no contractual obligation existed to conduct revisions at a fixed period (OSINERGMIN, 2016a).

Reliability of PV systems has already been an issue in Peru for the implemented systems, especially regarding O&M, as public EDCs are under considerable strain to make profits (and rural electrification is a losing deal for them). Moreover, several interviewees explained that most EDCs do not have spare parts for off-grid PV systems in their stock.

***Funding***

Sustainability of off-grid PV systems requires ensuring funding for the initial investment and the O&M. In Peru, government intervention is inevitable for ensuring funding because rural populations in remote areas are usually poor and can neither afford the systems nor their O&M. Fortunately, budget allocation to rural electrification has increased substantially since 2007, which has contributed to the great increase of the rural electrification rate, as shown by the red line in Figure 2. As explained above, the initial investment of off-grid PV systems may stem from different sources (e.g. state budget, fines, etc.).

**Figure 2**: Rural electrification budget (in Million S/.) vs. rural electrification rate.




Source: Own elaboration based on MEM (2015).

Nevertheless, even the poorest inhabitants of remote areas are expected to contribute to the O&M costs. In Peru, OSINERGMIN fixes the electricity tariffs for urban and remote users, including for off-grid PV systems. For the latter, tariffs are set every four years, and they may vary according to three main factors: 1) who is the investor (private or public company); 2) the size of the PV modules, and 3) the location (coastal lowlands, Andean highlands, Amazon basin, or special Amazon regions) that determines the amount of energy disposed respectively.

Since the tariff would far outweigh the spending capacity of the users, it is subsidized with a cross-subsidy fund, the Social Electric Compensation Fund (FOSE by its Spanish acronyms). According to Law No. 27510 (established in 2001 and modified to include off-grid PV systems in 2010), the FOSE is a cross-subsidy administered by OSINERGMIN for poor households with a monthly energy consumption of below 100kWh (OSINERGMIN, 2010). The contributions for the cross-subsidy scheme are stemming from users with a monthly electricity consumption of above 100kWh (usually from urban areas). While different subsidy ranks are defined, the greatest subsidy (currently 77.5%) is given to off-grid clients with an energy consumption of below 30kWh (Congreso de Perú, 2013). For example, the monthly tariff from a public EDC applied to a user with a system of 70Wp at the coastal lowlands amounts to S/.30.55 (about US$10) per month, but the users ultimately pay only S/.6.25

(about US$ 2) after applying the FOSE (OSINERGMIN, 2014b). Tariffs are higher for users from private companies (S/.47.12 in total and S/.9.42 user contribution in this example) to compensate for the private company's initial investment (OSINERGMIN, 2014b).

The FOSE seems to make electricity affordable to rural populations. According to a RE researcher, the MEM had conducted a baseline study to capture the spending capacity of the poor rural households. This study revealed that even the poorest communities paid between 5 and 6 dollars per month on traditional energy (e.g. candles and kerosene) before receiving the RE solution. Nonetheless, default payment rates vary considerably: Whereas AMP's default rate is below 1%, ADINELSA's rate varies between 15% and 40%, and the EDC Electro Oriente (ELOR) reported an average of 51.56% in Iquitos (OSINERGMIN, 2014c; Jáuregui, 2014; AMP, 2014). Though the reasons for these differences are manifold and will be further discussed below, the default seems not to be due to an excessive user tariff.

***Contribution to user income***

Business users of Peruvian rural areas considered the availability of electricity to be essential for their businesses (Yadoo, 2012). Still, rural electricity for productive uses have so far been limited to projects of grid expansion and some isolated pilot projects. However, there is huge potential for productive uses: e.g., fishing communities in the Amazon basin currently need to acquire ice for cooling the fishes in a city that is 3-4 hours away, incurring high costs. A freezer running on electricity powered by PV systems could not only substantially lower these costs, but also assure the cold chain for the fishes. Moreover, increasing output from production would result in higher incomes of the rural population. Despite these opportunities, local governments often don´t have the means to implement the projects. Interdisciplinary projects involving expertise from different disciplines and sectors are urgently needed to seize these opportunities.

The MIDIS was meant to assume this role; the Ministry was founded in 2010 to eradicate extreme poverty by coordinating different public organizations. The MIDIS administrates the Fund for Economic Inclusion in Rural Areas (FONIE by its Spanish acronyms), which was created in 2013 to finance interdisciplinary rural projects that attend needs for water and sanitation, electricity, local roads, and telecommunication (MIDIS, 2013). However, the FONIE only provides the fund for the project implementation itself without any support to the community after the project implementation.

### 5.3 Environmental Sustainability

***Environmental awareness***

Environmental awareness does not appear to be a priority for the Peruvian elite. Environmental measures that have been taken in this direction were mainly based on international pressure and the recent hosting of the Conference of the Parties (COP) 20 in 2014 in Lima. Although the creation of the Ministry of Environment (MINAM by its Spanish acronyms) in 2008 aimed to institutionalize environmental issues, the Ministry is still considered as emerging, mainly because it is lacking experts (Lanegra, 2014). Despite the protection of forest resources by law, projects including huge deforestation have been approved (EIA, 2015). In fact, the Worldbank revealed that notwithstanding major environmental reforms between 2003 and 2009, hardly any changes were registered concerning overfishing, deforestation, degradation of soil and water bodies caused by agriculture and mining, and poorly managed water resources (Liebenthal and Salvemini, 2011).

According to some interviewees, the lack of environmental awareness is also apparent in the population´s behaviour. For example, a study by McAllister (2015) found that trash management became an issue in the community La Zaranda (Province of Ferreñafe in Northern Peru), as littering was a socially accepted practice. Indeed, despite the Environmental Education Project implemented in 2011 and the National Prize for Environmental Citizenship (2009), considerable challenges remain for environmentally responsible citizens (ECLAC and OECD, 2016). In fact, the increase of socio-environmental conflicts arising from mining conflicts can hardly be associated with protesting against environmental impacts, but rather with a disconcert against the lacking social compensations from the mining industry (e.g. by creating jobs) (Paredes and de la Puente, 2014).

***Environmental impact***

In Peru there are neither specific regulations nor any enforcement policies for rural electrification to mitigate critical environmental issues such as battery disposal. For instance, an examination in Cajamarca conducted by OSINERGMIN showed the devastating consequences of abandoned batteries (Jané La Torre and Palacios, 2015). There are exceptions, however; according to several interviewees, ADINELSA does have a policy on proper battery handling, as batteries are returned to Lima for recycling.

Therefore, various studies from international institutions urge the government of Peru to further substantiate environmental policies for rural electrification based on RE (see e.g. MEM, 2007; Millones, 2005; JICA, 2008).

**5.3 Socio-Cultural Sustainability**

***Accessibility (disparity, equity)***

As pointed out above, access to electrification in rural areas has increased notably in Peru in recent years. Moreover, through the implementation of the "massive program", it is expected that other 150,000 households (in fact, as of December 2015, 190,000 systems were registered for installation; OSINERGMIN, 2016a) will get access to electricity for the first time. Although each of these households will receive systems of the same capacity (which appears to comply with a criterion of equity), the amount of energy supplied by the same off-grid PV systems in Amazon regions may be significantly lower than in the southern coastal lowlands (OSINERGMIN, 2016b). Further disparities arise from the fact that the tariff depends on the EDC; users who are attended by a private company have to pay more; e.g., in special Amazon regions, the tariff rises to S/.2.08 per kWh in the case of private EDCs, while it amounts to only S/1.26 per kWh in the Amazon basin and S/.1.39 per kWh in special Amazon regions (OSINERGMIN, 2016b).

Significant disparities in the access of energy affect the remote rural areas. Reaching these areas often requires trips of several hours by boat across the Amazon basin, and therefore they offer even less profits for EDCs. A representative of the MEM admitted that they don't properly attend these regions in the FONER program and they are not expected to be considered in the "massive program" either. Regarding the latter, the contract stipulates that Ergon (the tender bid winner) is expected to install the systems wherever it is "viable".

***Social Acceptance***

In general, the demand for access to electricity and the acceptance of off-grid PV solutions are both high in rural Peru. An Ergon representative declared that as part of the "massive project" they had censored more than 150,000 dwellings, and none of the households has refused the offered off-grid PV system. Several interviewees mentioned the importance of modern communication technologies such as cell phones or computers, which have diffused even to the most remote parts of the country.

Nonetheless, the interaction between the community members and outsiders (e.g. representatives of EDCs) seems to have become problematic in areas where the mining industry is operating. According to a social researcher, the community usually holds a historically conflictive relationship with the companies. As discussed elsewhere (e.g. Paredes and de la Puente, 2014), socio-environmental conflicts have indeed increased considerably in Peru.

These conflicts feed mistrust, which in turn appears to be related to default (that has plagued some off-grid PV projects by ELOR and ADINELSA). A representative from an NGO revealed that the level of mistrust due to conflicts with the mining industry have caused a loss of credibility also towards NGOs, such that gaining people's trust has been essential for reducing their current default rate to less than 1%.

Based on these experiences, NGO-sponsored project managers and university researchers concurrently agreed on the importance of a participative approach, meaning that the local community is embedded in the project from the beginning. Unfortunately this methodology is not used in government projects.

***Accuracy***

In order for a project to be accurate, it has to meet the specific local needs and consider the socio-cultural reality of each community. Unfortunately, it is not clear if Peruvian official are widely aware of the need of accuracy. For example, ADINELSA deploy off-grid PV systems with capacities of either 50Wp or 85Wp. The decision on the system capacity is based on the user's expenses for alternative energy sources (such as candles, kerosene) before electrification. The limited capacity of ADINELSA solutions has been criticized, since it was not defined according to community-specific energy needs; the EDC, however argues that higher capacity may be too expensive for some households (as the tariff depends on the capacity).

In the "massive program", Ergon will install 120Wp systems everywhere regardless of the user's habits of its region. A MEM representative and a high ranking official agreed that ideally the capacity of the systems would have been defined according to the real needs and the income level determined in a baseline analysis of each community and pursuant to the different local, cultural, and geographical circumstances. Yet, this has not been done to save costs.

***Cultural Justice***

Peru is culturally extremely diverse, with multiple indigenous communities living across the country. Besides gender issues and language differences, there is diversity in the community organization and the willingness to participate in projects. However, culture has mostly been neglected in the public sector. Although the request for tenders of the "massive program" stipulated that "*[t]he Investor will design the autonomous RER [Renewable Energy Resources] installations taking into consideration the background and the social economic characteristics of the user"* (OSINERGMIN, 2014:57-58), there are no specific indications (except for translating system handbooks to indigenous languages) of how this should be put into practice.

The disregard of socio-cultural particularities of rural communities has also been reported regarding the role of women in rural electrification, who were found to hardly participate in the projects (Lillo et al., 2015). This deficiency in socio-cultural aspects has led to project failures or payment defaults. The EDCs tend to attribute these defaults to an excessive price, or to the users' unwillingness to pay. However, in NGO-sponsored projects that have succeeded in engaging the community, the default rate is much lower.

Regarding each sustainability indicator considered in this paper, Table 4 provides a summary of the strengths and weaknesses of rural electrification efforts in Peru based on off-grid PV solutions.

**Table 4:** Strengths and weaknesses of rural electrification efforts in Peru based on off-grid PV solutions.

| Indicator | Strength | Weaknesses |
|---|---|---|
| **Stability** | | Frequent rotation of high-ranking officials. |

| | | |
|---|---|---|
| **Regulation and Standards** | Technical standards and regulations have been defined. | Adopted technical standards are obsolete.<br><br>The regulatory framework does not consider some technologies (e.g. SPS or micro-grids), which avoids their adoption.<br><br>No service standards have been adopted.<br><br>Neither adopted standards nor regulations are enforced. |
| **Decentralization and Openness to participation** | Decentralization efforts have been conducted, including budget allocation to local governments (i.e. municipalities). | Lack of technical know-how at local level (i.e. municipalities), which has resulted in failure of municipality-sponsored projects.<br><br>No interaction or coordination between different sectors, institutions or government levels. |
| **Adaptability (ability to meet future needs)** | | Duplicity of agencies with overlapping competences and responsibilities.<br><br>Peru lacks a single decentralized agency for overseeing off-grid electrification programs.<br><br>Widespread outsourcing with weak quality controls by regulators or EDCs. |
| **Affordability** | Cross subsidies for subsidizing rural electrification efforts.<br><br>Adequate tariff scheme for users of off-grid PV systems. Tariff is below previous expenditures on traditional fuels like candles. | |
| **Cost effectiveness** | Official have recognized that off-grid PV systems are a cost-effective alternative to grid expansion. They have also recognized the advantages of economies of scale in the case of stand-alones PV solutions. | |
| **Consideration of operation and maintenance costs** | Costs, tariffs, and subsidies have been calculated considering both the initial costs and the O&M costs by using a sophisticated model. | The O&M costs (and subsequently tariffs and subsidies) may still be underestimated by not properly considering geographical differences between regions. |
| **Contribution to income of users** | Enormous potential for productive use (e.g. refrigerating fresh fish). | Productive use has only been considered in electrification projects based on the grid-expansions. |
| **Reliability of supply** | | The lack of spare parts/maintenance of off-grid PV systems in rural areas has caused high failure rates. |

| | | |
|---|---|---|
| **Environmental awareness** | Rural populations (especially in areas where mining is intensive and has caused externalities) have developed a notion of environmental awareness**.** | Environmental awareness is not widespread in the Peruvian elite. Environmental measures appear to be mainly based on international pressure, but the mining activities for example are subjected to few and weak environmental regulations. |
| **Environmental impact** | The National Evaluation System of the Environmental Impact also applies for rural electrification. | The lack of specific regulations and enforcement policies on environmental hazards has resulted in negative environmental impacts such as abandoned batteries. |
| **Accessibility (disparity, equity)** | Cross subsidy tariff scheme as well as initiatives (such as the "massive program"), demonstrate the willingness of the Peruvian elite to ensure access to electricity. | EDCs and regulators have shown little interest in providing electricity to inhabitants of remote areas.<br><br>Disparities between regions (price per kWh). |
| **Accuracy** | | System capacity is determined by its affordability rather than in the needs of the populations. As a consequence, systems often fell short of energy demand. |
| **Social acceptance** | | There is a significant mistrust between the government and rural population (especially in areas where mining is extensive). This conflictive relationship jeopardizes social acceptance of electrification projects and may result in the rejection of the PV systems. |
| **Cultural Justice** | | MEM projects are designed without the engagement of the community, as Peruvian officials appear to be unaware of the importance of local participation. |

Source: Own elaboration

## 7. Summary and Conclusions

In this paper, we assess the sustainability of rural electrification programs in Peru, paying special attention to the "massive program" (that aims to deploy a minimum of 150,000 off-grid PV solutions in the upcoming years). Our assessment was based on a set of indicators corresponding to the four dimensions of sustainability considered in this paper: institutional, economic, environmental, and socio-cultural.

The sustainability of rural electrification programs demands for strong formal institutions with a flexible and decentralized structure. However, we found that the organization of the MEM/DGER hardly meets these criteria. Two agencies (DFC and DPR) both under the MEM/DGER, currently conduct off-grid PV projects for rural electrification. Competences of both agencies (DFC and DPR) appear to be overlapping, which has caused rivalry between them. Moreover, steady staff rotation has caused disturbing changes in the regulatory framework of Peru; this instability has inhibited following a strategic line in rural electrification as projected by the PNER.

Drawbacks in the Peruvian decentralization process have significantly affected prior rural electrification efforts. Decentralization (understood as redistribution of the funds to elected local governments) has allowed local or regional governments to implement electrification projects by themselves. However, these projects have been rarely successful, since the capacities on the regional and local scale on RE projects are basically non-existent. Moreover, the MEM is centrally designing its projects without the participation of those who are closest to the community. Indeed, the role of the rural communities in Peru is limited and they are normally not involved in the design and implementation of projects sponsored by the government.

Despite the country's huge potential, systems for productive uses that increase the user's income have not been considered so far. This is due to a lack of basic skills and know-how of the rural population on the opportunities and uses of energy as well as on business know-how in general. Interdisciplinary programs (e.g. including drinking water and sanitation, roads, education, etc.) could help assessing this gap, but recent attempts by MIDIS have fallen behind expectations. This inhibits seizing opportunities regarding productive uses of off-grid PV systems.

Widespread outsourcing as currently occurring in Peru (in rural electrification, off-grid PV system installations and O&M of off-grid PV system are outsourced) requires strong quality control. However, the technical standards for off-grid PV systems are not up to date, while service standards do not exist in Peru. As a consequence, the reliability of off-grid PV systems has been an issue in Peru, especially regarding O&M.

Cross subsidies for subsidizing rural electrification efforts have facilitated a notable increase in the electrification rate of the country in recent years. However, system capacity is determined by its affordability rather than by the needs of the populations. As a consequence, systems often fell short of energy demand. Although some adaptations of the tariff model should be considered (especially regarding tariff equity between regions/between private and public EDCs), we found that the tariff scheme has made off-grid PV systems affordable for users (the tariff is below previous expenditures on traditional fuels like candles).

We also found that MEM projects are still designed without considering the fact that Peru is culturally diverse, which has often led to payment defaults; especially in projects sponsored by the government that failed in engaging the community. Indeed, Peruvian officials often appear to be unaware of the importance of local participation (as local values and lifestyles are disregarded), and there is a significant mistrust between the government and the rural population (especially in areas where mining is extensive).

Environmental awareness is not yet an issue for the majority of the Peruvian elite, such that overfishing, deforestation, and degradation of soil and water bodies caused by agriculture and mining are frequent. Although communities affected by these problems show early signs of the awakens of environmental awareness, we found that there are neither specific regulations nor any enforcement policies aimed at the mitigation of critical environmental issues associated with off-grid PV systems (such as battery disposal).

As the Peruvian case revealed, assuring the sustainability of the off-grid PV systems cannot be achieved by only providing funds for the initial investment and the O&M. Attention must be paid to the other dimension of the sustainability (environmental, socio-cultural and institutional). We expect that our conclusions may help Peruvian institutions to address the most severe drawbacks affecting their rural electrification efforts, particularly those that can compromise the sustainability of the ongoing "massive program".

**References**


1. ACCIONA Microenergía Perú (AMP) (NA). FUNDACIÓN ACCIONA MICROENERGÍA Available at: http://www.acciona.com/es/sostenibilidad/sociedad/fundacion-acciona-microenergia/Accessed on 12 July 2016.
2. ACCIONA Microenergía Perú (AMP) (2014). Luz en Casa. Acceso A Energía Sostenible En Comunidades Rurales De Perú (in Spanish)
3. Agencia de Cooperación Internacional de Japón (JICA) (2008). Estudio del Plan Maestro de Electrificación Rural con Energía Renovable en la República del Perú. Informe Final <Resumen Ejecutivo> (in Spanish)
4. Van der Akker (2008). Electrificación Rural a base de Energía Fotovoltaica en el Perú – proyecto PER/98/G31.
5. Arráiz, I., & Calero, C. (2015). From Candles to Light: The Impact of Rural Electrification. Inter-American Development Bank.
6. Bernhardt, J. The Effectiveness of Science-Policy Interactions: Case Studies on Climate Change Mitigation and Sustainable Development in Pan-European Forest Research and Politics. 2015. Doctoral Thesis, Univerity of Hamburg, Hamburg, Germany. Available online: http://ediss.sub.uni-hamburg.de/volltexte/2015/7160/ Accessed on 24 March 2015.
7. Bhattacharyya, S. C. (2012). Energy access programmes and sustainable development: A critical review and analysis. Energy for sustainable development, 16(3), 260-271.
8. Brent, A. C., & Rogers, D. E. (2010). Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context. Renewable Energy, 35(1), 257-265.
9. Canessa, R., Santome, J.M., Buss, I.N. (2014). EvaluacióN Ex Post Del Programa Euro-Solar. Informe Final Contrato específico N°2013/332211. Available at: https://ec.europa.eu/europeaid/sites/devco/files/eurosolar-informe-final_es.pdf Accessed on 3 July 2016 (in Spanish)
10. Chaurey, A., & Kandpal, T. C. (2010). Assessment and evaluation of PV based decentralized rural electrification: An overview. Renewable and Sustainable Energy Reviews, 14(8), 2266-2278.
11. Cook, P. (2011). Infrastructure, rural electrification and development. Energy for Sustainable Development, 15(3), 304-313.
12. Defensoría del Pueblo (2010). La Electrificación Rural en el Perú: Derechos y Desarrollo para Todos. Informe Defensorial No 149. Biblioteca Nacional del Perú: No 2010-04176 (In Spanish).
13. Environmental Investigation Agency (EIA) (2015). Deforestation by Definition:
14. The Peruvian Government Fails to Define Forests as Forests, while the Malaysian Influence and Palm Oil Expansion Threaten the Amazon. EIA, Washintont DC. Available at: http://eia-global.org/images/uploads/150325.1_EIA_Peru_Palm_Report_P06-WEB.pdf .Accessed on 11 September 2016.
15. Congreso de la Republica (2006). Ley general de electrificación rural LEY No 28749 (in Spanish)
16. Congreso de Perú (2013). Proyecto de Ley No. 3466/2013-CR. (in Spanish)
17. Damonte, G., Fuller, N., & Valcárcel, M. (2009). Minería, turismo y agroindustria: nuevos ejes económicos. Pontificia Universidad Católica del Perú. Departamento de Ciencias Sociales. (in Spanish)
18. Derakhshan, F. (2011). On sustainability in local energy planning. Lund University.
19. Dincer, I., & Acar, C. (2015). A review on clean energy solutions for better sustainability. International Journal of Energy Research, 39(5), 585-606.
20. Dunmade, I. (2002). Indicators of sustainability: assessing the suitability of a foreign technology for a developing economy. Technology in Society, 24(4), 461-471.
21. Egido, M. A., Vega, P., & Horn, M. J. 19th European Photovoltaic Solar Energy Conference, 7-11 June 2004, Paris.
22. Fenner, R. A., Ainger, C. M., Cruickshank, H. J., & Guthrie, P. M. (2006). Widening engineering horizons: addressing the complexity of sustainable development. Proceedings of the ICE-Engineering Sustainability, 159(4), 145-154.
23. Fernandez, M. (2015). Experiencias con Sistemas Fotovoltaicos de Tercera Generacion en Argentina, Bolivia y Peru. ESMAP, Worldbank, Washington DC (in Spanish).

24. Feron, S., Heinrichs, H., & Cordero, R. R. (2016). Are the Rural Electrification Efforts in the Ecuadorian Amazon Sustainable?. Sustainability, 8(5), 443.
25. Fischedick, M., Borbonus, S., & Scheck, H. (2011). Towards Global Energy Governance-Strategies for Equitable Access to Sustainable Energy. Policy Paper, 34, 12.
26. Fondo de Inclusion Social Energetico (FISE) (2016). AÑO 3- No1 / REVISTA SEMESTRAL / SEPTIEMBRE 2016 Available at: http://www.fise.gob.pe/pags/PublicacionesFISE/Revista-Semestral-FISE-2016-I.pdf Accessed on 3 October 2016 (in Spanish).
27. Frame, D., Tembo, K., Dolan, M. J., Strachan, S. M., & Ault, G. W. (2011, July). A community based approach for sustainable off-grid PV systems in developing countries. In Power and Energy Society General Meeting, 2011 IEEE (pp. 1-7). IEEE.
28. Garniati, L., Owen, A., Kruijsen, J., Ishadamy, Y., & Wibisono, I. (2014). Interface between appropriate technology and sustainable energy policy in vulnerable societies. Sustainable Cities and Society, 12, 9-15.
29. Gollwitzer, L. (2014). Community-based Micro Grids: A common property resource problem. STEPS working paper 68.
30. Hall, A. L., & Rist, R. C. (1999). Integrating multiple qualitative research methods (or avoiding the precariousness of a one‐legged stool). Psychology & Marketing, 16(4), 291-304.
31. Heinrichs, H.; Laws, N. "Sustainability State" in the Making? Institutionalization of Sustainability in German Federal Policy Making. Sustainability 2014, 6, 2623–2641.
32. Holland, R., Perera, L., Sanchez, T., & Wilkinson, R. (2006). Decentralised rural electrification: the critical success factors. Experience of ITDG (Intermediate Technology Developmental Group).
33. Horn, M. (2003). Solar Photovoltaics for Sustainable Rural Electrification in Developing Countries: the Experiences in Peru. Universidad Nacional de Ingeniería–Centro de Energías Renovables.
34. Hugé, J.; Mukherjee, N.; Fertel, C.; Waaub, J.P.; Block, T.; Waas, T.; Dahdouh-Guebas, F. Conceptualizing the effectiveness of sustainability assessment in development cooperation. Sustainability 2015, 7, 5735–5751.
35. Ilskog, E. (2008) Rural electrification sustainability indicators—manual for field workers. Available online: http://swepub.kb.se/bib/swepub:oai:DiVA.org:kth-9132?tab2=abs&language=en (accessed on 27 June 2014).
36. Instituto para la Democracia y la Asistencia Electoral (IDEA)(2008). Estado: Funcionamiento, Organización y Proceso De Construcción De Políticas Públicas (in Spanish)
37. Instituto Nacional de Estadistica e Informatica (INEI), (2015). Día Mundial de la Poblacion (in Spanish)
38. Instituto Nacional de Estadistica e Informatica (INEI), (NA). Población en Situación de Pobreza Monetaria, según Ámbito Geográfico, 2004 – 2014. Available at: https://www.inei.gob.pe/estadisticas/indice-tematico/sociales/ Accessed on January 28th 2016. (in Spanish)
39. International Energy Agency (IEA)(2013). " Pico Solar PV Systems for Remote Homes
40. A new generation of small PV systems for lighting and communication" Available at: https://www.iea.org/media/openbulletin/Pico_Solar_PV_System.pdf Accessed on April 21st 2016
41. Jané La Torre, E., Palacios, D. (2011). Resultados De La Supervisión A Sistemas Eléctricos Rurales Aislados a Cargo De Municipalidades y Entidades Locales 2008 – 2010. Documento de Trabajo No 26-GFE, Gerencia de Fiscalización Eléctrica, Osinergmin. (in Spanish)
42. Jané La Torre, E., Palacios, D. (2015). Estado Situacional De La Prestación del Servicio Electrico Mediante Sistemas Fotovoltaicos Autónomos. Gerencia de Fiscalización Eléctrica, Osinergmin. (in Spanish)
43. Jáuregui Chinchay, J. (2014). Materiales Necesarios Para La Operación, Mantenimiento Y Gestión Comercial De Los Sistemas Fotovoltaicos Domiciliarios En Los Distritos De Indiana, Mazan Y Las Amazona. Informe Ejecutivo N° Gc-032-2014 (in Spanish)
44. Khandker, S. R., Barnes, D. F., & Samad, H. A. (2013). Welfare impacts of rural electrification: a panel data analysis from Vietnam. Economic Development and Cultural Change, 61(3), 659-692.
45. La Contraloría General de la República. (2014). Estudio del proceso de descentralización en el Perú. (in Spanish)

46. Lanegra, I. (2014). Institucionalidad ambiental peruana. In: Agenda de Investigación en Temas Socioambientales en el Perú: Una aproximación desde las ciencias sociales. CISEPA-PUCP | INTE | Facultad de Ciencias Sociales | GEA. Lima, 2014

47. Liebenthal, A., & Salvemini, D. (2011). Promoting Environmental Sustainability in Peru: A Review of the World Bank Group's Experience (2003–2009). IEG Working paper 2011/1. IFC. MIGA. World Bank: Washington, DC, USA.
48. Lillo, P., Ferrer-Martí, L., Boni, A., & Fernández-Baldor, Á. (2015). Assessing management models for off-grid renewable energy electrification projects using the human development approach: Case study in Peru. Energy for Sustainable Development, 25, 17-26.
49. Mainali, B., Pachauri, S., Rao, N. D., & Silveira, S. (2014). Assessing rural energy sustainability in developing countries. Energy for Sustainable Development, 19, 15-28.
50. Mainali, B. (2014). Sustainability of rural energy access in developing countries.
51. Magill-jessica, J. O., & Valdés-julio, J. E. (2011) "Acceso Universal A La Electricidad"…¿ Y Perú?. XVIII Simposio Peruano de Energía Solar y del Ambiente (XVIII-SPES), Lima, 14-19.11.2011
52. MAXQDA, software for qualitative data analysis, 1989-2016, VERBI Software – Consult – Sozialforschung GmbH, Berlin, Germany
53. McAllister, J. (2015). Factors Influencing Solid-Waste Management in the Developing World. All Graduate Plan B and other Reports. Paper 528.
54. Millones Olano, E. (2005). Marco De Evaluación De Impactos Ambientales Para El Proyecto De ElectrificacióN Rural En El Perú (in Spanish)
55. Ministerio de Desarrollo e Inclusion Social (MIDIS) (2013). Manual de Operaciones Fondo para la Inclusión Económica en Zonas Rurales (FONIE). (in Spanish)
56. Ministerio de Economia y Finanzas (MEF) (NA). Proyecto de Presupuesto. Anexo 2. Available at: https://www.mef.gob.pe/index.php?option=com_content&view=article&id=4129&Itemid=101156&lang=es Accessed on January 29th 2016. (in Spanish)
57. Ministerio de Economia y Finanzas (MEF) (NAb). Banco de Proyectos SNIP. Available at: http://www.mef.gob.pe/contenidos/inv_publica/new-bp/operaciones-bp.php Accessed on Feburary 4th 2016. (in Spanish)
58. Ministerio de Energía y Minas (MEM) (NA). Directorio de las Empresas del Subsector Eléctrico. Available at: http://www.minem.gob.pe/_detalle.php?idSector=6&idTitular=6143&idMenu=sub113&idCateg=1039 Accessed on September 30th 2016. (in Spanish)
59. Ministerio de Energía y Minas (MEM) (NAb). Normas Técnicas Rurales. Available at: http://www.minem.gob.pe/_detalle.php?idSector=6&idTitular=628&idMenu=sub114&idCateg=342?qgmfbclgtkeplnay?ldgtmpvhfihfbcvx?vhvhyufkegmpclwj?homfihoaakluojzw?lwzfkeplwzfuvhfi?ydgmywjzpeihvxbc?vqgklnrixsklwqgd?kbjzpojqxbceiahf?dxbttmwsrgdnhfbc?ydgmynksbttdxbjc Accessed on September 2nd 2016. (in Spanish)
60. Ministerio de Energía y Minas (MEM) and Banco Mundial (2005). Mejoramiento de la Electrificación Rural Mediante La Aplicación de Fondos Concursables. Estudio de Preinversión a nivel de Pre – Factibilidad. Lima (in Spanish).

61. Ministerio de Energía y Minas (MEM) (2007). Guia De Instalación De Sistemas Fotovoltaicos Domésticos (SFD)" (in Spanish)
62. Ministerio de Energía y Minas (MEM) (2011). Proyecto De Mejoramiento de la Electrificación Rural mediante aa aplicación de Fondos Concursables II (FONER II). Manual de Operaciones del Proyecto. Reviewed August 2015 (in Spanish)
63. Ministerio de Energía y Minas (MEM) (2012). Plan Nacional De Electrificacion Rural (PNER) Periodo 2013 – 2022. (in Spanish)
64. Ministerio de Energía y Minas (MEM) (2014). Normatividad Electrica. Ley de Concesiones Eléctricas y Reglamento Decreto Ley N° 25844 y Decreto Supremo N° 009-93-EM
65. Ley Para Asegurar el Desarrollo Eficiente de la Generación Eléctrica y Reglamentos
66. Ley N° 28832 (in Spanish)
67. Ministerio de Energía y Minas (MEM) (2015). Plan Nacional De Electrificacion Rural (PNER) Periodo 2016 – 2025. (in Spanish)

68. Nguyen-Trinh, H.A.; Ha-Duong, M. Perspective of CO2 capture & storage (CCS) development in Vietnam: Results from expert interviews. Int. J. Greenh. Gas Control 2015, 37, 220–227.
69. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN) (NA). Available at: http://www.osinergmin.gob.pe Accessed on: January 31st 2016 (in Spanish)
70. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN) (2010). Resolución De Consejo Directivo N° 235-2010-OS/CD (in Spanish)
71. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN) (2014). Tender Documents for Auction of Electricity Supply with Renewable Energy Resources in Areas Not Connected to Network. Available at: http://www2.osinerg.gob.pe/EnergiasRenovables/contenido/1eraSubastaOffGrid.Bases.html Accessed on February 1st 2016.
72. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN) (2014b). Fijación de la Tarifa Rural para Sistemas Fotovoltaicos 2014-2018. Publicación del Proyecto de Resolución. Expediente N° 0248-2014-GART (in Spanish)
73. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN) (2014c). Informe No 403-2014-GART Informe legal sobre la procedencia de aprobar la Resolución que fija la Tarifa Eléctrica Rural para Suministros no Convencionales (Sistemas Fotovoltaicos). (in Spanish)
74. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN) (2016a). Resolución Del Consejo Directivo Organismo Supervisor De La Inversión en Energía y Mineria OSINERGMIN N° 139-2016-OS/CD. Available at: http://www2.osinerg.gob.pe/Resoluciones/pdf/2016/OSINERGMIN%20No.140-2016-OS-CD.pdf Accessed on 28 June 2016 (in Spanish).
75. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN) (2016b). Tarifa Eléctrica Rural para Sistemas Fotovoltaicos (Vigente a partir del 04/ene/2016). Available online: http://www2.osinerg.gob.pe/Tarifas/pdfsTarifas/TFBT8_04012016.pdf Accessed on 8 May 2016 (in Spanish)
76. Paredes, M. and de la Puente, L. (2014). Protestas y negociaciones socioambientales. El caso de las industrias extractivas. In: Agenda de Investigación en Temas Socioambientales en el Perú. Una aproximación desde las ciencias sociales. CISEPA-PUCP | INTE | Facultad de Ciencias Sociales | GEA. Lima, 2014 (in Spanish)
77. Polack, A. (2010). Drivers and barriers of renewable energy in the electrification of Vanuatu (Doctoral dissertation, Murdoch University).
78. Prialé Ugás, M. (2012). Sistematización del Proyecto: "Evaluación integral para la promoción de fuentes de energía renovables, como alternativa para mejorar la calidad de vida de poblaciones aisladas de la Amazonía en América Latina. Informe Final." Soluciones Practicas, EUEI (in Spanish).
79. Pyhala, A. (2002, June). Institutions, Participation, and Protected Area Management in Western Amazonia. In Commons in an Age of Globalisation," the Ninth Conference of the International Association for the Study of Common Property, Victoria Falls, Zimbabwe, June (pp. 17-21).
80. Ramos Rivas, R. (2014). Subasta De Suministro de Electricidad con Recursos Energeticos Renovables en Areas no Conectadas a Red. Available at: http://webcache.googleusercontent.com/search?q=cache:1OucQ96Vxh0J:www2.osinerg.gob.pe/EnergiasRenovables/contenido/Documentos/1SubastaOffGrid/Actas/Acta%2520de%2520Adjudicacion%2520Buena%2520Pro.pdf+&cd=1&hl=en&ct=clnk&gl=us&client=safari Accessed on 4 August 2016 (in Spanish).
81. Reddy, B. S. (2015). Measuring and Evaluating Energy Security and Sustainability: A Case Study of India.
82. Retnanestri, M. (2007). The I3A framework–Enhancing the sustainability of off-grid photovoltaic energy service delivery in Indonesia. University of New South Wales (UNSW): PhD thesis. OpenURL.
83. Ribeiro, F., Ferreira, P., & Araújo, M. (2011). The inclusion of social aspects in power planning. Renewable and Sustainable Energy Reviews, 15(9), 4361-4369.
84. Rickerson, W., Uppal, J., Glassmire, J., Lilienthal, P., Sanders, E., Colson, C., ... & Couture, T. (2012). Renewable energies for remote areas and islands (REMOTE). International Energy Agency-Renewable Energy Technology Deployment (IEA-RETD). Paris, France.

85. Rosen, M. A. (2009). Energy sustainability: A pragmatic approach and illustrations. sustainability, 1(1), 55-80.
86. Ruiz-Caro, A. (2002). El proceso de privatizaciones en el Perú durante el período 1991-2001 (Vol. 22). United Nations Publications (in Spanish).
87. Sharma, T., & Balachandra, P. (2015). Benchmarking sustainability of Indian electricity system: An indicator approach. Applied Energy, 142, 206-220.
88. R.E.H. Sims, R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martínez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang, 2007: Energy supply. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

89. Ritchie, J., Lewis, J., Nicholls, C. M., & Ormston, R. (Eds.). (2013). Qualitative research practice: A guide for social science students and researchers. Sage.
90. Stringer, L. C., & Paavola, J. (2013). Participation in environmental conservation and protected area management in Romania: a review of three case studies. Environmental Conservation, 40(02), 138-146.
91. Thoenig, J. C. (2008). Territorial institutions. In: Rhodes, R. A., Binder, S. A., & Rockman, B. A.,. The Oxford handbook of political institutions. Oxford University Press 2008, 281-302.
92. Torero, M., & Pasco-Font, A. (2001a). The social impact of privatization and the regulation of utilities in Peru. United Nations University, World Institute for Development Economics Research.Discussion Paper No 2001/17.
93. Torero, M., & Pasco-Font, A. (2001b). El impacto social de la privatización y de la regulación de los servicios públicos en el Perú. Documento de trabajo 35, Grupo de Analisis para el Desarrollo (GRADE), Lima, Peru (in Spanish).
94. United Nations Development Program and Global Environment Facility (UNDP and GEF) (2006). Analisis De Programas Y Modelos De Gestión En Electrificación Rural Aplicados En Latinoamerica y El Mundo y Propuestas de Modelos de Aplicación Nacional. Proyoecto PER/98/G31, "Electrificación Rural a base de Energía Fotovoltaica en el Perú" Available at: http://dger.minem.gob.pe/archivos/309_Inf_ProgNacionales.pdf Accessed on 15 June 2016 (in Spanish).
95. United Nations Economic Commission for Latin America and the Caribbean (ECLAC) and Organisation for Economic Cooperation and Development (OECD) (2016). Environmental Performance Reviews Peru. Highlights and recommendations. Available at: https://www.oecd.org/environment/country-reviews/16-00312-environmental%20performance%20review-peru-web.pdf Accessed on September 12 2016.
96. Vera, I. A., Langlois, L. M., Rogner, H. H., Jalal, A. I., & Toth, F. L. (2005). Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency. In Natural Resources Forum (Vol. 29, No. 4, pp. 274-283). Blackwell Publishing Ltd.
97. Verástegui Gubler, A., Moreno Morales A.I., Cordero Torres V. (NA).Evaluación en campo de funcionamiento, aceptación e impactos de sistemas pico fotovoltaicos en la región San Martín. Deutsche Gesellschaft für Internationale Zusammenarbeit. Available at: https://energypedia.info/images/1/1a/Primeras_experiencias_de_sistemas_pico_PV_en_el_Perú.pdf Accessed on 18 October 2016 (in Spanish).
98. Wimmler, C., Hejazi, G., de Oliveira Fernandes, E., Moreira, C., & Connors, S. (2015). Multi-Criteria Decision Support Methods for Renewable Energy Systems on Islands. Journal of Clean Energy Technologies, 3(3).
99. Worldbank (NA). World Development Indicators. Available at: http://databank.bancomundial.org. Accessed on January 28th 2016.
100. Yadoo, A. 2012. Delivery models for decentralised rural electri cation: case studies in Nepal, Peru and Kenya. International Institute for Environment and Development, London.

# 6 Inter-Country Comparison (Paper 5: Sustainability of rural electrification efforts based on off-grid Photovoltaic systems in the Andean Region)

In this paper, I comparatively assess the sustainability of rural electrification efforts based on off-grid solutions in Chile, Ecuador, and Peru. Following the theoretical framework described in Chapter 2, my assessment considers four dimensions of sustainability (institutional, economic, environmental, and socio-cultural).

I found that Ecuador and Chile have consistently failed in ensuring mechanisms for funding O&M of the deployed off-grid systems (which has made these solutions in poor Chilean and Ecuadorian communities inevitably unsustainable). Although Peru has adopted a cross-tariff scheme, the Peruvian case shows that ensuring the funding of off-grid PV solutions is by far not sufficient. Peruvian officials appear to be unaware of the importance of local participation (local values and lifestyles are often disregarded) and most of the projects have been designed without the participation and engagement of the communities, which has frequently led to project failures and payment defaults.

The article also evinces that the Andean countries have consistently ignored the importance of strong formal institutions (coursed on rural electrification) with a flexible and decentralized structure. This fundamental drawback has resulted in inconsistent laws or lacking regulations, which in turn has been a major impairment of the sustainability of rural electrification projects in all three Andean countries.

*Article*

# Rural Electrification Efforts Based on Off-Grid Photovoltaic Systems in the Andean Region: Comparative Assessment of Their Sustainability

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**Abstract:** In this paper, we comparatively assess the sustainability of rural electrification efforts based on off-grid solutions in Chile, Ecuador, and Peru. Our assessment considers four dimensions of sustainability (institutional, economic, environmental, and socio-cultural). We found that Ecuador and Chile have consistently failed to ensure mechanisms for the operation and maintenance of the deployed off-grid systems, which has made these solutions in poor Chilean and Ecuadorian communities inevitably unsustainable. Although Peru has adopted a cross-tariff scheme, the Peruvian case shows that ensuring the funding of off-grid PV solutions is not enough. Peruvian officials appear to be unaware of the importance of local participation (local values and lifestyles are constantly disregarded) and most of the projects have been designed without the participation and engagement of the communities, which has often led to project failures and payment defaults. However, although each country has its particular challenges, we found that the three Andean countries have consistently neglected the importance of strong formal institutions with a flexible and decentralized structure, which in turn significantly compromised the rural electrification effort in these countries.

**Keywords:** off-grid PV systems; rural electrification; developing countries; sustainable energy; Andean countries

## 1. Introduction

Out of the approximately 1.2 billion people who still lack electricity worldwide, the vast majority live in rural areas [1]. In 2015, the United Nations (UN) declared global access to clean and reliable energy one of its 17 Sustainable Development Goals (SDG) [2]. In remote areas of Developing Countries (DCs), where a grid expansion is unviable, off-grid Photovoltaic (PV) systems can be a feasible alternative to reach this goal.

In recent decades, Chile, Ecuador, and Peru have significantly improved their rural electrification rates (reaching 97.8% in Chile, 92.3% in Ecuador, and 63% in Peru) [3,4]. Rural electrification efforts included the deployments of off-grid PV solutions in remote areas such as the Ecuadorian and Peruvian Amazon basin [4,5], as well as in isolated Chilean peripheral locations [6]. Communities of these areas are characterized by low energy demand, low income, high dispersion, and difficult accessibility (see e.g., [7,8]).

Unfortunately, rural electrification projects based on off-grid PV systems have been plagued by technical failures and payment defaults, which has seriously compromised their sustainability [9–12]. In this paper, we critically assess the sustainably of rural electrification programs (based on off-grid PV systems) in the Andean countries. We aim to better understand drivers of success as well as to highlight flaws that have compromised the sustainability of these efforts. Our assessment was based on a set of indicators (adopted from [13]; see Table 1) corresponding to the four dimensions of sustainability considered in this paper: institutional, economical, environmental, and socio-cultural. A definition for each of these sustainability indicators is provided in Table 1.

| Sustainability Dimension | Indicator | Definition |
|---|---|---|
| **Institutional** | Stability (Durability) | Stability concerns the durability of the (national and local) formal institutions of a country. This may refer to the organization itself, its legal existence, as well as the stability of personnel within the organization (staff turnover). |
| | Regulation and Standards | Regulations embrace the legal framework of a country including its consistency, coherence, and liability. Standards refer to the implementation and verification of technical standards for off-grid PV systems and their accessories including the legal bounding for quality assurance. |
| | Adaptability | Adaptability implies the formal institutions' ability to adapt to the needs of the population and its socio-cultural circumstances. The concept embraces flexible, decentralized institutional structures that have the (technical and socio-cultural) know-how and the (de facto and de jure) power to effectively steer rural electrification. |
| | Decentralizatio n/ Participation | Decentralization and participation refer to the degree to which formal and informal institutions work jointly together on the local projects. The participation of a local community usually requires a degree of decentralization of the agents in charge of the rural electrification project. |
| **Economic** | Funding (Initial investment/ O&M) | Funding consists of both the funds provided for the initial investment of the off-grid PV systems (including its components, installation costs, costs for user training and handbooks) as well as the funds to operate and maintain the systems over their entire lifetime (including operational costs for repairing services and substitutions (e.g., batteries), the administration of the systems (such as tariff collection), the provision and storage costs for spare parts, all kinds of travel expenses to the dwellings and back, and disposal costs). |
| | Cost effectiveness | Cost-effectiveness of a solution is defined by the degree to which monetary resources are efficiently invested by the deployment of an accurate (see indicator accuracy below) energy system for a community with the lowest costs over the system's lifetime. |
| | Reliability | Reliability requires the systems to be constantly operational. Defects are corrected in a short (and previously defined) time span. Reliability requires spare parts and know-how to be available at the local site. |
| | Productive Use | Energy systems are expected to contribute to the economic development of the users. This can be achieved by (partially) using the systems for productive uses, which generates user income (users might then even bear O&M costs) due to a higher productivity/performance associated with energy. |
| **Environment al** | Environmental awareness | Environmental awareness is defined as the consciousness of the society on the importance of the environment. It often requires an understanding of the connections between environmental, energy, and social/economic issues and its value for wellbeing. |

| | | |
|---|---|---|
| **Socio-Cultural** | Environmental impact | Environmental impact refers to the positive as well as negative effects that a technology has on the environment. These impacts may be local or global in nature. Examples for the former are the handling of disposals (such as batteries) from the systems, noise disturbances, pollution aesthetics, etc. The latter refers to impacts on the climate system (due to greenhouse gases) or the loss of biodiversity worldwide. Positive impacts may, e.g., be the avoidance of these gases due to the adoption of "clean" renewable technologies. |
| | Equity | Equity (disparity) is the degree of equal (distinct) treatment for different groups of a population, e.g., rural and urban populations or different ethnic groups on the one hand, and within groups (i.e., similar rural populations from one vs. another community) on the other hand. Equity relies on the underlying concept of justice.<br><br>Equity (disparity) issues may refer to the point in time when a community is electrified (temporal equity), the provided energy quality and quantity (system size) for/within each group, and the differences between energy tariffs. |
| | Accuracy | Accuracy in sustainable rural electrification is defined as the degree to which the solutions are conforming to the lifestyle and needs of the users. Accuracy often refers to the off-grid system capacity for present and future energy demand, as well as technological specifications that consider socio-cultural factors (such as ease of use, community lifestyle, etc.). |
| | Social Acceptance | Social acceptance in sustainable rural electrification is understood as the degree to which a community agrees with a project and the installed technology, approves it, and ideally identifies with it. Social acceptance is often facilitated by involving and engaging the users in the project and by making them part of the solution, such that they understand its advantages and limitations and agree on the conditions (their rights and obligations). |
| | Cultural Justice | Cultural justice refers to the consideration of/and respect for the culture, and the motivations and values of the population (e.g., concerning environmental awareness). |

**Table 1.** Definition of indicators of sustainability adopted in this study (adapted from [13]). The different colors in the first column stand for the different dimensions of sustainability considered in this paper.

Institutional sustainability has been acknowledged as a precondition for the sustainability of rural electrification initiatives (see e.g., [14,15]). For institutions to be sustainable, they need to be stable and durable [16–18]. In that context, Gollwitzer [19] highlights the importance of adopting and enforcing norms and regulations. Authors further agree on the relevance of the openness to people's participation [20–22] and of decentralization [23,24], which favors the adaptability to local needs [14,17,21,25].

Economic sustainability of electrification solutions requires ensuring the affordability of the systems [25,26]), which implies adopting cost-effective solutions and procuring (in the case of poor communities) funding for both the initial investment and the operation and maintenance (O&M) of the systems [17,27–29]. Sustainability of energy projects further requires ensuring the reliability of the systems [30]. Dunmade [28] and Chaurey and Kandpal [31] therefore allude that spare parts must be locally available to reduce downtimes, such that productive uses can contribute to an increase in the user income [32,33].

Environmental sustainability demands for citizen participation and environmental awareness [34], which is then again relevant for the prevention of negative environmental impacts [17,21,26]; improper disposal of batteries may make presumably clean technologies such as off-grid PV systems unsustainable [35,36].

Socio-cultural sustainability [14,17,18,26] implies favoring equity regarding the amount of energy provided to different groups (e.g., according to gender, ethnical background, etc.) as well as regarding the accessibility to energy [15,16,26,37]. Moreover, socio-cultural sustainability of energy solutions requires gaining the acceptance of society by respecting their culture and traditions [28,38], and ensuring the participation of the local community [15,21,39].

The dimensions of the sustainability (institutional, economical, environmental, and socio-cultural) are strongly interwoven and are deeply interdependent. Therefore, ensuring the sustainability requires adopting an integrated and holistic approach. Indeed, as shown below, successful rural electrification projects (based on off-grid PV systems) in the Andean countries are those within which all the dimensions of the sustainability are ensured.

## 2. Materials and Methods

We applied a multiple-case study approach (for details on this methodology, see [40,41]) for an inter-country comparison between Chile, Ecuador, and Peru. The material used to conduct the case studies was obtained from a variety of data sources that included legal/public statements, energy policies and regulations, statistical databases (on energy uses and technologies), strategic energy documents and roadmaps, ex-post project evaluations from independent parties, and scientific papers. Quantitative data for comparisons were retrieved from the World Bank Indicator Database, from diverse Ministries such as the respective Ministry of Energy of each country, the Ministry of Development and Social Inclusion (Peru)/Ministry of Social Development (Chile); Ministry of Foreign Affairs Coordinating Ministry of Strategic Sectors (MICSE by its Spanish abbreviation) in Ecuador; from several public energy agencies/regulators (e.g., National Energy Commission (CNE by its Spanish abbreviation) in Chile; Agency for Regulation and Electricity Control (CONELEC, by its Spanish abbreviation) in Ecuador; and Organization for Investment in Energy and Mining (OSINERGMIN, by its Spanish abbreviation) in Peru; and from the National Statistical Institutions of the three countries.

We also analyzed 57 semi-structured interviews to key stakeholders that we had previously conducted in Chile, Ecuador, and Peru (see [13,42,43]). Interviews were held between 2014 and 2015, and since our main interest was to unveil the overall institutional and organizational conditions in the Andean countries, the interviewees were of higher hierarchical positions such as directors, project managers, leading researchers, and division leaders in each country. The interview guideline was identical for the three countries, and our interview partners in Chile, Ecuador, and Peru held similar positions. This structured proceeding assured an unbiased comparison of the three countries.

The conjunction of the analyzed data was used to assess the sustainably of rural electrification programs (based on off-grid PV systems) in the Andean countries. Our assessment was based on a set of indicators (see Table 1) that were rated relative to an ideal situation.

## 3. Country Comparison Brief

### *3.1. Geography and Demography*

As shown in Table 2, Peru's population is almost twice as high as Chile's and Ecuador's. However, given its smaller surface, Ecuador has a much higher population density. In addition, in relative terms, Ecuador's rural population is three times higher than Chile's, and twice as high as Peru's rural population. Whereas the Ecuadorian rural population has been growing during the last five years, it has decreased in Chile and Peru. It is also worth noting that the three countries all have a very diverse geography with different climate zones. These geographical features, including mountain areas above 5000 m, tropical forest in the Amazonian basin (Peru and Ecuador), islands (Chile and Ecuador), and fjords (Chile) with difficult access, contribute to the isolation of some rural communities in these countries.

**Table 2.** Key Demographic Data.

| | Chile | Ecuador | Peru |
|---|---|---|---|
| Total Population (2015) | 17,948.14 | 16,144.36 | 31,376.67 |
| Rural population (% of total; 2015) | 10.47 | 36.26 | 21.39 |
| Population density (people per sq. km of land area; 2015) | 24.20 | 65.00 | 24.51 |
| Rural population growth (%; average during last 5 years) | −0.7 | 0.98 | −0.2 |
| Surface Area ($km^2$) | 756,950 | 283,500 | 1,285,216 |

Source: Own elaboration based on data from [3].

*3.2. Politics and Economy*

The administrative organization of the three countries remains highly centralized despite of their efforts for power distribution [44–46]. While Ecuador has been more reluctant, Chile and Peru have enthusiastically embraced neoliberalism (since the 1990s in the case of Peru and since the 1980s in the case of Chile). As discussed below, this difference had strong implications for the energy sector and its organization.

Table 3 shows some key economic data for the Andean countries: According to the World Bank [3], Chile's economy is by far the wealthiest, followed by Peru and Ecuador; still, the GDP growth-rates during the last five years have been remarkable in all three cases. Chile's economic edge is also reflected in the higher Foreign Direct Investment, which is more than twice as high as in Peru and about eight times higher than in Ecuador [3]. Chile's GINI Index (a measure of inequality within a country; see [47]) is the highest (i.e., Chile has the greatest income/consumption disparity), albeit inequality seems to be an issue in each of the three nations [3]. The countries share their high dependency on commodities that account for more than 50% of their exports: Chile mainly depends on the mining sector, Ecuador on its petroleum reserves, and Peru on mining and petroleum, respectively [48–50].

**Table 3.** Selected Economic Data.

| | Chile | Ecuador | Peru |
|---|---|---|---|
| GDP per capita, PPP (constant 2011 international $; 2015) | 22,145.10 | 10,717.60 | 11,672.14 |
| Annual GDP Growth (%; average of last 5 years) | 3.8 | 4.4 | 4.8 |
| GINI Index (2013) | 50.5 | 47.3 | 44.7 |
| Foreign Direct Investment net inflows (percent of GDP; 2015) | 8.5 | 1.1 | 3.6 |
| Exported Commodities (in percent of total exports) | 54.2 | 56.5 | 62 |

Source: Own elaboration based on data from [3,48–50].

*3.3. Energy*

The energy sector differs notably between the three Andean countries, as shown in the overview of Table 4. Ecuador has a primary energy surplus, with the main destination of its energy exports being United States, followed by Chile, Peru, and Panama [51]. Despite of this surplus, Ecuador's energy sufficiency index is actually negative. This is due to the fact that its exports are crude oil, while it still needs to import diesel, gasoline, and liquefied petroleum gas (LPG) [52]. It should be noted that Ecuador currently subsidizes these imports: for example in 2014, subsidies on energy fuels represented 3.89% of the country's GDP, amounting to US$3.907 million [53].

In Peru, the energy generation is approximately equal to its consumption, while Chile is highly dependent on energy imports that accounted for about 61% of the total energy consumption in 2013 [3]. At the same time, the per capita electricity consumption is more than three times higher in Chile than in Ecuador and in Peru [3], which can be partially attributed to its higher GDP per capita (as energy consumption is correlated with income [37,54].

For energy consumption, Peru's and Chile's share of RE (including hydro energy) is almost 1/3 of the total energy consumption, whereas in Ecuador it accounted for only about 13.4% in 2012 [3] (World Bank, NA); however, several major hydro-power plants are currently constructed in Ecuador with a total power capacity of about 2.5 gigawatts (GW) [55]. This will increment the power production by 50% and also substantially adjust the RE consumption rate upwards (as the government is also promoting a policy to foster a shift in its energy consumption from gas to electricity to curb the enormous subsidies on fuels).

As far as Non-Conventional Renewable Energies (NCRE) are concerned, their energy generations have a minor share of the total power generation in Ecuador and Peru, but a more important role in Chile [56–58].

**Table 4.** Key Energy Data.

| | Chile | Ecuador | Peru |
|---|---|---|---|
| Net Energy Imports (percent of energy use; 2013) | 61.3 | −93.8 | −0.2 |
| Electricity consumption (kilo Watts hours (kWh) per capita; 2013) | 3879 | 1333 | 1270 |
| Generation rate of NCRE for electricity (percent of total generation of electricity) | 13 | 2 | 3.1 |
| RE consumption (percent of total final energy consumption; 2012) | 30.3 | 13.4 | 28.3 |
| Rural Electrification Rate (%; 2012) | 97.8 | 92.3 | 63 |

Source: Own elaboration based on data from [3,4,56–58].

### *3.4. Rural Electrification*

Figure 1 shows the progression of the rural electrification rate of the analyzed Andean countries between 1993 and 2012. In 1990s, their rural electrification rate was quite low (with Peru significantly lacking behind), though the Andean countries were able to make up leeway after tremendous expansions, although off-grid solutions were adopted when grid expansions were found to be electrification efforts in the 1990s and 2000s. The improvements have mainly been due to grid expansions, although off-grid solutions were adopted when grid expansions were found to be unviable.

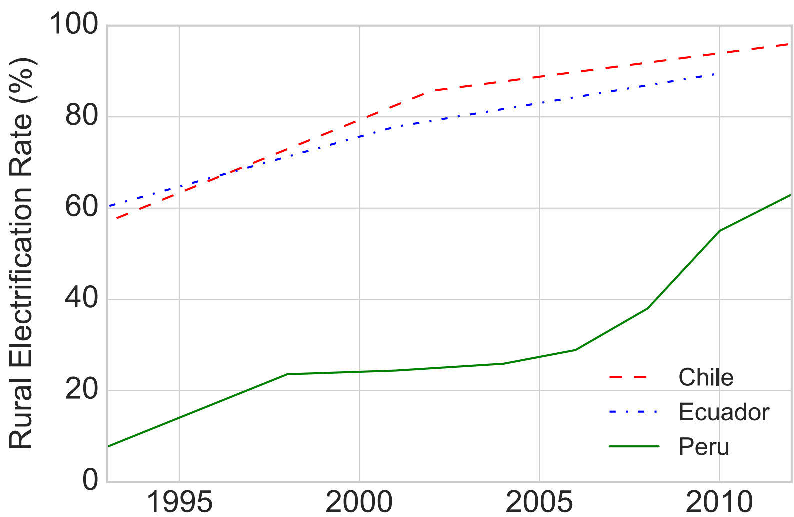


**Figure 1.** Rural Electrification Rate in Chile, Ecuador, and Peru. Source: Own elaboration based on

data from [4,59,60] (for Ecuador data are only available until 2010). data from [4,59,60] (for Ecuador data are only available until 2010).

Rural electrification is usually unprofitable in DCs due to a high dispersion of dwellings, a low energy demand, and a difficult access to these areas. Therefore, in the Andean countries, electrifying rural areas has primarily been responsibility of the public sector (mainly through the respective Ministry of Energy or equivalent [61–63].

In Ecuador, all Electric Distribution Companies (EDCs) are state-owned; in Peru, they can be public or private (EDCs that operate outside big urban areas are all public except for those under the control of Non-Governmental Organizations (NGOs)); and in Chile they are all private.

In the case of on-grid solutions, the EDCs in the three countries provide the electricity to the end-users, but none of them generates electricity from its own plants (due to policies in the 1990 that fostered the separation of generation, transmission, and distribution in the three countries). In the case of off-grid PV solutions however, the EDCs can also generate the electricity by installing the systems themselves.

In Ecuador, the public EDCs are prompted by law to provide electrification to the whole country, such that they have been deploying off-grid PV solutions in remote rural areas (especially in the Amazon basin) since the early 1990s. In the case of Chile, the national government pays private companies (selected via call for bids) to electrify dwellings in remote areas, although local authorities such as municipalities can also commission the deployment of small-scale PV systems without the supervision of the Chilean Ministry of Energy. In Peru, public EDCs are also leading electrification efforts in rural areas by using off-grid solutions, but their responsibilities are constrained to certain areas of the country. To take electrification beyond these areas, the Peruvian government issued call for bids to install at least 150,000 off-grid PV systems through a public-private partnership [64]; the private company will be in charge of the installation as well as the O&M across Peru's remote areas for 15 years, whereas public EDCs will cover the administration (e.g., fee collection) [64]. NGOs, NPOs, and universities have also conducted off-grid installations in the Andean countries.

## 4. Results

### *4.1. Institutional Sustainability*

#### 4.1.1. Stability/Durability

Institutional sustainability requires strengthened and stable formal institutions. However, stability is quite problematic in Ecuador and in Peru [65]. In Ecuador, new Ministries, regulators, and EDCs were created and later disappeared, which ultimately led to the failure of entire off-grid PV programs (when the responsible entity just vanished) [13]. Similar issues were found in Peru, where according to an expert from a NGO (and verified by the regulatory trajectory), permanent staff turnovers in leading positions as well as changes in energy policies inhibited the implementation of a strategic policy line. The lack of institutional stability has moreover seriously affected the creation of know-how and human capital training in these countries.

Moreover, the prevalent neoliberalism in Peru and in Chile has prevented the development of strengthened formal institutions by reducing their role to a minimum [66]. For example, the Chilean Ministry of Energy enthusiastically embraced the concept of "technology neutrality" (since in its view any form of facilitation or promotion of RE may lead to market distortions) [42]; the Peruvian Ministry of Energy is meanwhile committed to outsourcing: in Peru, the installation of off-grid PV system is outsourced, O&M of off-grid PV system is outsourced; even the supervision of the outsourced activities is outsourced, as confirmed by several government agents.

#### 4.1.2. Regulations and Standards

In Ecuador, there is a lack of coherence between the Constitution and the regulations. Several interviewees (including scholars and NGO experts) stated that this incoherence had direct consequences on rural electrification, as for instance the right for energy declared in the Constitution was not anchored in the law, and consequently it is often not enforced. Moreover, rural electrification lacks any kind of technical and quality standards, such that different EDCs frequently deploy incompatible off-grid systems [13].

In Chile, technical standards for rural electrification have been defined, but project managers from energy companies admitted that in the projects they are not enforced, especially in the case of off-grid PV systems. The lack of enforcement of technical standards has often compromised the sustainability of small-scale programs conducted by private entities as well as public agencies or municipalities. Indeed, according to the current regulation, when the investment cost of a rural electrification project is lower than approximately US$140,000, it can be carried out without the supervision of the Ministry of Energy [42].

In Peru, although technical standards were formally adopted from the International Organization for Standardization (ISO), representatives of the agencies in charge of the quality control assured that they have been neglected by the Ministry of Energy and Mining in their rural electrification projects. Consequently, these technical standards were also found to be outdated.

A major issue for rural electrification in these countries is that the regulatory framework does not clearly reveal what actions to take and who to hold responsible if the off-grid PV systems stop operating. This fundamental drawback contributes to the unreliability of off-grid PV system in the Andean countries.

#### 4.1.3. Adaptability

Rural electrification requires that the institutions are able to adapt to the (changing) circumstances in a country, which implies in the context of rural electrification, having a strong formal institution (such as an agency) with a flexible and decentralized structure (see e.g., [67]).

Chile and Ecuador lack a decentralized public agency focused on rural electrification. Such an agency may support local authorities and users, and it could be in charge of O&M as well as of the quality assurance of the systems. In the case of Chile, several small-scale projects failed because their sponsors (local authorities such as municipalities in remote rural areas) were unable to keep the systems operating in the long-term (e.g., because of the deployment of low quality parts, the lack of technological skills in remote area, missing spare parts, etc.) and they did not receive timely support or training from the Chilean Ministry of Energy [42].

In the case of Ecuador, a decentralized public agency could help to improve coordination among the Ecuadorian EDCs, and to facilitate the transfer of know-how from EDCs that have successfully deployed off-grid PV systems (for example, the "CentroSur" EDC) to less successful EDCs (for example the "Sucumbíos" EDC) [13]. Therefore, the ongoing reorganization of the Ecuadorian electricity sector, which implies merging the current 11 EDCs into a single company (see [68]), may help to foster the exchange of valuable know-how.

In Peru, there are two agencies (the Direction of Grant Funds (DFC by its Spanish abbreviation) and the Project Management Direction (DPR by its Spanish abbreviation)) both conducting off-grid PV projects for rural electrification under the Peruvian Ministry of Energy. Competences of both agencies (DFC and DPR) appear to be overlapping, which has caused rivalry between them and contributed to the dispersion of know-how.

The main problem in all three countries that impedes a better adaptability of formal institutions to the needs of the population seems to be the lack of a flexible, decentralized institutional structure with the (technical and socio-cultural) know-how and the (de facto and de jure) power to effectively steer rural electrification. The lack of coordination between the institutions dealing with rural electrification in these countries has often constrained the transfer of know-how (although Ecuador is trying to correct this flaw by merging its EDCs).

#### 4.1.4. Decentralization and Openness to Participation

In Ecuador, the energy sector, in particular the distribution of electricity, is subject to a process of recentralization, which means that the 11 EDCs in the country will be merged to a single company. Recentralization may lead to short-term benefits in the Ecuadorian energy sector (by facilitating the adoption of coherent technical and quality standards of service; see above). However, recentralization may also weaken local institutions (inhibiting in turn local participation; see for example [69]).

In Chile and Peru, decentralization has allowed local or regional governments to implement electrification projects by themselves. However, as mentioned above, these projects have often failed. NGO representatives and social scientists have attributed this issue to the fact that decentralization efforts were merely understood as a redistribution of funds to elected local governments, which did not include any transfer of know-how or training.

In Peru and Ecuador, most of the electrification projects based on off-grid PV systems are still sponsored by the corresponding Ministry of Energy. These projects have primarily been designed and conducted without the participation of the local population (usually indigenous communities). As explained below, this lack of engagement and participation has led to inaccurate solutions (such as insufficient system capacities unable to match the actual needs of the population).

Although in Chile the Ministry of Energy appears to be aware of the importance of openness to participation [42], a participative approach (involving user training and transfer of technical know-how) is not always applied. For example, harming system interventions from users due of a lack of user training has plagued small-scale PV projects in rural areas of Chile [42,70,71].

The problems detected in the three countries show that ensuring the sustainability of off-grid systems requires, in addition to decentralization and openness to participation that local know-how and capabilities are built.

### *4.2. Economic Sustainability*

#### 4.2.1. Cost Effectiveness

Off-grid PV systems are a cost-effective alternative for rural electrification in areas where the grid expansion is too difficult or too expensive. However, in Chile the Ministry of Energy failed to recognize this fact for years. Indeed, diesel generators were often preferred in the past, since only the initial investment costs were considered in the decision-making [72] without taking the significantly higher O&M costs, including fuel costs and its transport to remote areas into account. Fortunately, this flaw has been corrected in recent years, such that a lifecycle cost calculation is now used, and diesel generators are substituted by off-grid solutions [42,73]. In Ecuador, the potential of off-grid PV systems has also been ignored as a cost-effective alternative for the countries' remote areas, as e.g., the expansion of the national grid has been preferred even if direct and indirect costs (e.g., environmental impacts) were substantial. This could mainly be attributed to political promises to bring the national grid to the specific locations (as the grid was considered a more popular solution) [13].

On the other hand, the Peruvian Ministry of Energy did recognize the potential of off-grid PV systems for remote areas. This is why it recently approved the installation of at least 150,000 systems across the country. The systems will all be installed by a single private company, which allows for significant economies of scale, and the price per system can be reduced significantly. However, the lack of coordination between DPC and DPR (as well as with municipalities) in previous projects has seriously affected the cost-effectiveness in rural electrification: project managers arrived at remote communities that were already electrified because the DPC, the DPR, and the municipalities had not communicated with each other, which has caused substantial costs due to wasted efforts.

The three countries should update the evaluation of their electrification projects properly by considering the costs over the system's lifetime (including the O&M costs).

4.2.2. Reliability

Economic sustainability requires that the solution remains operational during its lifetime. This is particularly important for off-grid PV systems, as their initial investment is high, while O&M costs are very low compared to other solutions. In Chile, PV systems often became unreliable (particularly in small-scale projects), not only because technical standards are voluntary, but also because of the lack of a decentralized agency (see above) to ensure O&M.

In Ecuador, several EDCs have also deployed off-grid PV systems with mixed results; successful projects (in terms of reliability of the systems) were conducted by Ecuadorian EDCs that formed a well trained team or special units focused on off-grid solutions [13]. However, the lack of local know-how coupled with missing spare parts seriously compromised the reliability of the majority of off-grid PV systems in Ecuador [74].

In Peru, the reliability of off-grid PV systems is still an issue. For instance, in two inspections conducted by the energy regulator in 2011 and 2013, out of the 1110 systems, 34% were inoperative, with the majority of broken systems stemming from public EDCs [75]. Part of the problem is the widespread outsourcing: all Peruvian EDCs have outsourced both the installations and O&M services to local firms or to users while disregarding the indispensable supervision and training of these firms.

Sustainability of off-grid PV systems requires ensuring funding for the initial investment and the O&M of the systems over their lifetime. In the Andean countries, government intervention is in many cases inevitable for ensuring funding, because the rural populations in remote areas are usually extremely poor and cannot afford the systems or their O&M on their own (especially when access to the rural households is difficult and the population density is particularly low).

The Andean countries have allocated significant resources to rural electrification in recent decades, which has contributed to the great increase of the rural electrification rate (see Figure 1). However, these sources of funding are generally not permanent, which makes it dependent on political changes. This is particularly problematic in Chile and in Ecuador where initial investments for off-grid-systems solely rely on the government budget.

In Chile, rural electrification funding can be changed every year by the regional governments (that sponsors most of the off-grid projects in the country) when distributing its annual budget [76]. Although Ecuador used to have a cross-subsidy (the initial investment for rural electrification projects was funded by a 10% tax added to the electricity tariff of urban inhabitants), since 2008 funds for rural electrification depend on the national budget and have missed out for several succeeding years [77].

By contrast, funds for rural electrification in Peru come from a broader variety of sources (e.g., state budget, utilities of energy companies of the electricity sector, external funds, sanctions, donations, etc.) [4,78], which makes them less exposed to political changes.

4.2.4. Operation and Maintenance

According to numerous interviewees, O&M costs of off-grid PV systems significantly exceed the spending capacity of inhabitants in remote areas of the three countries. Although their governments appear to be aware of this fact, Chile and Ecuador have largely failed to ensure O&M funds even in the case of government-sponsored off-grid projects. By contrast, Peru implemented a cross-subsidy aimed at covering O&M costs of off-grid PV users. The system is based on a fee for clients with higher energy consumptions (>100 kwh; usually from urban areas), and it favors poor households with a monthly energy consumption of below 100 kWh [79].

The Peruvian cross-subsidy allows users of a 70 Wp off-grid PV system to pay a tariff of only about US$2 (US$3 for users from private companies) per month [80]. Indeed, the Peruvian Ministry of Energy has properly regulated the tariffs for both grid-connected and off-grid users. Moreover, when O&M costs exceed the tariffs, the EDCs are compensated according to their real expenditures (including costs of transportation to the communities, personnel costs, costs for spare parts, etc.). The situation is different in Chile and Ecuador where no tariff regulation for off-grid users exists [42].

In Chile, the sponsor of the project (usually a regional government or municipality) may choose the tariff. Often, the tariff per kWh for off-grid users is the same as that charged to grid-connected neighbors [81]. Since the O&M costs of off-grid-systems in remote areas are relatively high, there is a gap between the user tariff and the actual O&M costs that is not automatically covered in Chile. Regional governments—being the sponsor of the off-grid projects in most cases—need to annually request compensation to the CNE [82], which makes the programs vulnerable to political priorities.

In Ecuador, the sponsor and operator of off-grid projects is normally the EDC. These companies use to apply the so-called "dignity tariff" for poor on-grid and off-grid users, which means that users with a consumption below 130 kwh/month (110 kWh/month in the Andean highlands), only pay half of the tariff charged to grid-connected users with higher consumptions [83]. However, several EDC representatives in Ecuador complained that the gap between the user tariff and the actual O&M costs is expected to be assumed by the EDC, which strongly disincentives the deployment of off-grid solutions by these companies.

4.2.5. Productive Use

Chile exhibits some successful cases of off-grid PV-powered water pumps that have been adopted by poor farmers in remote areas of the northern territory. Contrary, in Peru and Ecuador, off-grid solutions for productive uses have so far been limited to projects of grid expansions and some isolated pilot projects.

In Chile, a subdivision of the Chilean Ministry of Agriculture, the Agency for Agrarian Development (INDAP by its Spanish abbreviation), promoted the substitution of water pumps powered by diesel generators by PV-powered pumps [84]. Around 1400 systems were installed from 2012 to 2013 (investment: US$7.5 million). The success of the program may be related to the decentralized structure of INDAP, whose personnel is in close and permanent contact with the farmers. This permanent contact facilitated the basic training to the final users, and ultimately ensures the success of the program [42]. Apart from INDAP, the Ministry of Agriculture has implemented a wide variety of pilot projects aiming to repeat the success of the PV-powered pumps program.

In Ecuador, government initiatives of rural electrification aimed at productive uses are limited to one microgrid project (10 mega Watts peak (mWp)) for households, schools, public lightning, and health centers [85]. NPOs have also implemented several pilot projects for productive uses such as corn dryers powered by PV energy, solar boats for transportation, and energy for milk collection centers. However, representatives of the Ministry of Energy acknowledged that the main issue with productive use projects is that the users still lack basic knowledge on energy uses and its potentials on the one hand, and administrative skills to manage them on the other hand. To attain these skills, interdisciplinary projects across different sectors (health, education, housing Ministry, etc.) become essential [86]. Unfortunately, the Ecuadorian Ministry of Energy appears to be unaware of this fact.

In Peru, the Ministry of Development and Social Inclusion (MIDIS by its Spanish abbreviation) was created in 2010 to eradicate extreme poverty by implementing interdisciplinary projects (for water and sanitation, electricity, local roads, and telecommunication) in the poorest and most remote areas of the country [87]. However, according to a MIDIS representative, the Ministry's initiatives have so far focused on the project implementation without accompanying the community after the project finished.

### *4.3. Environmental Sustainability*

#### 4.3.1. Environmental Awareness

Most interviewees of Ecuador and Peru agreed that environmental awareness is not widespread in their country, neither on a government level, nor in civil society. In Ecuador, although environmental protection is anchored in its current Constitution, the government recently decided to drill for oil in the Yasuni National Park, one of the most biologically diverse forests located in the Ecuadorian Amazon [88]. Similarly, in Peru, neither the creation of the Ministry of Environment (2008) nor the host of the 20th Conference of the Parties (COP 20) in 2014 could foster major progress in environmental awareness. For example, overfishing, deforestation, degradation of soil and water bodies continue to be substantial issues in the country [89,90]. Although part of the problem is the lack of experts on environmental issues (e.g., in the Ministry of Environment) [91], social scientists reported that there is also a lack of environmental awareness in civil society. Despite numerous environmental reforms and educational programs, people's behavior change towards more environmental friendly practices did not occur yet [92].

In Chile, civil society (mainly the younger population) shows rising environmental awareness, which resulted in several social movements opposing energy generation projects [93,94]. Nonetheless, their motivation is still commonly limited to reducing local environmental effects (as people are directly affected by some energy projects) [42]. Moreover, resistance is often not against non-RE generation projects, but against any form of generation (RE and non-RE), like e.g., hydro-energy [95–99] or even PV systems [42]. Like in Peru and Ecuador, Chilean politicians often lack awareness on broader and long-term impacts related to climate change for example, and they are usually driven by ideological and neoliberal ideas [100].

The lack of environmental awareness is particularly obvious in rural electrification efforts conducted in the past by these three countries. Although the use of off-grid PV systems generate long-term benefits for the environment in terms of pollution abatement, noise reduction, and climate change mitigation (as opposed to contaminating technologies), the representatives in charge of rural electrification acknowledged in all three countries that they do not account for these benefits in the evaluation of rural electrification investments. Indeed, only direct costs determine the decision for a rural electrification technology.

#### 4.3.2. Environmental Impact

The oil drilling in the Peruvian and Ecuadorian Amazon basin has led to devastating impacts on the rich biodiversity of this area, while the mining industry in the Chilean Atacama desert has affected local/indigenous communities by exploiting the scarce water resources in the area [88,101–103]. The rural electrification efforts based on off-grid systems may help to reduce the environmental co-impacts in these areas. However, off-grid PV systems can also do harm, especially if waste (particularly the batteries) disposal or treatment is not considered.

The battery disposal of the off-grid PV systems is not even regulated in Ecuador and Peru, while it is voluntary in Chile. As a result, in Peru numerous batteries have been found abandoned in communities of remote areas [75], and in Ecuador batteries have even been buried by the users [13]. The nonexistence of a recycling infrastructure for the batteries and the low environmental awareness of users seem to be the main reasons for this behavior.

Negative environmental impacts arise not only from batteries. Unreliable systems (see above) have also led to additional problems related to a proper disposal of solar modules. Unfortunately, recycling of the systems is not regulated (neither considered in project designs) in the three countries, leading to additional negative environmental impacts.

### *4.4. Socio-Cultural Sustainability*

#### 4.4.1. Equity (Disparity)

Though Peru is still behind, the rural electrification rates of all three countries have registered substantial increases since the 1990s (see Figure 1). In spite of this positive trend, equity issues have emerged, particularly in Peru: Indeed, despite of notable electrification achievements, awareness regarding equity remains low in Peru, and the (EDCs) rejection of electrifying remote rural areas became obvious during the interviews. Consequently, regions that are most vulnerable and hard to reach have by far the lowest electrification rate [4].

In Chile, most rural communities have been electrified, but a (minimum) system capacity is not legally fixed. Therefore, representatives of the Ministry of Energy confessed that communities that are better organized and who placed higher requirements to the government usually received solutions with higher capacities than those who did not make specific requests. This trend has led to indigenous communities with a much lower electrification rate than other better organized ethnic groups [104].

In Ecuador, there is broader consensus on the importance of providing electricity for all. This may explain why, in the early 1990, the rural electrification rate in Ecuador already exceeded Chile's rate despite of a much lower GDP per capita. An equity issue remains, however, as microgrids have been installed to very few communities, while other communities without electricity still have to wait to leave behind matches and candles [13].

In all three countries, energy tariffs still diverge between different user groups despite of the subsidies for off-grid PV systems from the governments. For example, in Chile, users that were further away from urban centers had to pay higher tariffs (on-grid and off-grid), because tariffs were based on market conditions, and costs are higher in remote areas; this inequality has however been recently corrected by a new law on tariff equity [105]. In Peru, notwithstanding the cross-subsidy tariff, off-grid users with similar incomes but from different geographical areas still have varying electricity prices per kW/h. In Ecuador, inequities persist since user tariffs are not even regulated for off-grid PV systems, such that tariffs are fixed individually by each EDC.

#### 4.4.2. Accuracy

Meeting the specific local needs and considering the socio-cultural reality of each community to assure accurate solutions has been an issue in the three countries for different reasons. In Ecuador, for instance, the government installed microgrids (which are more difficult to maintain) in communities where the necessary management skills to operate them are still lacking, thus making them inappropriate for the local circumstances [106]. In other Ecuadorian projects, Solar Home Systems (SHS) were installed without taking requirements of the community or needs of particular users (e.g., gender specific necessities) into account [74].

Chile and Peru faced accuracy issues regarding the capacity of the systems, which was usually too low and hence not sufficient for the energy needs of the households. In Chile, this led to situations where the users only had 1.5–2 h of electricity per day and were forced to use their traditional energy sources (candles, matches, or batteries) [71]. Nonetheless, Chile has recently acknowledged this shortcoming, and is shifting from basic electrification to a more holistic "energization" approach. The latter also targets the electrification of schools and health centers, providing systems with greater capacities according to the users' needs [42]. Furthermore, in Peru, the selection of technologies was often random due to the lacking technological know-how of the sponsors.

#### 4.4.3. Social Acceptance

Experiences with social acceptance were mixed in the three countries, depending on the extent to which the local community was involved and participated in the projects.

In Ecuador, one of the few EDCs that successfully deployed off-grid PV systems got the community involved by creating an electrification committee (consisting of the head of each beneficiary household), a steering committee (members of the community to represent the EDC), and an elected local officer in charge of accounting [83]. Although this successful approach was considered an interesting model for the rest of country, it was not vigorously adopted by other EDCs [13].

In Chile, projects where communities were engaged, got organized, and actively helped to carry out the project were the most successful ones. However, many Chilean communities rejected off-grid PV systems because they previously heard about technical problems or restricted system capacities from neighboring communities. The negative word of mouth and the imposition of solutions they did not agree on made off-grid PV systems unacceptable for them [42].

In Peru, social scientists and NPOs explained that the difficult relation between the communities and the mining industry had caused reluctance from the rural population towards "strangers", such that social acceptance of energy projects implemented by foreigners (i.e., NPOs or EDCs) is problematic as a result of mistrust. Moreover, many projects conducted by Peruvian public EDCs that did not properly engage the users (e.g., for clearing the users' doubts) have been plagued by social acceptance issues that turned into high default payments. The most successful off-grid projects in Peru have been conducted by NPOs that worked with the communities, and adapted the technology to local needs.

#### 4.4.4. Cultural Justice

The three Andean countries are culturally diverse, with multiple indigenous communities living in remote and rural areas [107,108]. This diversity has been recognized in Chile, where public officials and NPOs highlighted the need of respecting the local culture when implementing rural electrification projects.

The situation is different in Peru and Ecuador where officials involved in national electrification programs are unfortunately not yet aware of the relevance of culture for rural electrification [13]. In Peru, cultural aspects are hardly mentioned in national rural electrification programs designed by Peruvian officials (see for example [109]). In Ecuador, although the Constitution recognizes the rights of ethnic groups, their cultural values are in fact not taken into account. For instance, nomad indigenous communities in the Ecuadorian basin have been re-located to community centers built by the government to reduce the dispersion of the inhabitants and to facilitate electrification more easily [13].

### *4.5. Direct Comparison between the Andean Countries*

Ecuador, Peru, and Chile have understood the need of a government intervention for providing electrification by off-grid PV systems to inhabitants of remote areas, but their approaches have been different. We have compared and rated these approaches regarding the indicators of sustainability considered in this paper. A summary of the comparisons of the rural electrification efforts in the three countries is illustrated in the spider graph in Figure 2, where the wider each point (for each indicator) is to the outside, the better its performance.

For instance, as shown by the indicator "funding" in Figure 2, we have highly rated the enormous efforts that Peru has made to ensure the affordability of off-grid PV systems for rural electrification. Indeed, the Peruvian administration has adopted a cross-subsidy scheme (which also aims to reduce economic inequities), which makes the tariff affordable to the users by providing funds for both the initial investment and the O&M of the systems. As opposed to Peru, Ecuador has no mechanism at all aimed at subsidizing O&M costs over the lifetime of the off-grid PV systems, while in Chile funds aimed at O&M are not ensured and need to be annually approved. Therefore, we rate the policies of Chile and Ecuador lower than those in Peru regarding the indicator "funding" (see Figure 2).

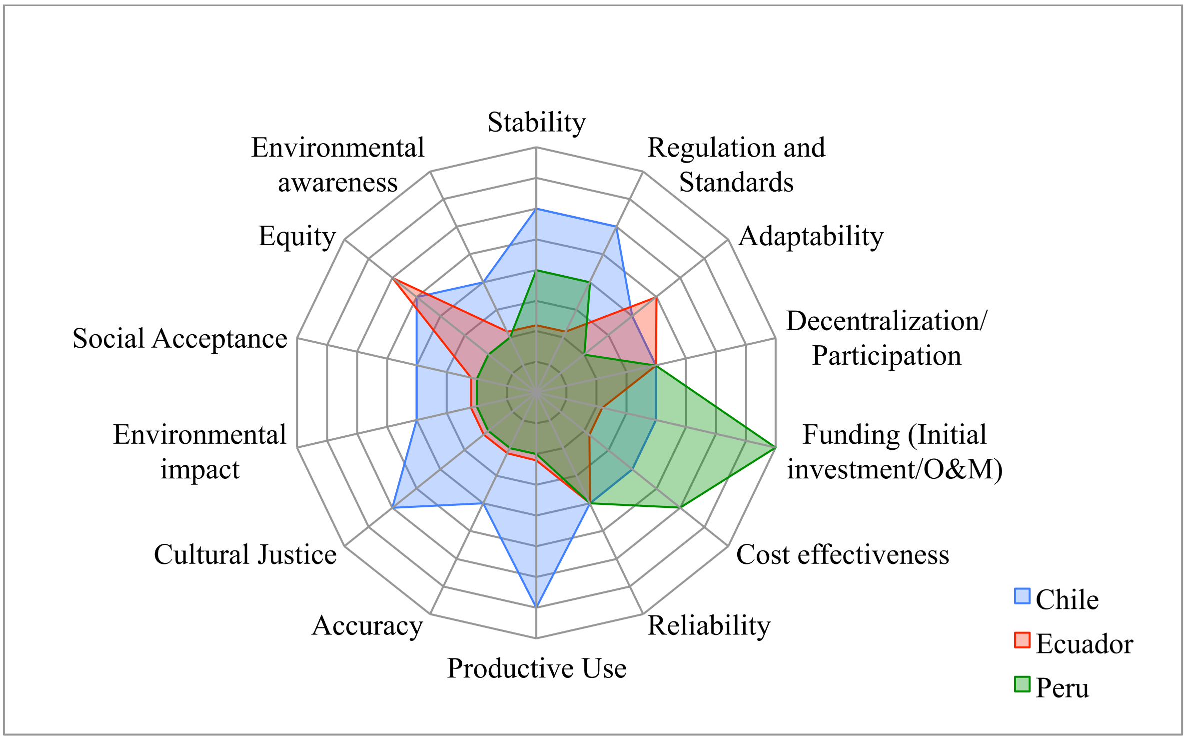


**Figure 2.** Assessment of approaches/policies in Chile, Ecuador, and Peru for rural electrification. Source: Own elaboration.

Failure in ensuring funding for O&M makes off-grid PV systems for rural electrification inevitably unreliable. This is why we have poorly rated the approaches/policies in Chile and Ecuador regarding "Reliability". However, the Peruvian case shows that ensuring the funding is not enough. Indeed, Peru provides financial assistance for O&M, but the off-grid PV systems deployed in Peru have still been unreliable. Causes are manifold, but the widespread outsourcing may have played a role; in Peru, installation, O&M, and even supervision and control have been outsourced to small private firms, which often do not have the required technical know-how.

Off-grid PV systems may be a cost-effective alternative for rural electrification in remote areas of the Andean countries. This fact was recognized first by Peruvian authorities. In addition, lifecycle cost calculations recently promoted by Chilean officials are leading to the substitution of diesel generators by off-grid solutions. In Ecuador, authorities have not conducted any cost studies yet, such that we evaluate the indicator "cost effectiveness" as poor.

As shown in Figure 2, we have rated the rural electrification approaches/policies for "Environmental awareness" and "Environmental impact" as poor in Chile, Ecuador, and Peru. Indeed, environmental awareness is still low in the three cases, though Chile came off better thanks to its younger population. However, due to lacking awareness, potential negative environmental impacts from off-grid PV systems (such as the battery disposal) have not been considered in the three countries.

Successful projects for rural electrification based on off-grid PV systems show the importance of respecting and taking the socio-cultural reality of each community into account. However, this has not yet been acknowledged in Peru and Ecuador. In these countries, the culture of the communities is often not considered in the design and implementation of the projects, which in turn has led to inaccurate solutions (i.e., too small power capacities), mistrust, and ultimately to the rejection of projects in Peru. Although in Ecuador the Constitution proclaimed special rights to indigenous people for cultural justice, these rights are not considered in the projects, such that de facto they do not exist. Indeed, there is a discrepancy between their claims (what is officially stated) and reality (how the policies are implemented). This is why we have poorly rated the approaches/policies in Ecuador and Peru for rural electrification regarding "Cultural Justice", "Social acceptance" and "Accuracy". Chileans on the other hand perform better on these indicators, since they appear to have understood the importance of respecting the cultural values of the communities not only on paper, but also in the implementation of the projects. Moreover, Chile is currently improving the accuracy of its solutions for rural electrification by considering the users' energy needs in the design of the projects.

We evaluate the Chilean and Ecuadorian "Equity" policies positively, given the awareness among all actors of the need to electrify the whole country. However, disparities remain in the power capacity of the deployed systems in Chile, as better-organized communities have greater chances of receiving off-grid solutions with a higher power capacity. Peru on the other hand performs poor on this indicator despite of the cross subsidy tariff, as awareness on equity in rural electrification was found to be low among the actors who implement the projects. Neoliberal policies embraced in Chile and Peru may partially explain the lack of awareness for equity in Peru, and the approach used in Chile to privilege better-organized communities.

Strengthened and stable formal institutions have shown to be a precondition for ensuring the sustainability of projects for rural electrification based on off-grid PV systems. Chile outperforms Peru and Ecuador in the "stability" of its institutions. The instability of institutions in the latter cases became apparent in terms of changing decision makers (Peruvian case) or the substitution of whole organizations (several Ministries in Ecuador). Institutional instability has resulted in inconsistent laws or lacking regulations; furthermore, it has made the enforcement of the few adopted regulations difficult and provided incentives for opportunistic behavior (since people expect rules and regulators to disappear). The causes of institutional instability are often complex and manifold, but, in both countries, it seems that mistrust in institutions may be playing an important role. This is why we poorly rate both Peru and Ecuador on their institutional "stability" and "regulations".

Successful off-grid PV projects for rural electrification have shown the importance of having a strong formal institution (such as an agency) with a flexible and decentralized structure, able to adapt to the (changing) circumstances. A decentralized agency may contribute to the transfer of know-how to rural areas and better engage the communities. The lack of such an agency in Peru explains its poor score on "adaptability". In this regard Ecuador is in better shape, since the ongoing merging of the 11 EDCs may allow them to create a stronger institution, but only if a decentralized structure is maintained and the operation at a local level remains reasonably flexible. Chile also missed to establish a decentralized rural electrification agency for residential systems, but it has some agencies (such as INDAP) that have shown remarkable adaptability and have promoted the successful adoption of off-grid solutions aimed at productive use in rural communities. The program of PV-powered water pumps successfully sponsored by INDAP therefore explains Chile's high rate on "productive use".

Decentralization (understood as the transfer of funds and responsibilities to local officials) may facilitate the engagement of the communities and improve the accuracy. However, projects sponsored by local official (such as municipalities) in the Andean countries show that if decentralization is not accompanied by the transfer of know-how, projects can quickly become unsustainable. All three countries have made attempts of decentralization to different degrees, but all of them have failed to accompany their financial/administrative decentralization with the indispensible transfer of know-how to local players. Moreover, numerous NGO initiatives in the three countries have demonstrated that a participative approach and the engagement of the communities prevent alienation and contribute to the sustainability of the rural electrification projects based on off-grid systems. However, openness to participation of the communities is not widespread in the Andean countries and therefore additional efforts are required regarding “decentralization and participation”.

## 5. Discussion

Ecuador, Peru and Chile share similar challenges for electrifying remote areas where a grid expansion may be unviable. In these areas, the countries have deployed off-grid solutions for electrification. Inhabitants of these areas are culturally diverse and have dissimilar necessities, but they are predominantly poor and unable to afford neither the initial investment nor the O&M of off-grid PV systems.

In this paper, we critically assess the sustainably of rural electrification programs (based on off-grid PV systems) in these Andean countries. Our assessment was based on a set of indicators corresponding to the four dimensions of sustainability considered in this study: institutional, economical, environmental, and socio-cultural. These dimensions are strongly interwoven and are deeply interdependent.

Therefore, ensuring the sustainability of off-grid PV systems requires a multidimensional and integrated approach. For instance, Peru strongly focused on parts of the economic dimension by allocating funds to the systems’ initial investment costs as well as to the O&M costs. However, this one-dimensional approach frequently led to project failures, payment defaults, and inhibited seizing opportunities regarding productive uses of off-grid PV systems. Part of the problem was that Peruvian officials consistently ignored the participation and engagement of the communities such that, despite the allocation of O&M funding, the systems turned to be unreliable. As the short operational period of the systems could not compensate for the investment, the lack of attention to the socio-cultural dimension of sustainability has in turn made the projects in Peru economically unsustainable.

Those cases in which a multidimensional and integrated approach was applied exhibited remarkable success. For example, the PV-powered water pump program conducted by INDAP in Chile boosted the productivity of small farmers in remote areas of the country, thus increasing their income, and allowing them to cover the O&M costs of the systems. The multidimensionality of the program explains its success. It was sponsored and conducted by a decentralized agency whose employees work in close contact with farmers. Its structure, adapted to the farmers’ local conditions, allowed the agency to quickly respond to issues, and to provide accurate solutions according to the users’ real needs, which in turn led to social acceptance.

The success of the PV-powered water pump program in Chile shows how strong and decentralized formal institutions are fundamental for ensuring the accuracy and reliability of the systems, transferring the required know-how, facilitating the productive use of the energy, and gaining the social acceptance. Indeed, the decentralized structure of INDAP with its employees working in close contact with final users, could serve as a model for other countries. These lessons are particularly important considering the recentralization plans in Ecuador (where the 11 EDCs are merged to one EDC). Although this fusion may facilitate the sharing of know-how and economies of scales, it may be significantly negative for rural electrification efforts in Ecuador if it implies losing adaptability of the resulting single EDC, further restricting the engagement between the ground operatives and final users.

Boosting productive activities explains Ecuador’s plans to deploy microgrids for rural electrification (whose capacity may power a community of dozens of inhabitants). Although increasing the income of the community appears to be laudable, it arises an equity dilemma: If project funds for rural electrification are limited, a more expensive solution with a higher capacity could only be provided to a very limited number of communities, while others may have to wait for years to get electrified. This dilemma underlines the interdependency of sustainability dimensions and highlights the need for a balanced multidimensional approach for ensuring the sustainability of off-grid PV systems. However, as shown in Figure 2, some countries have paid more attention to some dimensions than others, but the three analyzed countries have consistently ignored the importance of the institutional dimension.

Indeed, the absence of strengthened and stable formal institutions appears to be a major drawback in the Andean countries that, by inhibiting law enforcement, also compromises the environmental and socio-cultural sustainability of rural electrification efforts. This problem is particularly apparent in Ecuador where institutional instability has led to changing regulations that are often inconsistent with the Constitution. For instance, although anchored in the Constitution, both environmental protection and indigenous rights are frequently disregarded by Ecuadorian decision makers. Moreover, in Peru, people's distrust in formal institutions has negatively affected the social acceptance of rural electrification projects. Chile, in contrast, has more stable institutions than its peers, but its highly centralized policies as well as a neoliberal vision embraced by the Chilean administrations constrain the operative role of its formal institutions. Some small-scale projects in Chile failed due to the lack of a decentralized public agency focused on ensuring the O&M of the installed systems.

The analyzed cases highlight the fact that the dimensions of the sustainability (institutional, economical, environmental, and socio-cultural) are strongly interwoven and are deeply interdependent. As shown above, successful rural electrification projects (based on off-grid PV systems) in the Andean countries were those within which all the dimensions of the sustainability are ensured. Therefore, ensuring the sustainability of rural electrification projects in Ecuador, Peru and Chile (and likely in any other country) requires an integrated and holistic approach.

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## References


1. International Energy Agency (IEA). World Energy Outlook. Electricity Access Database. 2015. Available online: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/ (accessed on 16 December 2015).

2. United Nations General Assembly. *Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution Adopted by the General Assembly on 25 September 2015*; United Nations: New York, NY, USA, 2015. Available online: http://www.un.org/ga/search/view_doc.asp (accessed on 14 October 2016).

3. World Bank. *World Bank Indicators*; Producer and Distributor; The World Bank: Washington, DC, USA, 2017. Available online: http://databank.worldbank.org/data/home.aspx (accessed on 21 February 2017).

4. Ministerio de Energía y Minas (MEM). *Plan Nacional De Electrificacion Rural (PNER) Periodo 2016—2025*; El Peruano: Lima, Peru, 2015. (In Spanish)

5. Ten, M. *Revisión de los Resultados de la Operación 2608/OC-EC: Electrificación Rural y Urbano-Marginal del Ecuador*; Programa de Electrificación Rural y Urbano-Marginal (FERUM) (IADB): Washington, DC, USA, 2013. (In Spanish)

6. Ministerio de Desarrollo Social. Banco Integrado de Proyectos (BIP). 2016. Available online: http://bip. ministeriodesarrollosocial.gob.cl/bip-consulta/ (accessed on 14 September 2016). (In Spanish)

7. Ministerio de Energía y Minas (MEM). *Proyecto De Mejoramiento de la Electrificación Rural Mediante Aplicación de Fondos Concursables II (FONER II). Manual de Operaciones del Proyecto*; Reviewed August 2015; Controlaría General de la República: Lima, Peru, 2011. (In Spanish)

8. Estay, C. *Remoción de Barreras para la Electrificación Rural con Energías Renovables. Informe Catastro de Campo XI Region*; Comisión Nacional de Energía: Santiago de Chile, Chile, 2006. (In Spanish)

9. Nieuwenhout, F.D.J.; Van Dijk, A.; Lasschuit, P.E.; Van Roekel, G.; Van Dijk, V.A.P.; Hirsch, D.; Wade, H. Experience with solar home systems in developing countries: A review. *Prog. Photovolt. Res. Appl.* **2001**, *9*, 455–474. [CrossRef]

10. International Renewable Energy Agency (IRENA). Accelerating Off-Grid Renewable Energy. Second International Off-Grid Renewable Energy Conference. Key Findings and Recommendations. 2014. Available online: http://www.irena.org/DocumentDownloads/Publications/IRENA_2nd_IOREC_2015.pdf (accessed on 3 March 2017).

11. Elusakin Julius, E.; Olufemi, A.O.; Chuks, D.J. Challenges of sustaining off-grid power generation in Nigeria rural communities. *Afr. J. Eng. Res.* **2014**, *2*, 51–57.

12. Mabuza, L.; Brent, A.; Mapako, M. The Transfer of Energy Technologies in a Developing Country Context towards Improved Practice from Past Successes and Failures. 2007. Available online: https://repository.up. ac.za/handle/2263/4854 (accessed on 11 October 2016).

13. Feron, S.; Heinrichs, H.; Cordero, R.R. Are the Rural Electrification Efforts in the Ecuadorian

Amazon Sustainable? *Sustainability* **2016**, *8*, 443. [CrossRef]

14. Ilskog, E. Rural Electrification Sustainability Indicators—Manual for Field Workers. 2008. Available online: http://swepub.kb.se/bib/swepub:oai:DiVA.org:kth-9132?tab2=abs&language=en (accessed on 27 June 2014).

15. Derakhshan, F. On Sustainability in Local Energy Planning. Ph.D. Thesis, Lund University, Lund, Finland, 2011.

16. Sharma, T.; Balachandra, P. Benchmarking sustainability of Indian electricity system: An indicator approach. *Appl. Energy* **2015**, *142*, 206–220. [CrossRef]

17. Wimmler, C.; Hejazi, G.; de Oliveira Fernandes, E.; Moreira, C.; Connors, S. Multi-Criteria Decision Support Methods for Renewable Energy Systems on Islands. *J. Clean Energy Technol.* **2015**, *3*, 185–195. [CrossRef]

18. Reddy, B.S. *Measuring and Evaluating Energy Security and Sustainability: A Case Study of India*; WP-2015-08; Indira Gandhi Institute of Development Research: Mumbai, India, 2015.

19. Gollwitzer, L. *Community-Based Micro Grids: A Common Property Resource Problem*; STEPS Working Paper 68; Steps Center: Brighton, UK, 2014; ISBN 978-1-78118-192-8.

20. Frame, D.; Tembo, K.; Dolan, M.J.; Strachan, S.M.; Ault, G.W. A community based approach for sustainable off-grid PV systems in developing countries. In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–29 July 2011; pp. 1–7.

21. Retnanestri, M. The I3A Framework–Enhancing the Sustainability of Off-Grid Photovoltaic Energy Service Delivery in Indonesia. Ph.D. Thesis, University of New South Wales (UNSW), Sydney, Australia, 2007.

22. Holland, R.; Perera, L.; Sanchez, T.; Wilkinson, R. Decentralised Rural Electrification: The Critical Success Factors. Experience of ITDG (Intermediate Technology Developmental Group). 2006. Available online: http://www.its.caltech.edu/~e105/readings/Rural_Electrification.pdf (accessed on 2 August 2015).

23. Sims, R.E.H.; Schock, R.N.; Adegbululgbe, A.; Fenhann, J.; Konstantinaviciute, I.; Moomaw, W.; Nimir, H.B.; Schlamadinger, B.; Torres-Martínez, J.; Turner, C.; et al. Energy supply. In *Climate Change 2007: Mitigation*; Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007.

24. Fischedick, M.; Borbonus, S.; Scheck, H. Towards Global Energy Governance-Strategies for Equitable Access to Sustainable Energy. *Policy Pap.* **2011**, *34*, 12.

25. Brent, A.C.; Rogers, D.E. Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context. *Renew. Energy* **2010**, *35*, 257–265. [CrossRef]

26. Mainali, B. Sustainability of Rural Energy Access in Developing Countries. Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2014.

27. Dincer, I.; Acar, C. A review on clean energy solutions for better sustainability. *Int. J. Energy Res.* **2015**, *39*, 585–606. [CrossRef]

28. Dunmade, I. Indicators of sustainability: Assessing the suitability of a foreign technology for a developing economy. *Technol. Soc.* **2002**, *24*, 461–471. [CrossRef]

29. Mainali, B.; Pachauri, S.; Rao, N.D.; Silveira, S. Assessing rural energy sustainability in developing countries. *Energy Sustain. Dev.* **2014**, *19*, 15–28. [CrossRef]

30. Garniati, L.; Owen, A.; Kruijsen, J.; Ishadamy, Y.; Wibisono, I. Interface between appropriate technology and sustainable energy policy in vulnerable societies. *Sustain. Cities Soc.* **2014**, *12*, 9–15. [CrossRef]

31. Chaurey, A.; Kandpal, T.C. Assessment and evaluation of PV based decentralized rural electrification: An overview. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2266–2278. [CrossRef]

32. Cook, P. Infrastructure, rural electrification and development. *Energy Sustain. Dev.* **2011**, *15*, 304–313. [CrossRef]

33. Khandker, S.R.; Barnes, D.F.; Samad, H.A. Welfare impacts of rural electrification: A panel data analysis from Vietnam. *Econ. Dev. Cult. Chang.* **2013**, *61*, 659–692. [CrossRef]

34. Stringer, L.C.; Paavola, J. Participation in environmental conservation and protected area management in Romania: A review of three case studies. *Environ. Conserv.* **2013**, *40*, 138–146. [CrossRef]

35. Polack, A. Drivers and Barriers of Renewable Energy in the Electrification of Vanuatu. Ph.D. Thesis, Murdoch University, Murdoch, Australia, 2010.

36. Rosen, M.A. Energy sustainability: A pragmatic approach and illustrations. *Sustainability* **2009**, *1*, 55–80. [CrossRef]

37. Bhattacharyya, S.C. Energy access programmes and sustainable development: A critical review and analysis. *Energy Sustain. Dev.* **2012**, *16*, 260–271. [CrossRef]

38. Ribeiro, F.; Ferreira, P.; Araújo, M. The inclusion of social aspects in power planning. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4361–4369. [CrossRef]

39. Lähtinen, K.; Myllyviita, T.; Leskinen, P.; Pitkänen, S.K. A systematic literature review on indicators to assess local sustainability of forest energy production. *Renew. Sustain. Energy Rev.* **2014**, *40*, 1202–1216. [CrossRef]

40. Stake, R.E. *Multiple Case Study Analysis*; Guilford Press: New York, NY, USA, 2013.

41. George, A.L.; Bennett, A. *Case Studies and Theory Development in the Social Sciences*; MIT Press: Cambridge, MA, USA, 2005.

42. Feron, S.; Heinrichs, H.; Cordero, R.R. Sustainability of rural electrification programs based on off-grid photovoltaic (PV) systems in Chile. *Energy Sustain. Soc.* **2016**, *6*, 32. [CrossRef]

43. Feron, S.; Cordero, R.R. Sustainability of Rural Electrification Programs based on off-grid Photovoltaic Systems in Peru. *Int. J. Sustain. Dev.* **2017**. submitted.

44. Pressacco, C.F.; Rivera, S. Democracia, participación y espacio local en Chile. *Papel Político* **2015**, *20*, 65–89. (In Spanish) [CrossRef]

45. Ministerio de Economia y Finanzas (MEF). Proyecto de Presupuesto. Anexo 2. Available online: https://www.mef.gob.pe/index.php?option=com_content&view=article&id=4129&Itemid=10

1156&lang=es (accessed on 29 January 2016). (In Spanish)

46. Escudero-Sánchez, C.C.L. Desafíos de la descentralización para la gestión del patrimonio cultural en el Ecuador. *Santiago* **2015**, *136*, 197–213. (In Spanish)

47. Yitzhaki, S. Relative deprivation and the Gini coefficient. *Q. J. Econ.* **1979**, *93*, 321–324. [CrossRef]

48. Ministerio de Relaciones Exteriores. Informe Anual Comercio Exterior de Chile 2014–2015. 2015. Available online: https://www.direcon.gob.cl/wp-content/uploads/2015/07/Informe-anual-de-Comercio-Exterior- de-Chile-2014-2015.pdf (accessed on 4 February 2016). (In Spanish)

49. Ministerio de Energía y Minas (MEM). *Anuario Minero 2015. Estadística Minera*; Biblioteca Nacional de Peru: Lima, Peru, 2016; Available online: http://www.minem.gob.pe/_publicaSector.php?idSector=1& idCategoria=19 (accessed on 20 August 2016). (In Spanish)

50. Ministerio Coordinador de Sectores Estrategicos (MICSE). Políticas Energéticas en Ecuador. 2014. Available online: http://www.nist.gov/iaao/upload/3-_Presentacion_Politica_Energia__v2-pptx_DARWIN_COSTA. pdf (accessed on 24 August 2015). (In Spanish)

51. World Integrated Trade Solution. Ecuador Fuels Exports by Country 2015. 2015. Available online: http://wits.worldbank.org/CountryProfile/en/Country/ECU/Year/LTST/TradeFlow/Export/Partner/by-country/Product/27-27_Fuels (accessed on 20 September 2017).

52. Secretaría Nacional de Planificación y Desarrollo (Senplades). *Plan Nacional de Desarrollo/Plan Nacional para el Buen Vivir 2013–2017*; Gobierno Nacional de la República del Ecuador: Quito, Ecuador, 2013; ISBN 978-9942-07-448-5. (In Spanish)

53. Sánchez, L.; Reyes, O. *La Demanda de Gasolinas, Gas Licuado de Petróleo y Electricidad en el Ecuador. Elementos Para una Reforma Fiscal Ambiental*; CEPAL: Santiago de Chile, Chile, 2016; p. S.16-00529.

54. Vera, I.A.; Langlois, L.M.; Rogner, H.H.; Jalal, A.I.; Toth, F.L. Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency. In *Natural Resources Forum*; Blackwell Publishing Ltd.: Oxfort, UK, 2005; Volume 29, pp. 274–283.

55. Ministerio de Electricidad y Energias Renovables (MEER). Available online: http://www.energia.gob.ec/ coca-codo-sinclair/# (accessed on 28 August 2015). (In Spanish)

56. Comision Nacional de Energia (CNE). Balance Nacional de Energía. Available online: http://energiaabierta. cne.cl/visualizaciones/balance-de-energia/ (accessed on 19 September 2015). (In Spanish)

57. CONELEC. Centrales Renovables No Convencionales. Available online: http://www.conelec.gob.ec/images/documentos/doc_10238_CENTRALES_RENOVABLES_NO_CONVENCIONAL.pdf (accessed on 18 June 2015). (In Spanish)

58. Comite de Operacion Economica del Sistema Interconectado Nacional (COES) (NA). Producción de Energía Eléctrica por Tipo de Generación del Coes 2013–2014. Available online: http://www.coes1.org.pe/post-operacion/Publicaciones/WebPages/estadisticaanual.aspx (accessed on 30 January 2016). (In

Spanish)

59. Instituto Nacional de Estadisticas y Censos (INEC). REDATAM. Available online: http://www.inec.gob.ec/ estadisticas/?option=com_content&view=article&id=104&Itemid=76 (accessed on 3 December 2015).

60. Instituto Nacional de Estadisticas (INE) (NA). Chile: Censo de Población y Vivienda. Available online: http:// www.ine.cl/canales/chile_estadistico/censos/censo_poblacion_vivienda.php (accessed on 17 January 2014). (In Spanish)

61. Central de Energía (NA). Autoridad—Coordinación. Available online: http://www.centralenergia.cl/ actores/autoridad-energia-chile/ (accessed on 30 April 2016). (In Spanish)

62. Ministerio de Electricidad y Energias Renovables (MEER). Plan Estratégico Institucional 2014–2017. Available online: http://www.energia.gob.ec/wp-content/uploads/downloads/2014/09/PLAN-ESTRATÉGICO- 2.pdf (accessed on 17 October 2014). (In Spanish)

63. Ministerio de Energía y Minas (MEM). *Reglamento De Organización y Funciones (Rof)*; El Peruano: Lima, Peru, 2007. (In Spanish)

64. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN). Informe N 063-2015-GART Gerencia Adjunta de Regulación Tarifaria División de Distribución Eléctrica. Fijación del Cargo RER Autónomo Para el Suministro de Electricidad con Recursos Energéticos Renovables en Áreas No Conectadas a Red Publicación del Proyecto de Resolución. 2015. Available online: http://www.osinergmin.gob.pe/seccion/centro_documental/gart/procesosregulatorios/ electricidad/fijacion-cargo-rera/2015/INF_063_2015_Fijación_del_Cargo_RER_Autónomo.pdf (accessed on 8 November 2016). (In Spanish)

65. Levitsky, S.; Murillo, M.V. Construyendo instituciones sobre cimientos débiles: Lecciones desde América Latina. *P. Rev. Cienc. Polít.* **2012**, *3*, 17–44.

66. Aguilar, J.; Zepeda, R. Política neoliberal y democracia en América Latina. In *Contextualizaciones Latinoamericanas*; No.9; Universidad de Guadalajara: Guadalajara, Mexico, 2013.

67. Stern, J.; Cubbin, J. *Regulatory Effectiveness: The Impact of Regulation and Regulatory Governance Arrangements on Electricity Industry Outcomes*; World Bank-Free PDF; World Bank: Washington, DC, USA, 2005; Volume 3536.

68. Asamblea Nacional República del Ecuador. Ley Orgánica del Servicio Público de Energía Eléctrica. Tercer Suplemente. Año II—No 418. Quito, 16 January 2015. Available online: http://www.regulacionelectrica.gob. ec/ley-organica-de-servicio-publico-de-energia-electrica-da-paso-a-la-creacion-de-la-arconel/ (accessed on 21 February 2017). (In Spanish)

69. Pyhala, A. Institutions, Participation, and Protected Area Management in Western Amazonia. In *Commons in an Age of Globalisation, Proceedings of the Ninth Conference of the International Association for the Study of Common Property, Victoria Falls, Zimbabwe, 17–21 June 2002*; IASCP: Victoria Falls, Zimbabwe, 2002; pp. 17–21.

70. Deuman. Evaluación Ex-Post del Primer Proyecto de Electrificación Mediante Sistemas

Fotovoltaicos en las Comunas de Tortel, Villa O'Higgins y Cochrane de la Provincia de Capitán Prat, Región de Aysén del General Carlos Ibáñez del Campo. 2012. Available online: http://dataset.cne.cl/Energia_Abierta/Estudios/Minerg/23_Evaluación%20%20Expost%20Sistemas%20FV%20Provincia%20Capitán%20Prat%20Reg%20%20Aysén_Serv%20Ing%20Deuman_584105-10-LE12.pdf (accessed on 11 January 2015). (In Spanish)

71. Covarrubias, F.; Irarrázaval, I.; Galáz, R. *Programa de Asistencia a la Gestión del Sector de la Energía: Desafíos de la Electrificación Rural en Chile*; Banco Internacional de Reconstrucción y Fomento: Washington, DC, USA, 2005. (In Spanish)

72. Gobierno Regional de Aysén. Sistemas de Generacion Fotovoltaicos Varios Sectores Comuna de Aysen CODIGO BIP: 30125568-0. Available online: https://www.mercadopublico.cl/Procurement/Modules/Attachment/ViewAttachment.aspx?enc=POxTpc8k5kEehmdX82SavZIQCfSKkB5w%2fMuND7DysolmQMtod18DSfVAjxSA77MOtaEelk6qsw6Y804hSA6nr45%2b8ndDK%2b3WmB23KeufdQIbaBcUcpmlF9E9Z5TiT00pEgAvs1lvZFCICIDRphX58IpxZyTMBIE5zvsj1il2HWizs4gLOxZyAfrovwOwyuFqPN6TJw%2bUKvPU0x08o6ZStxBbIsfOB9ibwT8rQoSADfPOjWko4sZCKexwXnIlpzGoaBPHPa3ci527OsAIP7qYdcSAcRApjPp3lhdwjfq QieKylQ%2fSUyz6IEGSYceVDRfs (accessed on 22 September 2016).

73. Rodriguez, H. Programa Remoción de Barreras Para la Electrificación Rural. UNDP-GEF Project (Project CHI/00/G32 (11799). 2012. Available online: https://www.thegef.org/sites/default/files/project_ documents/843_1320_Chile_CCM_TE.pdf (accessed on 4 April 2015). (In Spanish)

74. Fundación Ecuatoriana De Tecnología Apropiada (FEDETA). *Modelo de Gestión para Sistemas Energéticos Aislados—Articulación Energética Territorial para Poblaciones Indígenas de la Región Amazónica Ecuatoriana*; FEDETA: Quito, Ecuador, 2014. (In Spanish)

75. Jané La Torre, E.; Palacios, D. *Estado Situacional de la Prestación del Servicio Electrico Mediante Sistemas Fotovoltaicos Autónomos*; Gerencia de Fiscalización Eléctrica, Osinergmin: Lima, Peru, 2015. (In Spanish)

76. Argomedo, R. Financiamiento Estatal en Chile. In Proceedings of the Programa Electrificación Rural (PER) Workshop on Energy Storage for Sustainable Development, Rio de Janeiro, Brazil, 16–17 April 2015. (In Spanish)

77. Consejo Nacional de Electricidad (CONELEC). *Plan Maestro de Electrificación 2012–2021*; CONELEC: Deland, FL, USA, 2012.

78. Congreso de la Republica. *Ley General de Electrificación Rural LEY No 28749*; El Peruano: Lima, Peru, 2006. (In Spanish)

79. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN). *Resolución de Consejo Directivo N 235-2010-OS/CD*; OSINERGMIN: Lima, Peru, 2010. (In Spanish)

80. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN). *Fijación de la Tarifa Rural para Sistemas Fotovoltaicos 2014–2018*; Publicación del Proyecto de Resolución. Expediente N 0248-2014-GART; OSINERGMIN: Lima, Peru, 2014. (In Spanish)

81. Ministerio de Desarrollo Social. Metodología de Formulación y Evaluación de Proyectos de Electrificación Rural. 2015. Available online: http://sni.ministeriodesarrollosocial.gob.cl/fotos/11%20Metodolog%C3%

ADa%20de%20Electrificación%20Rural%202015.pdf (accessed on 11 November 2015). (In Spanish)

82. Comision Nacional de Energia (CNE). Resolucion Exenta No. 137. 2009. Available online: http://www.cne. cl/archivos_bajar/Resolucion%20Exenta%20%20N137.pdf (accessed on 9 September 2016). (In Spanish)

83. Urdiales Flores, L.E. Procedimiento para la Electrificación en Zonas Aisladas: Caso Cantón Taisha, Morona Santiago. Master's Thesis, Universidad de Cuenca, Cuenca, Ecuador, 2015. Available online: http://dspace. ucuenca.edu.ec/handle/123456789/21428 (accessed on 5 May 2015). (In Spanish)

84. Doberti, G. ERNC en la Agricultura familiar campesina y Programa Nacional de Bombeo Fotovoltaico INDAP. 2013. Available online: http://docplayer.es/3949063-Ernc-en-la-agricultura-familiar-campesina- y-programa-nacional-de-bombeo-fotovoltaico-indap-ministerio-de-agricultura-indap.html (accessed on 5 June 2015). (In Spanish)

85. Ministerio de Electricidad y Energias Renovables (MEER). *Informe—Rendición de Cuentas*; Ministerio de Electricidad y Energias Renovables (MEER): Quito, Ecuador, 2014. (In Spanish)

86. Feron, S. Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review. *Sustainability* **2016**, *8*, 1326. [CrossRef]

87. Ministerio de Desarrollo e Inclusion Social (MIDIS). *Manual de Operaciones Fondo para la Inclusión Económica en Zonas Rurales (FONIE)*; MIDIS: Lima, Peru, 2013. (In Spanish)

88. Fileccia, C.M.; Caravaggio, N.; Conte, E. Buen Vivir: Sumak Kawsay and reality. In Proceedings of the 25th Annual EAEPE Conference, Paris, France, 7–9 November 2013. Available online: https://www.academia. edu/15369034/Buen_Vivir_between_Sumak_Kawsay_and_reality (accessed on 22 March 2015).

89. Liebenthal, A.; Salvemini, D. *Promoting Environmental Sustainability in Peru: A Review of the World Bank Group's Experience (2003–2009)*; IEG Working Paper 2011/1; IFC, MIGA, World Bank: Washington, DC, USA, 2011.

90. De Queiroz, J.S.; Silva, F.; Ipenza, C.; Hernick, C.; Batallanos, L.; Griswold, D.; Rogers, A.E. *Peru Tropical Forest and Biodiversity Assessment*; US Foreign Assistance Act, Section 118/119 Report August; Sun Mountain International and The Cadmus Group, Inc.: Quito, Ecuador, 2014.

91. Lanegra, I. Institucionalidad ambiental peruana. In *Agenda de Investigación en Temas Socioambientales en el Perú: Una Aproximación Desde las Ciencias Sociales*; CISEPA-PUCP|INTE|Facultad de Ciencias Sociales|GEA: Lima, Peru, 2014.

92. United Nations Economic Commission for Latin America and the Caribbean (ECLAC); Organisation for Economic Cooperation and Development (OECD). Environmental Performance Reviews Peru. Highlights and Recommendations. 2016. Available online: https://www.oecd.org/environment/country-reviews/16- 00312-environmental%20performance%20review-peru-web.pdf (accessed on 12 September 2016).

93. Scherman, A.; Arriagada, A.; Valenzuela, S. Student and environmental protests in Chile: The role of social media. *Politics* **2015**, *35*, 151–171. [CrossRef]

94. Schaeffer, C. Democratizing the Flows of Democracy: Patagonia Sin Represas in the Awakening of Chile's Civil Society. In *Social Movements in Chile*; Donoso, S., von Bülow, M., Eds.; Palgrave Macmillan: New York, NY, USA, 2017; ISBN 978-1-349-95091-1.

95. Hernando, A. *El sector Energético en Chile y la Agenda de Energía 2014: Algunos Elementos Para la Discusión*; Centro de Estudios Publicos: Santiago de Chile, Chile, 2014. (In Spanish)

96. Comisión Ciudadana-Técnico-Parlamentaria para la Política y la Matriz Eléctrica (CCTP). Chile Necesita una Gran Reforma Energética. 2011. Available online: http://www.patagoniasinrepresas.cl/final/dinamicos/ chile_necesita_una%20gran_reforma_energetica.pdf (accessed on 17 June 2016). (In Spanish)

97. Barton, J.R. Climate change adaptive capacity in Santiago de Chile: Creating a governance regime for sustainability planning. *Int. J. Urban Reg. Res.* **2013**, *37*, 1916–1933. [CrossRef]

98. Comunidades Energeticas (NA). Luces y Sombras Para las Comunidades Energéticas Aisladas en Patagonia. Documento de Trabajo. REDES-Conicyt. N 14001. Available online: http://www.comunidadesenergeticas.com/wp-content/uploads/2016/04/Luces-y-sombras-para-las-comunidades-energéticas-aisladas-en-Patagonia.23-marzo.pdf (accessed on 10 September 2016).

99. Newbold, J. Balancing economic considerations and the rights of indigenous people. The Mapuche people of Chile. *Sustain. Dev.* **2004**, *12*, 175–182. [CrossRef]

100. Parker,C.;Letelier,M.;Muñoz,J.Elites,climatechangeandagencyinadevelopingsociety:The Chilean case. *Environ. Dev. Sustain.* **2013**, *15*, 1337–1363. [CrossRef]

101. Bass,M.S.;Finer,M.;Jenkins,C.N.;Kreft,H.;Cisneros Heredia,D.F.;McCracken,S.F.;DiFiore, A. Global conservation significance of Ecuador's Yasuní National Park. *PLoS ONE* **2010**, *5*, e8767. [CrossRef] [PubMed]

102. Damonte, G. Ciencias Sociales y gran minería: Una agenda de investigación. In *Minería, Turismo y Agroindustria. Nuevos Ejes Económicos*; Damonte, G., Fuller, N., Valcárcel, M., Eds.; PUCP: Lima, Peru, 2009; pp. 7–31.

103. Romero,H.;Méndez,M.;Smith,P.MiningdevelopmentandenvironmentalinjusticeintheAtacama Desert of Northern Chile. *Environ. Justice.* **2012**, *5*, 70–76. [CrossRef]

104. MinisteriodeDesarrolloSocial.EncuestraCasen.2012.Available online: http://www.redatam.org/redchl/ mds/casen/casen2011/Index.html (accessed on 28 January 2016). (In Spanish)

105. Ministerio de Energia. Congreso Nacional aprueba proyecto de Equidad Tarifaria.2016. Available online: http://www.energia.gob.cl/tema-de-interes/congreso-nacional-aprueba-proyecto (accessed on 1 June 2016). (In Spanish)

106. Leid,L.H.LlegóLaLuz:ACaseStudyoftheImpactsofSolarPhotovoltaicElectricityinLasBalsas,Ecuador. Ph.D. Thesis, University of Texas, Austin, TX, USA, 2014. Available online: https://tdl-ir.tdl.org/tdl-ir/ handle/2152/26125 (accessed on 31 March 2015).

107. RexelFoundationandMicrosol.StudyofthePotentialtoSpreadEnergyEfficiency'sCarbonPrograms in Andean Countries. Available online: http://www.microsol-int.com/recursos/2014_0627_Microsol_Rexel_ study_final_report_(WITH_conclusions)_rev.pdf (accessed on 9 November 2016).

108. Means,P.A.RaceandSocietyintheAndeanCountries.*Hisp.Am.Hist.Rev.***1918**,*1*,415–

425.[CrossRef]

109. Organismo Supervisor de la Inversión en Energía y Minería (OSINERGMIN). Tender Documents for Auction of Electricity Supply with Renewable Energy Resources in Areas Not Connected to Network. 2014. Available online: http://www2.osinerg.gob.pe/EnergiasRenovables/contenido/1eraSubastaOffGrid. Bases.html (accessed on 1 February 2016). 

## 7 Conclusions and Outlook

The research question "*Are the rural electrification programs (based on off-grid PV Systems) in the Andean countries sustainable?"* was assessed by breaking the thesis down into three main sections: a generic literature review (Paper 1), an empirical part (Papers 2, 3, and 4), and a comparative analysis (Paper 5).

Formal institutions, characterized by their stability (durability) and their enforcement, tended to be low in DCs worldwide, which is problematic for the sustainability of off-grid PV systems. This was also an issue in the three analyzed countries, and in particular in Ecuador, which was plagued by disruptive changes in electrification policies, weak enforcement of the constitutional rights regarding energy, and a feeble coherence of the legal frame in rural electrification.

The existence of a regulatory agency can help to enhance the sustainability. However, the enforcement of these formal institutions strongly depends on informal institutions, such that adopting formal institutions, as well as ensuring their enforcement is indispensable for sustainable rural electrification based on off-grid PV systems. The institutional separation of the Peruvian rural electrification into two separate agencies with similar competences inhibited this adaptation. Similarly, the lack of a decentralized public RE agency in Chile to oversee the O&M of the off-grid PV systems threatened the sustainability of the projects.

Adapting to the local needs of the rural population may be reached by decentralization, which is meant to facilitate adaptability based on participative decision-making. However, many cases worldwide have shown that decentralization may also increase the risk of a weak coordination between local and national governments and the lack of expert know-how (often not available in remote areas). Indeed, the capacities on the regional and local scale on RE projects were basically non-existent in all three analyzed countries, resulting in unreliable systems. Ecuador therefore initiated an administrative recentralization process to take advantage of the know-how from some of their electricity distribution companies (EDCs).

Global experiences have shown that the unavailability of financial products (such as microcredits) and the higher initial investment of PV systems make off-grid PV solutions unattainable for rural households in DCs, and often force the poor population to choose costly alternatives. Hence, an effective focalized subsidy scheme is needed for disperse and poor rural areas, but unfortunately numerous project failures could be ascribed to the lack of funds for covering O&M. Peru on the other hand has established a financially sustainable model based on cross-subsidies to make the systems affordable to the poor; the model also assures the compensation of all O&M costs to the EDCs, and may therefore be adopted by other countries.

Although electrification is expected to contribute to a higher income of the users, several cases worldwide show that the provision of electricity does not automatically lead to productive uses (mainly owing to the lack of user know-how and proper training). Indeed, neither Peru nor Ecuador was able to implement projects based on off-grid PV systems for productive uses. The Chilean case of the PV-powered water pumps program from the Ministry of Agriculture on the other hand offers an example of how off-grid RE may successfully contribute to the income of its users.

The global review of off-grid PV programs for rural electrification have also revealed that even presumably clean technologies may become environmentally unsustainable (e.g., by missing to ensure recycling and proper disposal of PV modules and batteries) in the context of the scarcity of environmental awareness and regulations, weak enforcement of regulations, and the lack of incentives. These challenges were ratified in the three analyzed countries, where environmental awareness was still low, and potential negative environmental impacts from off-grid PV systems were not considered.

As several cases worldwide have shown, an understanding of the rural lifestyle is needed to tailor a technology and improving the accuracy, reducing in turn user rejection and deception. Albeit small-scale energy approaches may have a higher social acceptance than large-scale solutions, a lack of communication concerning the applications and limitations of off-grid PV systems have repetitively led to false expectations and negative perceptions, thus constraining their social acceptance. Indeed, inaccurate low-capacity systems have also caused the rejection of off-grid PV solutions in the three countries, though Chile has recently changed its policy from an electrification approach to a more holistic "energization" approach, aiming to consider the users' energy needs in the design of the projects.

The global review found furthermore that the culture of small rural communities is often not considered in the execution of public policies in DCs. This issue was particularly alarming in Ecuador and Peru, where the ignorance of culture (especially of indigenous communities) caused mistrust and the abandonment of the PV systems.

Although the dimensions of sustainability (institutional, economic, environmental and socio-cultural) are strongly interwoven and are deeply interdependent, prior experiences have underlined the importance of paying special attention to the institutional dimension. Indeed, the absence of strengthened and sustainable formal institutions appears to be a major drawback in DCs that, by inhibiting law enforcement, compromises the environmental and socio-cultural sustainability of rural electrification efforts, especially in rural areas.

This holds also true in the Andean countries: Although Chile, Ecuador, and Peru handle each challenge of rural electrification differently and with different degrees of success, my results indicate that a major obstacle for sustainable rural electrification in the Andean region have been the weak and changing institutions associated with rural electrification in all three countries (though Chile was found to have stronger and more stable institutions than its peers).

In any way, the review on global efforts on rural electrification has shown that ensuring sustainability requires an integrated and multidimensional approach. The findings from the three Andean countries have ratified this: For instance, Peru strongly focused on the economic dimension by covering the initial investment costs as well as the O&M costs, but ignored the participation and engagement of the communities. This one-dimensional approach has frequently led to project failures, payment defaults, and inhibited seizing opportunities regarding productive uses of off-grid PV systems.

This thesis has shown that the qualitative assessment of the multidimensional indicators of sustainability can facilitate a better understanding of the flaws affecting rural electrification projects. Though several studies have already proposed using quantitative indicators for measuring sustainability in rural electrification, this thesis has demonstrated that a qualitative assessment can be striking for understanding the issues behind unsustainable practices. For instance, although laws and regulations are established (even in a country`s constitution), this does not mean that they are actually enforced and complied with in practice. Different and complex temporal courses are often hard to measure quantitatively, especially in environments where political changes are frequent. Moreover, the advantage of complementing quantitative with qualitative indicators lies in the fact that the latter are much more capable of illustrating the interwoven and deeply interdependent connections between indicators and dimensions. Indeed, quantitative indicators tend to measure only one isolated aspect of an issue, whereas sustainability in rural electrification demands for a broader understanding of the problem and the impacts of one indicator on the other indicators/dimensions.

This thesis has also exposed the importance of the institutional dimension for ensuring the sustainability of rural electrification projects. Institutional sustainability was previously identified as a key component of sustainable energy planning in general (Derakhshan, 2011), and has also been included in several prior studies on rural electrification (e.g. Ilskog, 2005). Still, systematic analyses of the role of institutions and the strength of formal institutions (as defined by Levitsky and Murillo, 2009) for rural electrification efforts are still scarce so far. This is particularly important in DCs, where institutions or organizations cannot be simply substituted by new institutions, as it may sometimes be the case in developed countries (e.g. in highly competitive fields). Future research may therefore consider paying special attention to the role of institutional sustainability for rural electrification.

Based on the finding from this thesis, I consider that the method (qualitative assessment of the multidimensional indicators of sustainability) applied throughout the thesis can also be helpful for future studies to assess the sustainability of off-grid PV systems in other countries. Indeed, it would be interesting to investigate how countries from other continents perform on each indicator, and if political, geographical, or cultural patterns can be deduced. It may also be useful for governments or NGOs to make a diagnosis of current issues in rural electrification for a particular country, and to develop a sustainable strategy for an off-grid PV program.

Future studies may moreover adapt the method to other RE technologies by adding/removing indicators according to the particularities of a technology. In fact, it would be interesting to see if other renewable technologies in rural electrification confront similar challenges within a country and make a contrast between them.

## Bibliography


1. Acemoglu, D., Robinson, J. A. (2005). Economic origins of dictatorship and democracy. Cambridge University Press.
2. Acemoglu, D., Robinson, J. A. (2006). De facto political power and institutional persistence. The American economic review, 325-330.
3. Adger, W. N., Brown, K., Fairbrass, J., Jordan, A., Paavola, J., Rosendo, S., & Seyfang, G. (2003). Governance for sustainability: towards a thick analysis of environmental decision making. Environment and planning A, 35(6), 1095-1110.
4. AGECC. 2010. *Energy for a Sustainable Future*. New York: The Secretary-General's Advisory Group on Energy and Climate Change.
5. Agrawal, A. (2010). Local institutions and adaptation to climate change. Social Dimensions of Climate Change. Equity and Vulnerability in a Warming World. R. Mearns (ed.), 173-198.
6. Alvial-Palavicino, C., Garrido-Echeverría, N., Jiménez-Estévez, G., Reyes, L., & Palma-Behnke, R. (2011). A methodology for community engagement in the introduction of renewable based smart microgrid. Energy for Sustainable Development, 15(3), 314-323.
7. Akiki, G., Hinrichs, F., Zuylen, R. A., & Rojas-Solórzano, L. (2010, November). Pre-feasibility study for PV electrfication of off-grid rural communities. International Renewable Energy Congress November 5-7, 2010–Sousse, Tunisia.
8. Aman, M. M., Solangi, K. H., Hossain, M. S., Badarudin, A., Jasmon, G. B., Mokhlis, H., ... & Kazi, S. N. (2015). A review of Safety, Health and Environmental (SHE) issues of solar energy system. Renewable and Sustainable Energy Reviews, 41, 1190-1204.
9. Andersson, K. P., & Ostrom, E. (2008). Analyzing decentralized resource regimes from a polycentric perspective. Policy sciences, 41(1), 71-93.
10. Aron, Janine (2002) : Building institutions in post-conflict African economies, WIDER Discussion Papers // World Institute for Development Economics (UNU- WIDER), No. 2002/124, ISBN 9291903752
11. Assembly, U.G. Transforming Our World: The 2030 Agenda for Sustainable Development; Resolution Adopted by the General Assembly on 25 September 2015; United Nations: New York, NY, USA, 2015.
12. Balcombe, P., Rigby, D., & Azapagic, A. (2015). Environmental impacts of microgeneration: Integrating solar PV, Stirling engine CHP and battery storage. Applied Energy, 139, 245-259.
13. Ball, D., & Frei, C. (1999). Health and environmental impacts of electricity generation systems. International Atomic Energy Agency.
14. Banse, G. (2003). nachhaltige Entwicklung und Technikfolgenabschätzung. Utopie kreativ, 680.
15. Barbier, E. B. (1987). The concept of sustainable economic development. Environmental conservation, 14(02), 101-110.
16. Bhattacharyya, S. C. (2013a). To regulate or not to regulate off-grid electricity access in developing countries. Energy policy, 63, 494-503.
17. Bhattacharyya, S. C. (2013b). Financing energy access and off-grid electrification: A review of status, options and challenges. Renewable and Sustainable Energy Reviews, 20, 462-472.
18. Bhattacharyya, S.C. Energy access programmes and sustainable development: A critical review and analysis. Energy Sustain. Dev. 2012, 16, 260–271.
19. Bhattacharyya, S. C., & Palit, D. (2016). Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required?. Energy Policy, 94, 166-178.
20. Blackorby, C., Bossert, W., & Donaldson, D. (2002). Utilitarianism and the theory of justice. Handbook of social choice and welfare, 1, 543-596.
21. Böni, H., Schluep, M., & Widmer, R. (2015). Recycling of ICT equipment in industrialized and developing countries. In ICT Innovations for Sustainability (pp. 223-241). Springer International Publishing.
22. Bowen, G. A. (2009). Document analysis as a qualitative research method. Qualitative research journal, 9(2), 27-40.

23. Brent, A. C., & Rogers, D. E. (2010). Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context. Renewable Energy, 35(1), 257-265.
24. Breton, Albert (2002). An introduction to decentralization failure. In Managing fiscal decentralization, ed. Ehtisham Ahmad, and Vito Tanzi. New York: Routledge.
25. Breyer, C., Koskinen, O., & Blechinger, P. (2015). Profitable climate change mitigation: The case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 49, 610-628.
26. Bruckner T., I.A. Bashmakov, Y. Mulugetta, H. Chum, A. de la Vega Navarro, J. Edmonds, A. Faaij, B. Fungtammasan, A. Garg, E. Hertwich, D. Honnery, D. Infield, M. Kainuma, S. Khennas, S. Kim, H. B. Nimir, K. Riahi, N. Strachan, R. Wiser, and X. Zhang (2014): Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
27. Brundtland, G. H., & Khalid, M. (1987). Our common future. World Comission on Environment and Development: Brussels.
28. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) 2004. Erneuerbare Enrgien Innovationen fuer die Zukunft
29. Burford, G., Hoover, E., Velasco, I., Janoušková, S., Jimenez, A., Piggot, G., ... & Harder, M. K. (2013). Bringing the “missing pillar” into sustainable development goals: Towards intersubjective values-based indicators. Sustainability, 5(7), 3035-3059.
30. Cabraal, R. A., Barnes, D. F., & Agarwal, S. G. (2005). Productive uses of energy for rural development. Annu. Rev. Environ. Resour., 30, 117-144.
31. Chaurey, A., & Kandpal, T. C. (2010). Assessment and evaluation of PV based decentralized rural electrification: An overview. Renewable and Sustainable Energy Reviews, 14(8), 2266-2278.
32. Chaurey, A., Ranganathan, M., & Mohanty, P. (2004). Electricity access for geographically disadvantaged rural communities—technology and policy insights. Energy policy, 32(15), 1693-1705.
33. Corsair, H.J. Causes of Success and Failure of Stand-alone Solar Electric Systems in Rural Guatemala. Ph.D. Thesis, Johns Hopkins University, Baltimore, MD, USA, 2014.
34. Cropanzano, R., Ambrose, M. L., Greenberg, J., & Cropanzano, R. (2001). Procedural and distributive justice are more similar than you think: A monistic perspective and a research agenda. Advances in organizational justice, 119, 151.
35. De Wild-Scholten, M. (2013), “Energy payback time and carbon footprint of commercial PV systems”, Solar Energy Materials & Solar Cells, n°119: 296-305.
36. Del Río, P., & Burguillo, M. (2008). Assessing the impact of renewable energy deployment on local sustainability: Towards a theoretical framework. Renewable and sustainable energy reviews, 12(5), 1325-1344.
37. Derakhshan, F. (2011). *On sustainability in local energy planning*.Doctoral Thesis, Lund University, Sweden. ISBN: 978-91-7473-110-1. Available at: http://lup.lub.lu.se/record/1939379 Accessed on 5 June 2017,
38. De Soysa, I., & Jütting, J. (2006). Informal Institutions and Development–What do we know and what can we do?. OECD Development Center, International Seminar.
39. Díaz, P., Arias, C. A., Gomez‐Gonzalez, M., Sandoval, D., & Lobato, R. (2013). Solar home system electrification in dispersed rural areas: a 10‐year experience in Jujuy, Argentina. Progress in Photovoltaics: Research and Applications, 21(3), 297-307.
40. Dornan, M. (2011). Solar-based rural electrification policy design: The Renewable Energy Service Company (RESCO) model in Fiji. Renewable Energy, 36(2), 797-803.
41. Eakin, H., & Lemos, M. C. (2006). Adaptation and the state: Latin America and the challenge of capacity-building under globalization. Global environmental change, 16(1), 7-18.

42. Estache, A., & Wren-Lewis, L. (2009). Toward a theory of regulation for developing countries: Following jean-jacques laffont's lead. *Journal of Economic Literature*, *47*(3), 729-770.
43. Etxano Gandariasbeitia, I. (2012). New Insights into the Assessment of Protected Areas–Integrating Rural Development. In: Rural Development – Contemporary Issues And Practices. InTech, Rijeka, Croatia. ISBN 978-953-51-0461-2
44. Fishbein, R. E., Sanghvi, A. P., & Unit, A. E. (2003). Survey of productive uses of electricity in rural areas. *Washington, DC*.
45. Fraunhofer Institute for Solar Energy Systems Ise (2014). Photovoltaics Report. Available at: http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf Accessed on January 2015.
46. Fritsch, O., & Newig, J. (2007, May). Under which conditions does public participation really advance sustainability goals? Findings of a meta-analysis of stakeholder involvement in environmental decision-making. In Amsterdam Conference on the Human Dimensions of Global Environmental Change: Earth System Governance: Theories and Strategies for Sustainability. Vrije Universiteit Amsterdam (pp. 24-26).
47. Fritsch, O., & Newig, J. (2012). Participatory governance and sustainability. Reflexive Governance for Global Public Goods, 181.
48. García, V. G., & Bartolomé, M. M. (2010). Rural electrification systems based on renewable energy: The social dimensions of an innovative technology. Technology in Society, 32(4), 303-311.
49. Garimella, A., Shardul, M., Chaudhury, S., & Palit, D. (2015). Institution as the catalyst for productive use of electricity in livelihood cluster: A Case for energy plus approach from Andhra Pradesh, India. Micro Perspectives For Decentralized Energy Supply, 142.
50. Garniati, L., Owen, A., Kruijsen, J., Ishadamy, Y., & Wibisono, I. (2014). Interface between appropriate technology and sustainable energy policy in vulnerable societies. Sustainable Cities and Society, 12, 9-15.
51. Gläser, J., & Laudel, G. (2010). Experteninterviews und qualitative Inhaltsanalyse. Springer-Verlag.4. Auflage ISBN 9783531172385
52. Gläser, J., & Laudel, G. (2009). Experteninterviews und qualitative Inhaltsanalyse. Springer-Verlag.3. Auflage. ISBN 3531156845, 9783531156842
53. Gómez, M., & Silveira, S. (2011). The institutional dimension of rural electrification in the Brazilian Amazon. In World Renewable Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden (No. 057, pp. 3444-3451). Linköping University Electronic Press.
54. Grindle, M. S. (2004). Good enough governance: poverty reduction and reform in developing countries. Governance, 17(4), 525-548.
55. Guerrero, L. A., Maas, G., & Hogland, W. (2013). Solid waste management challenges for cities in developing countries. Waste management, 33(1), 220-232.
56. Haanyika, C. M. (2006). Rural Electrification Policy and Institutions in a Reforming Power Sector.
57. Haselip, J. A., Nygaard, I., Hansen, U. E., & Ackom, E. (2011). Diffusion of renewable energy technologies: case studies of enabling frameworks in developing countries.
58. Hawkes, J. (2001). The fourth pillar of sustainability. Culture's essential role in public planning.
59. Hayami, Y., & Godo, Y. (2005). Development economics: From the poverty to the wealth of nations. Oxford University Press.
60. Helmke, G., & Levitsky, S. (2012). Informal institutions and comparative politics: a research agenda. International Handbook on Informal Governance, 85-113.
61. High, Chris; Pelling, Mark and Nemes, Gusztav (2005). Understanding informal institutions: Networks and communities in rural development. In: Transition in Agriculture, Agricultural Economics in Transition II, Institute of Economics, Hungarian Academy of Sciences, 28-29 Oct 2005, Budapest, Hungary.
62. HOMER (2011). Getting Started Guide for HOMER Legacy (Version 2.68). Available at: http://www.homerenergy.com/HOMER-getting-started-guide.html Accessed on July 2014

63. Hong, G. W. C. (2012). Sustainable development of renewable energy systems for rural electrification: off-grid solar PV cases from the Philippines (Doctoral dissertation, 東京工業大学).
64. Hong, G. W., & Abe, N. (2012). Sustainability assessment of renewable energy projects for off-grid rural electrification: The Pangan-an Island case in the Philippines. Renewable and Sustainable Energy Reviews, 16(1), 54-64.
65. Houtart, F. (2011). El concepto de Sumak kawsay (buen vivir) y su correspondencia con el bien común de la humanidad. Revista de filosofía, 69(3).
66. Huld, T., Jäger-Waldau, A., & Szabó, S. (2014, May). Mapping the cost of electricity from grid-connected and off-grid PV systems in Africa. In 1st Africa Photovoltaic Solar Energy Conference and Exhibition,(S151–155). Durban, South Africa.
67. IADB (2013). Ideas for Development in the Americas. A Local Focus to a Global Problem. In: IDEA.
68. International Energy Agency (IEA) (NA). Modern energy for all: why it matters. Available at: http://www.worldenergyoutlook.org/resources/energydevelopment/modernenergyforallwhyitmatters/ accessed on January 2015
69. International Energy Agency (IEA) (2015a). World Energy Outlook 2015—Methodology for Energy Access Analysis. 2015. Available online: http://www.worldenergyoutlook.org/media/weowebsite/2015/EnergyAccess_ Methodology_2015.pdf (accessed on 25 June 2016).
70. International Energy Agency (IEA) (2015b). World Energy Outlook. Electricity Access Database. Available online: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/ (accessed on 16 December 2015).
71. International Energy Agency (IEA) (2014). World Energy Outlook Factsheet. IEA Publishing. Available at http://www.worldenergyoutlook.org/media/weowebsite/2014/141112_WEO_FactSheets.pdf Accessed on January 2015
72. International Energy Agency (IEA) (2013). Pico Solar PV Systems for Remote Homes A new generation of small PV systems for lighting and communication. IEA PVPS Task 9, Report IEA-PVPS T9-12: 2012
73. International Energy Agency (IEA) and the World Bank (2015). "Sustainable Energy for All 2015—Progress Toward Sustainable Energy" (June), World Bank, Washington, DC. Doi: 10.1596/978-1-4648 -0690-2 License: Creative Commons Attribution CC BY 3.0 IGO
74. Ilskog, E. (2008). Rural electrification sustainability indicators—manual for field workers. Available online: http://swepub.kb.se/bib/swepub:oai:DiVA.org:kth-9132?tab2=abs&language=en (accessed on 27 June 2014).
75. Ilskog, E. (2005). And then they lived sustainably ever after?: part I, experiences from rural electrification in Tanzania, Zambia and Kenya (Doctoral dissertation, Luleå tekniska universitet).
76. International Renewable Energy Agency (IRENA) (2015). Accelerating Off-Grid Renewable Energy. Second International Off-Grid Renewable Energy Conference (IOREC 2014) Key Findings and Recommendations. 2014. Available online: http://www.irena.org/DocumentDownloads/Publications/IRENA_2nd_IOREC_ 2015.pdf (accessed on 12 October 2016).
77. James, B. (1998). Equity and empowerment: possible outcomes of the rural electrification programme.
78. Karakaya, E.; Sriwannawit, P. Barriers to the adoption of photovoltaic systems: The state of the art. Renew. Sustain. Energy Rev. 2015, 49, 60–66.
79. Kaygusuz, K. (2012). Energy for sustainable development: A case of developing countries. Renewable and Sustainable Energy Reviews, 16(2), 1116-1126.
80. Kemausuor, F., & Ackom, E. (2017). Toward universal electrification in Ghana. Wiley Interdisciplinary Reviews: Energy and Environment, 6(1).
81. Khan, M. J., & Iqbal, M. T. (2005). Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland. Renewable energy, 30(6), 835-854.

82. Klöpffer, W. (2003). Life-cycle based methods for sustainable product development.
83. Kolk, A., & van den Buuse, D. (2012). In search of viable business models for development: sustainable energy in developing countries. Corporate Governance, 12(4), 551-567.
84. Lalander, R. (2014). Rights of nature and the indigenous peoples in Bolivia and Ecuador: A Straitjacket for Progressive Development Politics?. Iberoamerican Journal of Development Studies, 3(2), 148-173.
85. Lemaire, X. (2011). Off-grid electrification with solar home systems: the experience of a fee-for-service concession in South Africa. Energy for Sustainable Development, 15(3), 277-283.
86. Levitsky, S., & Murillo, M. V. (2012). Building Institutions on Weak Foundations: Lessons from Latin America. In conference "Guillermo O'Donnell and the Study of Democracy," in Buenos Aires, March (pp. 26-27).
87. Levitsky, S., & Murillo, M. V. (2009). Variation in Institutional Strength. Annu. Rev. Polit. Sci, 12, 115-33.
88. Liu, X., Sun, Y., & Kaloustian, T. S. (2015). Cultural factors influencing domestic adoption of solar photovoltaic technology: perspectives from China. China Media Research, 11(4), 28-42.
89. Machado, F. V. (2013). Decentralization and Accountability: The Curse of Local Underdevelopment.
90. Mainali, B. (2014). Sustainability of rural energy access in developing countries.
91. Mainali, B., Pachauri, S., Rao, N. D., & Silveira, S. (2014). Assessing rural energy sustainability in developing countries. Energy for Sustainable Development, 19, 15-28.
92. Martinot, E., Chaurey, A., Lew, D., Moreira, J. R., & Wamukonya, N. (2002). Renewable energy markets in developing countries*. Annual Review of Energy and the Environment, 27(1), 309-348.
93. MAXQDA, software for qualitative data analysis, 1989-2016, VERBI Software – Consult – Sozialforschung GmbH, Berlin, Germany
94. McKay,K.H.Socio cultural dimensions of cluster vs. Single home photovoltaic solar energy systems in Rural Nepal. Sustainability 2010, 2, 494–504.
95. McMann, M., Zipprich, A., Macer, D. R., Nyambati, A. R., Ngo, D., Cheng, M., ... & Wolbring, G. (2011). Energy equity and environmental security. UNESCO Bangkok.
96. Meadows, D. H. (1998). Indicators and information systems for sustainable development.
97. Means, P. A. (1918). Race and Society in the Andean Countries. Hispanic American Historical Review, 415-425.
98. Merriam, S. B., & Tisdell, E. J. (2015). Qualitative research: A guide to design and implementation. John Wiley & Sons.
99. Meuleman, A. A. M., & Veld, R. J. (2009). Sustainable development and the governance of long-term decisions. RMNO. ISBN: 9072377893, 9789072377890
100. Meuser, M., & Nagel, U. (2002). ExpertInneninterviews—vielfach erprobt, wenig bedacht. In Das Experteninterview (pp. 71-93). VS Verlag für Sozialwissenschaften.
101. Minogue, M. (2013). Regulatory Governance of Off-Grid Electrification. In Rural Electrification Through Decentralised Off-grid Systems in Developing Countries (pp. 253-270). Springer London.
102. Misra, K.B. (2009). Role of performance engineering in sustainable development. In: Principles of Sustainable Development - Volume III. EOLSS Publications, 2009. ISBN:1848260814, 9781848260818
103. Moloney, S., Horne, R. E., & Fien, J. (2010). Transitioning to low carbon communities—from behaviour change to systemic change: Lessons from Australia. Energy Policy, 38(12), 7614-7623.
104. Mufiaty, H. (2014). Solar home systems performance in rural area in aceh case study: Deah mamplam village, aceh besar. Energy procedia, 47, 133-142.
105. Murphy, J. (2012). Governing technology for sustainability. Earthscan. London, UK.
106. Nerini, F. F., Howells, M., Bazilian, M., & Gomez, M. F. (2014). Rural electrification options in the Brazilian Amazon: a multi-criteria analysis. Energy for Sustainable Development, 20, 36-48.
107. Newig, J. (2007). Does public participation in environmental decisions lead to improved environmental quality?: towards an analytical framework. Communication,

Cooperation, Participation (International Journal of Sustainability Communication), 1(1), 51-71.
108. Nieuwenhout, F.D.J.; van Dijk, A.; Lasschuit, P.E.; van Roekel, G.; van Dijk, V.A.P.; Hirsch, D.; Wade, H. Experience with solar home systems in developing countries: A review. Prog. Photovolt. Res. Appl. 2001, 9, 455–474.
109. North, D. C. (1992). Institutionen, institutioneller Wandel und Wirtschaftsleistung (Vol. 76). Mohr siebeck.
110. North, D. C. (1989). Institutions and economic growth: An historical introduction. World development, 17(9), 1319-1332.
111. Nozick, R. (2003). Distributive justice. Debates in contemporary political philosophy, 73.
112. Nurse, K. (2006). Culture as the fourth pillar of sustainable development. Small states: economic review and basic statistics, 11, 28-40.
113. Obeng, G.Y;Evers H.D. (2009). Solar PV rural electrification and energy-poverty: A review and conceptual framework with reference to Ghana. Technology Consultancy Centre Kwame Nkrumah Univ. of Science & Technology Kumasi, Center for Development Research (ZEF), University of Bonn, Germany. MPRA Paper No. 17136
114. OECD/IEA (2014). Technology Roadmap. Solar Photovoltaic Energy
115. OECD/IEA (2010). ENERGY POVERTY. How to make modern energy access universal?
116. Special early excerpt of the World Energy Outlook 2010 for the UN General Assembly on the Millennium Development Goals. Available at http://www.se4all.org/wp-content/uploads/2013/09/Special_Excerpt_of_WEO_2010.pdf Accessed on Jan 2015
117. OECD (2001). Policies To Enhance Sustainable Development. Meeting of the OECD Council at Ministerial Level, 2001. Paris, France.
118. Olk, H.; Mundt, J. (2016). Photovoltaics for productive use applications : a catalogue of DC-appliances / Implemented by: GIZ on behalf of Federal Ministry for Economic Cooperation and Development (BMZ) Eschborn, Bonn : Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. URN: urn:nbn:de:hbz:5:2-95753
119. Oumer, A. M., & de Neergaard, A. (2011). Understanding livelihood strategy-poverty links: empirical evidence from central highlands of Ethiopia. Environment, Development and Sustainability, 13(3), 547-564.
120. Parekh, Bhikhu (2004) Redistribution or recognition?: A misguided debate. In: Ethnicity, nationalism, and minority rights. Cambridge University Press, Cambridge, UK, pp. 199-213. ISBN 9780521603171
121. Pachauri, S. (2011). Reaching an international consensus on defining modern energy access. Current Opinion in Environmental Sustainability, 3(4), 235-240.
122. Pejovich, S. (2012). The effects of the interaction of formal and informal institutions on social stability and economic development. Journal of Markets & Morality, 2(2).
123. Peña-López, I. (2008). Global economic prospects 2008: Technology diffusion in the developing world.(Chapter 2).

124. Quang, C. T. (2013). ASEAN guideline on off-grid rural electrification approaches. Renewable Energy Support Program for ASEAN (ASEAN-RESP) ASEAN Centre for Energy, Jakarta, 12950.
125. Radcliffe, S., Laurie, N., & Andolina, R. (2002). Indigenous people and political transnationalism: globalization from below meets globalization from above. University of Oxford. Transnational Communities Programme.
126. Radzi, A., & Droege, P. (2014). Latest Perspectives on Global Renewable Energy Policies. Current Sustainable/Renewable Energy Reports, 1(3), 85-93.
127. Rawls, J. (1999). A Theory of Justice, revised edition. Cambridge, MA: The Belknap Press of Harvard University Press, 11, 53-55.
128. Rehman, I. H., Kar, A., Banerjee, M., Kumar, P., Shardul, M., Mohanty, J., & Hossain, I. (2012). Understanding the political economy and key drivers of energy access in addressing national energy access priorities and policies. Energy Policy, 47, 27-37.

129. Reiche, K., Tenenbaum, B., & de Mästle, C. T. (2006). Electrification and regulation: principles and a model law. Energy and Mining Sector Board, The World Bank.
130. Rendall, M. (2011). Climate change and the threat of disaster: the moral case for taking out insurance at our grandchildren's expense. Political Studies, 59(4), 884-899.
131. Ritchie, J., Lewis, J., Nicholls, C. M., & Ormston, R. (Eds.). (2013). Qualitative research practice: A guide for social science students and researchers. Sage.
132. Rodríguez-Pose, A. (2013). Do institutions matter for regional development?. Regional Studies, 47(7), 1034-1047.
133. Rolland, Simon. "Rural electrification with renewable energy." Alliance for Rural Electification, Brussels (2011).
134. Rondinelli, Dennis ; McCullough, James S.; Johnson, Ronald W. Analysing decentralization policies in developing countries: a political‐economy framework. Development and change, 1989, 20. Jg., Nr. 1, S. 57-87.
135. Sachs, J., McArthur, J. W., Schmidt-Traub, G., Kruk, M., Bahadur, C., Faye, M., & McCord, G. (2004). Ending Africa's poverty trap. Brookings papers on economic activity, 2004(1), 117-240.
136. Sandgren, A. Batteries Used within Solar Electric Systems in Rural Uganda; Lund University: Lund, Sweden, 2001.
137. Sathaye, J., Lucon, O., Rahman, A., Christensen, J., Denton, F., Fujino, J., ... & Shmakin, A. (2011). Renewable energy in the context of sustainable development.
138. Sawin, J. (2006). National policy instruments: Policy lessons for the advancement & diffusion of renewable energy technologies around the world. Renewable Energy. A Global Review of Technologies, Policies and Markets.
139. Schillebeeckx, S. J., Parikh, P., Bansal, R., & George, G. (2012). An integrated framework for rural electrification: Adopting a user-centric approach to business model development. Energy Policy, 48, 687-697.
140. Sen, A. (2014)How does culture matter? In Culture and Public Action;Rao,V.,Walton,M.,Eds.;Stanford University Press: Stanford, CA, USA, 2004; pp. 37–58.
141. Sen, R., & Bhattacharyya, S. C. (2014). Off-grid electricity generation with renewable energy technologies in India: An application of HOMER. Renewable Energy, 62, 388-398.
142. Shamsul Haque, M. (1997). Local Governance in Developing Nations: Reexamining the Question of Accountability. Regional Development Dialogue, 18, iii-iii.
143. Siegel, J.R.; Rahman, A. The Diffusion of Off-Grid Solar Photovoltaic Technology in Rural Bangladesh; Energy, Climate, and Innovation Program Report; Tufts University: Medford, MA, USA, 2011.
144. R.E.H. Sims, R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martínez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang, 2007: Energy supply. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
145. Sindhu, S.; Nehra, V.; Luthra, S. Identification and analysis of barriers in implementation of solar energy in Indian rural sector using integrated ISM and fuzzy MICMAC approach. Renew. Sustain. Energy Rev. 2016, 62, 70–88.
146. Solis, M. P. S. (2015). From right to light: a human rights-based approach to universal access to modern energy services (Doctoral dissertation). University Of Adelaide, Australia.
147. Sovacool, B. K. (2013). A qualitative factor analysis of renewable energy and Sustainable Energy for All (SE4ALL) in the Asia-Pacific. Energy Policy, 59, 393-403.
148. Sovacool, B.K.; D'Agostino, A.L.; Jain Bambawale, M. The socio-technical barriers to Solar Home Systems (SHS) in Papua New Guinea: Choosing pigs, prostitutes, and poker chips over panels. Energy Policy 2011, 39, 1532–1542.
149. Sovacool, B. K., & Dworkin, M. H. (2015). Energy justice: Conceptual insights and practical applications. Applied Energy, 142, 435-444.

150. Steiner, A., Wilde, T., Bradbrook, A. J., & Schutyser, F. (2006). International institutional arrangements in support of renewable energy. Renewable Energy. A Global Review of Technologies, Policies and Markets. London, 152-162.
151. Stigka, E. K., Paravantis, J. A., & Mihalakakou, G. K. (2014). Social acceptance of renewable energy sources: A review of contingent valuation applications. Renewable and Sustainable Energy Reviews, 32, 100-106.
152. Subbarao, S., & Lloyd, B. (2011). Can the clean development mechanism (CDM) deliver?. Energy Policy, 39(3), 1600-1611.
153. Sun, M., Yang, X., Huisingh, D., Wang, R., & Wang, Y. (2015). Consumer behavior and perspectives concerning spent household battery collection and recycling in China: a case study. Journal of Cleaner Production, 107, 775-785.
154. Tang, T., & Bhamra, T. (2008). Changing energy consumption behaviour through sustainable product design. In DS 48: Proceedings DESIGN 2008, the 10th International Design Conference, Dubrovnik, Croatia.
155. Thiam, D. R. (2011). Renewable energy, poverty alleviation and developing nations: Evidence from Senegal. Journal of Energy in Southern Africa, 22(3), 23-34.
156. Tillmans, A., & Schweizer-Ries, P. (2011). Knowledge communication regarding solar home systems in Uganda: the consumers' perspective. Energy for Sustainable Development, 15(3), 337-346.
157. Tomei J. and Gent, D. (eds) (2015). Equity and the energy trilemma: delivering sustainable energy access in low-income communities. International Institute for Environment and Development, London.
158. United Nations (UN) (1992a). Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3-14 June 1992 (United Nations publication, Sales No. E.93.I.8 and corrigenda), vol. I: Resolutions adopted by the Conference, resolution 1, annex I.
159. United Nations (UN), (1992b). Results of the World Conference on Environment and Development: Agenda 21. UNCED United Nations Conference on Environment and Development, Rio de Janeiro, United Nations, New York.
160. Urmee, T. (2009). Solar PV electrification programs in developing countries: towards an holistic approach (Doctoral dissertation, Murdoch University).
161. Urmee T, Harries D., Schlapfer A. (2009). Issues related to rural electrification using renewable energy in developing countries of Asia and Pacific. Renewable Energy 2009, 34, 354–357
162. Urmee, T., & Md, A. (2016). Social, cultural and political dimensions of off-grid renewable energy programs in developing countries. Renewable Energy, 93, 159-167.

163. van Els, R. H., de Souza Vianna, J. N., & Brasil, A. C. P. (2012). The Brazilian experience of rural electrification in the Amazon with decentralized generation–The need to change the paradigm from electrification to development. Renewable and Sustainable Energy Reviews, 16(3), 1450-1461.
164. Vanhulst, J., & Beling, A. E. (2014). Buen vivir: Emergent discourse within or beyond sustainable development?. Ecological Economics, 101, 54-63.
165. Van Norden, S. Investigation of the Barriers for the Diffusion of Photovoltaic Systems in Cape Town. Master's Thesis, KTH School of Industrial Engineering and Management (ITM), Stockholm, Sweden, 2015.
166. Veldhuis, A. J., & Reinders, A. H. M. E. (2015). Reviewing the potential and cost-effectiveness of off-grid PV systems in Indonesia on a provincial level. Renewable and Sustainable Energy Reviews, 52, 757-769.
167. Waas, T., Hugé, J., Block, T., Wright, T., Benitez-Capistros, F., & Verbruggen, A. (2014). Sustainability assessment and indicators: Tools in a decision-making strategy for sustainable development. Sustainability, 6(9), 5512-5534.
168. Wimmler, C.; Hejazi, G.; de Oliveira Fernandes, E.; Moreira, C.; Connors, S. Multi-criteria decision support methods for renewable energy systems on Islands. J. Clean Energy Technol. 2015, 3, 185–195.

169. World Bank (2011). Decentralized Infrastructure for Rural Transformation Project. Implementation Completion and Results Report (IDA-37880 IDA-3788A). Available at: http://projects.worldbank.org/P073367/decentralized-infrastructure-rural-transformation?lang=en&tab=documents Accessed on 31 March 2017
170. World Bank (2010). Addressing the Electricity Access Gap. Background Paper for the World Bank Group Energy Sector Strategy. The World Bank, Washington DC, USA.
171. World Bank (2008a). Policy and governance framework for off-grid rural electrification with renewable energy sources. Washington, DC: World Bank. Available at: http://documents.worldbank.org/curated/en/479041468288044964/Policy-and-governance-framework-for-off-grid-rural-electrification-with-renewable-energy-sources Accessed on 1st April 2017
172. World Bank (2008b). Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices. The World Bank, Washington DC, USA.
173. World Bank (2008c). Africa Development Indicators 2007. Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/12363 License: CC BY 3.0 IGO.
174. World Bank (2008d). The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits, An IEG Impact Evaluation, Washington DC, World Bank.
175. World Commission on Environment and Development (WCED) (1987): Our Common Future. Available at: http://www.un-documents.net/our-common-future.pdf (accessed on 13th February 2014)
176. World Energy Council (2016). World Energy Resources. Solar. Available at: https://www.worldenergy.org/wp-content/uploads/.../WEResources_Solar_2016.pdf Accessed on 7th April 2017
177. Young, I. M. (1990). Justice and the Politics of Difference.
178. Zalengera, C., Blanchard, R. E., Eames, P. C., Juma, A. M., Chitawo, M. L., & Gondwe, K. T. (2014). Overview of the Malawi energy situation and A PESTLE analysis for sustainable development of renewable energy. *Renewable and Sustainable Energy Reviews*, *38*, 335-347.
179. Zografakis, N., Sifaki, E., Pagalou, M., Nikitaki, G., Psarakis, V., & Tsagarakis, K. P. (2010). Assessment of public acceptance and willingness to pay for renewable energy sources in Crete. Renewable and Sustainable Energy Reviews, 14(3), 1088-1095.

## Appendix

**Authors' Contributions**

Overview of articles included in this cumulative Ph.D. thesis

(in accordance with the guideline for cumulative dissertations in Sustainability Science [January 2012], in the following termed "the guideline")

Title of Ph.D. thesis: "Sustainability of off-grid PV systems in rural electrification: Evidence from the Andean Countries Chile, Peru and Ecuador"

Papers included:

[1] Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review. Sustainability, 8(12), 1326.

[2] Sustainability of rural electrification programs based on off-grid photovoltaic (PV) systems in Chile. Energy, Sustainability and Society, 6(1), 32.

[3] Are the Rural Electrification Efforts in the Ecuadorian Amazon Sustainable?. Sustainability, 8(5), 443.

[4] Sustainability of Rural Electrification Programs based on off-grid Photovoltaic Systems in Peru. Submitted

[5] Sustainability of rural electrification efforts based on off-grid Photovoltaic systems in the Andean Región. Sustainability 2017, 9(10), 1825

Authors' contributions to the articles and articles publication status (according to §16 of the guideline):

| Article # | Short title | Specific contributions of all authors | Author status | Weighting factor | Publication status | Conference contri-butions |
|---|---|---|---|---|---|---|
| [1] | Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review | | Single authorship | 1.0 | Published in Sustainability (ISSN 2071-1050; CODEN: SUSTDE). Indexed in: Science Citation Index Expanded Social Sciences Citation Index Current Contents - Agriculture, Biology & Environmental Sciences Current Contents - Social & Behavioral Sciences IF: 1.789 (2016) | |
| [2] | Sustainability of rural electrification programs based on off-grid photovoltaic (PV) systems in Chile | SF conceptualized and structured the paper. SF was solely responsible for the conception, the data collection (interviews) and analysis. HH and RC contributed with content revision and discussions The whole paper was jointly drafted and developed by the authors to bring to the current state. All authors read and approved the final manuscript. | First author with predominant contribution | 1.0 | Published in Energy, Sustainability and Society ISSN: 2192-0567<br><br>Indexed in: Emerging Sources Citation Index | |
| [3] | Are the Rural Electrificatio | SF conceptualized | First author | 1.0 | Published in Sustainability | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | n Efforts in the Ecuadorian Amazon Sustainable? | and structured the paper. SF was solely responsible for the conception, the data collection (interviews) and analysis. HH and RC contributed with content revision and | with predom inant contrib ution | | (ISSN 2071-1050; CODEN: SUSTDE). Indexed in: Science Citation Index Expanded Social Sciences Citation Index Current Contents – Agriculture, Biology & Environmental Sciences Current Contents – Social & Behavioral Sciences IF: 1.789 (2016) | |
| [4] | Sustainability of Rural Electrificatio n Programs based on off-grid Photovoltaic Systems in Peru | SF conceptualized and structured the paper. SF was solely responsible for the conception, the data collection (interviews) and analysis. RC contributed with content revision and discussions The whole paper was jointly drafted and developed by the authors to bring to the current state. All authors read and approved the final manuscript. | First author with predom inant contrib ution | (1.0) | Submitted | |
| [5] | Sustainability of rural electrification efforts based on off-grid Photovoltaic systems in the Andean Region | SF conceptualized and structured the paper. SF was solely responsible for the conception, the data collection (interviews) | First author | 1.0 | Published in Sustainability (ISSN 2071-1050; CODEN: SUSTDE). Indexed in: Science Citation Index Expanded Social Sciences Citation Index | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | and analysis. RC and FL contributed with content revision and discussions. The whole paper was jointly drafted and developed by the authors to bring to the current state. All authors read and approved the final manuscript. | with predom inant contrib ution | | Current Contents – Agriculture, Biology & Environmental Sciences Current Contents – Social & Behavioral Sciences IF: 1.789 (2016) | |
| Sum: | | | | 4.0 | | |

**Explanations**

Specific contributions of all authors

FL- Fernando Labbe
HH-Harald Heinrichs
RC- Raúl Cordero
SF – Sarah Feron

*Author status*
according to §12b of the guideline:

Single author [Allein-Autorenschaft] = Own contribution amounts to 100%.

Co-author with predominant contribution [Überwiegender Anteil] = Own contribution is greater than the individual share of all other co-authors and is at least 35%.

Co-author with equal contribution [Gleicher Anteil] = (1) own contribution is as high as the share of other co-authors, (2) no other co-author has a contribution higher than the own contribution, and (3) the own contribution is at least 25%.

Co-author with important contribution [Wichtiger Anteil] = own contribution is at least 25%, but is insufficient to qualify as single authorship, predominant or equal contribution.

Co-author with small contribution [Geringer Anteil] = own contribution is less than 20%.

*Weighting factor*

according to §14 of the guideline:

| | |
|---|---|
| Single author [Allein-Autorenschaft] | 1.0 |
| Co-author with predominant contribution [Überwiegender Anteil] | 1.0 |
| Co-author with equal contribution [Gleicher Anteil] | 1.0 |
| Co-author with important contribution [Wichtiger Anteil] | 0.5 |
| Co-author with small contribution [Geringer Anteil] | 0 |

*Publication status*

IF= ISI Social Sciences Citation Index – Impact Factor

*Conference contributions (acronym, society, date, venue, website)*

**Declaration (according to §16 of the guideline)**

I avouch that all information given in this appendix is true in each instance and overall.