GIS-based sustainability assessment of decentralized rural electrification in the Amazon region

case study Ecuador

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To Tamya

ABSTRACT

Decentralized rural electrification (DRE) is necessary for electricity supplies in remote and disadvantaged areas in the Amazon region and improvement of the living conditions of the people there. However, the sustainability of DRE is often challenged by an unfavorable policy environment, limited institutional and organizational capacities, restricted financial resources, users' cultural attitudes and values as well as technology and environmental constraints. This study investigates how geographic information system (GIS) and system thinking can be linked for assessing and simulating the sustainability of DRE to enable stakeholders to explore policy scenarios to ensure a long-term electricity supply while improving the peoples' wellbeing and protecting the environment. Research objectives were accomplished by applying an interdisciplinary, participatory and multi-method approach in the Ecuadorian Amazon as a case study.

The aspects that favor or hinder sustainable operation of DRE in the Ecuadorian Amazon were identified through semi-structured interviews with decision makers and a survey in households using solar home systems (SHS). DRE is influenced by an intertwined network of technological, economic, social, institutional and environmental aspects. This complexity was disclosed through a participatory system analysis identifying DRE as a system of interconnected variables that form mostly reinforcing feedback structures without self-regulation. Thus, the provision of electricity in the Ecuadorian Amazon is perceived as an unstable system, not self-sufficient, and politically, technically and financially dependent on external inputs. Therefore, DRE needs to be carefully monitored to provide a basis for proactive and participatory management of a sustainable electricity system.

Linking GIS with fuzzy cognitive mapping (FCM) and multi-criteria decision analysis (MCA) is demonstrated as being capable of capturing the complexity of DRE and assessing and simulating its sustainability in a participatory, systemic and spatial explicit manner. In a workshop with researchers, decision makers and the staff responsible for the solar program ‘Yatsa Ii Etsari’ in Morona Santiago, Ecuador, the viewpoints of the participants on sustainable DRE were integrated into a fuzzy cognitive map (system model) represented by a set of interconnected sustainability variables that allowed the simulation of the developing behavior of the DRE system and predicted future sustainability. Using data from the workshop and a household survey with users of SHS, MCA and GIS allowed the computation and mapping of sustainability for a spatial assessment of DRE at a regional scale and at different levels of aggregation, i.e. indicators, variables and sustainability indexes. The integration of GIS, FCM and MCA thus allowed scenario development and analysis in order to study long-term sustainability trends that might result from different interventions in the DRE system. Simulation results show that the proposed approach can be used to facilitate stakeholder discussions, as it immediately provides plausible outcomes and feedbacks that stakeholders can interpret and, if appropriate, they can revise or reset their ideas for policy interventions. The approach assesses DRE from perspectives other than the conventional, e.g. economic or technological, perspective and has the potential to serve as a learning tool for participatory decision making allowing insights that otherwise would not be possible.

GIS-basierte Bewertung der Nachhaltigkeit dezentraler ländlicher Elektrifizierung im Amazonasbecken: Fallstudie Ecuador

KURZFASSUNG

Dezentrale ländliche Elektrifizierung (DLE) spielt in den abgelegenen und unterentwickelten Gebieten Amazoniens eine wichtige Rolle, um die Stromversorgung zu gewährleisten und die Lebensqualität der Bevölkerung zu verbessern. Jedoch wird die Nachhaltigkeit von DLE durch widrige politische Rahmenbedingungen, niedriger institutioneller Organisationsgrad, begrenzte finanzielle Ressourcen, kulturelle Eigenheiten und Wertesysteme der Nutzer sowie technologische und umweltbedingte Einschränkungen in Frage gestellt.

Die vorliegende Studie untersucht, inwiefern geographische Informationssysteme (GIS) und Systemdenken in die Bewertung und Simulation der Nachhaltigkeit von DLE einfließen können, um Stakeholders die Möglichkeit zu geben, politische Szenarien durchzuspielen und zu erörtern, mit dem Ziel, die Stromversorgung langfristig zu sichern, die Lebensqualität der Bevölkerung zu verbessern und die Umwelt zu schützen. Dabei kam ein interdisziplinärer, partizipativer und multimethodischer Ansatz am Beispiel des ecuadorianischen Amazonasgebietes zur Anwendung. Die Faktoren, die eine nachhaltige Betreibung von DLE begünstigen, wurden durch Interviews mit Entscheidungsträgern und Befragungen von Haushalten, die Solar Home Systems (SHS) nutzen, ermittelt.

Die dezentrale ländliche Elektrifizierung wird von einem Netzwerk aus technologischen, ökonomischen, sozialen, institutionellen und umweltbezogenen Faktoren beeinflusst. Diese Komplexität wurde in einer partizipativen Systemanalyse erfasst, die DLE als ein System von miteinander verbundenen Variablen darstellt, das vorrangig durch verstärkende Rückkopplungseffekte ohne Selbstregulierung charakterisiert ist. Die Stromversorgung im ecuadorianischen Amazonasgebiet stellt ein instabiles System dar, das nicht autark ist und politisch, technisch und finanziell von externen Inputs abhängt. Daher muss DLE sorgfältig überwacht werden, wodurch die Basis für ein proaktives und partizipatives Management geschaffen wird.

Durch die Verknüpfung von GIS mit Fuzzy Cognitive Mapping (FCM) und Multi Criteria decision Analysis (MCA) konnte die Komplexizität von DLE aufgezeigt und deren Nachhaltigkeit partizipativ, systemisch und räumlich explizit untersucht und simuliert werden. In einem Workshop in Morona Santiago, Ecuador, mit Wissenschaftlern, Entscheidungsträgern und den Verantwortlichen des Solarenergieprogramms „Yatsa li Esari“ wurden die unterschiedlichen Einschätzungen von nachhaltigen DLE-Systemen als Nachhaltigkeitsvariablen in eine Fuzzy Cognitive Map“ (Systemmodel) integriert. Dadurch konnte das Entwicklungsverhalten von DLE-Systemen simuliert und deren Nachhaltigkeit prognostiziert werden. Die Verwendung von Daten aus dem Workshop und der Haushaltsbefragung mit Nutzern von SHS ermöglicht mit Hilfe von MCA und GIS die Simulierung und Kartierung der Nachhaltigkeit von DLE auf regionaler Ebene sowie auf verschiedenen Aggregationsebenen wie z.B. Indikatoren, Variablen und Nachhaltigkeitsindizes. Basierend auf der Integration von GIS, FCM und MCA konnten

Szenarien erstellt und analysiert werden, die erlauben, die Nachhaltigkeit von DLE-Systemen unter verschiedenen Interventionen zu bewerten.

Die Ergebnisse der Simulation zeigen, dass der beschriebene Ansatz Stakeholderdiskussionen insofern unterstützt als unmittelbar mögliche Auswirkungen und Rückkopplungen aufgezeigt werden, die dann von den Stakeholders interpretiert werden und, wenn nötig, die Revision von geplanten politischen Interventionen ermöglichen. Der Ansatz beleuchtet DLE von einer Perspektive, die über die konventionellen ökonomischen und technologischen Betrachtungen hinaus geht. Er kann als Lernansatz für partizipative Entscheidungsprozesse genutzt werden und ermöglicht damit Erkenntnisse, die andernfalls nicht hätten gewonnen werden können.

Evaluación de la sostenibilidad basada en GIS de la electrificación rural descentralizada en la región Amazónica: Caso de estudio Ecuador.

RESUMEN

La electrificación rural descentralizada (ERD) es necesaria para el suministro de electricidad en áreas remotas y desfavorecidas de la región Amazónica, y así mejorar las condiciones de vida de su población. Sin embargo, la sostenibilidad de la ERD a menudo es amenazada por un entorno político desfavorable, capacidades institucionales y organizativas limitadas, actitudes y valores culturales de los usuarios, así como restricciones tecnológicas y medioambientales. Este estudio investiga como sistemas de información geográfico (SIG) y enfoques de pensamiento sistémico pueden ser integrados para la evaluación y simulación de la sostenibilidad de ERD que permita a los actores explorar escenarios y políticas para garantizar un suministro de electricidad a largo plazo que mejore el bienestar de la población y protección del medio ambiente. Los objetivos de esta investigación se lograron mediante la aplicación de un enfoque interdisciplinario, participativo y multi-método en la Amazonia ecuatoriana como caso de estudio.

Los aspectos que favorecen o dificultan la operación sostenible de ERD en la Amazonía ecuatoriana fueron identificados a través de entrevistas semiestructuradas con tomadores de decisión y encuestas en hogares que usan sistemas solares fotovoltaicos residenciales (SHS, de sus siglas en inglés). La ERD está influenciada por una red compleja de aspectos tecnológicos, económicos, sociales, institucionales y ambientales. Esta complejidad se explicó mediante un análisis de sistemas participativo identificando a la ERD como un sistema de variables interconectadas que forma mayoritariamente estructuras de retroalimentación reforzantes sin autorregulación. Por lo tanto, el suministro de electricidad en la Amazonía ecuatoriana es percibida como un sistema inestable, no autosuficiente y dependiente política, técnica y financieramente de insumos externos. Por lo tanto, la ERD debe monitorearse cuidadosamente para sentar las bases para una gestión proactiva y participativa de un sistema eléctrico sostenible.

Se demostró que la integración de SIG con el mapeo cognitivo difuso (FCM, de sus siglas en inglés) y el análisis de decisiones multi-criterio (MCA, de sus siglas en inglés) son capaces de capturar la complejidad de la ERD, evaluar y simular su sostenibilidad de una manera participativa, sistémica y espacial. En un taller con investigadores, tomadores de decisiones y personal responsable del programa solar 'Yatsa Ii Etsari' en Morona Santiago, Ecuador, los puntos de vista de los participantes sobre una ERD sostenible se integraron en un mapa cognitivo difuso (modelo del sistema), el cual fue representado por un conjunto de variables de sostenibilidad interconectadas que permitieron simular el comportamiento de desarrollo del sistema de la ERD y predecir la sostenibilidad futura. Utilizando datos del taller y de las encuestas de hogares que usan SHS, el MCA y SIG permitió el cálculo y mapeo de la sostenibilidad para una evaluación espacial de la ERD a una escala regional y a diferentes niveles de agregación, es decir, indicadores, variables e índices de sostenibilidad. La integración de SIG, FCM y MCA permitió así el desarrollo y análisis de escenarios con el fin de estudiar las

tendencias de la sostenibilidad a largo plazo que podrían resultar de diferentes intervenciones en el sistema de la ERD. Los resultados de la simulación demuestran que el enfoque propuesto puede utilizarse para facilitar discusiones entre los actores interesados, ya que proporciona inmediatamente resultados plausibles y retroalimentación que los actores pueden interpretar y, si es apropiado, pueden revisar o reajustar sus ideas para intervenciones políticas. El enfoque propuesto evalúa la ERD desde una perspectiva distinta de las convencionales, por ejemplo, económica o tecnológica; y tiene el potencial de servir como una herramienta de aprendizaje para la toma de decisiones participativa, permitiendo obtener conocimiento que de otro modo no sería posible.

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LIST OF ACRONYMS AND ABBREVIATIONS

AS	Active Sum
ARCONEL	Agency of Regulation and Control of Electricity
BCE	Central Bank of Ecuador
DRE	Decentralized Rural Electrification with renewable energy
EC	European Commission
ESRI	Environmental System Research Institute
FCM	Fuzzy Cognitive Mapping
FERUM	Rural and Urban-Marginal Electrification Fund
GIS	Geographical Information System
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IIM	Interest and Influence Matrix
INEC	Ecuadorian National Institute of Statistics and Censuses
MCA	Multi-criteria decision analysis
MEER	Ministry of Electricity and renewable energy of Ecuador
PS	Passive Sum
R	R Project for Statistical Computing/Software Language
SE4ALL	Sustainable Energy for all global initiative
SHS	Solar Home System
SI	Sustainability Index
SIDENPE	Indicators System of Nationalities and People of Ecuador
SNA	Social Network Analysis
UN	United Nations
UNEP	United National Environmental Programme
WB	World Bank
WCED	World Commission on Environment and Development

1 INTRODUCTION

Electricity access is frequently associated with human development (Cook 2011; Bhattacharyya 2012; Shyu 2014). However, 1,5 billion people living in developing countries (99%), and here mainly in rural areas (84%), do not have access to electricity (IEA 2011; SE4ALL 2014). The United Nations General Assembly declared "access to affordable, reliable, sustainable and modern energy service for all" as one of the seventeen "Sustainable Development Goals" to be achieved by 2030 (SE4ALL 2014). Thus, increasing the number of people with electricity is not the only objective, the aim is also that electricity services should be sustainable, maintained in the long term and at the same time promote human development and preserve the environment.

The Amazon region is a special case in the expansion of electricity services. It is a trans-boundary region that covers 40% of the South American continent supporting the economy and development of eight countries (Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname and Venezuela). These countries are also responsible for conservation of the Amazon region (Landazuri 1987; UNEP et al. 2004), which is threatened by the overexploitation of its resources (Soares-Filho et al. 2006; Moraes et al. 2013; Swann et al. 2015). Historically, this region has provided vital ecosystem services to sustain the life of a multicultural indigenous population, who have retained a relatively autonomous lifestyle and their cultural identity while incorporating some aspects of modern life (e.g. electricity). Preserving their cultural choice is another challenge in the region. The Amazonian population is characterized by high rates of poverty and lack of basic services, and it is argued that electricity will improve their living conditions (Di Lascio and Fagundes 2009; Andrade et al. 2011; Valer et al. 2014).

Traditionally remote areas of the Amazon region have been excluded from national rural electrification plans because electric grids are technically and economically unfeasible (Gómez and Silveira 2010; Slough et al. 2015). In Ecuador, the case study for this research, electric grids have reached 95% of the total population (ARCONEL 2014). However, the Ecuadorian Amazon has the lowest electrification coverage (73.3%) (INEC 2010). Current scenarios suggest that remote communities in the Amazon region will not have electricity within the foreseeable future unless a decentralized rural electrification (DRE) approach is adopted (Andrade et al. 2011; van Ruijven et al. 2012; Gómez and Silveira 2015). The abundance of local renewable energy resources make DRE an environmentally friendly and cost-effective alternative (Schmid and Hoffmann 2004; Sanchez et al. 2015) suitable to produce enough electricity for the low demand of scattered indigenous Amazon communities (Morante and Zilles 2007; Valer et al. 2014). Thus, countries in the region could leapfrog the old centralized grid-oriented approach to a more inclusive, reliable and sustainable electricity supply in remote areas of the Amazon region (Zhang 2014; Levin and Thomas 2016)

However, there are still multiple barriers that hinder the scale-up of DRE and make it prone to failure (Schäfer et al. 2011; van Els et al. 2012; Yaqoot et al. 2016). It is also arguable that when DRE is introduced in traditional communities like those in the Amazon region, social and cultural aspects strongly influence the adoption of the technology that are usually not taken into account during the decision making, which leads to failure of DRE (Serpa and Zilles 2007; Fedrizzi et al. 2009; Sovacool et al. 2011). Thus, to attain sustainable DRE, a shift from traditional disciplinary (engineering) to interdisciplinary approaches with an active participation of stakeholders is needed to incorporate environmental, social, institutional, economic and technological aspects in decision-making processes (Cherni et al. 2007; Brent and Rogers 2010).

It is recognized that the root causes for the failures of non-sustainable DRE solutions originate from poor decisions that neither captured the above-mentioned multidimensional complexity of DRE nor promoted stakeholder participation (Cherni et al. 2007; Ilskog and Kjellström 2008; Brent and Rogers 2010). Most decisions are based mainly on technical designs or cost-effective analysis (Bhattacharyya 2011), but the rapidly evolving scenario of DRE implies that new actors and technology will interplay, bringing significant challenges for decision-making processes (Gómez and Silveira 2015) and sustainable DRE plans. Thus, better decision support tools that can assess and simulate the sustainability of DRE are needed for taken better decisions.

In this study, is thus proposed that an appropriate decision support tool for the assessment of DRE should integrate a systems thinking, stakeholder, and spatial perspective. The systems thinking perspective allows the defining of specific aspects required for DRE to work sustainably, recognizing the complex interrelations between environmental, institutional, social, economic and technological aspects (Hughes 1983; Bale et al. 2015). Regarding the stakeholder perspective, distinguishing people's expectations in relation to sustainable DRE allows the design of a substantive and effective policy (Bijlsma et al. 2011; Andrade et al. 2011). Also, people's knowledge helps to overcome the lack of information and enhances the knowledge base to understand the complexity of DRE (Brent and Rogers 2010). The spatial perspective, which usually is overlooked, is fundamental for sustainable energy system transitions (Stoeglehner et al. 2011) due to, for example, the spatio-temporal variation of energy needs and renewable energy resources (Amador and Dominguez 2005), the density of electric grids that influence DRE plans (Levin and Thomas 2012), and the effect of remoteness on electricity supply cost (Szabó et al. 2011).

Different decision support tools are documented in literature. The use of system thinking approaches has demonstrated the ability to capture the complexity of DRE and facilitated stakeholder participation (Bhattacharyya 2011), but this has failed to incorporate the spatial dimension of DRE. The advancement of geographic information systems (GIS) allowed the study of technical or economic aspects of DRE in a spatially explicit manner (Fronius and Gratton 2001; Kaijuka 2007; Dominguez and Pinedo-Pascua 2009; Tiba et al. 2010) but failed to capture the complexity of sustainable DRE. Therefore, based on these two fields of literature, a GIS-based decision support tool was developed suitable for assessing and simulating the sustainability of DRE while also supporting group-based decision making.

DRE in the Amazon region is still in an early phase, and many challenges constrain its survival over time and contribution to expected development impacts. What are the specific barriers and drivers that hinder or favor DRE from working sustainably in the Ecuadorian Amazon? Who is involved and influencing the introduction, maintenance, and outcomes of DRE? By identifying stakeholders of DRE, drawing on their understanding of local contexts, and relating this to the literature, the complexity of DRE can be understood and disclosed. Then relevant aspects to ensure sustainable DRE can be identified and incorporated in spatially explicit decision support tools with the potential to support a holistic, integrated and participatory decision-making process for DRE in the Ecuadorian Amazon. Above all, this study aims to answer the following main research question: How can the sustainability of DRE be effectively captured, assessed and simulated in a participatory and spatially explicit way to support a pro-active management of sustainable DRE?

1.1 Research objectives

Based on the slow pace and modest results of DRE in remote communities of the Amazon region, the general objective of this study is to investigate the complexity of sustainable DRE in the Ecuadorian Amazon and, based on the acquired information, develop a decision support tool that links GIS and system thinking methods for the assessment and simulation of the sustainability of DRE in order to support a holistic and participatory decision-making process and a pro-active management of sustainable DRE. The specific research objectives are:

1. To identify the specific barriers and drivers of sustainable DRE in the Ecuadorian Amazon as are perceived by relevant stakeholders,
2. To disclose and evaluate the complexity of sustainable DRE through the identification of relevant variables and their interlinkages grounded on stakeholders' viewpoints,
3. To develop and test a decision support tool suitable for a participatory, and integrated assessment and simulation of the sustainability of DRE.

1.2 Thesis structure

This thesis is organized into six chapters. Chapter 1 gives a general introduction and overview of the thesis.

Chapter 2 presents the background for the thesis and a description of the study area. A definition of concepts and a literature review of rural electrification, theories and methods for sustainability assessment, and GIS applied in rural electrification are presented. The conceptual framework of this study is also given, including an overview of data collection and analytical methods used during the research process.

Chapter 3 provides a comprehensive review of DRE in the Ecuadorian Amazon. Relevant stakeholders were identified and categorized, and their role and importance in DRE is assessed and discussed. From the analysis of a household survey and semi-structured interviews with relevant stakeholders, barriers and drivers for sustainable DRE as perceived by stakeholders are identified and discussed accordingly.

Chapter 4 presents the results of a participatory system analysis where stakeholder knowledge was integrated into a small but highly relevant set of variables that comprehensibly capture the complexity of DRE. The interaction between variables and their differing impact on the system are evaluated and discussed. A ‘cause-effect’ system model of DRE is proposed, and general assertions of the system dynamic behavior of DRE were studied and discussed.

Chapter 5 presents a decision support tool that integrates geographical information systems (GIS), multi-criteria decision analysis (MCA) and fuzzy cognitive mapping (FCM) for an integrated assessment and simulation of the sustainability of DRE. Scenarios were developed and simulated to study the effect of external interventions on the sustainability of a DRE case in the Ecuadorian Amazon. The applicability of the proposed decision support tool is tested and discussed.

Chapter 6 summarizes the main findings and conclusions of this study. It also presents study limitations, suggestions for future research and sketches policy recommendations.

2 BACKGROUND OF THE RESEARCH

2.1 The Ecuadorian Amazon

While this research is intended to be generalized across the Ecuadorian Amazon, it is based on a case study in the province Morona Santiago (Figure 2.1).

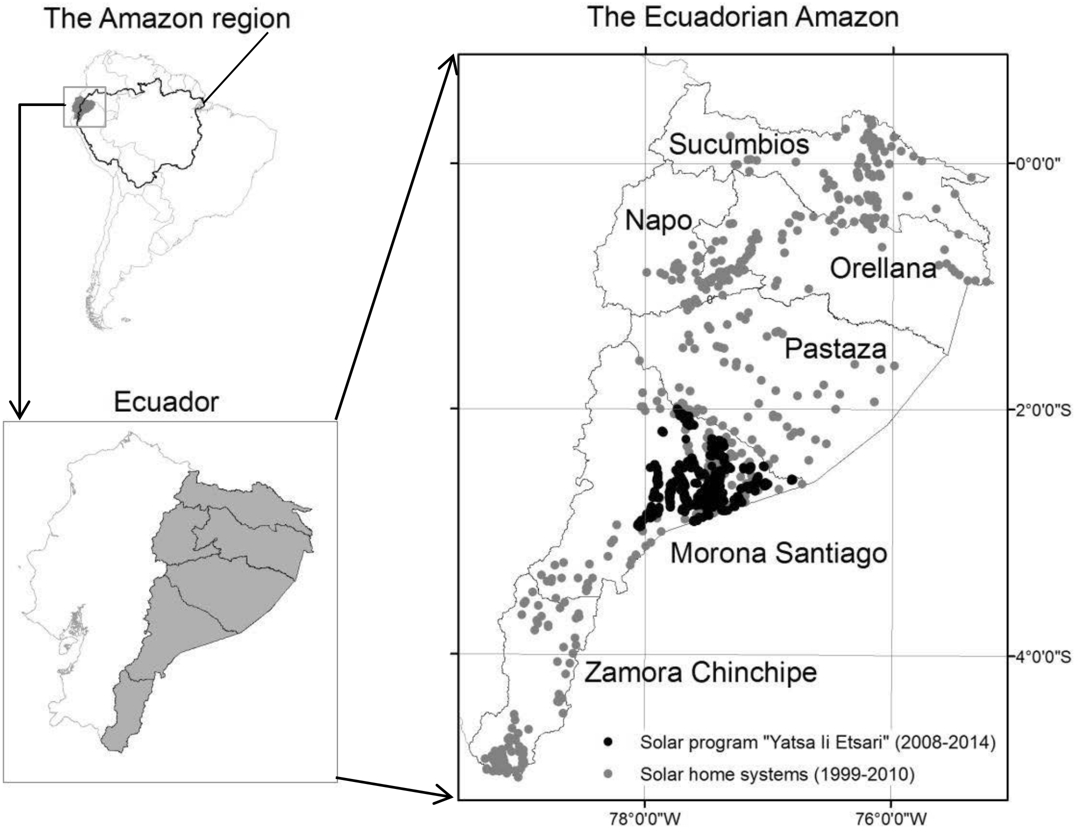

Figure 2.1 Geographic location of the Ecuadorian Amazon and the solar home systems installed between 1999 and 2010, including the case study solar program "Yatsa Ii Etsari" in Morona Santiago. Sources: Centrosur (2014), Vasconez (2010)

The Ecuadorian Amazon covers 2% of the total area of the Amazon region[1] (UNEP et al. 2004) but represents 46.8% of Ecuador's territory (132.705km^2), including six provinces with a population of 740.000 (INEC 2010), which represents 5,1% of the

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[1] Brazil (69.1%), Peru (11.4%), Bolivia (10.7%), Colombia (5.9%), Ecuador (2%), Venezuela (0.8%), Guyana (<0.1%)

total population of Ecuador, and a population density of 7 inhabitants/km^2. Also, 34% of the Ecuadorian Amazon people belong to one of nine indigenous nationalities (A'I Cofan, Secoya, Siona, Huaroni, Shiwiar, Zapara, Achuar, Shuar), which are characterized as having their own language and political organization (SIDENPE 2014). There are also two groups living in deliberate isolation (i.e. Taromenane, Tagaeri), eschewing all contact with the modern world (Pappalardo et al. 2013). Moreover, a high share of the Ecuadorian Amazon population (78%) is living in poverty (INEC 2010) while paradoxically the main source of income for Ecuador's economy is oil extracted from this region, which in 2015 represented 35% of total exports (BCE 2016).

2.1.1 Overview of the Ecuadorian electricity sector

Historically, electricity supply in Ecuador has been in government hands. Between 1894 and 1960, small hydropower plants managed by municipalities provided electricity to hardly 17% of the whole territory (Peláez-Samaniego et al. 2007). In 1961, the Basic Law of Electrification was enacted, and the public Ecuadorian Institute for Electrification (INECEL) was created to control all activities in the electricity sector (i.e. generation, transmission and distribution). Between 1976 and 1983, INECEL constructed the hydropower plant “Paute” (1075MW), which currently remains one of the largest, and thus provided a significant impulse for the establishment of what is known today as the "national interconnected system". After a transition period between 1996 and 1999, INECEL ended its operations due to the promulgation of the Law of the Electric Sector (Ecuador 1996) which sought to improve the reliability and quality of electricity supply by converting public utilities (generation, transmission and distribution) into corporations with the aim of selling it to private investors, thereby ending the state monopoly. However, the expected aims were not accomplished, and after the new National Constitution enacted in 2008 (Ecuador 2008) the electricity sector again fell under state ownership. Furthermore, the Organic Law of the Electric Service Sector was promulgated (Ecuador 2015). This law declared electricity as a public and subsidized service aiming at universal access, provision of a reliable, efficient electricity service, and environment conservation by promoting energy efficiency and the use of renewable energies.

Since the origins of the electricity sector, significant progress on expanding the generation and distribution of electricity has been achieved but this has been unequally distributed among the population living in remote areas. The installed capacity has tripled from 1080MW in 1980 to 3452MW in 2015 including fossil-fuel based generators (49%), hydropower (46%), solar, wind and biomass (2%); and imports from Colombia and Peru (3%). Moreover, in 2008 the construction of eight hydroelectric power plants (4170MW) was started, and the country expects to convert the electricity matrix to 100% renewable energy sources by 2022. Also, electrical grids have been extended and now reach a large share of the inhabited national territory (95%) throughout urban and rural populations (ARCONEL 2014). However, the progress in generation and distribution of electricity has not benefited the most remote areas of the country due to economic and technical limitations of the centralized and on-grid based approach, which would need to be extended to isolated and non-accessible areas of Ecuador. As a result, remote communities, mostly living in extreme poverty, are usually left behind with respect to rural electrification plans. Overcoming this challenge is one of the main aims of the Ecuadorian electricity sector (ARCONEL 2013), which is in agreement with the new constitution and electricity law that guarantees universal access for all citizens.

2.1.2 Evolution of rural electrification in Ecuador

The "Rural and Urban-Marginal Electrification Fund" (FERUM) created during the reform of 1996 (Ecuador 1996) has been fundamental to financing rural electrification with national resources[2] (Figure 2.2). The historic trend of high investment for the expansion of electrical grids has continued and indeed increased. In contrast, the investment of DRE in isolated and scarcely populated areas has been low and sporadic. It can be inferred that rural electrification aims have been utilitarian in the sense that the largest

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[2] Initially FERUM resources came from the commercial and industrial sector (Peláez-Samaniego et al. 2007). Since 2008, FERUM has been reformed and now resources come from the national budget or multilateral mechanisms (Ecuador 2015)

number of people possible are to be served as electrical grids allow the interconnecting of densely populated areas. This has translated into a lack of interest in DRE. The national rural electrification plan aims to increase rural coverage to 96% by 2022 (ARCONEL 2013) and ultimately universal access by 2030 (Gomelsky 2013). However, both aims will require a steady and higher investment in DRE, which is not happening at present.

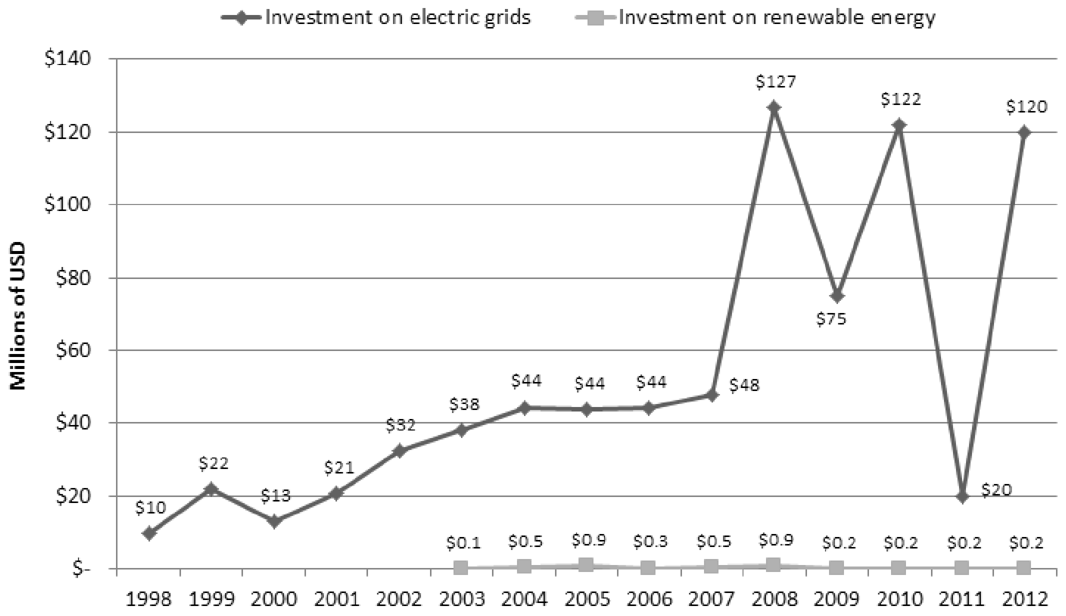


Figure 2.2 FERUM allocation for rural electrification between 1998 and 2012. Sources: Gomelsky (2013); CONELEC (2009); CONELEC (2007)

The FERUM investment has helped to provide electricity to 92% of the rural population of Ecuador (ARCONEL 2013), but with an unequal distribution for those isolated. Figure 2.3 shows rural electrification coverage at the parish level (i.e. the smallest administrative unit) and for each province of the Ecuadorian Amazon. The disproportionate distribution of electricity within and between provinces is evident. For instance, in some parishes less than 1% of the population has electricity (i.e. Napo). In total, it is estimated that 200,000 people in approximately 35,000 isolated and scattered households are still waiting for electricity access (ARCONEL 2013). These figures are expected to remain unchanged unless ongoing efforts are increased in terms of investment, policy and institutional arrangements conducive for the scaling up DRE.

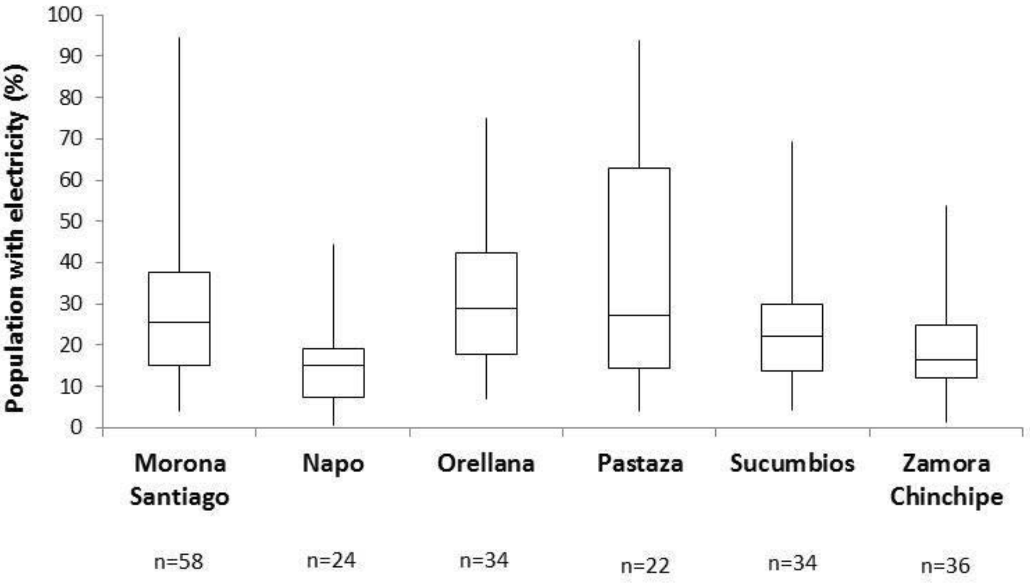


Figure 2.3 Boxplot representing percentage of people with electricity by province at parish level in the Ecuadorian Amazon (n=number of parishes). Source: (INEC 2010)

2.1.3 Local experience with decentralized rural electrification

Different DRE initiatives from government and international donors have been implemented in the Ecuadorian Amazon (Table 2.1). The most common technology used is Solar Home Systems (SHS), suitable for low demand in scattered households or communal services such as schools and health posts. International donors were the initial investors (investment not reflected in Figure 2.2) who helped to pilot and test renewable energy technology in Ecuador (Vasconez 2010). Although the government has been investing in DRE since 2003, it was not until 2008 that a significant investment took place to initiate the solar program “Yatsa Ii Etsari” (Light from our Sun), which during the course of this research was the largest DRE initiative implemented in Ecuador (Figure 2.1).

Table 2.1 Main decentralized rural electrification projects implemented in the Ecuadorian Amazon. Sources: Green et al. (2005); MEER (2008); World Bank (2008); Vasconez (2010); Jara-Alvear and Urdiales (2014)

Period	Name	Investment (USD million)	Funding source	Technology	Quantity	Location
2003	PROMEC	7,4	WB	SHS	1741	P, N
2005	ESMAP	0,062	WB	PH	31	N,
2008	EUROSOLAR	4,9	FE, EC	PV	91	S, O P, M
2008-2010	YATSA II ETSARI	7,8	FE	SHS	2565	M

Name: PROMEC=power and communications sectors modernization and rural services project, ESMAP=energy sector management assistance program, EUROSOLAR=electricity supply and community healthcare and communication/information services, YATSA II ETSARI=light of our sun.
Funding source: FE=FERUM, WB=World Bank, EC= European Commission.
Technology: SHS=Solar Home Systems, PH=Pico-hydro, PV=individual photovoltaic system.
Location: P=Pastaza, N=Napo, S=Sucumbíos, O=Orellana, M=Morona Santiago, Z=Zamora Chinchipe.

DRE in the Ecuadorian Amazon has been recognized as being prone to failure (Vasconez 2010; Ten et al. 2015). Most DRE projects have been installed using SHS without a long-term strategy for maintenance, which has resulted in a high share of SHS installations (40%) that stop working after only 3-4 years when the batteries have completed their life cycle. Furthermore, most regulations and institutional arrangements designed for grid expansions were found unsuitable for supporting DRE plans. Moreover, the low capacity of renewable energy technologies and low-quality installations has been also documented as a cause of failure. Currently, no systematic evaluation of DRE projects in the Ecuadorian Amazon exists. It is unknown what the effects of electricity have been in terms of improving the living conditions of remote and indigenous communities and preserving the environment. Here especially the effects of waste generated such as batteries during the life cycle of DRE are still unclear (Ten et al. 2015). To improve the situation, the Ecuadorian government, financed by the Inter-American Development Bank (IDB), started a program in 2013 to enhance national capacities for the scale-up of DRE. This included the defining of monitoring and assessment methods to increase the sustainability of DRE (IDB 2013).

In summary, several DRE projects have been launched with the aim of ensuring universal access in remote and rural areas of the Ecuadorian Amazon. These have shown modest results, and the effects of electricity in traditional indigenous communities as well as the technical, economic and institutional aspects required for the introduction and scale-up of DRE are still unclear. Thus, besides increasing the number of people with access to electricity, the management of DRE to ensure a reliable electricity service and promote sustainable rural development in remote areas is a high concern among decision makers (ARCONEL 2013).

2.2 Decentralized rural electrification

2.2.1 Development and electricity access in the Amazon region

The Amazon region is characterized by a complex and delicate socio-ecological system (Nugent 1981; Salati and Vose 1984). It comprises 7% of the global vegetation cover, 50% of all life forms on earth (i.e. plant species, anthropoids, birds, fish, mammals and microscopic life forms) and 20% of the earth's non-frozen water supply (Andrade et al. 2011). The total carbon content of Amazonian's biomass is 86 x 10^9 tons (Saatchi et al. 2007), and if released would change carbon concentrations in the atmosphere and thus the regional and global climate equilibrium (Moraes et al. 2013; Swann et al. 2015). The Amazonian ecosystems needed thousands of years to develop but they can be gravely degraded in only a short time (Salati and Vose 1984). Deforestation (Scouvart et al. 2008; RAISG 2013). Agriculture (Soares-Filho et al. 2006), oil extraction and mining (San Sebastian and Hurtig 2005; Warnaars 2012) as well as hydropower development (Yue and Yang 2007; Stickler et al. 2013) are threatening the Amazon biome, though these are important activities that provide resources for development and national economies (UNEP et al. 2004).

Although the Amazon region is recognized for its ecological value, it is also characterized by a highly culturally diverse population, composed of hundreds of indigenous communities and descendants of immigrants from colonial times, miners, and missionaries among others (UNEP et al. 2004; Cleary 2010). In the Ecuadorian Amazon, the indigenous population had been relatively isolated until the 1960s when petroleum was discovered and an agrarian reform declared uncultivated lands as uninhabited and thus available for colonization (Perreault 2001). As a result, indigenous territories used for hunting, fishing or small-scale farming were granted by the government to the oil industry, and colonizers arrived for agriculture and cattle raising (Perreault 2001) converting the Ecuadorian Amazon into one of the most important regions for the national economy. The region is also under constant exploration for resources (e.g. mining, oil, hydropower) (Warnaars 2012; Escribano 2013). Since then, indigenous people, who had a relatively autonomous lifestyle and their own cultural identity, started incorporating some aspects of modern life (e.g. electricity), but most of all their livelihoods (Bozigar et al. 2016) and health (San Sebastian and Hurtig 2005) have been diminished by extractive activities. As a result, many are living in precarious conditions with high levels of poverty and demographic outflow. Furthermore, numerous social conflicts and clashes between government and indigenous people are normal occurrences (Perreault 2001; Widener 2007). Thus, preserving cultural choices and the traditional knowledge of natural resources management) as well as tackling poverty whilst maintaining the autonomy of these indigenous people are major challenges for the conservation of the Amazon region.

It is argued that electricity will have a positive impact on sustainable development in remote areas of the Amazon region (Di Lascio and Fagundes 2009; Gómez and Silveira 2010; Valer et al. 2014). Electricity has been proven capable of supporting the human development and wellbeing of remote and indigenous populations (Figure 2.4). It is the basis for covering basic human needs, providing community services, promoting productivity and enabling the use of modern electrical appliances. However, if electricity drives economic growth and development, the ongoing environmental degradation of the Amazon region could increase (Salati and Vose 1984; Soares-Filho et al. 2006; Scouvart et al. 2008). Thus, electricity supply in the context of the Amazon region is a complex development problem (van Els et al. 2012) that requires a compromise between local actions to improve people’s lives while conserving the natural resources and environment (Andrade et al. 2011).

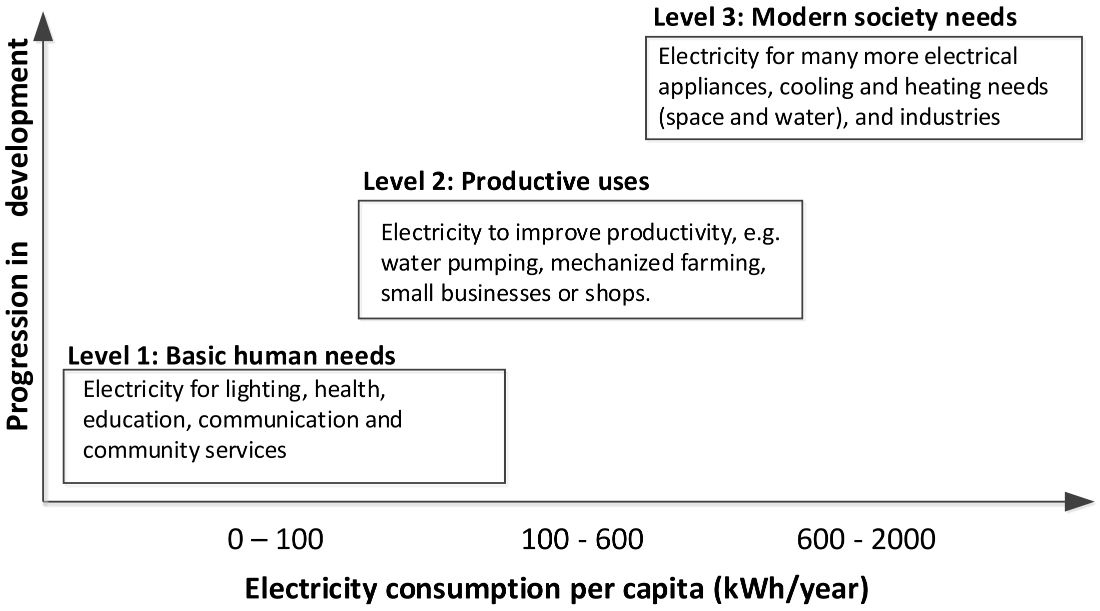


Figure 2.4 Progression in development through electricity consumption. Sources: Valer et al. (2014); Gómez & Silveira (2010)

2.2.2 Concept and technological options

In this study, DRE refers to the production and supply of electricity using local and renewable energy resources close to the user (Mandelli et al. 2016). Diverse technological options suitable for different conditions exist. Individual solutions such as solar lanterns and home systems are suitable for low demands and highly dispersed households, which is an attractive option for the Amazon region characterized by areas with very low population density (Gómez and Silveira 2010; Valer et al. 2014; Sanchez et al. 2015). Solar lanterns are used mainly to improve home lighting by replacing diesel or kerosene lamps (Hong and Abe 2012a; Chamania et al. 2015), and home systems can provide power for the use of small electrical appliances such as radios and televisions. Home systems can use solar panels, wind turbines or pico-hydro turbines for electricity generation. Solar Home Systems (SHS) are the most commonly used worldwide (Nieuwenhout et al. 2001; Kempener et al. 2015).

Mini-grids are appropriate for relatively densely populated communities (Paleta et al. 2012) and for meeting higher electricity demands (e.g. electrical machines). Conventional mini-grids coupled with diesel or gasoline generators are extensively used in isolated communities in the Amazon region (Gómez and Silveira 2012). However, the high cost of operation due to fuel transport and maintenance costs and environmental impacts like emissions and oil spills have proven harmful for Amazonian ecosystems (Schmid and Hoffmann 2004). Thus, renewable energy or hybrid micro-grids have proven to be an alternative as a total or partial replacement of diesel generators (Schmid and Hoffmann 2004; Borges Neto et al. 2010; Silva et al. 2013). However, mini-grids show a higher technological complexity that can hinder their application in remote communities if local capacity and skills are not available (Blum et al. 2015).

2.2.3 Drivers and barriers identified

DRE based on renewable energy is influenced by manifold drivers and barriers that favor or hinder its application and scaling up. A summary of technological, social, economic, institutional, and environmental drivers and barriers of DRE was extracted from a global literature review (Table 2.2). Regarding drivers, DRE based on renewable energy has proven to be a cost-effective alternative to electrical grids and polluting diesel generators (Schmid and Hoffmann 2004; Sanchez et al. 2015). Also, the low demand of un-electrified communities in the Amazon region favors the small-scale and renewable energy generation options such as SHS used in DRE approaches (Morante and Zilles 2007). Furthermore, and perhaps most importantly, DRE provides a feasible means for local electricity supply to support poverty alleviation and preservation of indigenous autonomy (Andrade et al. 2011). Foreseeing the technological trend of cost reduction in renewable energy especially in the photovoltaic technology (Feldman et al. 2012; Nemet and Husmann 2012; de La Tour et al. 2013), DRE is becoming a growing consideration in Amazon countries (Langevine 2000; Silva Herran and Nakata 2012; Fuso Nerini et al. 2014; Gómez and Silveira 2015; Sanchez et al. 2015). This could disrupt the continuation of centralized approach paradigms and allow universal access in the Amazon region.

Table 2.2 Barriers and drivers for decentralized rural electrification from literature. Sources: Mandelli et al. (2016); Yaqoot et al. (2016); Holtorf et al. (2015); Zhang (2014); van Els et al. (2012); Schäfer et al. (2011)

Dimension	**Barriers**	**Drivers**
Technological	• Lack of skills and technical knowledge • Poor installation and maintenance • Lack of spare parts • Resources availability and low generation capacity • Solutions not adapted to local realities	• Technology progress and cost reduction trend of renewable energy • Limitations to expand electrical grids • Increased reliability of electricity services in remote areas
Social	• Misperception of technology • No link to societal structure, norms and value systems • Awareness and risk perception	• Enforcement of the right of electricity access in remote areas • Promotion of autonomy • Poverty alleviation and rural development
Economic	• Lack of capital • High up-front cost • Improper subsidies and lack of financing mechanism • Limited renewable energy markets for equipment and services supply • Low rural income	• Reduction in electricity distribution costs • Reduction in the risk of large centralized systems • Promotion of economic growth and development
Institutional	• Lack of policies and regulations • Low organizational capacity • Lack of private sector involvement • Donor dependency	• Decreased fossil fuel subsidies and importation dependency • Reduced vulnerability in centralized systems • Enhancing energy security
Environmental	• Pollution and waste production • Remoteness and logistics	• Climate change mitigation • Opposition to construct new distribution lines

However, DRE is hindered by multiple barriers. The restricted access and wide spatial dispersion of Amazon communities hamper the logistics and communication, increasing the cost of electricity supply (Silveira et al. 2013) and hindering the viability of DRE projects (Andrade et al. 2011). Also, the isolation of indigenous populations from market-oriented activities has led to communities with low income that make it difficult to apply a business rationality with respect to electricity supply (Andrade et al. 2011). Moreover, DRE implies that renewable energy systems must be operated and maintained locally by the traditional communities which, however, often lack the necessary skills and capacity to deal with modern technologies (Serpa and Zilles 2007; Fedrizzi et al. 2009). Cultural and behavioral values of traditional communities, which are difficult to predict and usually out of the scope of electricity suppliers, hinder technology adoption (Sovacool et al. 2011; van Els et al. 2012).

2.3 Sustainability assessment of decentralized rural electrification

As presented in previous sections, DRE is prone to failure and has shown only modest results. A gap exists in understanding and addressing the 'sustainability' of DRE in terms of the implications of extending electricity services for sustainable development of remote and culturally diverse indigenous communities in the Amazon region and ensuring a continuous and reliable electricity service. Social aspects are just as important as economic and technical aspects to ensure the sustainability of DRE (Hughes 1983; Sovacool et al. 2011; Miller et al. 2015). Thus, a shift from single-discipline (e.g. engineering, economics) to interdisciplinary approaches is needed for a sound decision making and management of DRE (Brent and Rogers 2010), and demands holistic, integrated and participatory decision support tools (Cherni et al. 2007; Ilskog and Kjellström 2008; Brent and Kruger 2009).

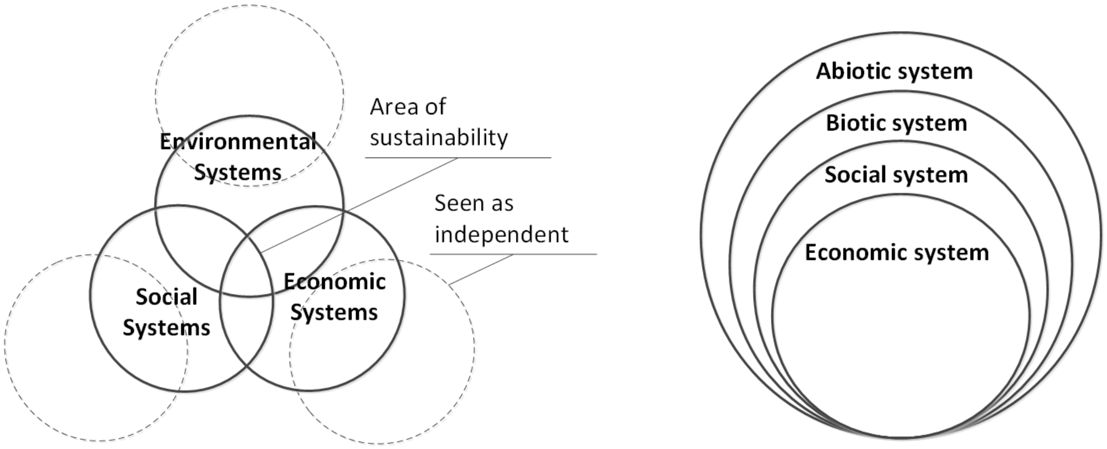
The progress on decision support tools to identify, assess and monitor local sustainability values, goals or targets for DRE (i.e. environmental, social, institutional, economic and technological) has been slow. Disciplinary (i.e. technical, economic, environmental) approaches dominate (Bhattacharyya 2011). Though practical and relevant for decision makers, these cannot capture the complexity and multidimensionality of sustainable DRE (Cherni et al. 2007; Ilskog 2008; Brent and Kruger 2009; Schäfer et al. 2011) Most of the existing research focused on the introduction of DRE (Bhattacharyya 2011; Mandelli et al. 2016) and only few on post-installation phases and management of DRE (Tiba et al. 2010). By monitoring and assessing the sustainability of DRE, public or private electricity companies can identify potential threats and plan mitigation measures accordingly to overcome the continued failure cycle of DRE and ensure a reliable, affordable and sustainable electricity service (Ilskog and Kjellström 2008). Such decision support tool should not be constructed only from an operational viewpoint (e.g. technical failures of DRE), but should also include theories and concepts within sustainability and rural development thinking (Brent and Kruger 2009). In this regard, sustainability assessment has become a new and rapidly evolving research area (Pope 2004; Ness et al. 2007; Clark 2007; Singh et al. 2009; Jerneck et al. 2010; Morrison-Saunders et al. 2014).

Through an extensive literature review, theories and possible options to study the sustainability of DRE are presented below. It will be shown that there is a need to step back from traditional technical or economic approaches and focus on the complex dynamics between humans, technology, and environment at a system and spatial level.

2.3.1 Definition of sustainable decentralized rural electrification

To understand sustainable DRE, one must investigate first the meaning of 'sustainability'. From a general viewpoint, the Brundtland report (WCED 1987), which is the most cited, defines sustainability as "sustainable development that meets present needs without compromising the ability of future generations to meet their own”. This encompasses two key concepts, i.e. the fulfillment of people's needs or expectations regarding development, and the limiting aspect of the technology and environment to meet these needs (Mebratu 1998), which are predominantly depicted through the intersection of economic, social and environment spheres (Figure 2.5). In Mebratu (1998), however, this is highlighted as reductionist because the economy, society, and environment are supposedly independent systems, whereas sustainability is attained only in the intersection of the three spheres. The author thus proposes an alternative conceptual model (Figure 2.5) where social and economic systems are not separate parts independent of the abiotic and biotic systems (i.e. environment), and sustainability is attained along multiple intersections between them.

Generic and conceptual models of sustainability



Conceptual model for sustainability assessment of decentralized rural electrification

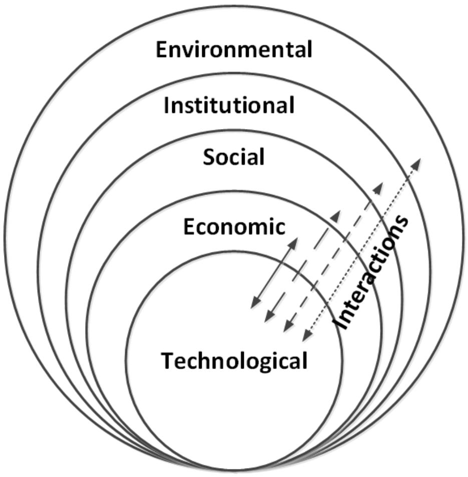


Figure 2.5 Top left: Conceptual model of sustainable development. Top right: Cosmos independence model from Mebratu (1998) Below: Conceptual model of sustainability applied for technology assessment. Sources: Musango & Brent (2011); Ilskog (2008); Mebratu (1998)

For the context of DRE, in literature (Ilskog 2008; Mainali and Silveira 2015) the importance of incorporating technological and institutional dimensions is recognized (Figure 2.5). The technological dimension needs to be studied to identify the effects of reliable and efficient technology on the environment, economy, lifestyle, cultural development, and overall social welfare (Musango and Brent 2011), and the institutional dimension because local capacities, institutions, and stakeholder arrangements are a major concern in rural settings, where technology is not well established or in an early stage like in traditional communities in the Amazon region (Serpa and Zilles 2007; Fedrizzi et al. 2009).

Altogether, sustainability of DRE is defined through numerous and complex interactions between environmental, societal, institutional, economic and technological dimensions. Some authors (Afgan et al. 2000; Ilskog and Kjellström 2008; Brent and Rogers 2010; Hong and Abe 2012b; Terrapon-Pfaff et al. 2014) have attempted to define each of these dimensions, which can be summarized as: (i) Environmental dimension refers to direct and indirect impacts on the environment that might result from electricity service provision, (ii) institutional dimension refers to the viability of organizations and institutions to ease technology management and deployment in rural areas, (iii) social dimension refers to the equitable and acceptable benefits obtained from electricity, but also social behaviors and values that influence technology deployment. In literature, this is highlighted as the most difficult to understand. (iv) Economic dimension relates to covering electricity services costs on a short- and long-term basis, avoiding disruptions or discontinuities in the services, and (v) technological dimension relates to the deployment of technology that is reliable, safe and manageable by local communities.

Sustainability definitions have been criticized for being inconsistent (Gatto 1995), dynamic and changeable over time (Mebratu 1998), and overall dependent on society needs, viewpoint and values (Meadows 1998; Wiek and Binder 2005). Thus, sustainability definitions must be reviewed and re-defined with an active participation of stakeholders.

2.3.2 Approaches to study the sustainability of decentralized rural electrification

System thinking and stakeholder perspectives

As presented in the previous sections, sustainable DRE resembles a socio-technical system[3] and thus it needs to be addressed by a systems thinking perspective. According

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[3] A system is defined as a set of components that are coherently organized and interconnected in a structure that produces a certain set of behaviors often classified as its function (Meadows 1998)

to Bale et al. (2015), an energy system such as DRE consists of three components: (i) agents (e.g. households, electricity suppliers, policy makers) interacting through social and physical networks influenced by social norms and institutional rules, which determine emergent properties and co-evolutionary dynamics of the system, (ii) objects (e.g. technology, infrastructure), which are relatively stable but whose adoption is dynamic and might not be attained if their characteristics do not fit the current system (e.g. unreliable technology, high electricity costs, maintenance difficulties), and (iii) the environment in which agents and objects are embedded and interact, which provides the resources (e.g. solar radiation) and determines the social, cultural and institutional scenarios (e.g. electricity contracts, new regulations, management rules). Moreover, the complex interactions between agents, objects and the surrounding environment vary among regions, and as a result different energy systems emerge around the world (Hughes 1983). Thus, to disclose the complexity of DRE, a systems thinking perspective with an active participation of stakeholders immersed in a given energy system is required (Boulanger and Brechet 2005; Cherni et al. 2007; Brent and Kruger 2009).

System thinking has its roots in the General System Theory (GST) (Bertalanffy 1968), but it has also developed in other theoretical fields for its practical application. Some relevant examples are cybernetics (Wiener 1948; Ashby 1956), system dynamics (Forrester 1973), graph theory (Harary 1969), or complexity theory (Manson 2001). The main aim of system thinking is to produce simplified models to capture the holism of an energy system guided by the concepts of emergence, dynamics, co-evolution, path dependency, self-organization, and adaptation (Table 2.3).

Table 2.3 System thinking concepts and examples applied to decentralized rural electrification. Source: Bale et al. (2015)

Concept	Definition	Example for DRE in rural areas
Emergence	The system behavior at some level (e.g. macro) cannot be deduced from an understanding of the lower level (e.g. micro) and the arrangement of parts	Household electricity consumption emerges from non-rational human behavior influenced by the surrounding environment (e.g. weather) or interaction with others agents (e.g. social gathering in villages to watch TV)
Dynamics and feedbacks	A system is not static, its state moves around a continuous changeable point of equilibrium due to the complex interaction of its components	The arising of renewable energy from perceived opportunities, environmental risks (e.g. climate change), and entrepreneurship produced structural changes in rural electrification processes towards a decentralized approach
Co-evolution	A system co-exists with other systems, as they compete and rely on each other for survival	Maintenance of DRE in remote areas is interdependent on transport and communication system. Also, DRE requires new business models and policies for rural electrification as a whole
Path dependency	A system has a memory, its evolution is determined by past behaviors	Changing the old tradition of fossil fuel use and grid expansion for electricity supply to a more decentralized approach by using local renewable energy resources is still a challenge
Self-organization	A system adapts autonomously, and its organization arises even if there is no agent with overall control	DRE value chain implies decision-making at different levels: household (e.g. electricity consumption), electricity supplier (e.g. investment, planning), manufacturer (e.g. discoveries of new technology), all on their own level responding to the changing environment around them
Adaptation	A system can adapt to improve functionality within a changing environment, modifying or keeping essential parts of its structure	Households adapt their electricity consumption behavior and ability to operate renewable energy systems based on experimentation

The results of an extensive literature review revealed that the approaches to assessing the sustainability of DRE include indicators, multi-criteria decision analysis (MCA), system dynamics and network analysis.

Indicators[4] are extensively used to capture and measure sustainability (Meadows 1998; Bossel 1999; Ness et al. 2007; Hak et al. 2016) These are simple measures that represent an attribute of a system's components to simplify its complexity and convey understandable and accessible measures for decision makers (Ott 1978; Nardo et al. 2005). In the context of DRE, Ilskog (2008) proposes a list of potential indicators for sustainability assessment of rural electrification which, according to the author, overcame the limitations of macro-level indicators used for assessment of energy systems (World Bank 2001; World Bank 2003; IAEA 2005). Other authors used indicators for sustainability assessment of electricity sectors at a national level (Mainali et al. 2014; Sharma and Balachandra 2015). The definition of indicators includes methodological challenges that, if not addressed adequately, can lead to misinterpreted or manipulated measurements (Böhringer and Jochem 2007). The definition and selection of indicators need to take into account the interactions among indicators (an indicator represents a part of the system) (Mainali and Silveira 2015). This is usually overlooked in literature but is necessary to capture effectively the reality from a system thinking viewpoint (Bossel 1996).

MCA has been extensively used in energy research to handle complex decisions through the study of multiple and competing criteria in participatory approaches (Pohekar and Ramachandran 2004; Wang et al. 2009). Also, MCA has been used to develop sustainability indicators (Mendoza and Prabhu 2000) making this and the previous approach complementary. In the context of DRE, MCA has been used mainly to assess and select technological options in terms of economic, social, and environmental criteria (Kablan 1997; Zangeneh et al. 2009; Ahammed and Azeem 2013; Rahman et al. 2013; Fuso Nerini et al. 2014; Mainali and Silveira 2015; Rojas-Zerpa and Yusta 2015) Cherni et al. (2007) differ from previously cited works by focusing on a

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[4] They also include composite indicators or indices, which result from the aggregation of indicators (Ness et al. 2007).

participatory approach to assess expected electricity outcomes of sustainable rural livelihoods, a perspective which more closely aligns with this study. MCA has also been applied to scenario analysis and sustainability assessment of energy systems at a national level (Wang et al. 2010; Santoyo-Castelazo and Azapagic 2014). Although MCA provides a useful framework for fostering participation and dealing with uncertainty, it is a static method of analysis not suitable for studying the dynamics and feedback effects between multiple criteria, an essential concept of system thinking approaches.

Systems dynamics has its root in the cybernetics theory (Wiener 1948; Ashby 1956) and is applied to study the inherent connectedness between system components, formulate feedback hypotheses, simulate qualitative or quantitative system behavior, and devise strategies to enhance system sustainability (Wolstenholme 1990; Sterman 2000; Vester 2007). Three general branches of systems dynamics approaches are defined: (i) qualitative system dynamics is useful when there is a poorly defined problem and quantitative data is not available, which means relying on eliciting and integrating the knowledge of stakeholders who are part of the system. The result is a holistic portrayal of the reality through 'causal loop diagrams' (nodes as elements of the system and signed arrows as the links among these elements). By examining these diagrams, one is thus able to qualitatively simulate a system's behavior to postulate strategies in order to increase its viability (Wolstenholme 1990). This approach has been used extensively in natural resources management (Purnomo and Mendoza 2004; Mendoza and Prabhu 2006), but there are limited applications in the context of DRE. Notably, however, Tejeda & Ferreira (2014) developed a qualitative system model to assess wind energy sustainability. (ii) Quantitative systems dynamics (Forrester 1973; Sterman 2000) translates 'causal loop diagrams' into mathematical models to quantitatively simulate system behavior, carry out sensitivity analysis, and design alternatives to steer the behavior of the system. It has numerous applications in energy research (Ford 1997; Sterman 2000), but its application in DRE is still limited (Bhattacharyya 2011). Some relevant examples include Alam et al. (1990) and Alam et al. (1997), who simulated the complex interlink between rural energy, farming and quality of life. Xiaohua et al. (2006) studied the interactions between energy and economy of a village in China. Motawa &

Oladokun (2015) simulated household energy consumption and CO_2 emission interrelations. Musango et al. (2011) presented a model to assess the sustainability of biodiesel production in South Africa. Lastly, Robalino-López et al. (2014) projected greenhouse gas emissions studying the feedbacks between energy and gross domestic product in Ecuador. (iii) Semi-quantitative systems dynamics presented by Vester (2007) through the "Sensitivity Model®" is a compromise between the two aforementioned approaches. It is argued that its foundations on fuzzy logic (Zadeh 1965) and bio-cybernetic principles (Vester 2007) ease stakeholder knowledge integration through a systematic and participatory system analysis overcoming the constraint of data requirements in quantitative systems dynamics, and allowing a semi-quantitative simulation of complex systems (Vester 2007). It has been applied in research related to the fields of energy (Schlange 1995; Jüttner and Schlange 1996), urban development (Huang et al. 2009), rural development (Chan and Huang 2004), bio-waste management (Lang et al. 2006), agriculture (Penker 2005), and business sectors (Gomez and Probst 1999; Hub 2004). All in all, systems dynamics is perhaps one of the most suitable methods for analyzing complex problems (Boulanger and Brechet 2005; Heckbert et al. 2010). However, its application in DRE is still limited. The major limitations are its inadequacy for explicitly modeling agent's rationality evolution (Heckbert et al. 2010) or design organizational structures (Schwaninger and Perez-Rios 2009).

Agent-based modeling (ABM) analyzes complex problems through the representation of artificial societies that include agents, the environment in which they interact, and the norms that govern their interaction decisions (Boulanger and Brechet 2005). It is suitable when feedback structures can evolve, are autonomous and heterogeneous, and the modeler wants to make adaptive decision making explicit (Heckbert et al. 2010). Most literature in this context has focused on planning centralized energy networks and no application has been found in DRE. Alfaro & Miller (2011) developed a model to forecast the electrification coverage in rural and urban areas to support planning and scenario building. Zhao et al. (2011) combine quantitative system dynamics and ABM for policy analysis to foster grid-connected photovoltaic installations. Coupling ABM with systems dynamics is an emergent and promising field of research to effectively capture complexity in energy systems.

Network analysis has its roots in the graph theory (Harary 1969) and portrays complex systems as networks of nodes symmetrically or asymmetrically interconnected by edges. These are used to predict emergent network outcomes and also for participatory qualitative modeling of complex systems (Bale et al. 2015). Two different approaches based on network principles were identified: (i) Structural analysis of networks which includes two-subgroups. First, social network analysis (Borgatti et al. 2013) is a method extensively used in social sciences to study power relations. It has been applied, for instance, in energy research to understand human dynamics and their influence on the adoption of improved cook stoves in rural areas (Ramirez et al. 2014). Second, interpretative structural modeling is a method to evaluate direct and indirect relations of network elements (Warfield 1974). It has been used to study barriers that hinder the development of solar photovoltaic installations (Ansari et al. 2013) and the implementation of energy efficiency measures (Saxena et al. 1992; Wang et al. 2008). (ii) Simulation of networks, which includes two subgroups. First, bayesian networks portray influence diagrams (acyclic directed graphs) to encode probabilistic relationships among random variables and their conditional dependence, as well as to model influence of sequence of variables (Jensen 1997). Second, fuzzy cognitive mapping (Kosko 1986) depicts system elements such as ideas, concepts, and expectations and their interrelations as a directed graph by integrating qualitative and partial knowledge of multiple stakeholders, the outcome of which is a representation of the reality perceived by those immersed in the system and used for simulations in data-poor conditions (Ozesmi and Ozesmi 2004). It has been used for building and analyzing scenarios for an exploratory study of solar energy (Jetter and Schweinfort 2011). Overall, network analysis facilitates participation; it has a great value in managing uncertainty, and for initial phases of systems modeling. However, it does not allow simulating time delays and non-linear relationships, as opposed to quantitative systems dynamics (Mendoza and Prabhu 2006).

Spatial perspective

Electricity access disparities between urban (i.e. core) and rural (i.e. periphery) resemble a core-periphery development model (Figure 2.6). According to this theoretical model[5] and spatial metaphor (Chirot and Hall 1982; Friedmann 1986), the underdevelopment of a periphery (e.g. lack of access to electricity) is the result of market forces that concentrate on the development of the core. And, as the core needs to develop, it is necessary to exploit (or leave behind) the periphery. This has led to the debate to explain the historical modes of electricity supply (i.e. centralized power systems), as well as the unequal exchange of asymmetric energy resource flow in the periphery (i.e. unreliable electrical grids, fuel supply channels, or no electricity at all). Electricity supply through traditional centralized power systems (i.e. electrical grids) is generally limited to main cities and nearby rural towns (i.e. core) where it is profitable and people can afford a connection (Gómez and Silveira 2015). In isolated rural areas where grids cannot be expanded (i.e. periphery), electricity is not supplied or fuel supply channels are set up to power small-scale diesel or gasoline generators, which are both expensive to operate and unreliable (Gómez and Silveira 2012) resulting in a low-quality electricity service and hence an unequal distribution of electricity services (Andrade et al. 2011). However, using local renewable energy resources for electricity supply (i.e. DRE) is recognized as an opportunity to provide reliable and sustainable electricity services that could tackle this core-periphery electricity access disparity in the Amazon region (Gómez and Silveira 2015).

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[5] World systems theory, a sociological perspective to study system dynamic process of unequal distribution (Jerneck et al. 2010)

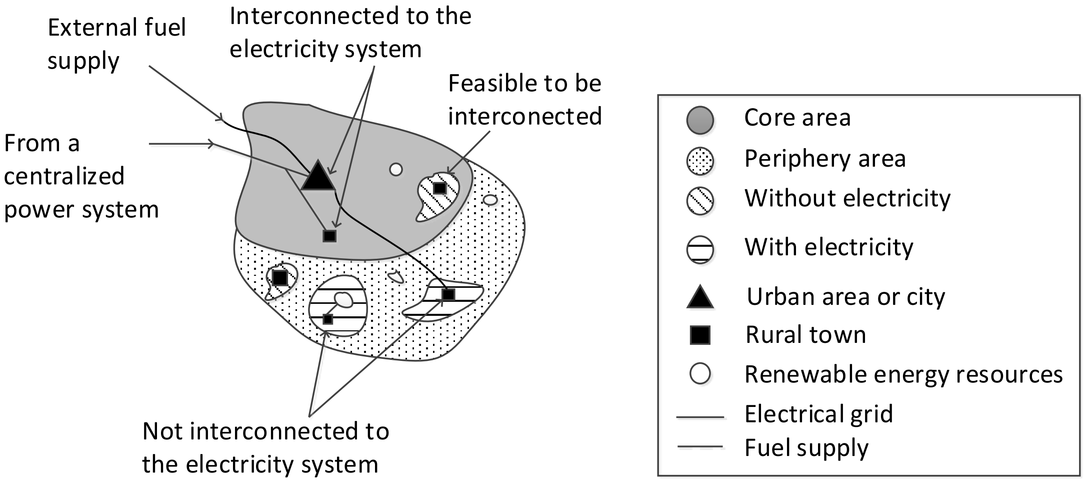

Figure 2.6 Example of the electricity access-disparity problem. Source: Silva Herran & Nakata (2012)

To support the paradigm change of sustainable DRE, a spatial planning and management is needed. Stoeglehner et al. (2011) argued that "sustainable energy society needs to draw on space as its fundamental wealth" because spatial structures have considerable influence on the demand, use, and availability of energy resources. They also state that integrated spatial energy planning frameworks and development plans cannot be separated but rather must be integrated to (i) account for the spatial and temporal dependence of renewable energy resources that determine technological choices, (ii) account for the spatial densities of energy networks (e.g. electricity grids, fuel supply) that determine the feasibility of DRE or electrical grid extensions within the territory, (iii) differentiate development needs and functionality of urban, sub-urban and rural areas within the spatial-resource-planning continuum.

The literature review revealed that the approaches to operationalize the spatial perspective in the study of sustainable DRE include three research areas: (i) Spatio-temporal assessment of renewable energy resources for electricity production (Nygaard et al. 2010; Robba et al. 2011) including solar (Rehman and Ghori 2000; Hofierka and Šúri 2002; Šúri et al. 2005) biomass (Voivontas et al. 2001; Batzias et al. 2005), and hydropower (Palomino Cuya et al. 2013; Bayazıt et al. 2017) which are relevant for sustainable DRE in the Amazon region (Fuso Nerini et al. 2014), (ii) technology selection and techno-economic analysis (Muselli et al. 1999; Byrne et al. 2007; Szabó et al. 2011),

(iii) planning and scheduling rural electrification plans based on cost-effectiveness of technology options (Dominguez and Pinedo-Pascua 2009). Other authors have also incorporated criteria of expected benefits of electricity supply in rural development in order to prioritize areas to be electrified (Banks et al. 2000; Kaijuka 2007), and still, more have combined political, financial, and social criteria in which project investment is prioritized (Fronius and Gratton 2001).

Previous studies have focused mainly on technical and economic aspects related to the introduction of DRE. However, the post-implementation phase of DRE, which is the focus of this study, has not been sufficiently covered. To the knowledge of the author at the time of writing, only one work of academic research is related to the management of DRE (Tiba et al. 2010). This research focuses, however, on technical aspects and lacks the capabilities to assess and simulate the sustainability of DRE in a participatory manner.

In this regard, other authors have captured and measured sustainability in a spatially explicit manner in fields related to urban development (Alshuwaikhat and Aina 2006), regional planning (Graymore et al. 2009), agriculture (Mohamed et al. 2014), and transport (Yigitcanlar and Dur 2010). In general, all these studies combined GIS with indicators and MCA. Indicators assess different and specific aspects of sustainability, e.g., employment diversity, land use, and wastewater generation, and MCA is used to aggregate these indicators into indexes which are mapped and provide an aggregated measurement of sustainability along the space (e.g. environmental index). A limitation of these studies, except for Graymore et al. (2009), is that the sustainability indicators were selected without an active participation of stakeholders and did not consider indicator interrelations. Also, none of the previous studies attempted to simulate system behavior in a spatially explicit manner. These aspects are important to accurately study the DRE sustainability from a systems thinking and stakeholder perspective.

Evaluating approaches for sustainability assessment of DRE

A qualitative evaluation of the previously discussed approaches was applied based on the framework proposed by Boulanger & Brechet (2005) (Table 2.4) in terms of: (i) interdisciplinary capacity to include variables from more than one discipline, (ii) uncertainty management of model quantities (parameters and initial conditions), structure (relations between variables) and pertinence (level of aggregation, selection of variables), (iii) temporal range flexibility for including various time spans long enough to disclose system dynamics, (iv) local-global viewpoint to deal with multi-level spatial scales and micro-macro relationships, and (v) participation to ease integration of stakeholders knowledge and values.

Table 2.4 Qualitative assessment of existing methods for sustainability assessment and modeling using the criteria of Boulanger & Brechet (2005) contrasting with literature (Mendoza and Prabhu 2006; Yaman and Polat 2009; Bhattacharyya 2011; Bale et al. 2015)

	Interdisciplinary capacity	**Tempora l range**	**Uncertainty management**	**Local Global**	**Participation**
Indicator	++++	+	+	++	++++
Multi-criteria analysis	++++	+	++	++	++++
Qualitative system dynamics	+++	+++	++	++	++++
Quantitative system dynamics	+++	+++	+	+	+++
Semi-quantitative system dynamics	+++	+++	++	++	++++
Agent based modeling	+++	+++	+++	+++	++++
Network analysis	++++	++	++++	+++	+++

Note: Very good: ++++, Good: +++, Acceptable: ++, Bad: +

There is no all-in-one model to capture the complexity and assess the sustainability of DRE. All methods score high concerning interdisciplinary capacity and participation. Regarding temporal range, simulation approaches ranked high (i.e. system dynamics, ABM, and fuzzy cognitive mapping in network analysis). Concerning uncertainty management, network analysis ranked high, and the local-global perspective of models is the biggest challenge for all methods (Meentemeyer 1989; Gibson et al. 2000). Overall, Keirstead et al. (2012) suggest that lack and reliability of data, model integration across disciplines, and policy relevance are key challenges to overcome the widespread implementation of system thinking approaches.

The extensive use and continued progress in GIS make it suitable for integrating system thinking, stakeholder, and spatial perspectives to study the sustainability of DRE. According to Nyerges & Jankowski (2010) "GIS are well suited for addressing complex concerns that by their nature require an integrative approach to information development and use"*.* Furthermore*,* GIS has proven able to effectively support group-based decision making (Malczewski 2006) and has been extensively applied in the electricity sector (Yalamas 2004; Amador and Dominguez 2005; Tiba et al. 2010). Thus, it is expected that combining GIS and systems thinking approaches can contribute to reducing knowledge gaps in decision support tools for a holistic, integrated and participatory decision making for the management of sustainable DRE in the Amazon region.

2.4 Research design and conceptual framework

The previous sections highlight the gaps for understanding DRE as a complex system and the need to address spatial phenomena that influence the sustainability of DRE in the Ecuadorian Amazon. It is shown that it is necessary to combine systems thinking and spatial perspectives to assess and simulate the sustainability for a sound management of DRE. It is also clear that sustainability is a local and flexible concept, therefore participation and interdisciplinarity is an important component of this research.

A conceptual framework (Figure 2.7) provided scientific guidance for this study and operationalization of a participatory and multi-method research approach. Based on existing approaches to address sustainability in complex problems (Wiek and Binder 2005; Brent and Rogers 2010), three essential research phases were defined: (i) defining stakeholder, drivers and barrier that influence DRE to work sustainable, (ii) investigating the systemic representation of sustainable DRE that captures the essence of the system with as much simplicity as possible (parsimony) and as much complexity as possible (sufficiency), and (iii) defining a decision support tool to assess and simulate the sustainability of DRE through an active participation of stakeholders that supports socially stable and scientifically founded decisions for the management of DRE in the Amazon region. Each research phase is described in detail in the following.

First, a qualitative research approach was applied (Flick 2009) to elicit local knowledge on sustainable DRE based on those who know and operate the system. This was done by combining stakeholder analysis methods (Reed et al. 2009) and grounded theory coding (Charmaz 2006). Relevant stakeholders that are directly engaged, are influencing the context of DRE, are potential coalitions or opposition, or have a low stake in DRE are identified and assessed. Then, drivers and barriers that favor or hinder sustainable DRE in the Ecuadorian Amazon as perceived by stakeholders were identified and discussed. Stakeholder analysis ensured representativeness in the participatory research approach.

Second, a participatory systems analysis was applied to integrate stakeholders' knowledge into a systems model that captures the complexity of sustainable DRE. The Sensitivity Model® (Vester 2007) was chosen due to the poorly defined nature of sustainable DRE, its ability to facilitate stakeholder participation, and most importantly because high amounts of data are not required; data availability is a serious research constraint in the Amazon region (dos Santos et al. 2015). A set of relevant variables and their interconnectedness were defined and evaluated. This provided deeper insights on the systemic role of variables in the sustainability of DRE. Also, the main feedback structures, processes, and functions of the system were identified and discussed. Ultimately a qualitative 'cause-effect' system model was proposed, which makes explicit the inherent complexity of sustainable DRE. Results were contrasted with the previous research phase.

Third, a decision support tool for the assessment and simulation of sustainability of DRE was developed and tested. This was done by combining GIS with system thinking approaches (i.e. multi-criteria decision analysis and fuzzy cognitive mapping). The overall aim was to provide a decision support tool focused on understanding the problem of DRE rather than making a precise forecast to convey clear and spatially explicit messages about sustainable DRE, and to support scenarios development and analysis to foresee sustainability trends of DRE in a participatory manner.

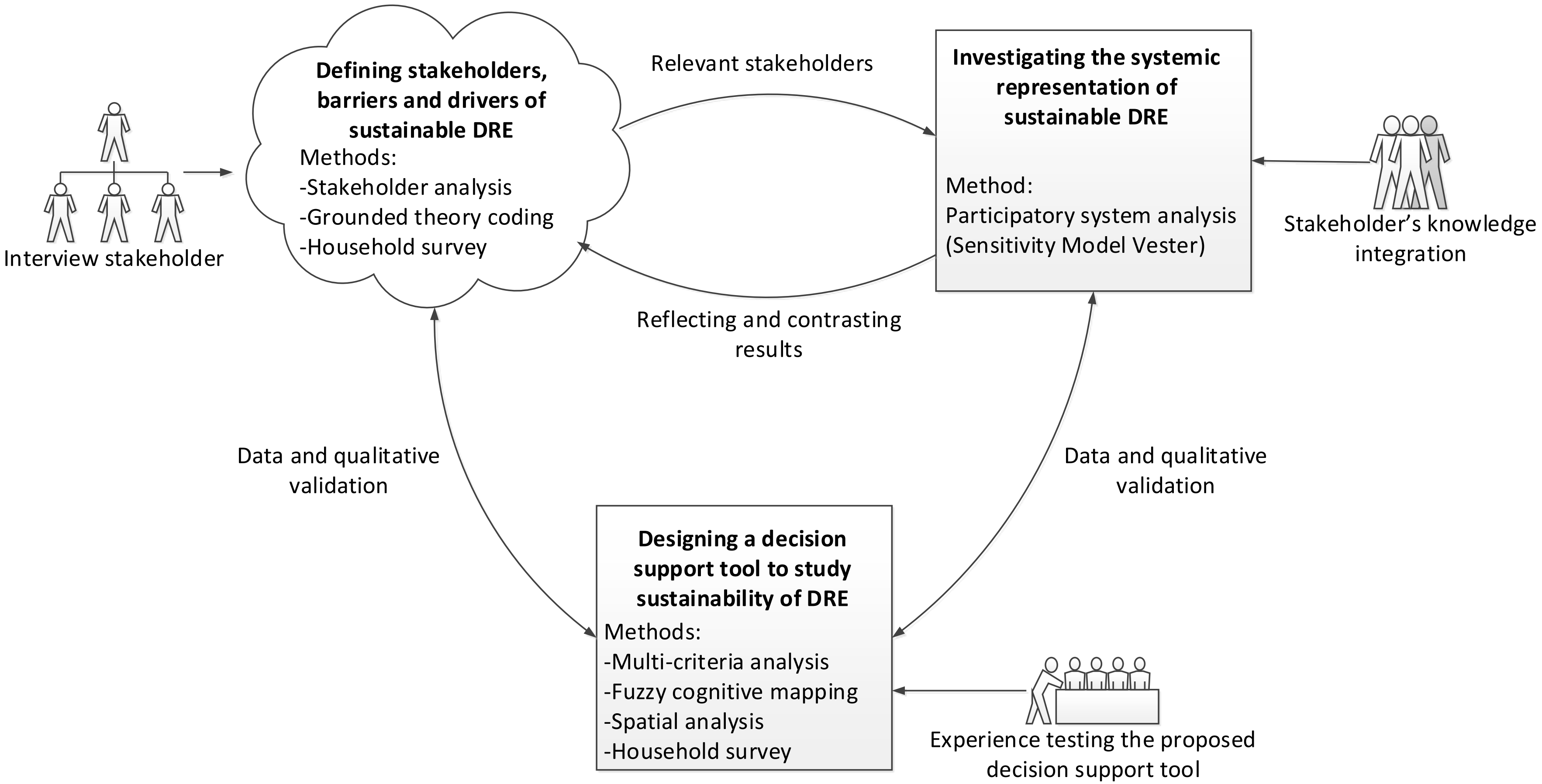

Figure 2.7 Conceptual framework and research design

3 DECENTRALIZED RURAL ELECTRIFICATION IN THE AMAZON REGION: STAKEHOLDERS, BARRIERS, AND DRIVERS

3.1 Introduction

In the last two decades, different DRE programs mainly using Solar Home Systems (SHS) have been implemented in the Ecuadorian Amazon with relatively limited success. The causes of DRE failure have been studied around the world (Table 2.2). However, research experiences from elsewhere are not directly transferrable to the Ecuadorian Amazon context due to the region's particular political, economic, and social settings (Hughes 1983). Hence, there is a need for the identification of the specific 'barriers' and 'drivers' that influence DRE to work sustainable in the long term and supports rural development in the Ecuadorian Amazon.

The concepts of barriers and drivers are commonly used to signify aspects that impede or favor DRE (Urmee and Harries 2009; Ahlborg and Hammar 2014). Existing studies have generally given more attention to economic, technical or institutional barriers (Table 2.2) and only a few have included the social and cultural barriers that are extremely important in multicultural and traditional communities (Sovacool et al. 2011) like those in the Amazon region (Serpa and Zilles 2007). For DRE to succeed, it is argued that a seamless web of economic, institutional, technical and social aspects need to be aligned (Hughes 1983; Sovacool 2009). Thus, a socio-technical system perspective is adopted in this study.

Despite the growing amount of literature on barriers and drivers, still little is known about the role and influence of stakeholders on DRE in the Amazon region. It is recognized that the success of DRE depends on the identification and management of stakeholders' relationships (Bourne and Walker 2005; Holtorf et al. 2015). Also, institutional structures need to be adapted and new rules defined to guide the incorporation of new actors to implement and operate DRE in remote areas of the Amazon region (Gómez and Silveira 2015). For example, Andrade et al. (2011) advocate for a high participation of indigenous communities at different levels of decision in order to ensure sustainable solutions while overall maintaining Amazon peoples' autonomy. Scaling up DRE while achieving social, economic and environmental goals in Amazon communities requires a broader vision beyond the competences of electricity suppliers (van Els et al. 2012), and hence greater cooperation with stakeholders from different sectors is needed (e.g. health, education, agriculture, environment, etc.) This implies that multiple stakeholders interact and influence DRE either in favor or against it depending on whether electricity outcomes may benefit or harm them (Ruggiero et al. 2014). The complex interactions between stakeholders and their multiple self-set goals must be accounted for to arrive at better strategies for sustainable DRE (Holtorf et al. 2015).

Thus, the aim of this part of this research is to provide a comprehensive portrayal of DRE in the Ecuadorian Amazon. It is done through the study of stakeholders' networks and roles, and identification of specific barriers and drivers that hinder and favor sustainable DRE as perceived by relevant stakeholders.

3.2 Material and methods

The lack of research on DRE in the Ecuadorian Amazon motivated a qualitative (Flick 2009) and ethnographically based research approach in order to generate concepts, understand values and perceptions from real life experiences and combine them with multiple data sources (Figure 3.1). Data collection methods included a literature review, semi-structured interviews with decision makers, and a household survey with beneficiaries of DRE. Data analysis included a stakeholder analysis to identify, categorize and assess stakeholders´ interest and influence on DRE and also to select interviewees and ensures representativeness during data collection. Triangulating a grounded theory coding (Charmaz 2006; Flick 2009) of transcribed semi-structured interviews and descriptive statistics of the household survey, the specific barriers and drivers of DRE in the Ecuadorian Amazon were identified and discussed. Although the research process seems linear it was, in fact, iterative.

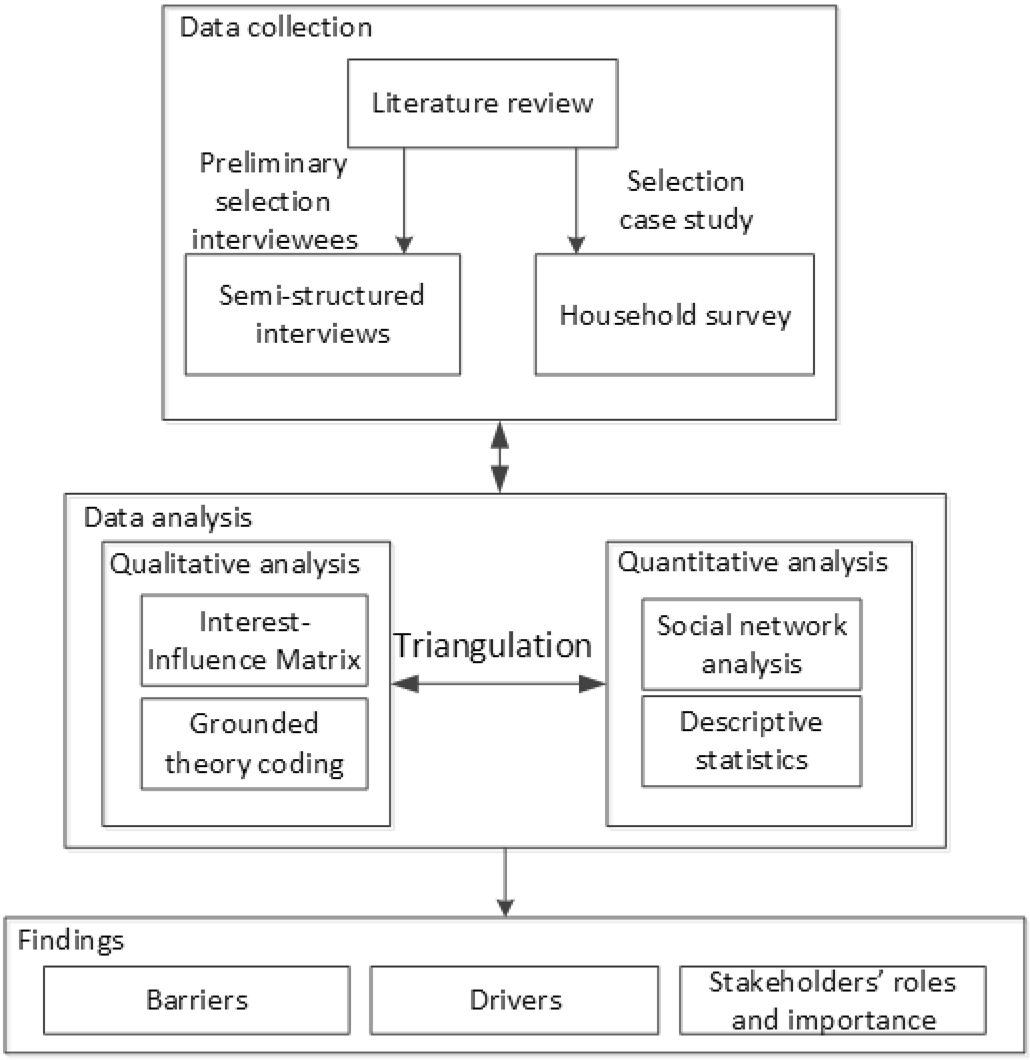

Figure 3.1 Overview of the methodology. Sources: Sovacool et al. (2011); Serpa & Zilles (2007); Painuly (2001)

3.2.1 Data collection

A review of project reports from official institutions and practitioners helped to contextualize DRE in the Ecuadorian Amazon, define a preliminary list of relevant stakeholders and identify a relevant case for the household survey.

Semi-structured and informal interviews with relevant decision makers were conducted to elicit local knowledge and complement written information. The interview protocol (Appendix 1-1) considered interviewees´ time restrictions and background and encouraged an open dialogue about barriers and drivers of DRE, qualitative assessment of stakeholders' influence and interest in DRE, and sustainability concepts in the context of DRE. All interviews were conducted in Spanish and recorded only if the interviewee agreed. Individual identities of the respondents were kept confidential. Each interview was transcribed and compiled with additional written information obtained from the interviewee. Between November 2012 and April 2014, 33 semi-structured and 10 informal interviews were applied to policy makers, engineers, technicians, consultants, researchers, medical doctors, indigenous leaders, a missionary, and NGO representatives, all with responsibilities at local, provincial, national and international decision levels.

A household survey was undertaken to provide quantitative information to reduce the possible bias from semi-structured interviews and also to incorporate local DRE beneficiaries' viewpoints (Urmee and Harries 2009). The "Yatsa Ii Etsari" solar program was selected as a case. During the research period, this was the largest currently operated DRE program in Ecuador that distributed 2553 solar home systems to indigenous families (Figure 3.2). Between August 2012 and April 2014, 430 structured interviews with household heads were conducted in Spanish or the native language (i.e. Shuar or Achuar) facilitated by a local translator. The sample size (430 household interviews) of the survey was determined after an initial field test and constraints such as community accessibility. The interviews included questions related to socio-economic characteristics, people's needs at community and household level, consumption of energy, perceived impact of electricity, technology adoption, and people's mobility (Appendix 1-2).

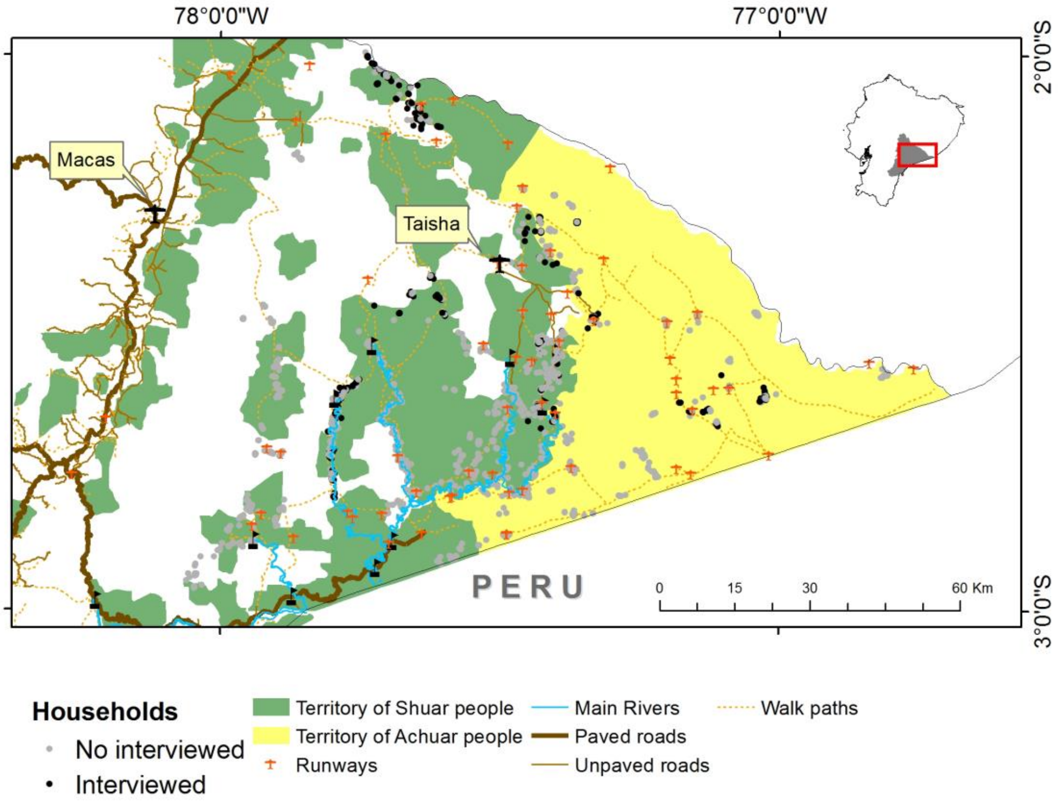

Figure 3.2 Spatial distribution of solar home systems in the solar program "Yatsa Ii Etsari" in Ecuador. Sources: Centrosur (2014); GAD-MS (2012)

3.2.2 Data analysis

Stakeholder analysis

A stakeholder analysis was applied to identify and assess stakeholder´s roles in DRE, avoiding marginalizing important stakeholders and bias research results (Ackermann and Eden 2011). The analysis included the identification and categorization of stakeholders, and inquiry of stakeholders´ relationships (Reed et al. 2009). Accordingly, semi-structured interviews, an interest-influence matrix (IIM) (Ackermann and Eden 2011), and a social network analysis (SNA) (Borgatti et al. 2013) were respectively applied.

Stakeholders' identification set the boundaries of the human and institutional landscape of DRE through an iterative process. A literature review provided a preliminary list of stakeholders from the different sectors (i.e. government, civil society, and private sector) and level of decision making (i.e. local, provincial, national and international). During semi-structured interviews, respondents confirmed this list and new stakeholders were added if deemed important by respondents or they provided a new viewpoint for the research (i.e. interview snowball sampling).

Stakeholders´ categorization provided a qualitative assessment of stakeholders' interest and influence along the process and outcome dimensions of DRE. During semi-structured interviews,[6] respondents were asked to quantify for each stakeholder their corresponding interest and influence on DRE using a qualitative rating scale of 1-3 (1=low, 2=middle, 3=high). The average interest and influence were calculated and used to categorize stakeholders in four classes (Figure 3.3)

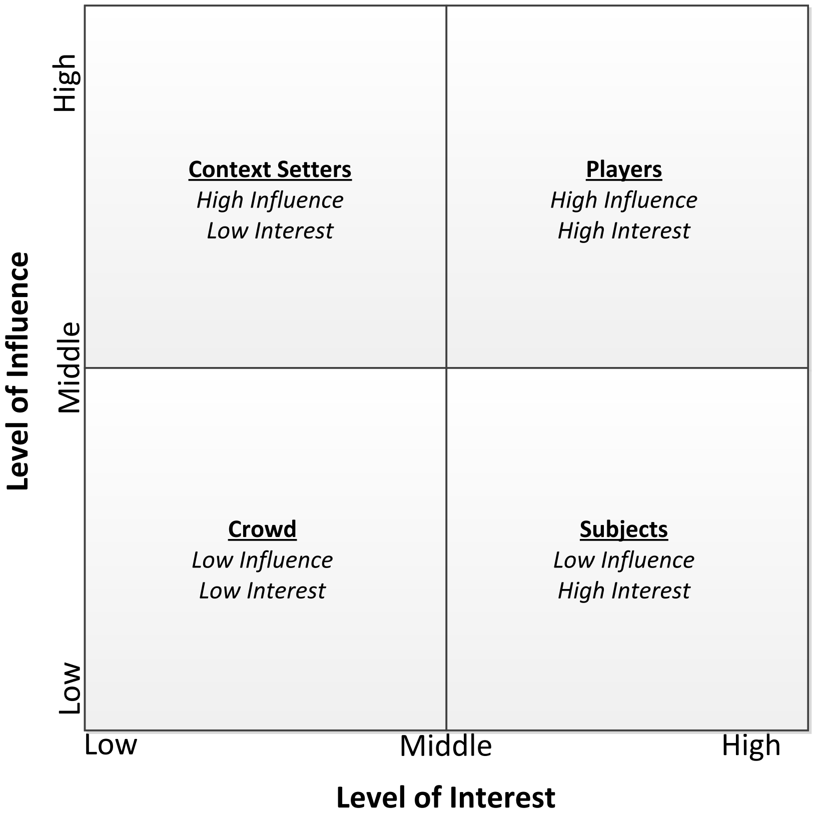

Figure 3.3 Interest and influence matrix to define stakeholder categories. Source: Ackermann & Eden (2011)

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[6] The IIM is usually implemented in workshops. However, power relationships during workshops could hinder the assessment process in the study area, so semi-structured interviews were preferred to allow respondents to confidentially assess other stakeholders.

Social network analysis provided insights on stakeholder relationships and complements the qualitative assessment of IIM (Lienert et al. 2013). From the analysis of the semi-structured interviews, a relational network was constructed by identifying who interacts with whom and how. The resulting network was analyzed using the software UCINET (Borgatti et al. 2013). First, the average density ($\bar{\boldsymbol{d}}$) of the network was calculated using equation 3-1. The higher the density, the greater the number of stakeholders who are interacting (Borgatti et al. 2013).

$$\bar{d} = \frac{T}{n(n-1)} \tag{3-1}$$

where T is the total number of existing ties among stakeholders and n is the total number of stakeholders.

Second, betweenness centrality (B_j) for each stakeholder was calculated using equation 3-2 which measures to what extent a stakeholder lies on the shortest path between other two stakeholders. It is zero if a stakeholder does not connect any one. It provides a measure of the mediating role of a stakeholder (gatekeeper) within the network (Borgatti et al. 2013). The higher its value, the more is the stakeholder integrated into the network, and holds thus a better position to influence the stakeholder network of DRE (Rowley 1997).

$$B_j = \sum_{i<k} \frac{g_{ijk}}{g_{ik}} \tag{3-2}$$

where Bj is the betweenness centrality of stakeholder j, gijk is the number of paths connecting stakeholder i, and k through j, and gij is the total number of paths connecting stakeholder i and k.

Finally, stakeholders were ranked by normalizing and averaging the interest and influence from the IIM and the betweenness centrality from the SNA (Bottero et al. 2014). It approximates the overall importance of each stakeholder for DRE in the study area.

Identification and analysis of barriers and drivers

Transcribed semi-structured interviews were analyzed through a grounded theory coding (Charmaz 2006; Flick 2009) supported by the software Atlas.ti®. An initial open coding was applied to segments of text that were meaningful to the research questions and according to the interview protocol (i.e. barriers, drivers, positive and negative impacts of electricity, productive uses of electricity, stakeholders of DRE, and sustainability criteria). Then, a focusing coding was applied resulting in fewer code numbers but at a higher level of conceptualization. The resulting codes provided a comprehensive list of barriers and drivers that reflected and triangulated with descriptive statistics from the household survey and the results of the stakeholder analysis support the final discussion.

3.3 Results and discussion

3.3.1 Identification of stakeholders

From the interviews, 31 stakeholders were identified (Table 3.1). They include all individuals or institutions with a direct or indirect role in the investment (10), planning (13), design (6), implementation (15), and post-implementation (19) of DRE. These stakeholders are representatives from government (19), civil society (9) and the business sector (3), with a role at local (8), provincial (5), national (15) and international (3) decision-making levels. Most stakeholders are from the government and at the national decision-making level, supporting the claim that DRE and development are highly centralized processes.

The high number of stakeholders in the post-implementation phase confirms the most multifaceted stage of DRE. There are stakeholders that influence directly (e.g. electricity company) or indirectly (e.g. transport business) electricity supply services. But others (e.g. teacher) become active when electricity arrives in remote communities to support productive uses of electricity (e.g. education). In general, stakeholder analysis of DRE focuses on manufacturers, investors, policy makers, wholesalers, electricity suppliers, and end-users (Tillmans and Schweizer-Ries 2011; Friebe et al. 2013), but, in the Ecuadorian Amazon DRE has a strong emphasis on stakeholders for the post-implementation phase (productive uses of electricity).

Table 3.1 Identified stakeholders for DRE in the Ecuadorian Amazon, extracted from interviews

Level of decision	ID	Stakeholder	Sector	Number of times mentioned during interviews	Stakeholder participation				
					Investment	Planning	Design	Implementation	Post-implementation
Local	1	Church and missionary orders	C	3	I				I
	2	Village president	C	3				I	I
	3	Village electrification committee	C	5				D	D
	4	Households	C	8				D	D
	5	Teachers	G	5				I	I
	6	Health staff	G	9				I	I
	7	Indigenous political organizations	C	11		I		I	
	8	Municipalities	G	11	I	I			
Provincial	9	Tourism business	P	1					I
	10	Transport business	P	2		I	I	I	I
	11	Radio stations	C	1				I	I
	12	Provincial governments	G	13	I	I	I		
	13	Electricity companies	G	19	D	D	D	D	D
National	14	Renewable energy business	P	6	I		D	D	
	15	Research and academia institutions	C	4					I
	16	Ministry of Electricity and Renewable Energy	G	12	D	D	D		
	17	Ministry of Education	G	5		I			I
	18	Ministry of Health	G	9	I	I			I
	19	Ministry of Social and Economic Inclusion	G	2					I
	20	Ministry of Agriculture	G	4					I
	21	Ministry of Telecommunications	G	8					I
	22	Ministry of Tourism	G	1					I

Level of decision	**ID**	**Stakeholder**	**Sector**	**Number of times mentioned during interviews**	**Stakeholder participation**				
					Investment	**Planning**	**Design**	**Implementation**	**Post-implementation**
	23	Ministry of Transport	G	1		I			
	24	Ministry of Environment	G	5				I	
	25	Army	G	1				I	
	26	Customs	G	1				I	
	27	Ecuadorian Institute of Standardization	G	1					
	28	National secretary of planning and development (SENPLADES)	G	6	D	I			
International	29	International donors	G, P	3	D	I		I	
	30	Energy NGOs	C	7	D		D	D	D
	31	Development NGOs	C	4	I		I	I	

G=government, P= private sector, C= civil society, I=indirectly involved, D=directly involved

3.3.2 Categorization of stakeholders

For each identified stakeholder, the level of influence and interest in DRE were calculated from the analysis of semi-structured interviews (see section 3.2.2 for methodological background) and thus allocated to a category (Figure 3.4). Stakeholders perceived as having great interest and influence are categorized as 'players', but if their influence was perceived low as 'subjects'. Both were seen as having a higher stake in DRE. Those that were perceived with low interest and low influence were categorized as 'crowd', but if their influence was high as 'context setters'. These latter two stakeholders are seen as potential stakeholders with varying degrees of influence.

‘Players’ (interest > 1.5, influence > 1.5, Figure 3.4) have a high interest and can influence DRE positively or negatively implying they are strong supporters or saboteurs of DRE (Ackermann and Eden 2011). Government stakeholders from the electricity sector (i.e. Ministry of Electricity and Renewable Energy, Electricity Company) have a high interest and influence (positive or negative) in its role in policy making, financing and implementation of DRE. Also, government stakeholders from the Ministry of Health and Ministry of Education sector were perceived having a high interest in DRE for the enhancement of their respective public services in remote Amazon communities, e.g. health posts and schools with electricity. Health was considered the most important. For instance, solar panels are being used for sustaining "cold chains" for life-saving vaccinations, with a significant effect on tackling the high morbidity and mortality among the indigenous people (Kuang-Yao Pan et al. 2010). Concerning civil society, indigenous political organizations and village presidents had a great interest in improving the electricity access in their communities and were also perceived as being highly influential regarding supporting or undermining DRE interventions. Their mediator role between Amazonian communities and outside society is well recognized in the literature (Perreault 2003). Also, the long historical presence from the 16th century of church and missionary orders in the Amazon region (Cleary 2010) meant that these were in highly influential positions.

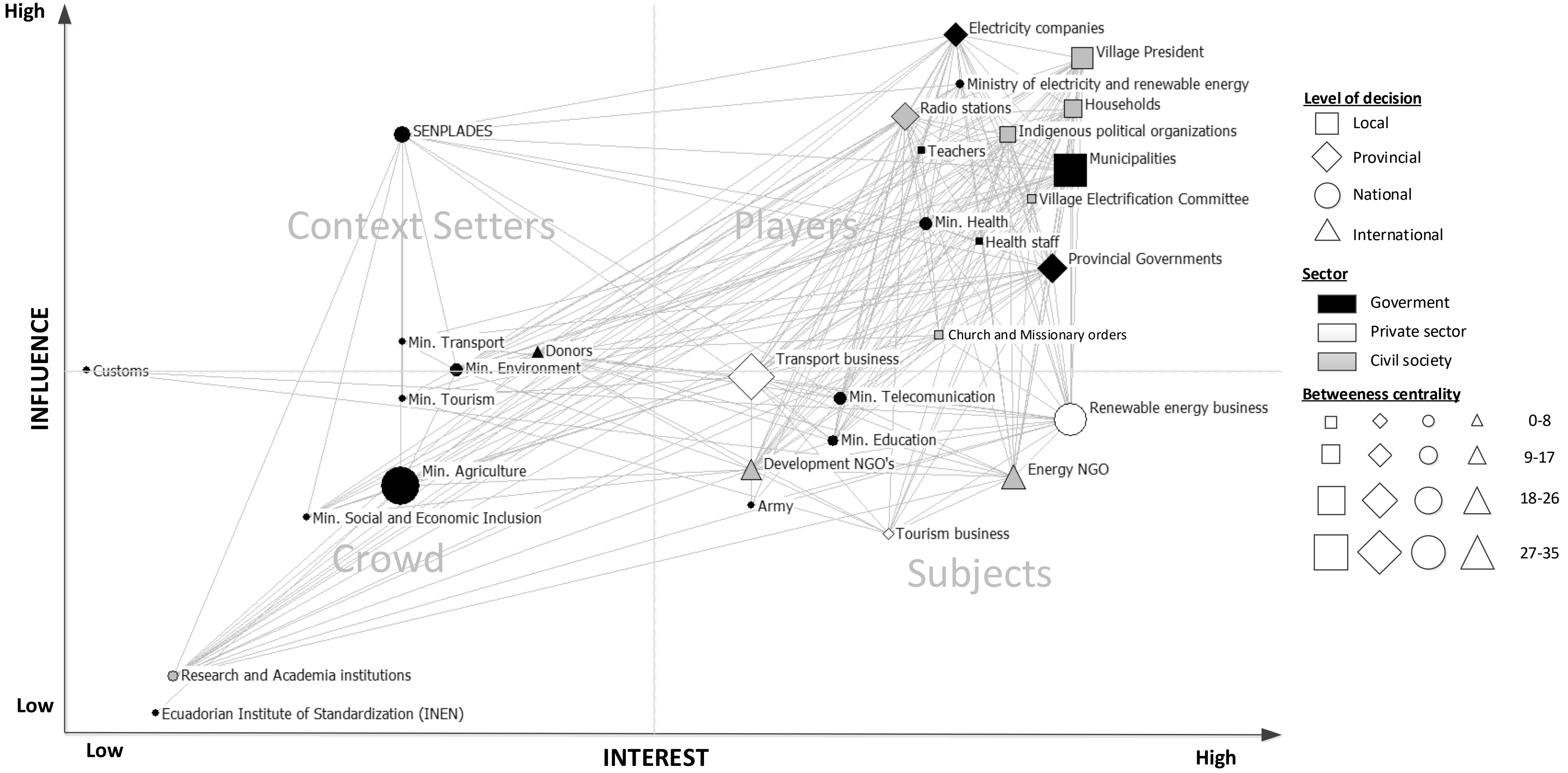

Figure 3.4 Stakeholders´ interest and influence on DRE, relationships, and betweenness centrality extracted from interviews

The x-y coordinates of each stakeholder correspond to interest and influence respectively. The lines between nodes indicate stakeholders' interaction, and the node size indicates the stakeholder's betweenness centrality.

‘Subjects’ (interest > 1.5, influence < 1.5; Figure 3.4) were perceived having a high stake in DRE but a low ability to influence DRE suggesting that they are either potential participants in a coalition or are in opposition to DRE (Ackermann and Eden 2011). Government stakeholders from the telecommunication sector have a high interest in DRE regarding the expansion of communication services such as telephone and the internet in remote areas, which were seen as important to enhance other public services, e.g. telemedicine (Martínez et al. 2004) but also to facilitate the logistics of DRE. However, at present their influence was perceived low. Concerning civil society, NGOs working in development areas and energy were seen as having a high interest and as being strong mediators to align DRE outcomes with rural development goals and households' interests. However, others felt that conflicting positions could arise if negative environmental and cultural impacts from DRE were to be observed. Regarding the business sector, renewable energy businesses have a high interest in DRE for the provision of consulting services and equipment provision. However, their participation is limited by existing regulations (Ecuador 2015) and the non-profit character of DRE. Transport companies such as boat owners and local airlines have a high interest in DRE since they expect it to increase their sales. They also have a medium influence on the final cost of DRE and transport safety of staff and equipment. Additionally, tourism businesses have a high interest in electricity access to improve touristic services, e.g. community and eco-tourism, which are becoming an emergent sector for income generation in Amazon communities (Gössling 2000; Ingles 2002; Hoefle 2016).

‘Context setters’ (interest < 1.5, influence > 1.5; Figure 3.4) were perceived as having a low interest but a significant influence on the context where DRE takes place suggesting that these were seen as powerful and potential stakeholders influencing the overall context of DRE (Ackermann and Eden 2011). Those with a high influence on financing DRE are SENPLADES, which is the government agency responsible for national development plans and prioritize social investment in Ecuador (SENPLADES 2013). In the past, international donors, i.e. international cooperation and multilateral organizations, have financed most of the DRE (Table 2.1) but during the period of this research had only a low participation, which explains the perceived low interest. Customs influence the importation of renewable energy equipment and have a significant effect on DRE costs. Other stakeholders in this category are the Ministry of Transport, which is responsible for the construction of roads. This influences the decisions of the rural electrification master plans regarding grid expansion or DRE. The Ministry of Environment has a high influence through environment regulations regarding control or mitigation of environmental impacts of DRE.

‘Crowd’ (interest < 1.5, influence < 1.5; Figure 3.4) have low interest and influence implying that they were seen as potential rather than actual stakeholders. If desirable, their interest must be raised to secure their participation (Ackermann and Eden 2011). Government stakeholders from the tourism and agriculture sectors were perceived as having a potential role in supporting income generation and reducing extractive activities in the Amazon communities. The government standardization office (INEN) has a low interest due to its limited scope in the electricity sector. However, standards are key to influence the success of DRE (Kumar et al. 2009). Research and academic institutions have a potential role regarding information generation, which will improve decision making of DRE, e.g. renewable resources assessment and demand studies.

3.3.3 Stakeholder network analysis

The stakeholder network analysis provided a quantitative analysis of the interaction among stakeholders and complements the qualitative assessment presented in the previous section. From the analysis of the semi-structured interviews, formal and informal relationships between stakeholders were identified and portrayed (Figure 3.4). Stakeholders’ interaction goes beyond formal institutional arrangements and includes informal decision-making activities at local, provincial, national and international levels and among multiple stakeholders.

The complex interaction among stakeholder as a whole is measured by the 'density' (equation 3-1) which was 0.417. In a fully collaborative network, a density value of 1 is expected (Borgatti et al. 2013). This suggests a rather fragmented network with medium-low cohesion (d<0,5). To have a deeper insight into network cohesion, the 'density' within and between stakeholder clusters is defined by the decision-making level and sector (Table 3.2 and Table 3.3). Stakeholders at the local level tend to interact more with those at international levels (d>0.8), but very little with stakeholders at the national level (d<0.4). Stakeholders from the government interact very little with stakeholders from the private sector (d<0.4).

Table 3.2 Density of stakeholders disaggregated by decision levels

	Local	**Provincial**	**National**	**International**
Local	0.679	0.450	0.392	0.833
Provincial		0.400	0.400	0.467
National			0.429	0.578
International				0.999

Table 3.3 Density of stakeholders disaggregated by sector

	Government	**Private Sector**	**Civil Society**
Government	0.532	0.316	0.456
Private Sector		0.333	0.370
Civil Society			0.583

The stakeholders' prominence within the network is measured by the betweenness centrality (Figure 3.4). It allowed identifying influential and peripheral stakeholders. High betweenness centrality means that the stakeholder has better and more direct access to the network, and hence has a considerable potential to influence others in the process of DRE. There are a higher number of stakeholders at local and provincial than at national levels with higher betweenness centrality. The two former are therefore well positioned to interconnect others and foster cooperation among the network. This agrees with the IIM in which all local stakeholders were perceived as being highly influential (i.e. 'players'). At the international level, NGOs working in energy projects have a higher betweenness centrality and were perceived as good mediators to link stakeholders from the government, civil society, and private sector. Their collaborative role is confirmed by the high 'density' between local and international actors (Table 3.2).

Regarding stakeholders from different sectors, government stakeholders such as municipalities, provincial governments, and the Ministry of Agriculture show the higher betweenness centrality. The latter, though it has a good position in the network, was perceived as having low interest and influence in the IIM. Regarding civil society, the results confirm the powerful mediator role of indigenous political organizations and village presidents among the network. The mediator role of radio stations interconnecting the network through communication and information is also confirmed (this and a network of UHF radios are the only means of communication), which usually is neglected in DRE plans. Regarding the private sector, renewable energy businesses have a high betweenness centrality so they hold a good position to influence the network better than government stakeholders; however, its influence on DRE was perceived low on the IIM. As expected, transport businesses have a strong facilitator role in the network because of the restricted access in the Ecuadorian Amazon.

3.3.4 Stakeholders overall importance

By normalizing and averaging the level of influence and interest and betweenness centrality, the overall importance of the stakeholders was calculated (Table 3.4). Also, based on previous analysis their role in the introduction and maintenance process of DRE, i.e. investment, planning, design, implementation and post-implementation; and, productive uses of electricity were highlighted. This forms the basis to initiate discussions and consultations about the barriers and drivers of DRE as well as to establish management strategies for stakeholder cooperation for succeeding with sustainable DRE plans.

Table 3.4 Stakeholders overall importance and role for DRE in the Ecuadorian Amazon

Sector	**Stakeholder**	**Overall importance**	**Stakeholders' role**	
			Introduction and maintenance of DRE	**Productive uses of electricity**
Civil society	Village President	0.781	x	
	Radio stations	0.747	x	
	Households	0.731	x	x
	Indigenous political organizations	0.667	x	x
	Village electrification committee	0.577	x	
	Energy NGO	0.569	x	
	Church and missionary orders	0.479	x	x
	Development NGOs	0.460		x
	Research and academia institutions	0.082	x	x
Government	Municipalities	0.832	x	x
	Electricity companies	0.748	x	
	Provincial governments	0.728	x	x
	MEER	0.617	x	
	Ministry of Health	0.575		x
	Teachers	0.568	x	x
	Health staff	0.529		x
	Ministry of Agriculture	0.488		x
	SENPLADES	0.470	x	x
	Ministry of Telecommunication	0.454	x	x
	Ministry of Education	0.409		x
	Donors	0.356	x	
	Ministry of Environment	0.347	x	x
	Army	0.324	x	
	Ministry of Transport	0.290	x	
	Ministry of Tourism	0.267		x
	Ministry of Social and Economic Inclusion	0.190		x
	Customs	0.167	x	
	Ecuadorian Institute of Standardization	0.023	x	
Private Sector	Transport business	0.719	x	
	Renewable energy business	0.706	x	
	Tourism business	0.378		x

3.3.5 Review of the solar program 'Yatsa Ii Etsari'

In this section, the solar program 'Yatsa Ii Etsari' is reviewed and an overview of the electricity impact on beneficiary families, i.e. mainly indigenous people, is provided. It complements the previous section by reviewing stakeholders’ engagement in a real case and provides additional information for the analysis of barriers and drivers of DRE in the Ecuadorian Amazon.

The 'Yatsa Ii Etsari' program started in 2008 triggered by a human rabies epidemic that impacted the study area. The use of artificial light helped to mitigate the epidemic by banishing vampire bats (*Desmodus rotundus*) which were responsible for spreading the disease. The program adopted a top-down and non-market approach. The Ministry of Electricity and Renewable Energy (MEER) provided the funds (USD 7,8 million) for the installation of 2,565 SHS (Figure 3.5) in the concession area of the electricity company Centrosur (Figure 3.2) which is responsible for the implementation, operation and maintenance of the SHS. During the planning and implementation phases, MEER, Centrosur, and indigenous political organizations selected and prioritized the communities to be electrified. Supported by local radio stations, the information and communication of the program intentions were distributed among the communities to confirm their need and acceptance to receive SHS. The participation of indigenous political organizations, radio stations, and households confirms their critical role in ensuring success during DRE implementation. An electricity service contract agreement was signed between the households and Centrosur. Households are committed to pay a subsidized fee (USD 1.46/month) and in return Centrosur guarantees a maintenance service.

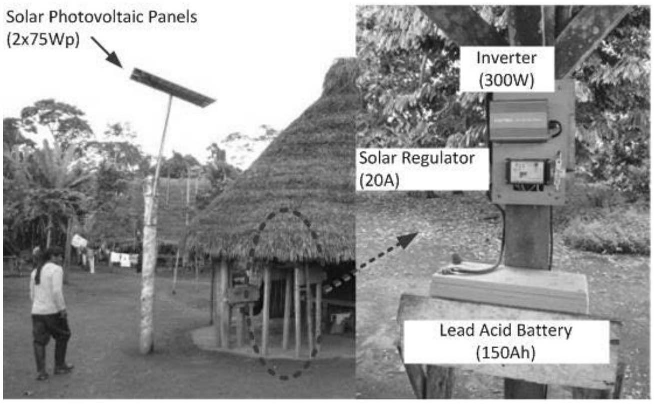

Figure 3.5 Example of a solar home system in the solar program 'Yatsa Ii Etsari' installed in a traditional Shuar house

Maintenance of solar home systems

The maintenance service of SHS includes periodic visits every 3 months to all 120 communities by two of Centrosur´s technical staff. Maintenance is supported by the village electrification committee consisting of volunteer members of the community who help with basic maintenance works and fee collection.

Regarding the reliability of the electricity service, between October 2010 and January 2014, 39.2% of the SHS failed (Table 3.5). Sensitive electronic equipment such as compact fluorescent lamps, charge controllers, and inverters had the highest failure rate. The average time for restoring the service after an SHS had failed was 180 days, and for 20% of the households, it was more than 750 days. The reasons for these long waiting times were the low number of technical staff, lack of spare parts, and low capacity of the village electrification committees to perform complex maintenance tasks.

Table 3.5 Failure rates of solar home system equipment between 2011 and 2014. Source: Centrosur (2014)

Equipment	Failure rate	Share
Compact fluorescent lamps	570	56.6%
Inverter	234	23.2%
Regulator	106	10.5%
Fuses and electric installations	89	8.8%
Battery	6	0.6%
Panel	2	0.2%
Total failure rates	1007	100%
Total number of installed SHS	2565	

The average maintenance cost was USD 30, USD 40 and USD 67 per year and per SHS for communities accessible via roads/walking trails (Figure 3.7-6), river (Figure 3.7-7) and air (Figure 3.7-8), respectively. The maintenance cost includes the salaries of the technical staff, transport, and spare parts. The share of these costs varies in the function of the type of access (Figure 3.6). Moreover, it was found than 39% of households did not pay the fees (USD 17.52/household/year) although most (>90%) considered the fee affordable suggesting there is a low willingness to pay for electricity services. Though the household fee was expected not to cover maintenance costs, the lag of payments increased the annual budget covering maintenance costs and thus making the solar program increasingly non-profitable.

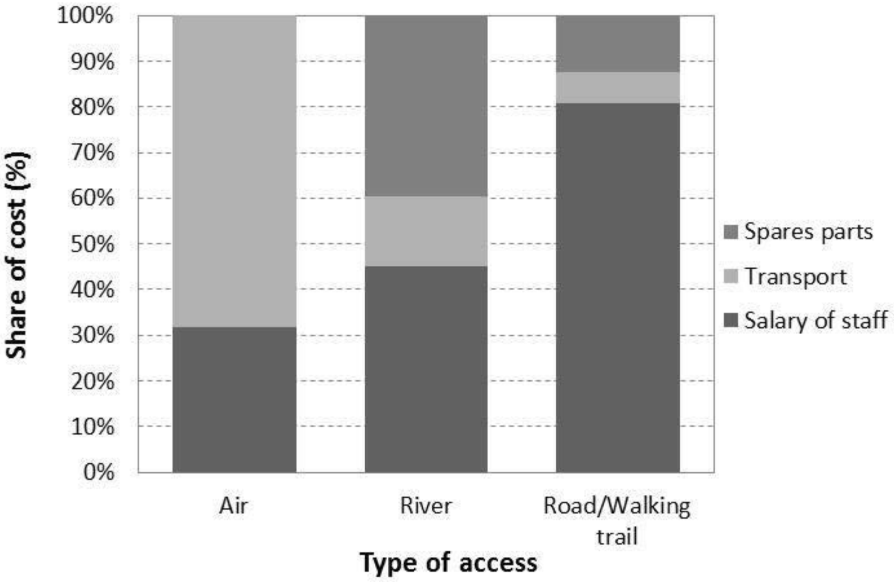

Figure 3.6 Share of maintenance cost of the solar program 'Yatsa Ii Etsari' between 2011 and 2014. Source: Centrosur (2014)

Socioeconomic situation of households

Most of the households (82%) lived in traditional houses built without room separations, and almost 50% had detached wooden houses with corrugated iron sheeting (Figure 3.7-1,2). On average, 6 people lived in each house, 97% were monogamous families and 3% polygamous; 70% of the respondents were aged between 25 and 50 years, 74% had finished schooling, and 7% had a university degree. 84% of households were more versatile in their native language, with only 2% speaking only Spanish and 13.7% both languages. However, the main language used to disseminate the program's instructions and training was Spanish.

Income was not consistent, but households revealed a figure of around USD 50 per month. However, 59% of households received a monthly bond of USD 50 per month from the government, i.e. human development bond (MIES 2014) without which the average income would have totaled around USD 20 per month. The main economic activity for 97% of the households was subsistence agriculture, 15% had small stores or manufactured handicrafts (Figure 3.7-3), 13% raised cattle, and 1% worked as teachers or health staff. The latter were the few with a stable income. Subsistence hunting and fishing were common activities among all households but only 4% commercially sold their bushmeat or fish.

The households were relatively isolated and 57%, 32%, and 11% were located in areas accessible via rivers, air and road/walking trails, respectively. Approximately 56% of the households travel regularly to the main cities (Figure 3.2-Macas), and 39% to the nearest small towns (Figure 3.2-Taisha) for buying and selling in local markets, accessing health services, visiting friends, and other administrative requirements or duties.

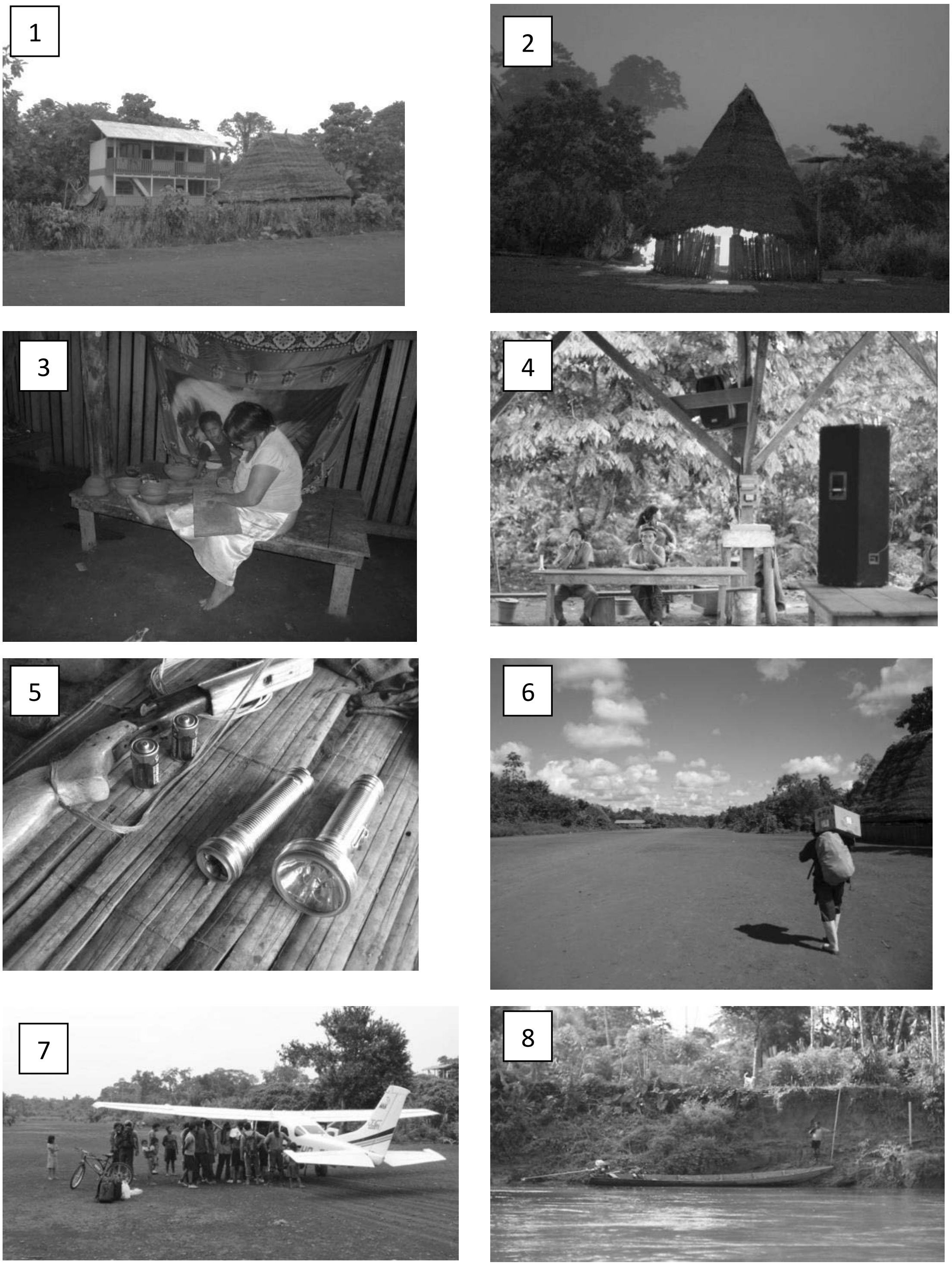

Figure 3.7. Illustration of solar program 'Yatsa Ii Etsari'

1) Typical detached wooden Shuar house, 2) Shuar house illuminated at night, 3) women manufacturing handicrafts during the night, 4) SHS used during a general assembly, 5) typical flashlights and batteries used for hunting, 6) electricity company technician visiting communities, 7) typical runway and airplanes, 8) typical canoes used in Amazon rivers

Electricity impacts

Electricity profoundly modified people's schedules and daily routines (Figure 3.8). SHS provided on average 400 Wh/day, which was consumed very early in the morning and during the night mainly for lighting, as only 25% of the households operated radios or televisions (12%). Before implementation of the program, most people went to bed around 18:00-19:00, and after electricity access, average bedtime was around 21:00-23:00.

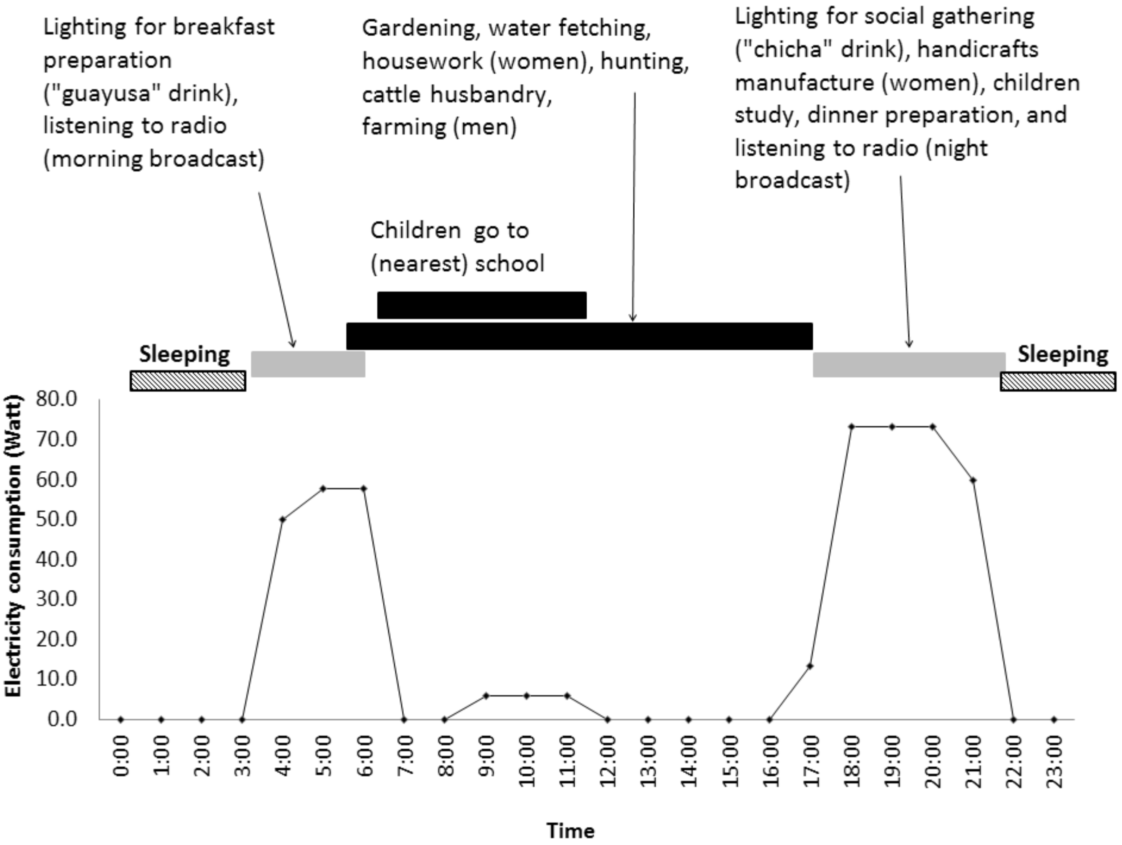

Figure 3.8 Typical load profile of electricity consumption superimposed with daily activities of households, extracted from household survey

Solar home systems have positively improved the average household expenses on energy sources. It reduced from USD 13.5 to USD 3.2 per month (Figure 3.9) because the consumption of diesel (4 l/month) and candles (4 units/month) used for lighting were replaced almost entirely (Figure 3.10). Moreover, the average consumption of batteries reduced from 3 to 1 unit per month, although 78% of people still used them mainly for flashlights, which are important for hunting and fishing (Figure 3.7-5). Gasoline consumption was not reduced because it is used sporadically to run small generators during community social events (Figure 3.7-4) or water pumping, which cannot be done with the installed SHS due to their limited capacity.

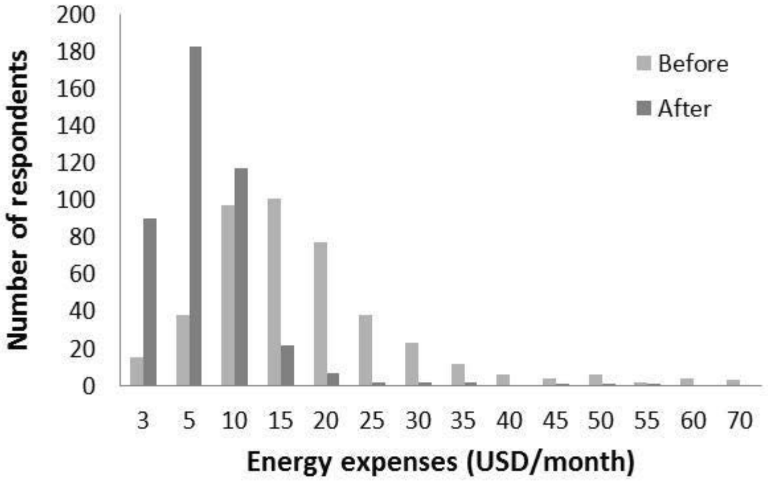

Figure 3.9 Household energy expenses before and after installation of solar home systems, extracted from household survey

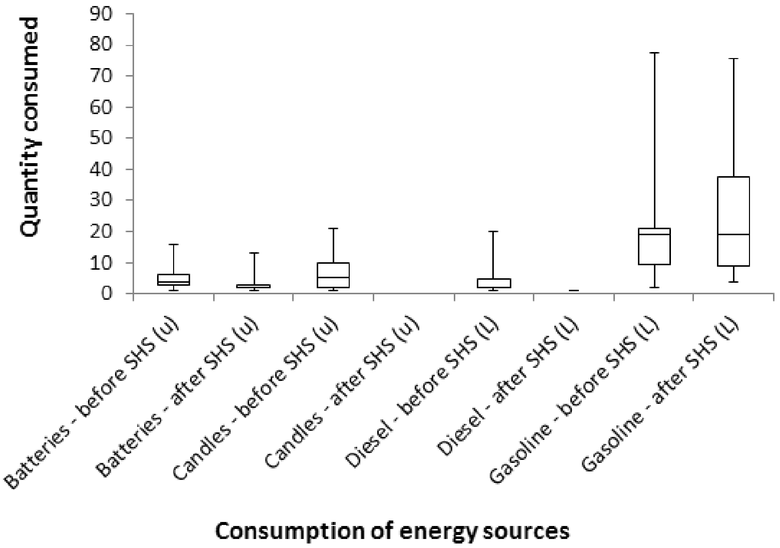

Figure 3.10 Substitution of energy sources after installation of solar home systems, extracted from household survey

Note: U=units, gal=gallons

Solar home systems also had positive environmental impacts. The replacement of diesel used before the installation of SHS for lighting in all households (23.857 l/year) resulted in a reduction of greenhouse emissions of approximately 65 t CO_2/year assuming an emission factor of 2.97 kg CO_2/l (Kaufman et al. 2000; Zhang 2014). Also, the reduced batteries consumption diminishes the risk of discharging toxic substances into the environment, since 67% of the households disposed worn-out batteries directly into the environment, and 34% burned them in open fires.

Most households perceived that there was a great improvement in different aspects of their quality of life after the installation of SHS (Figure 3.11). Household comfort, education, and social gathering were rated very high by more than 60% of the households, listening to recorded music or watching movies improved sociality at night and free time enjoyment. Improved lighting prevented accidents, e.g. burns and snake bites, facilitated food preparation and intake and the completion of household chores, and children's school work was easier as well as the practice of traditional activities, e.g. the brewing of 'chicha'. In terms of income generation, 33% of the households experienced little improvement. Better light improved production of handicrafts that are sold within the community, while small grocery shops remain open at night and people perform post-processing farming tasks after dark, e.g. peeling shell peanuts and cacao. Regarding the improvement of women´s lives, 50% of the respondents felt that the improvement was considerable, while the other 50% perceived the situation as unchanged. The increased working hours of women for gardening, food preparation, and distribution during social gathering activities from 13 hours to 16 hours per day could explain this degree of ambivalence.

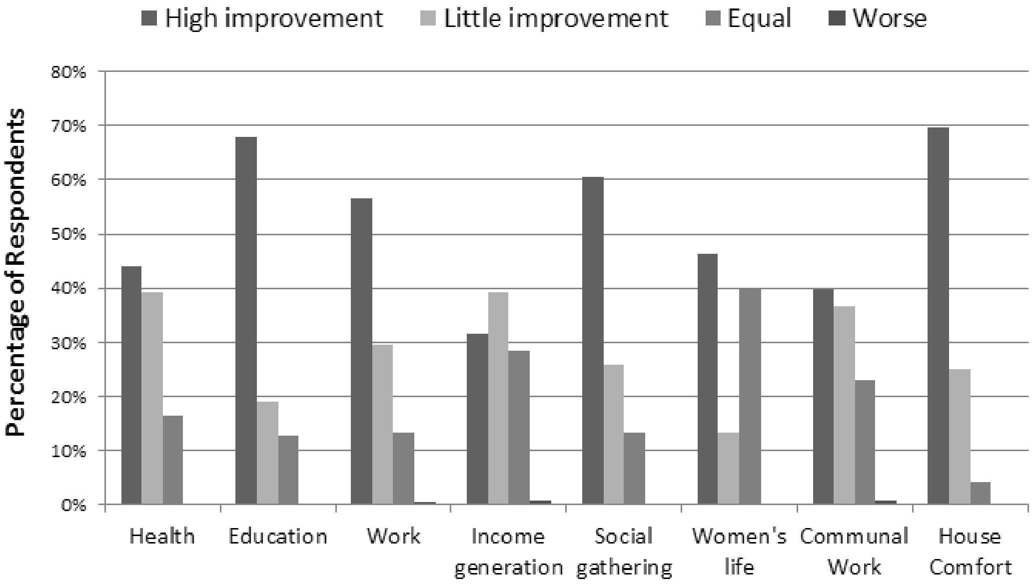

Figure 3.11 Opinions regarding the impacts of electricity on quality of life, extracted from household survey

3.3.6 Barriers

The technological, social, economic, environmental and institutional barriers that hinder DRE in the Ecuadorian Amazon as perceived by stakeholders from government, the private sector, and civil society were assessed (Table 3.6). The barriers are listed in order of concern indicated by the percentage of stakeholders mentioned in each barrier. For example, lack and variability of funding was perceived by 64% as the main economic barrier. Moreover, the difference between the percentages of stakeholders that mentioned a barrier gives a measure of the level of consensus for that barrier. Harsh environmental conditions for electronic equipment, for example, were a frequent concern for the private sector, i.e. engineers from renewable energy businesses, but not for the government policy makers.

Table 3.6 Barriers for DRE in the Ecuadorian Amazon identified in interviews

	% stakeholders that mentioned a barrier			
	Government[1]	Private Sector[2]	Civil Society[3]	Total
Technological				
Lack of training and knowledge communication	53%	100%	60%	61%
Lack of local technicians and spare parts	67%	33%	53%	58%
Low experience in developing DRE	67%	100%	33%	55%
Discredit of renewable energy	53%	33%	47%	48%
Social				
Cultural differences and priorities	47%	100%	60%	58%
Marginalization of indigenous people	40%	100%	67%	58%
Adoption of modern technology	47%	33%	47%	45%
Economic				
Lack and variability of funding	80%	67%	47%	64%
High electricity production costs	53%	100%	40%	52%
Lag of household fee payments	33%	67%	47%	42%
Low capacity to develop income generation activities	33%	100%	20%	33%
Environmental				
Accessibility and difficult logistics	67%	100%	80%	76%
Environmental risks	27%	67%	47%	39%
Harsh environment conditions for electronic equipment	7%	33%	20%	15%
Institutional				
Stakeholder conflicts and cooperation	40%	67%	80%	61%
Lack of regulations and standards for DRE	67%	100%	33%	55%
Political instability and low interest in DRE	67%	67%	27%	48%
Top-down approaches	33%	100%	47%	45%
Political and personal agendas	20%	100%	40%	36%

[1] Total respondents=15. Policy makers from the electricity (2), agriculture (1), health (3), education (1), and environment (1) sectors. Decision makers from public electricity companies (7)

[2] Total respondents=3 Renewable energy businesses that participated in most relevant DRE projects in the Ecuadorian Amazon since 2000.

[3] Total respondents=15. Indigenous political organizations (4), village electrification committee (1), energy NGOs (2), development NGOs (5), research and academia (2), missionary (1)

Technological barriers related more to the lack of knowledge and skills on DRE than to technological devices problems. The shortage of continuous training and knowledge communication using the native language was frequently mentioned as the main cause hindering technology adoption and favoring technology misuse by households thus causing high failures rates of technological devices (Table 3.5). Also, the lack of skilled local technicians and spare parts make DRE maintenance reliant on external assistance meaning that it took a long time to restore the electricity service after a failure (up to 780 days in the case study) leading to household discontent and consequently project abandonment. Moreover, electricity companies had extensive experience with grid electrification but little experience and knowledge about DRE in Amazon communities, and they perceived DRE as beyond their technical expertise. As one manager said: "We need engineers who should stay and know Amazon communities very well in order to succeed" (Interview No.6, 07/08/2013). Another consultant said: "Implementers always want to use solar home systems for the lack of knowledge on other potential technologies like hydropower or biomass" (Interview No.14, 27/09/2013). SHS is not always the best solution, especially not for higher demands as confirmed by Morante & Zilles (2007). Additionally, the frequent failures of DRE projects based primarily on SHS (section 2.1.3; Ten et al. 2015; Vasconez 2010) have discredited renewable energy technologies among decision makers and local beneficiaries reinforcing the commitment to grid electrification as the only real solution. DRE is seen as a temporary and ineffective means for electricity supply. There are promising technological options, e.g. biomass and micro-hydro for DRE in the Amazon region as confirmed by Sanchez et al. (2015), but in Ecuador, their potential is still unknown.

Social barriers relate to complex and deep social and cultural aspects that hinder the introduction and maintenance of DRE. It was regularly said that the great cultural differences between indigenous people[7] and implementers (electricity company, NGOs, renewable energy business) are usually neglected, which had led to project abandonments, failures or internal conflicts in the communities. As one researcher said: "Indigenous people have their own lifestyle, they are nomads, frequently abandon their home when land is not productive anymore" (Interview No.3, 22/06/2013); another consultant said: "When you give a solar home system to polygamous families, the men do not know how to distribute it because they have to give one system to each wife" (Interview No.9, 09/08/2013). Moreover, it was repeatedly revealed that the Ecuadorian

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[7] Nine different indigenous cultures each with their own language live in the Ecuadorian Amazon (SIDENPE 2014)

Amazon population faces high marginalization, inequality and accentuated the lack of social investment. Oil profits, which are the country's main source of income, contributed to the growth of urban areas but did not benefit the rural and remote areas of the Ecuadorian Amazon from where the oil is extracted. This is an issue confirmed by the high share of the population living in extreme poverty (78%; INEC 2015b). This leads to another barrier related to the lack of education services and low levels of formal education among indigenous people, which makes the adoption of modern technology such as solar home systems a very complicated endeavor. As one missionary said: "For hunting and fishing indigenous people build their own tools, and if there is not someone who can train them on how to use very complicated elements such as solar home systems, there is the likelihood that these elements will be destroyed" (Interview No.33, 24/04/2014), a barrier also recognized in literature (Serpa and Zilles 2007; Sovacool et al. 2011).

Economic barriers related primarily to financial and market impediments for DRE. The lack and variability of funding was recognized as the main economic barrier. The problem perceived was not the availability of funds (Figure 2.2) but rather the government or international donor’s interest to invest in DRE. One engineer said: “We had all documentation and funds approved and a tendering process started, but the project was canceled because authorities decided to stop investing” (Interview No.21, 14/01/2014). Other concern strongly emphasized was high electricity production costs in remote areas which cannot be covered by the subsidized electricity tariffs regulated by law. The high cost of transportation during maintenance (Figure 3.6), and the lag of payments for the electricity service by indigenous households (section 3.3.5, maintenance of SHS) has forced electricity companies to abstain from DRE plans in order to reduce their already high operational deficit; the latter was confirmed by Peláez-Samaniego et al. (2007). Additionally, improving people's income through productive uses of electricity to promote socioeconomic development and reduce lag of payments was commonly perceived as an impossible endeavor because of cultural aspects and geographical isolation, as one indigenous leader said “Indigenous people do not pay for electricity because they are not used to this, they are not trained for this and do not know they must pay" (Interview No.29, 22/04/2014). Also, one NGO director revealed, "our experience teaches us that it is very difficult to expect income improvements from electricity due to isolation from markets, low skills and lack of experience in market-oriented activities" (Interview No.4, 06/08/2013).

Environmental barriers primarily refer to geographical impediments and environmental risks of DRE. It was frequently said that the lack of transport infrastructure (Figure 3.7-7, 8) remoteness and harsh climate conditions make DRE a costly and high-risk enterprise. During the time of field research (2012-2014), there were six plane crashes in the Ecuadorian Amazon (El Comercio 2014). Moreover, it was frequently alleged that DRE poses environmental risks for the Amazon region. One aspect frequently highlighted was the difficulty of proper disposal of worn-out or broken equipment generated during the life cycle of DRE due to the absence of local waste management services and restricted access. For instance, the lead-acid batteries of SHS commonly used in DRE projects (Table 2.1) have a life cycle of 3-4 years. However, no evidence was found that the approximately 5000 batteries used were recycled in past projects after they had completed their life-cycle (Vasconez 2010), which left behind waste and toxic substances such as sulfuric acid with potential harming effects on the Amazon ecosystems. The environmental risk of batteries has been recognized in literature (McManus 2012; Zhang et al. 2016). Finally, environmental conditions of the Amazon regions, i.e. high temperatures and humidity, presence of insects, and thunderstorms and the form of the traditional houses without walls, with thatched roofs, and the effect of kitchen smoke (Figure 3.5), were perceived as harsh conditions for sensitive electronic equipment such as inverters and regulators that have the highest failure rates in DRE projects (Table 3.5)

Institutional barriers relate to stakeholder arrangements, regulatory challenges, and institutional capacities. The lack of cooperation and conflict between stakeholders was constantly acknowledged. Government and indigenous political organizations were said to be in constant dispute driven by resource extraction (oil, mining) in the Ecuadorian Amazon, an issue recognized in literature (Perreault 2001; Widener 2007; Warnaars 2012) that hinders DRE plans. As one NGO worker said: "The high opposition to oil extraction limits government actions in those zones due to the continuous confrontation between communities and government” (Interview No.11, 16/09/2013). Also, a lack of coordination among stakeholders responsible for DRE was frequently mentioned, as a former executive director said: "There should be an institution that properly coordinates and leads the DRE process in Ecuador" (Interview No.20, 14/01/2014). Stakeholder cooperation was worsened by two other barriers frequently mentioned. First, DRE always adopts a top-down approach limiting people´s participation (section 3.3.5). As one manager said: "Developing a project in the Amazon region is not the same as in the city, engineers do not like the canoe, the food or to sleep there, I mean they have to like it and have to stay to learn the reality” (Interview No.6, 07.08.2013). Second, personal and political interests of the government and donors were frequently mentioned, which has led to DRE projects that fulfill only short-term political agendas and neglect technical or social aspects that determine the long-term survival of projects. As one consultant said: “During installation works, I told them electric protections must be for direct current[8] but because they were in a hurry, they forced me to use protections for alternate current. That is why I am saying that when other (political) interests matter critical technical aspects are always overlooked" (Interview No.14, 27/09/2013). Most DRE projects in Ecuador were implemented using a 'donor gift' approach (Table 2.1), which lasted only 3-4 years after which the donor left the country (Vasconez 2010). Accordingly, DRE was perceived as not institutionalized. The lack of regulations and standards for DRE was frequently documented as the main cause of unsuitable designs, low-quality installation, lack of subsidies for maintenance, and differentiated tariffs for remote beneficiaries. Also, the ineffective bureaucracy that in combination with the frequently mentioned political instability manifested through periodic changes of administrations and the little interest of decision makers in DRE hinder large-scale and long-term plans for DRE in the Ecuadorian Amazon.

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[8] Direct current is the unidirectional flow of electricity and is produced by batteries or solar panels used in solar home systems, while alternate current is the bidirectional flow, which is the common form of electric power delivered to homes.

3.3.7 Drivers

Despite the recognition of electricity as a public service for all Ecuadorians, electricity supply in remote areas of the Ecuadorian Amazon has been slow and prone to failure, thus DRE needs to be stimulated. In this regard, the main drivers as perceived by stakeholders from government, the private sector, and civil society, were defined (Table 3.7) and are discussed below.

Table 3.7 Drivers for DRE in the Ecuadorian Amazon identified from interviews

	% stakeholders that mentioned a driver			
	Government [1]	Private sector[2]	Civil Society[3]	Total
Technological				
Periodic training and capacity building	60%	100%	80%	73%
Appropriate designs and technology	47%	100%	47%	52%
Local renewable energy markets	33%	67%	33%	36%
Local management of DRE	20%	100%	40%	36%
Successful local DRE experiences	13%	67%	20%	21%
Social				
Household participation and ownership	33%	67%	47%	42%
Indigenous culture, social cohesion and organization	7%	100%	53%	36%
Community entrepreneurship	20%	67%	33%	30%
Women participation	7%	67%	13%	15%
Economic				
Externalities of rural electrification	60%	100%	80%	73%
Alternative funding schemes	53%	100%	53%	58%
Community-based income generation	33%	67%	47%	42%
Public-private partnerships	13%	33%	27%	21%
Environmental				
Amazon region conservation	53%	67%	60%	58%
Improved transport infrastructure	7%	0%	7%	6%
Institutional				
Adopt bottom-up and integrated approaches	87%	100%	67%	79%
Regulations conducive to DRE	73%	100%	60%	70%
National constitution and public policies	53%	100%	33%	48%

[1] Total respondents=15. Policy makers from the electrical (2), agriculture (1), health (3), education (1) and environmental (1) sectors. Decision makers from public electricity companies (7)

[2] Total respondents=3. Renewable energy businesses that participated in most relevant DRE projects in the Ecuadorian Amazon since 2000.

[3] Total respondents=15. Indigenous political organizations (4), village electrification committee (1), energy NGOs (2), development NGOs (5), research and academia (2), missionary (1)

The leading technological driver relates to enhancing knowledge and skills of households, implementers and local and indigenous technicians. The latter were seen the key driver for a local management of DRE and reduce external assistance, but especially to speed up technology adoption. Tillmans & Schweizer-Ries (2011) confirm this and found that those socially and spatially close to electricity users can envisage and effectively communicate knowledge about renewable energy. The implementers, i.e. technical and administrative staff of electricity companies, need to be re-skilled on technical aspects to ensure appropriate DRE designs and high-quality installations, but also, and perhaps more important, on intercultural communication. Moreover, an independent and systematic evaluation of DRE by research and academic institutions was frequently demanded, especially to guarantee access to that information in order to transfer successful and local DRE experience as opposed to adopting experiences from other countries. Additionally, promoting local markets and renewable energy industries were commonly said to be needed to tackle the complex implementation process and reduce high technology up-front costs.

The social driver frequently mentioned was participation of indigenous people. It was perceived important to tackle traditional 'donor gift' approaches to DRE, promote project ownership and autonomy of the Amazon people who should be responsible for the proper use of solar home systems, and for improving their own situation once electricity arrives in their lives. This driver is also confirmed in literature (Andrade et al. 2011; van Els et al. 2012). Additionally, indigenous culture is characterized by a strong social cohesion, which was seen as an ally for success. It was frequently alleged that indigenous people value very highly their own rather than government authorities as also confirmed in literature (Hendricks 1988; Perreault 2003), making village presidents and indigenous political organizations powerful and central stakeholders (Figure 3.4) for effectively organizing communities along the process of DRE. Another social collaborator frequently emphasized was Amazon communities who entrepreneurs in market-oriented activities usually supported by NGOs. They were seen central for scaling up DRE effectively by communicating their own experiences with other communities. 'Word-ofmouth' was observed as an effective mechanism of communication that indigenous people trust, rather than information conveyed in word or writing by project implementers. This belief is confirmed by Ramirez et al. (2014). Lastly, women's participation which has been overlooked in DRE, was also seen as a collaborator for success as extensively recognized in literature (Batliwala and Reddy 2003; UNWOMEN 2013). From field observations, men go outside the community very often and for long periods for hunting or travels to cities, while women regularly stay at home, making them the main user and beneficiary of electricity (Figure 3.11) and also more reliable with respect to taking over local maintenance responsibilities.

The economic driver most cited was to account for externalities of electricity to stimulate public investments in DRE. Electricity is a public service (Ecuador 2015) and hence it was claimed that decisions should be based on the social returns of electricity rather than on the financial return. Literature suggests that the former frequently surpass the latter (World Bank 2002; World Bank 2009; Mishra and Behera 2016). For example, the case study demonstrates that electricity access mitigated a human rabies epidemic outbreak, and consequently reduced public health expenditures. This is confirmed by Mendes et al. (2009). Furthermore, an alternative funding mechanism was frequently demanded to ensure public investments in DRE. A co-funding strategy between government agencies was seen as an effective way to distribute the cost-benefits of electricity. Also, international carbon markets were frequently mentioned, because DRE helps to reduce greenhouse gas emissions (section 3.3.5, environmental impacts). A better coordination between the government and international donors is required to create possible alternative financing mechanisms for DRE (Bhattacharyya 2013). Moreover, it was frequently highlighted that DRE should promote community-based rather than household-based income generation activities. The economy of scale and community activities will smooth the transition from an economy based on bartering and subsistence agriculture to a market-oriented economy confirmed by Erazo (2010). Eco-tourism or organic farming were mentioned as promising alternatives for sustainable economic growth, also confirmed in literature (Ingles 2002; Hoefle 2016). Finally, private-public partnership between the government and renewable energy businesses was frequently mentioned as a new business model that can drive cost reduction in DRE but also promote renewable energy markets. This has proven to be successful in Bangladesh (Mithila and Sharif 2013), which is a low-income country with the largest number of installed SHS worldwide (Kempener et al. 2015).

It was recurrently perceived that DRE is an environmentally friendly electrification for the conservation of the Amazon region. Besides the reduction of greenhouse gas emissions, it was perceived that DRE can delay grid expansion reducing the risk of deforestation that might result from electricity grid constructions with their 6-m buffer zones along the cable networks or from electricity uses such as sawmills in the logging industries. Moreover, improving the infrastructure for river transportation was stated as a sustainable alternative to overcome the challenge of accessibility. Air transportation is very expensive, highly risky, and inefficient for transporting heavy and voluminous equipment (Figure 3.7-7). Road expansion is also not a good option, as it directly causes deforestation (Mena et al. 2006). The advancement on electric boats (Guaman et al. 2015) suggests that DRE and electric mobility in rivers can be complementary for a sustainable development in the Amazon region. The Ministry of Transport, municipalities, and provincial governments are responsible for transport infrastructure planning and development, and the MEER and electricity companies should be informed about road extensions to define long-term planning for grid expansion or DRE.

Regarding institutional drivers, it was frequently claimed that DRE should adopt an integrated and bottom-up approach. The former demands new or strengthening existing public partnerships between; for example, electricity companies, Ministry of Health, Ministry of Education, and Ministry of Telecommunications to make DRE congruent with development plans in the Ecuadorian Amazon. Bottom-up approaches require moving from consultation to an active participation of people incorporating their values of electricity service during the decision making of DRE. Hirmer & Cruickshank (2014) confirm and suggest that functional, social significance, epistemic, emotional, and cultural values are important for success in rural electrification plans. Moreover, existing regulations and technical standards of rural electrification need to be tailored for DRE in the Amazon region to stimulate appropriate designs and installations, which need to be simple, robust, modular and flexible enough for a secure installation in traditional houses, and better financial schemes with differentiated tariffs that ensure enough funds for the maintenance of DRE. Also, new organizational capacities and processes are needed at all levels of decision-making. The creation of specialized units of renewable energy, inexistent in most electricity companies, was perceived as the success factor in the case study. Finally, the actual political environment was frequently mentioned as positive. The new constitution (Ecuador 2008) and the Organic Law of the Electrical Sector (Ecuador 2015) are important legal instruments for the institutionalization of DRE, and enforcement of universal access, social inclusion, and environmental conservation.

3.4 Conclusions

Through a comprehensive stakeholder analysis, relevant individuals and institutions that have a direct or indirect role in the process and outcome dimension of DRE in the Ecuadorian Amazon were identified and their importance was evaluated (Table 3.4). Through semi-structured interviews with stakeholders, and contrasting the findings with a household survey with beneficiaries of a solar electrification program, barriers (Table 3.6) and drivers (Table 3.7) that hamper or favor the progress of a sustainable DRE in the Ecuadorian Amazon were identified and discussed.

DRE is the result of an entangled network of stakeholders with diverse types and levels of interest and influence (Figure 3.4). Although DRE is a government-dependent process, informal stakeholders´ relationships occur subtly but nevertheless significantly. Often neglected stakeholders were crucial for DRE in terms of supporting the process of electricity services provision or productive uses of electricity, and relevant interactions were found among stakeholders at the provincial and local levels. Thus, multiple stakeholders needs to engage in a decentralized decision-making process to ensure sustainable DRE.

Notorious barriers and drivers allowed drawing conclusions on the aspects needed to make DRE work sustainably in the Ecuadorian Amazon. From a technological viewpoint, sustainable DRE relates to proper knowledge and skills to locally operate and manage renewable energy, context-appropriate communication knowledge between beneficiaries (indigenous people) and electricity suppliers to stimulate an effective technology adoption, and appropriate DRE designs and installations resilient to harsh operating conditions. From a social perspective, sustainable DRE relates to a high participation of households at different levels of decision-making supporting people´s ownership and autonomy, a process supported by key actors of local and social organization structures such as indigenous technicians, indigenous political organization, village leaders, and women. From an economic viewpoint, as DRE will remain a public sector investment in Ecuador, economic sustainability relates to the social returns of electricity rather than to financial returns. Therefore, funding for the introduction and maintenance of DRE is always available supported by alternative funding mechanisms such as co-funding among government agencies and carbon markets. Also, DRE should promote community-based income generation activities such as tourism and farming perceived compatible with a sustainable economic growth in Amazonian communities. From an environmental standpoint, sustainable DRE relates to the effects that support the conservation of the Amazon region through reducing greenhouse gas emissions, waste generation, and deforestation. Also, accessibility to remote communities is supported by means of river transportation that eases electricity service provision while promoting socio-economic development and environmental conservation. From an institutional viewpoint, sustainable DRE relates to tailored regulations, standards and organizational capacities that are conducive for a bottom-up and integrated approach for electricity supply that integrates beneficiaries' values of electricity services during the design, implementation and post-implementation of DRE.

4 DECENTRALIZED RURAL ELECTRIFICATION IN THE AMAZON REGION: A PARTICIPATORY SYSTEM ANALYSIS

4.1 Introduction

As detailed in the previous chapter, DRE in remote areas of the Ecuadorian Amazon is influenced by a tangled network of social, economic, technological, institutional and environmental barriers. Addressing only technological barriers, for example, ensuring local technicians and spare parts, will not be enough to overcome social barriers like culture differences or marginalization of indigenous people. This is because DRE is a complex energy system in a state of flux whose behavior is difficult to predict if these barriers are addressed separately (Bale et al. 2015). Thus, a holistic understanding of DRE is essential to increase the probability of finding success (Pandey 2002; Brent and Kruger 2009). This implies that the analysis of DRE must focus on the complex relationships between technological, social, economic, environmental and institutional aspects that influence sustainable DRE through the application of systems thinking approaches (Brent and Kruger 2009; Bhattacharyya 2011; Bale et al. 2015).

To simplify this complexity, integrated assessment frameworks based on indicators are frequently used for setting targets and monitoring the sustainability of DRE (World Bank 2003; Ilskog and Kjellström 2008; Purwanto and Afifah 2016). However, these studies have overlooked the interlinkages between environmental, social, economic, technical, and institutional indicators, and failed to provide a holistic representation of the various structural and dynamic linkages of DRE (Mainali and Silveira 2015). According to Brent & Rogers (2010), indicators and their interlinkages must be defined by stakeholders to reduce uncertainty and improve the design and management of sustainable DRE. Thus, the complexity of DRE must be outlined from multiple stakeholder inputs to identify and incorporate key system processes at different levels of decision-making (Hiremath et al. 2007; Goldthau 2014), link knowledge and actions (Wiek and Binder 2005), and enhance the knowledge base for capturing underlying social, cultural or institutional aspects of DRE relevant for the sustainability of DRE (Brent and Kruger 2009; Brent and Rogers 2010). In this regard, participatory systems analysis approaches (Vester 2007) provide ideal frameworks of analysis for deeper insight into the complexity of DRE.

Thus, the aim of this part of the study is to identify the variables that interplay in the sustainability of DRE in the Ecuadorian Amazon grounded on stakeholder viewpoints and to evaluate variable roles within the system. Research outcomes will provide general arguments to define a 'cause-effect' system model of DRE, which is needed for the construction of decision support tools to assess and simulate the sustainability of DRE in the Amazon region context.

4.2 Material and methods

4.2.1 Sensitivity Model

The computerized Sensitivity Model® developed by Vester (2007) was adopted for this study. The Sensitivity Model has its foundations in cybernetics and is designed to guide stakeholders to visualize and analyze the dynamic of complex systems (Vester 1988). It has been shown to facilitate consensus building among stakeholders due to its linguistic and fuzzy logic reasoning (Chan and Huang 2004). Also, it is composed of a set of flexible system tools applied in stakeholder discussions that remain open and iteratively revised by the findings of subsequent steps (Vester 2007). Each contribution is considered only if it reaches a certain level of consensus. Thus, the sharing process prevents personal interest to be imposed. Also, the results emerge from the analysis of complex interlinkages between variables so results cannot be controlled by deterministic processes but from the consequence of aggregated knowledge (Hürlimann 2009). The Sensitivity Model has been applied to identify strategies for energy efficiency in industrial processes (Krenn et al. 2015), to study the sociopolitical mechanism of nuclear energy (Schlange 1995), and to assess and model sustainability of rural communities (Chan and Huang 2004) and urban development (Huang et al. 2009).

The adapted Sensitivity Model approach used in this study followed an iterative and participatory process applied in a two-day workshop and data exploration (Figure 4.1). Phase I defined system boundaries, variables that are relevant for stakeholders to describe the DRE system. In Phase II, stakeholders identified and assessed the inherent effect among variables. At this point, a deeper insight into the systemic role of variables was acknowledged and discussed. Phase III included a comprehensive and visual description of variable interactions and the construction of a qualitative 'cause-effect' system model of DRE in the Ecuadorian Amazon.

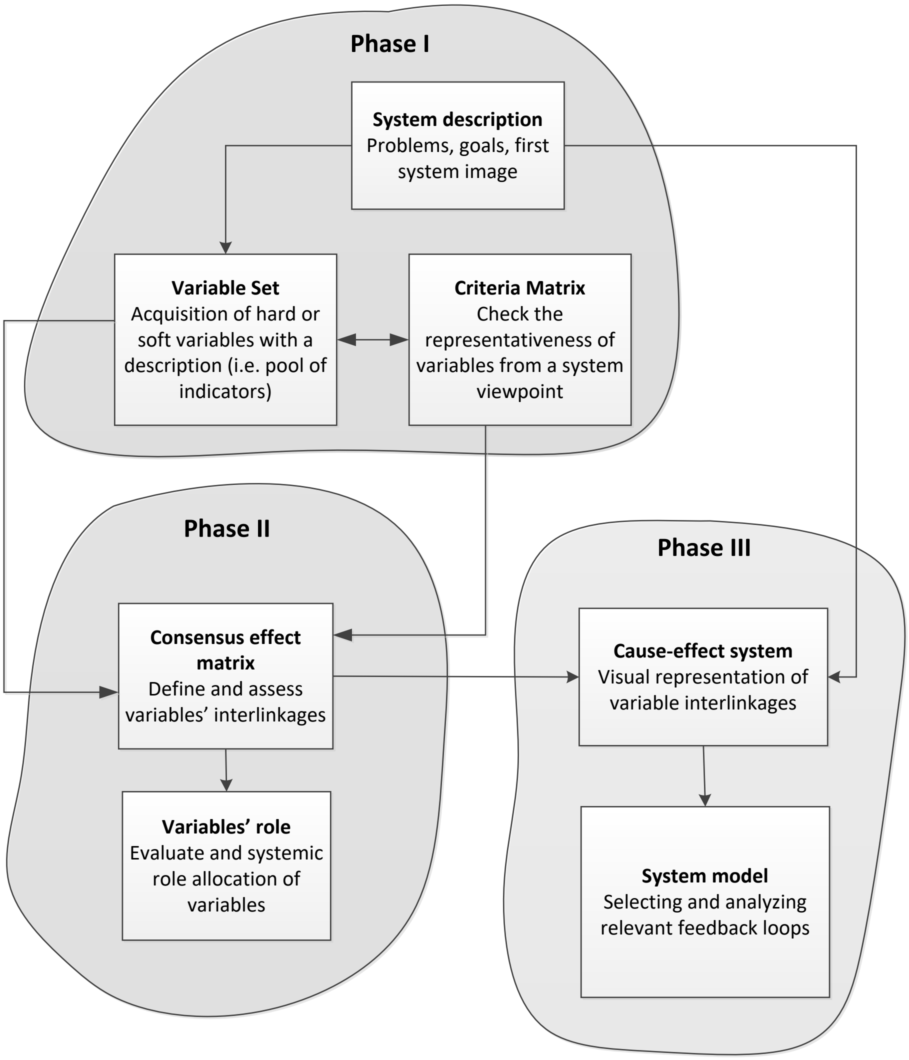

Figure 4.1 Overview of the applied participatory system analysis. Source: Vester (2007)

4.2.2 Design of the participatory process

The Sensitivity Model relies on stakeholder interaction and agreement (Vester 2007). Thus, a careful design of the workshop was carried out. A separation of participant roles is recommended (Vennix 1999), therefore following the work by Lendaris (1979) these were defined as (i) the 'method technician': i.e. the author of this study with a passive role during workshop to minimize bias, and (ii) the 'facilitating team': i.e. an external team knowledgeable on group dynamics and Sensitivity Model application in the study area. They were responsible for bridging the ‘method technician’ with the (iii) 'participants': i.e. representatives of different sectors of DRE selected via stakeholder analysis (Chapter 3; Table 4.1). Workshops were recorded for further compilation, analyses, and interpretation. Individual identities of participants were kept confidential and anonymity was guaranteed.

Table 4.1 Participants of the workshop

Stakeholder	Number of participants
Church and missionary orders	1
Donors	1
Research and academic institutions	3
NGOs working in energy and development topics	4
Village electrification committee coordinator	1
Electricity companies of the Ecuadorian Amazon	19
Ministry of Electricity and Renewable Energy	2
Ministry of Health (Director of hospitals and local health staff)	4
Ministry of Environment	1
Ministry of Tourism	1
Ministry of Agriculture	1
Ministry of Telecommunications	1
Municipalities	2
Transport business	1
Renewable energy business	3
TOTAL	45

4.2.3 Phase I: defining the set of variables

The definition of system boundaries and its variables is a critical step in system analysis (Wolstenholme 1990; Vester 2007). This process started with an unstructured but comprehensive participant discussion of DRE and development (Figure 4.2-1,3) guided by the facilitator team. Some of the questions used included: Where are the problems? What can be done? Where are the limits? Who is against what particular action and why? What needs to be preserved? How does the system hold up? What are specific characteristics? Then, the information collected (keywords) were aggregated by similarities, e.g. community health, household health, new sicknesses and health service provision were all aggregated under the umbrella of 'health', forming a preliminary set of variables (Figure 4.2-2). Also, a schematic representation of the system was used to facilitate discussions (Figure 4.2-4).

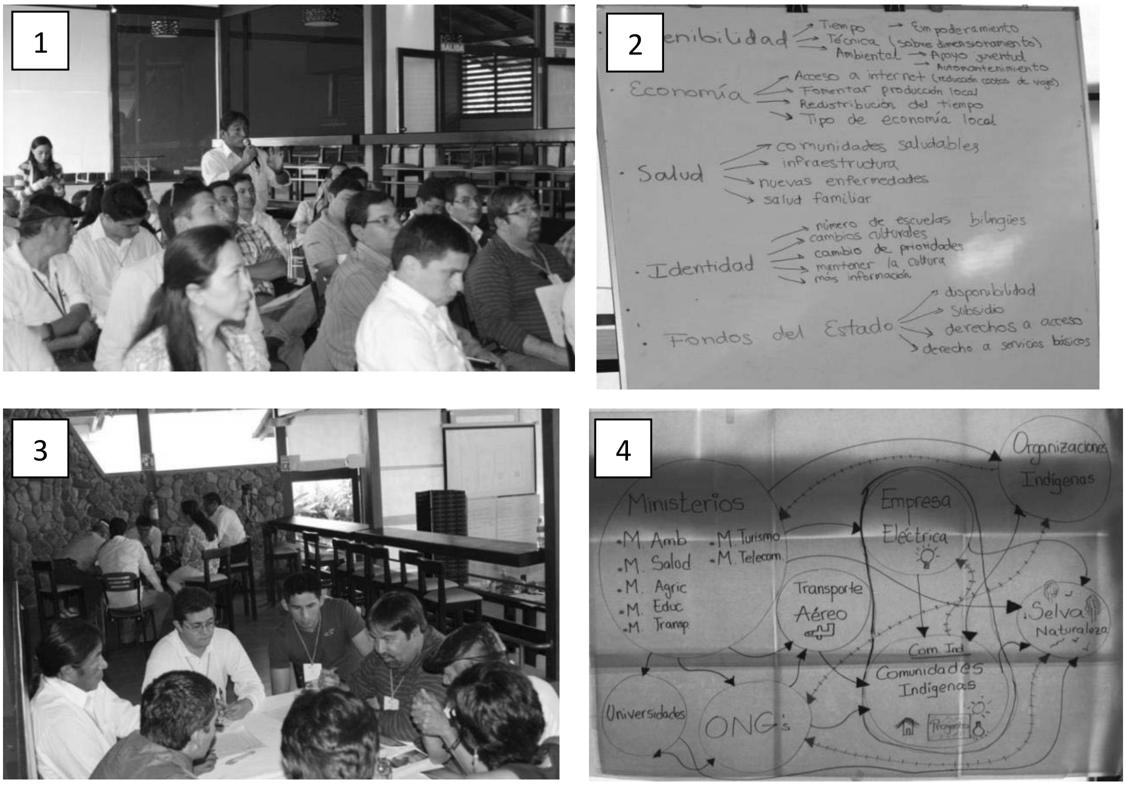

Figure 4.2 Stakeholder workshop: 1) open and unstructured discussions, 2) example of aggregating variables from participant discussions, 3) group discussions, 4) schematic diagram of the system supporting discussions.

The refinement of the set of variables was iterative and followed the principles suggested by Vester (2007): (i) creation of variable names should represent changeable values, e.g. management efficiency rather than management, (ii) description of the variables should convey objective facts based on stakeholder experiences, (iii) variables could be hard[9] or soft[10] and should be measured via quantifiable indicators (keywords),

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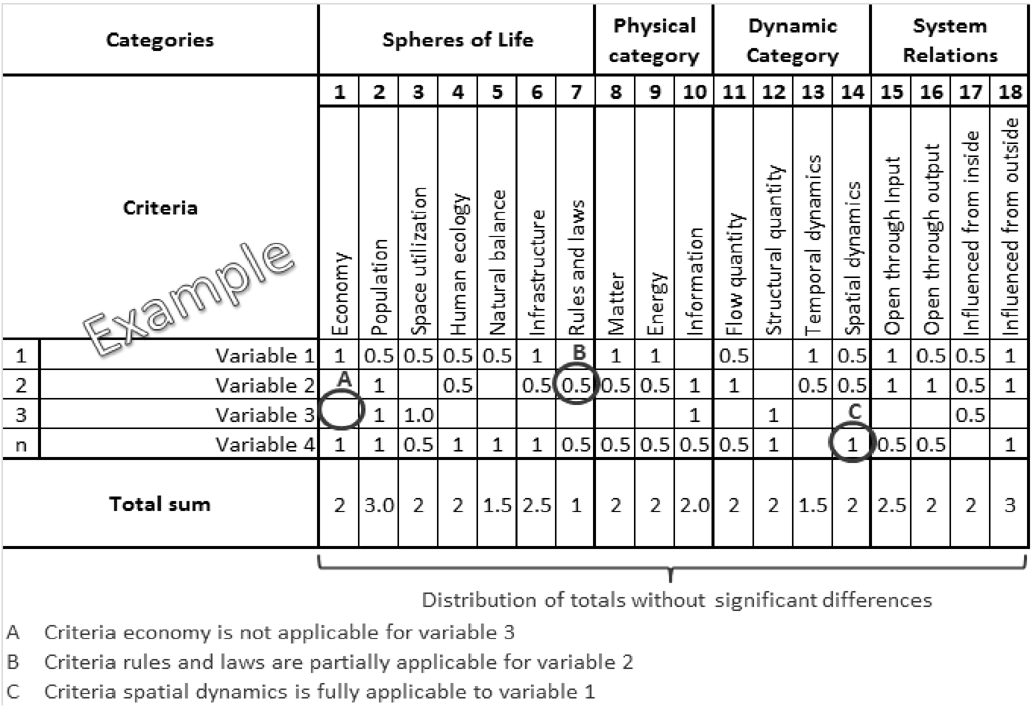
[9] variables that can be formulated with existing numerical data and quantitative metrics

[10] intangibles and numerical data usually is unavailable or non-existent

(iv) variables should be at the same level of aggregation, and should provide a complete representation of the system.

A `criteria matrix` was used to check the completeness of the set of variables from a systems viewpoint (Vester 2007). For a given variable, if a criterion was fully applicable, partly applicable or not applicable, values of 1, 0.5, or 0 were assigned to each variable, respectively (

Figure 4.3). The sum of the matrix columns evaluates the completeness of the set of variables for each criterion, i.e. 18 criteria in four categories. The totals were compared among each other, and if they showed a distribution without significant differences the set of variables could be considered to depict a comprehensive representation of the whole system.



Categories		**Spheres of Life**							**Physical category**			**Dynamic Category**				**System Relations**			
Criteria		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
		Economy	Population	Space utilization	Human ecology	Natural balance	Infrastructure	Rules and laws	Matter	Energy	Information	Flow quantity	Structural quantity	Temporal dynamics	Spatial dynamics	Open through Input	Open through output	Influenced from inside	Influenced from outside
1	Variable 1	1	0.5	0.5	0.5	0.5	1	B	1	1		0.5		1	0.5	1	0.5	0.5	1
2	Variable 2	A	1		0.5		0.5	0.5	0.5	0.5	1	1		0.5	0.5	1	1	0.5	1
3	Variable 3		1	1.0							1		1		C			0.5	
n	Variable 4	1	1	0.5	1	1	1	0.5	0.5	0.5	0.5	0.5	1		1	0.5	0.5		1
Total sum		2	3.0	2	2	1.5	2.5	1	2	2	2.0	2	2	1.5	2	2.5	2	2	3

Distribution of totals without significant differences

A Criteria economy is not applicable for variable 3
B Criteria rules and laws are partially applicable for variable 2
C Criteria spatial dynamics is fully applicable to variable 1

Figure 4.3 Example of criteria matrix to assess the representativeness of the set of variables. Source: Vester (2007)

4.2.4 Phase II: analyzing variable interlinkages and roles

Analyzing variable interlinkages

Once the set of variables was defined, participants were divided into groups, including one member of the facilitator team to guide discussions and amend any methodological error (Figure 4.2-3). Through pair-wise comparisons, participants assessed the direct effect of one variable upon every other supported by the scale shown in Figure 4.4 where the focus was on strength and not direction. The agreed value was transcribed on paper and titled “effect matrix” (Figure 4.5). The result of each group was compiled, discussed, and a 'consensus effect matrix' was agreed upon.

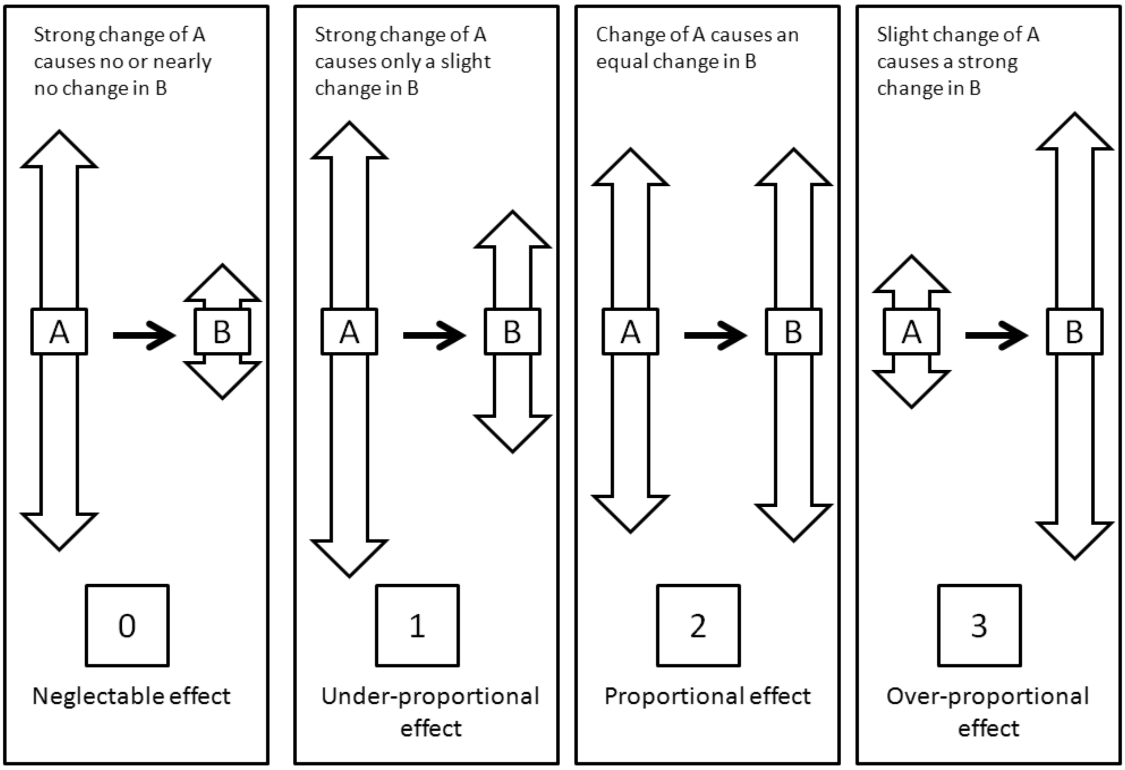
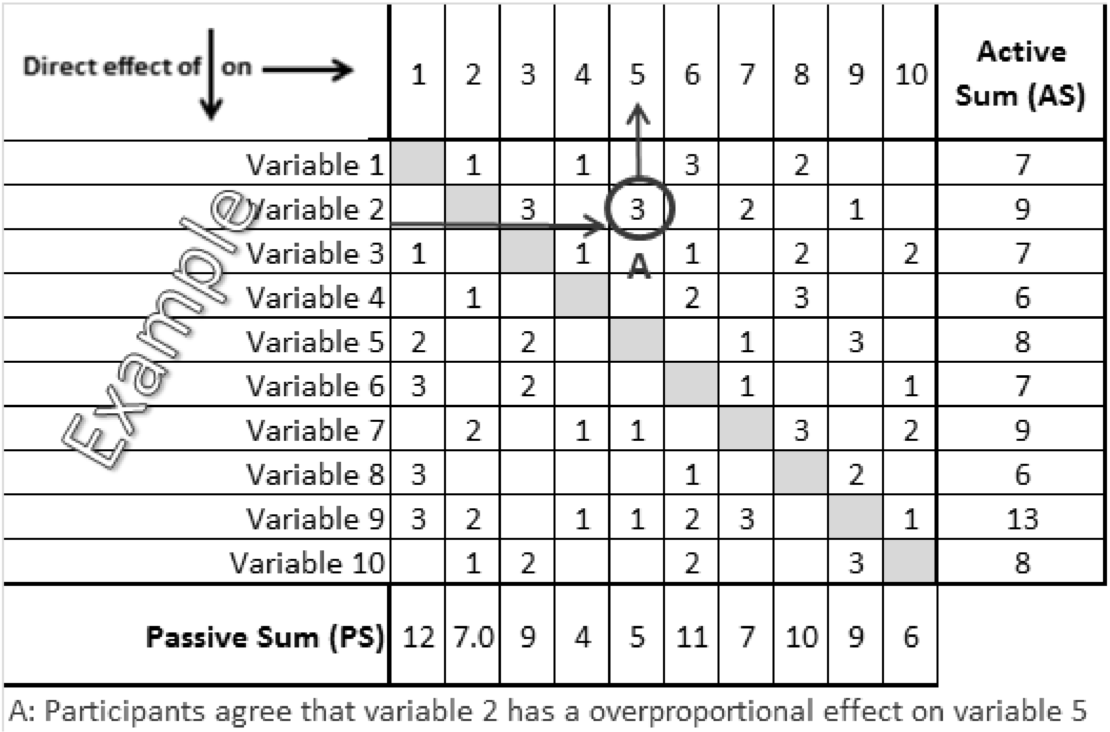


Figure 4.4 Scale to assess variable effects given by participants. Source: Vester (2007)



Direct effect of ↓ on →	1	2	3	4	5	6	7	8	9	10	Active Sum (AS)
Variable 1		1		1		3		2			7
Variable 2			3		3		2		1		9
Variable 3	1			1		1		2		2	7
Variable 4		1				2		3			6
Variable 5	2		2				1		3		8
Variable 6	3		2				1			1	7
Variable 7		2		1	1			3		2	9
Variable 8	3					1			2		6
Variable 9	3	2		1	1	2	3			1	13
Variable 10		1	2			2			3		8
Passive Sum (PS)	12	7.0	9	4	5	11	7	10	9	6	

A: Participants agree that variable 2 has a overproportional effect on variable 5

Figure 4.5 Example of a consensus effect-matrix. Source: Vester (2007)

From the 'consensus effect matrix' (Figure 4.5), the sum of rows calculates the active sum for each variable i (ASi), while the sum of columns calculates the passive sum for each variable i (PSi). ASi expresses the total effect of a given variable upon the system, while PSi describes the total effect of the system on a given variable. Both ASi and PSi were combined to calculate the P-value (Pi) (equation 4-1) and Q-value (Qi) (equation 4-2) for each variable i. These are metrics that define the systemic role of the variable within the system (Vester 2007).

$$P_i = AS_i * PS_i \tag{4-1}$$

$$Q_i = AS_i \,/\, PS_i \tag{4-2}$$

Defining the variable role

The role of the variables is determined by the range of P-values and Q-values (Table 4.2) and interpreted as follows: The higher the P-value (AS and PS high), the greater the variable influences other variables and is also influenced by them, and thus the more interconnected the variable is within the system. Such variables are called 'critical' and their opposites 'buffering'. On the other hand, the higher the Q-value (AS is much higher than PS), the greater the variable influences other variables while the variable itself is not much influenced by other variables. In this case, the variable´s impact strength is higher on the whole system. Such variables are called 'active' and their opposites 'reactive'.

Table 4.2 Scales for interpreting the variable role in the system. Sources: Wolff et al. (2010); Vester (2007); Schlange & Jottner (1997)

Impact strength	**Q-value limits**	**Interconnectedness**	**P-value limits**[1]
Highly active	Q > 2,25	Highly critical	P > 2,5a
Active	1,60 < Q > 2,25	Critical	1,70a < P > 2,5a
Moderately active	1,30 < Q > 1,60	Moderately critical	1,20a < P > 1,70a
Neutral	0,75 < Q > 1,30	Neutral	0,80a < P > 1,20a
Moderately reactive	0,60 < Q > 0,75	Moderately buffer	0,51a < P > 0,80a
Reactive	0,45 < Q > 0,60	Buffering	0,16a < P > 0,50a
Highly reactive	Q < 0,45	Highly buffering	P < 0,16a

Note 1: a= $(n-1)^2$, n = number of variables

To support a visual interpretation, the variables are plotted in a diagram that depicts the four metrics (Figure 4.6): PS and AS on the x- and y-axes, P-values from the bottom-left to top-right, and Q-values from bottom-right to top-left. Based on the location of the variables, their role within the system is categorized and interpreted accordingly.

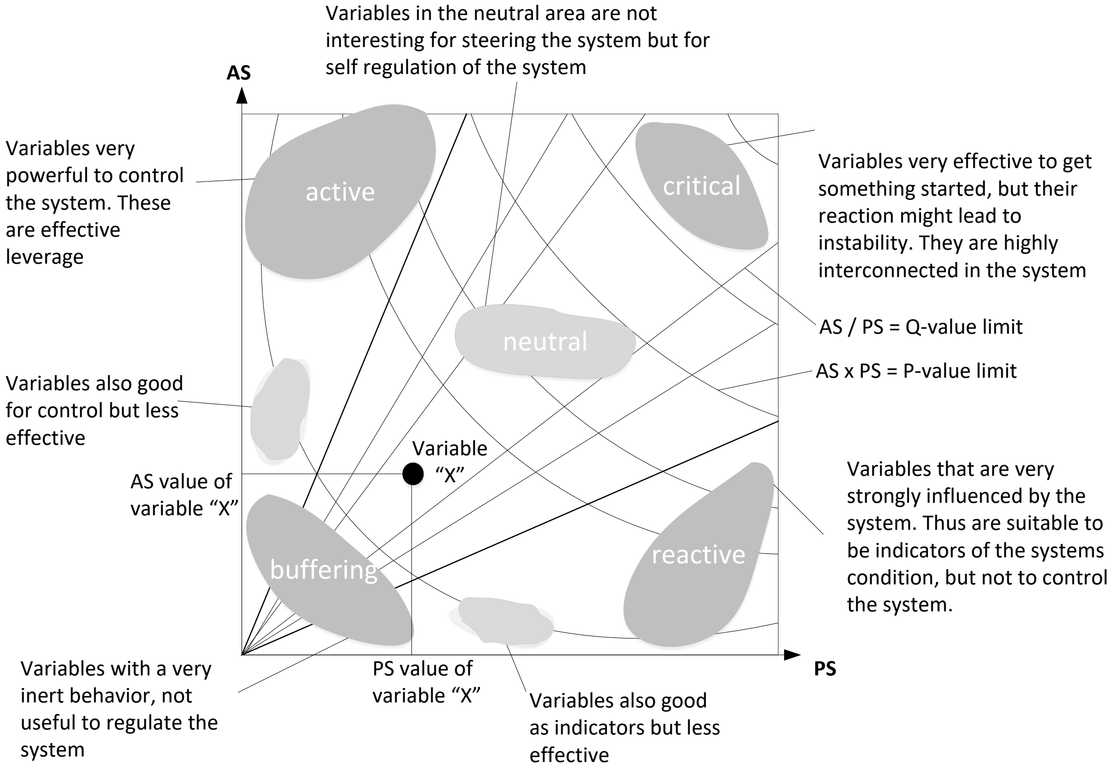


Figure 4.6 Diagram to allocate variable role within the system. Sources: Wolff et al. (2010); Vester (2007); Schwanck & Ehnis (2004)

4.2.5 Phase III: system model

The final step focused on portraying the direction of the effects between variables using the nomenclature shown in Figure 4.7. The resulting 'cause-effect' diagram provided a comprehensive visualization of system interconnectedness and facilitated the identification of feedback loop structures. Two types of feedback loops exist, i.e. reinforcing feedback loops, which can lead to extreme situations in the system, and balancing feedback loops, which can lead to self-regulation of the system (Vester 2007).

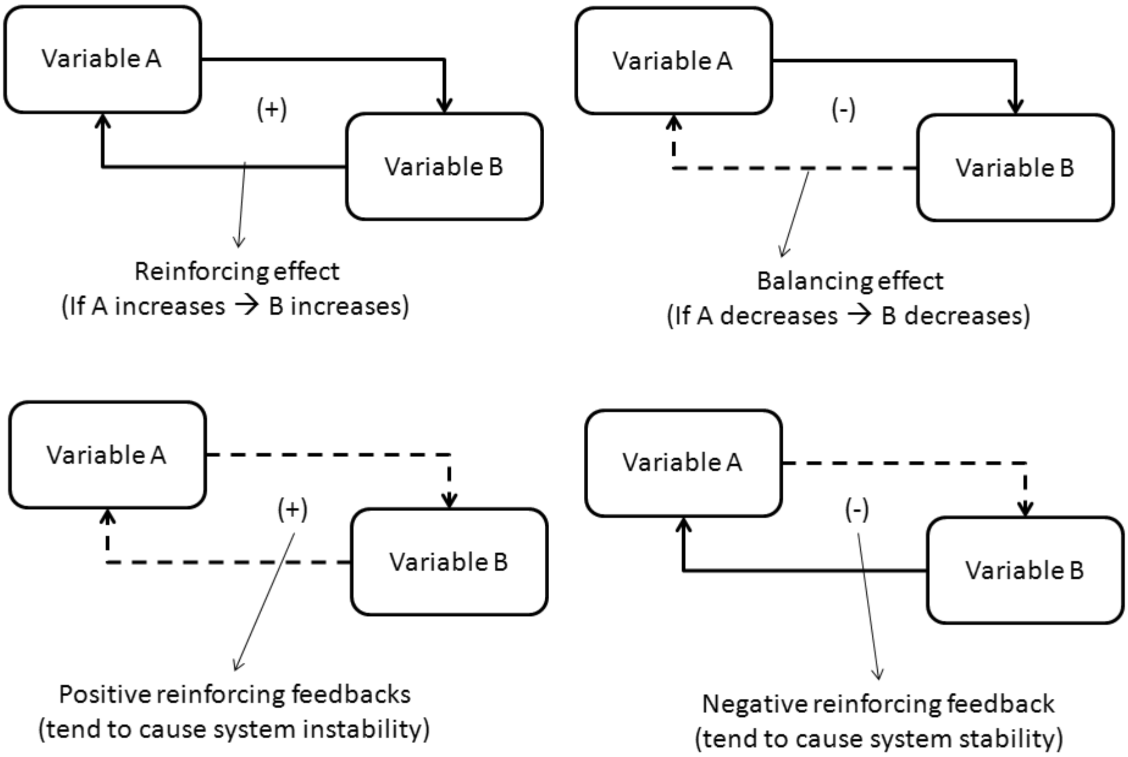


Figure 4.7 Nomenclature to construct the cause-effect diagram. Source: Vester (2007)

4.3 Results

4.3.1 Variables

The workshop participants defined seventeen (17) variables encompassing environmental, institutional, social, economic and technological aspects of DRE in the Ecuadorian Amazon (Table 4.3). A description of collected keywords (pool of potential indicators) used to form the variable's description is given in Appendix 2-1.

The set of variables provides an aggregated and holistic viewpoint and defines system boundaries to capture the overall sustainability of DRE as perceived by stakeholders. The completeness of the set of variables from a systems viewpoint was confirmed by cross-checking all variables against the 'criteria matrix' (Appendix 2-2 and Figure 4.3 for methodological background). Thus, the set of variables provides a complete image of the system ensuring salience and acceptance of research results.

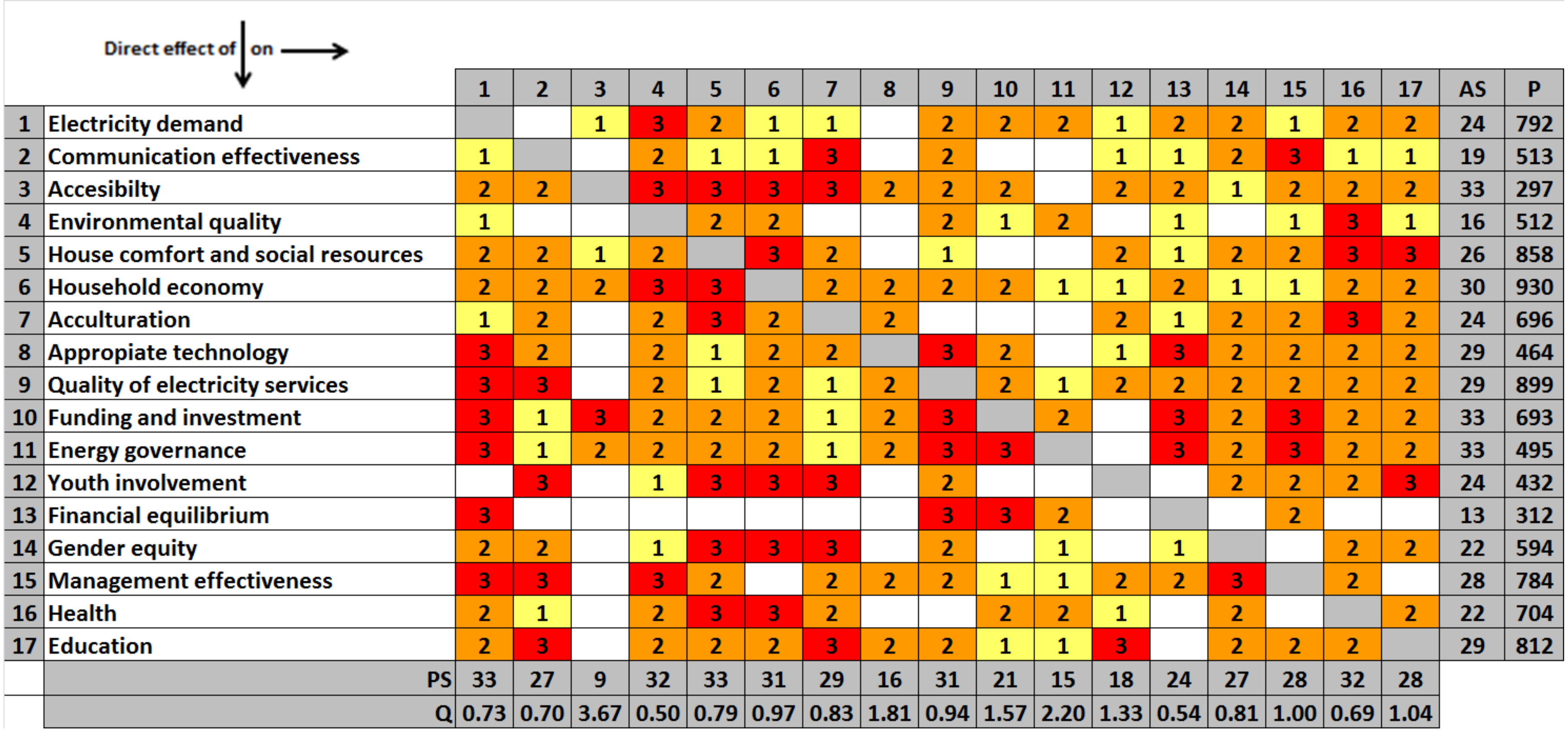
Table 4.3 System variables of DRE in the Ecuadorian Amazon, extracted from workshop

No	Variable	Description
1	Electricity demand	Sufficiency and coverage of user´s electricity demand
2	Communication effectiveness	Higher degree and effectiveness of communication among stakeholders (e.g. electricity suppliers, households, indigenous political organizations)
3	Accessibility	Better access to markets, urban centers, or other basic services (health, education, internet) nonexistent in Amazon communities
4	Environment quality	Non-harming effects of electricity supply and use on the Amazonian ecological system
5	Home comfort and social resources	Higher degree of comfort to support housework tasks, free time enjoyment and traditional and social practices that strength social networks
6	Household economy	Improved household ability for income generation and reduction of expenses on energy sources
7	Acculturation	Higher level of attachment to indigenous culture and traditional practices
8	Appropriate technology	Higher technology appropriateness for the local context in order to meet energy needs, local capacity to handle technology, and low environmental impact
9	Quality of electricity service	Higher degree of compliance with quality standards of electricity service (e.g. availability of electricity, low frequency of service loss)
10	Funding and investment	Higher availability of economic resources for a continuous electricity service provision, including other social investments that could influence electricity service economy
11	Energy governance	Higher political commitment and coherence on fostering universal access and development

No	Variable	Description
12	Youth involvement	Equitable participation and benefits for young indigenous population in the process of electricity service provision
13	Financial equilibrium	Higher degree of financial viability of electricity service provision considering income from households (i.e. regulated tariff) and subsidies (i.e. government disbursements) and economic returns
14	Gender equity	Equitable participation and benefits for men and women in the process of electricity service provision
15	Management effectiveness	Higher level of effectiveness of institutional and stakeholder arrangements to ensure continuous electricity service in remote communities
16	Health	Improvement of health conditions and services in Amazon communities
17	Education	Improvement of education services in Amazon communities

4.3.2 Variable interlinkages and roles

Five different groups of stakeholders discussed and assessed the variable effects on each other (section 4.2.4). The resulting matrices were compiled, the effects with significant differences discussed, and any inconsistency was amended (the differences between group matrices are given in Appendix 2-3) leading to a final 'consensus effect matrix' (Figure 4.8). Each cell is the direct effect's strength of the vertical variable on the horizontal variable agreed by workshop participants. The total sum of rows (AS, Figure 4.8) measures how strong the variable's effect on the system is. Variables with high AS (e.g. *'accessibility (3)'*) will significantly influence the system, while variables with low AS (e.g. *'financial equilibrium (13)'*) need to change extensively to influence the system. On the other hand, the total sum of columns (PS, Figure 4.8) measures the strength of the system's effect on a given variable. Variables with high PS (e.g. *'household economy (5)'*), will be influenced significantly by the system, while variables with low PS (e.g. *'energy governance (11)'*) will be influenced if there is an extreme change in the system.



Direct effect of ↓ on →		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	AS	P
1	Electricity demand			1	3	2	1	1		2	2	2	1	2	2	1	2	2	24	792
2	Communication effectiveness	1			2	1	1	3		2			1	1	2	3	1	1	19	513
3	Accesibilty	2	2		3	3	3	3	2	2	2		2	2	1	2	2	2	33	297
4	Environmental quality	1				2	2			2	1	2		1		1	3	1	16	512
5	House comfort and social resources	2	2	1	2		3	2		1			2	1	2	2	3	3	26	858
6	Household economy	2	2	2	3	3		2	2	2	2	1	1	2	1	1	2	2	30	930
7	Acculturation	1	2		2	3	2		2				2	1	2	2	3	2	24	696
8	Appropiate technology	3	2		2	1	2	2		3	2		1	3	2	2	2	2	29	464
9	Quality of electricity services	3	3		2	1	2	1	2		2	1	2	2	2	2	2	2	29	899
10	Funding and investment	3	1	3	2	2	2	1	2	3		2		3	2	3	2	2	33	693
11	Energy governance	3	1	2	2	2	2	1	2	3	3			3	2	3	2	2	33	495
12	Youth involvement		3		1	3	3	3		2					2	2	2	3	24	432
13	Financial equilibrium	3								3	3	2				2			13	312
14	Gender equity	2	2		1	3	3	3		2		1		1			2	2	22	594
15	Management effectiveness	3	3		3	2		2	2	2	1	1	2	2	3		2		28	784
16	Health	2	1		2	3	3	2			2	2	1		2			2	22	704
17	Education	2	3		2	2	2	3	2	2	1	1	3		2	2	2		29	812
	PS	33	27	9	32	33	31	29	16	31	21	15	18	24	27	28	32	28		
	Q	0.73	0.70	3.67	0.50	0.79	0.97	0.83	1.81	0.94	1.57	2.20	1.33	0.54	0.81	1.00	0.69	1.04		

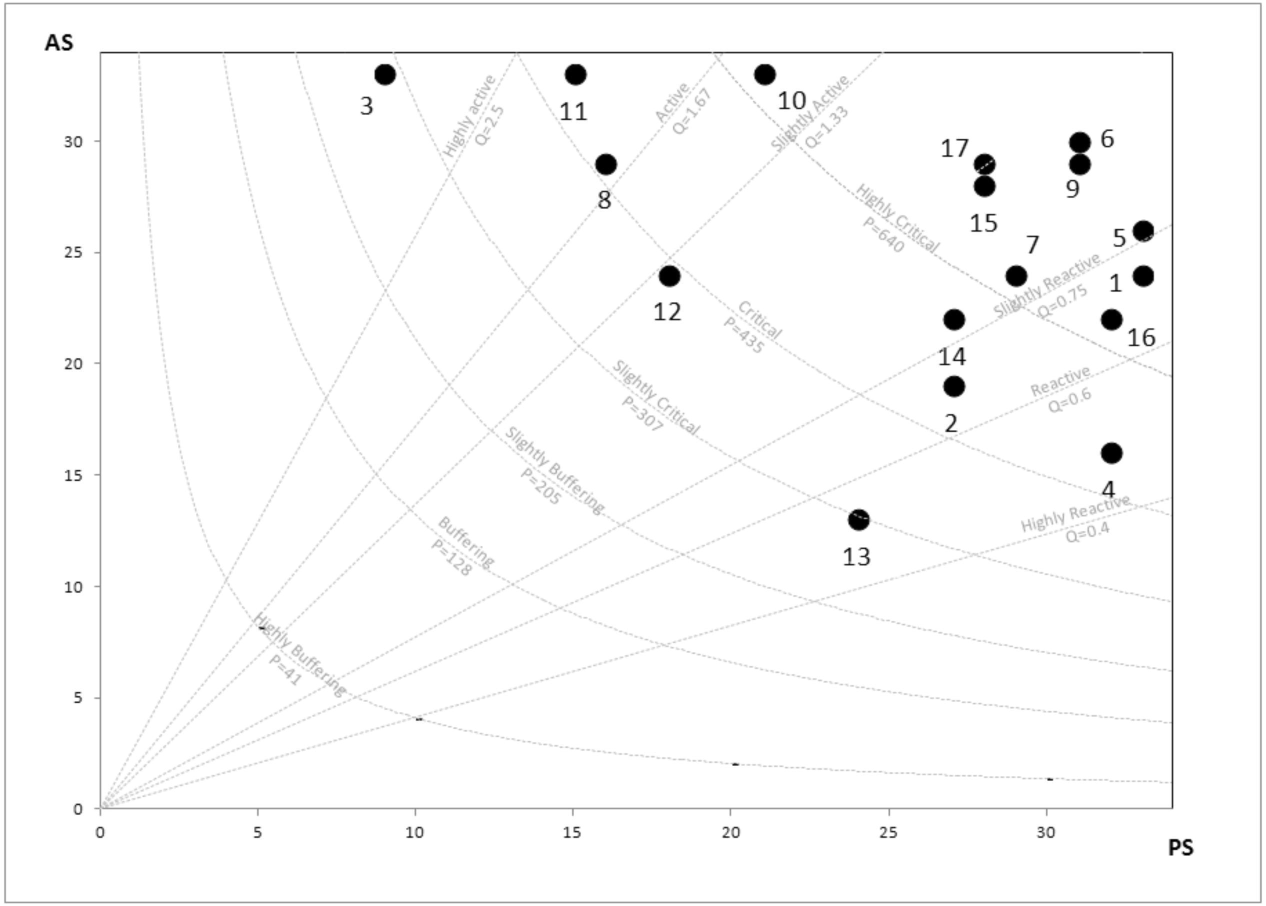
Figure 4.8 Consensus effect-matrix representing the strength of the direct effects among variables, extracted from workshop

0=Negligible effect (empty cells), 1=under-proportional effect, 2=proportional effect, 3=over-proportional effect. AS=Active Sum, PS=Passive Sum, P=P-value, Q=Q-value

Since AS and PS characterize one directional effect, both sums were combined to calculate P-values (equation 4-1) and Q-values (equation 4-2) (Figure 4.8 two last rows and columns), which are appropriate metrics to assess the systemic role of the variables (Vester 2007). All variables were plotted in Figure 4.9 to provide a geometrical visualization of AP, PS, P-value, and Q-value (see section 4.2.4 for methodological background) and to interpret the variable's role within the system by its location in the diagram:

(i) Active (top left) influence many other variables but are only slightly influenced by others. These are potential leverages to control the system;
(ii) Reactive (bottom right) are influenced by many other variables but have a low influence on others. As they are strongly influenced, they are ideal proxies that represent system conditions,
(iii) Critical (top right) influence many others variables and are also highly influenced by others. These are strong catalysts and bear the risk of uncontrollable development of the system;
(iv) Buffering (bottom left) do not influence other variables, neither are influenced by others. These are stabilizers with inert behavior within the system.

Results show that all variables belong to areas where combined roles emerge (e.g. reactive-critical, active-buffering), most variables are critical, and there are no buffering variables.



1.Electricity demand
2.Communication effectiveness
3.Accesibilty
4.Environmental quality
5.House comfort and social resources
6.Household economy
7.Acculturation
8.Appropiate technology
9.Quality of electricity services
10.Funding and investment
11.Energy governance
12.Youth involvement
13.Financial equilibrium
14.Gender equity
15.Management effectiveness
16.Health
17.Education

Figure 4.9 Diagram representing the systemic roles of the variables of DRE in the Ecuadorian Amazon, extracted from workshop
P: P-value limit, Q=Q-value limits, see Table 4.2 for methodological background

Active variables: potential leverages

'Accessibility (3)' was perceived as highly active-slightly critical, implying it is the strongest leverage of the system that influences many other variables. Better access to the Amazon region greatly impacts socioeconomic development (e.g. variables 5, 6), DRE management (e.g. variable 9, 15), but also the environment (e.g. variable 4). Restricted accessibility was confirmed as the main barrier for sustainable DRE (Table 3.6).

'E*nergy governance (11)'* and *'appropriate technology (8)'* were perceived as active-critical suggesting they are able to provoke changes in the system but have limited control over outcomes. The former is confirmed by the lack of adequate policies and regulations for DRE (Table 3.6). Concerning the appropriateness of technology, it is a strong leverage for electricity service reliability (e.g. variable 9), installation and maintenance cost (e.g. variable 13). However, it is highly contextual and is influenced by other variables such as the local skills and knowledge to handle modern technology (e.g. variable 17), and availability of local renewable energy industries that are lacking in Ecuador (Table 3.7).

'Funding and investment (10)' was seen as slightly active and highly critical suggesting a tough effect in the process of DRE (e.g. variable 1, 30), but strongly influenced by other variables (e.g. variable 11, 13) which is confirmed by the low and variable investment in DRE (Table 3.6 and Figure 2.2).

'Youth involvement' (12) was seen as slightly active-critical implying a moderate effect on steering the system that can be strengthened or weakened. Young people were perceived as life-long contributors of community well-being (e.g. income generation, communal works), culture preservation (e.g. variable 7), and communication knowledge (e.g. variable 2). However, the participation of communities including young populations has received limited attention in DRE plans (Table 3.6)

Critical variables: strong catalyst for change

'Household economy (6)' was seen as extremely critical implying that it is able to provoke either positive or negative change in the system and could lead to instability. It strongly

influences the capacity and willingness to pay for and promote electricity services (e.g. variable 10, 13). However, economic growth could foster environmental degradation in the Ecuadorian Amazon (e.g. variable 4) through the increase in extractive activities (e.g. pasture, agriculture, and logging). Also, income generation does not depend solely on electricity access, but on other aspects such as access to markets (Table 3.6).

'Quality of service (9)' and *'Management effectiveness (15)'* were also observed as highly critical. Compliance with regulations and quality standards influence service reliability, maintenance cost optimization, ensure people's satisfaction and enable DRE success (Table 3.7). However, both are strongly influenced by the lack of regulations (variable 10), isolation (variable 3) and unreliable technology (variable 8).

'Education (17)' was seen as highly critical as it supports local capacity, especially for young people (e.g. variable 12), and has the potential to reduce the acculturation process through preservation of local knowledge (e.g. variable 7). However, education services are currently strongly influenced by geographical isolation (e.g. variable 3), deficient infrastructure and lack of teachers. *'Home comfort and social resources (5)'* was also observed as highly critical because the progression to better lighting or the use of electric appliances improves living conditions, support traditional practices, and social gatherings, which take place at home on a daily basis, strengthening people's social networks (Figure 3.11). *'Acculturation (7)'* of indigenous people is also highly critical. The incorporation of indigenous cultural values in DRE plans and policy design is recognized as a driver for DRE success (Table 3.7). However, culture is not static and is influenced by many other variables (variables 2, 3, 12, 14).

'Gender equity (14)' was seen as critical as women have a key role in the community and household well-being (variables 5, 6, 7, 18) as they are responsible for gardening, food preparation, and childcare, and are the most benefited from electricity (Figure 3.11) and were perceived as a driver for sustainable DRE (Table 3.7). However, it was widely perceived that indigenous cultural values limit women's participation.

Reactive variables: sensitive and ideal to monitor system development

'Electricity demand (1)' and *'Health (16)'* were seen as slightly reactive-highly critical implying it is able to provoke profound changes in the system, but its effects can be slightly strengthened or weakened. Electricity strongly influences household health, economy, and education (Figure 3.11), also it could modify indigenous people's behavior (Figure 3.8) influencing traditional cultural practices. However, the availability and reliability of electricity are highly dependent on other variables (e.g. variable 9, 10, 11). Regarding health, it strongly influences people's well-being and capacity to work (e.g. variable 5, 6). However, health improvements are greatly hindered by isolation and the lack of health infrastructure and doctors.

'Communication effectiveness (2)' was seen as slightly reactive-critical suggesting it can provoke thoughtful changes in the system, but can also get out of control due to the effects of the system. Effective knowledge communication fosters technology adoption and is the main driver for DRE (Table 3.7). However, communication between indigenous people and outsiders such as electricity suppliers, government officers, and NGO staff is often hindered by language, and also by conflicting visions arising from resource extraction in the Amazon region (Table 3.6).

'Environmental quality (4)' was seen as reactive-critical implying that it is able to provoke fundamental changes to the system that are irreversible. The environment is the source of all indigenous livelihoods providing water and supporting hunting, farming, and house construction, but the ecological equilibrium can be disrupted by the construction of energy infrastructure or DRE interventions, e.g. through electronic waste and worn-out batteries.

'Financial equilibrium (13)' was seen as reactive-slightly critical suggesting it can incite moderate changes in the system but is more influenced by the effects of the system. Electricity is a public service and is highly subsidized in Ecuador (Figure 2.2), which helped to attain high rural electrification coverage but not in isolated areas of the Ecuadorian Amazon (Figure 2.3). Also, the financial viability of DRE is highly dependent on political and market factors which are unpredictable (Table 3.6).

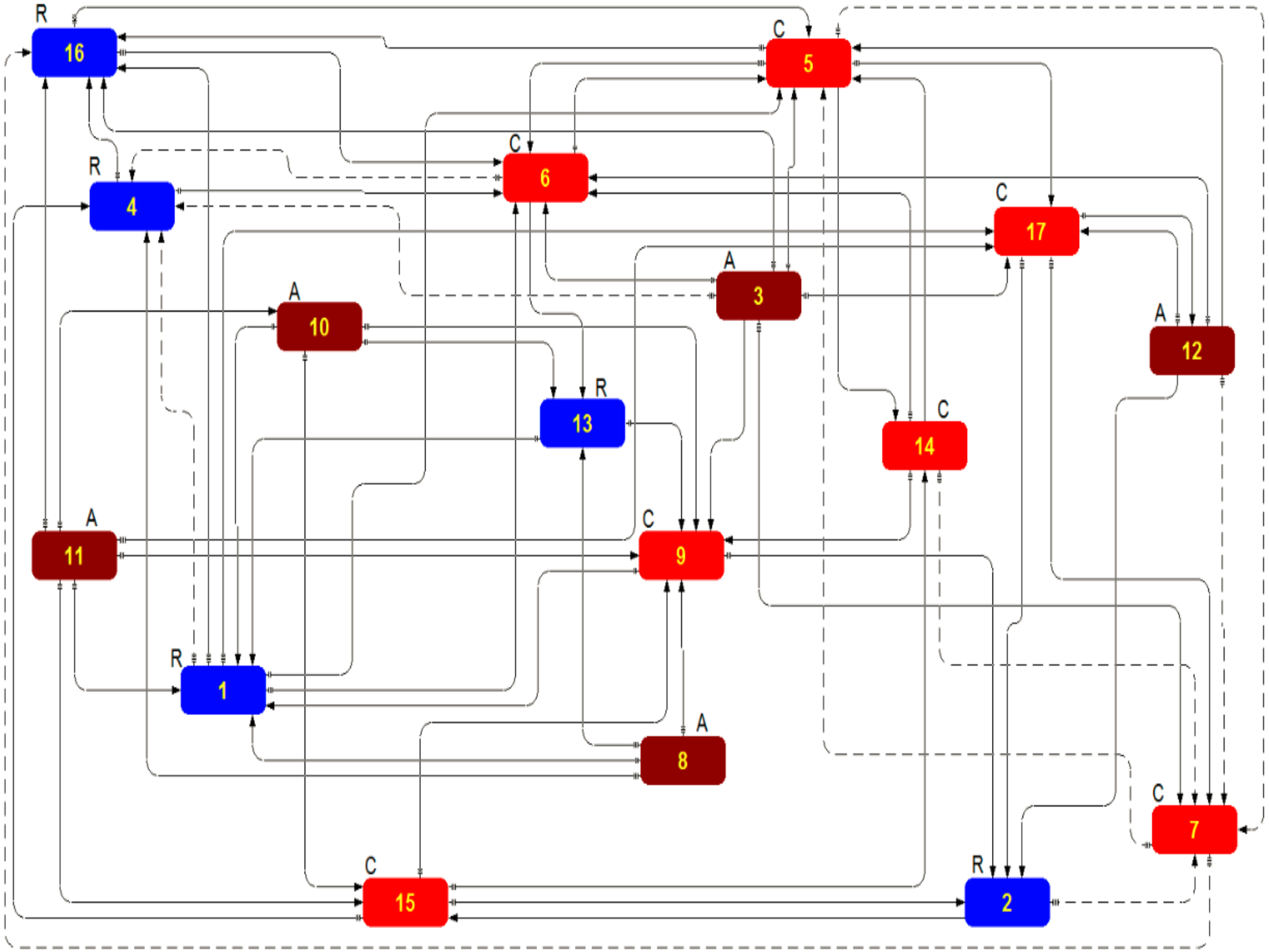
Neutral and buffering variables: important to stabilize the system

There are neither neutral (center) nor buffer (lower-left) variables (Figure 4.9). Neutral variables are not suitable for steering the system but are important for stabilization of the system. Hence, self-regulation mechanisms are not well developed.

In general, the DRE developing system in the Ecuadorian Amazon was seen as an unstable system. Most of the variables were located in a highly critical sector, meaning they are strongly interrelated. Changing some critical variables potentially changes the whole system positively or negatively. The system tends to be unstable in technical, economic, institutional, social and environmental terms. Thus, DRE represents a system that cannot be self-sustained and has a high dependence on external inputs.

4.3.3 Cause-effect diagram

The previous section provided only information about the individual behavior of the variables. But including their mutual and directed effect, i.e. reinforcing or balancing effect, offers a comprehensive and integrated insight into the feedback loop structure of the system as perceived by stakeholders. Considering the most relevant effects (i.e. proportional effect=2, over-proportional effect=3) a 'cause-effect diagram’ was sketched (Figure 4.10).



1.Electricity demand
2.Communication effectiveness
3.Accesibilty
4.Environmental quality
5.House comfort and social resources
6.Household economy
7.Acculturation
8.Appropiate technology
9.Quality of electricity services
10.Funding and investment
11.Energy governance
12.Youth involvement
13.Financial equilibrium
14.Gender equity
15.Management effectiveness
16.Health
17.Education

Figure 4.10. Cause-effect diagram of DRE in the Ecuadorian Amazon extracted from workshop

Continuous lines: balancing (positive) effects; dotted lines: reinforcing (negative) effects; A(brown): active, potential leverages; C(red): critical, strong catalyst, R(blue)=reactive, monitoring variables

From the ´cause-effect´ diagram, the total number of reinforcing (positive) and balancing (negative) feedback loops in which a variable is integrated were determined (Figure 4.11). There are 289 reinforcing and 66 balancing feedbacks in the system. Because there are more reinforcing than balancing feedbacks, the whole system can be seen as unstable, which is confirmed by the high number of critical variables discussed in the previous section. Results also show that highly critical variables *'house comfort and social resources (5)'*, *'household economy (6)'*, *'electricity demand (1)', 'education (17)',* and *'health (16)'* are found in more than 50 negative (balancing) feedback loops (75%) suggesting that they are important for system viability. Moreover, the variables of high leverage power, *'accessibility (3)', 'energy governance (11)', 'appropriate technology (8)',* and *'funding and investment (13)',* were not integrated into any feedback loop. Though they have certain interconnectedness in the system, i.e. they influence and are being influenced by other variables, results suggest their outcome cannot be self-controlled by the system but only from external inputs.

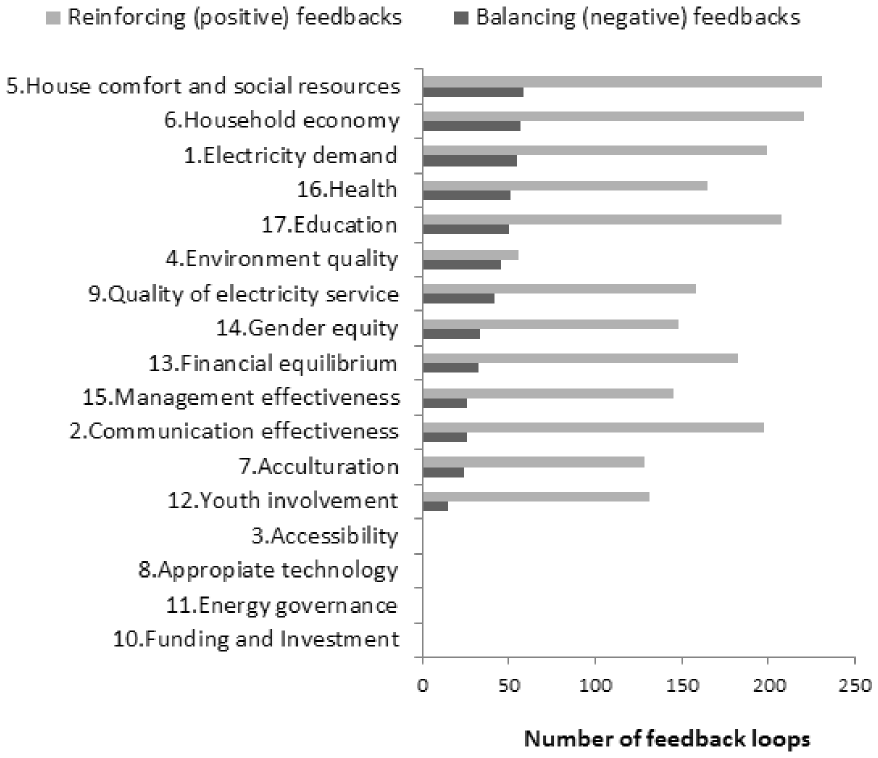


Figure 4.11 Number of feedback loops in which a variable is integrated

4.3.4 System model of DRE

To construct a system model of DRE, the analysis must focus on relevant parts of the cause-effect diagram (Vester 2007). Supported by the Sensitivity Model, all feedback loops were browsed and analyzed and six (6) partially coupled feedback loops were selected (Table 4.4). The selection was governed by two criteria (Vester 2007), a feedback loop should have (i) up to 10 variables, (ii) represent a regulatory mechanism (i.e. variables indirectly influence themselves) that depicts the main concerns of stakeholders, which are ensuring high quality electricity service, support rural development, environment and culture preservation. As literature suggests (Sterman 2000; Vester 2007), stakeholders' perceptions need to be cross-checked with other sources to develop salient system models and examine perceived effects in terms of reality. Thus reflecting on the findings from interviews with decision makers and households (Chapter 3) and literature, a discussion of the selected feedback loops is provided.

Table 4.4 Selected feedback loops of the cause-effect diagram of DRE

No	Feedback loop as perceived by workshop participants	Explanation and discussion
1	Economic growth and financial reinforcement: '*Electricity demand (1)'* → improves → '*household economy (6)'* → helps to enhance → *'financial equilibrium (13)'* → supports higher investments to covering → '*electricity demand (1)*'	Electricity influence the indigenous household economy (Valer et al. 2014) by supporting income generation activities (Figure 3.11) or reducing energy expenses (Figure 3.9), which is a driver for capacity and willingness to pay for electricity services (Table 3.7). Although existing tariffs cannot cover DRE costs in Ecuador (section 3.3.5, maintenance of SHS), a reduction in the lag of payments diminishes subsidies for DRE and hence electricity production costs (Gómez et al. 2015), which eventually increases the rate of economic returns (World Bank 2009; Giannini Pereira et al. 2011), and ultimately promotes DRE investments to cover electricity demand increments.

No	Feedback loop as perceived by workshop participants	Explanation and discussion
2	Electricity outcomes on education, and quality of service reinforcement: *'Electricity demand (1)'* → improves → *'education (17)'* → influence -> *'communication effectiveness (2)'* → enhances → *'management effectiveness (15)'* → increases → *'quality of electricity services (9)* → ensures coverage of → *'electricity demand (1)'*	Electricity supports improvements in education (Figure 3.11) (Kanagawa and Nakata 2008). Better education and knowledge improve communication effectiveness between electricity supplier and beneficiaries and support skills enhancement of local technicians (Tillmans and Schweizer-Ries 2011), which are drivers for an effective local-based management of DRE (Table 3.7). Consequently, it influences the quality of electricity services, e.g. reducing human-related failures of DRE and the time to restore electricity services after a failure (Table 3.5), ultimately influencing a continuous and reliable coverage of the electricity demand.
3	Electricity outcomes on health, gender equality and quality of services: 'Electricity demand (1)' → *improves* → 'health (16)' → generate → *'home comfort and social resources (5)'* → enhances → *'gender equity (14)'* → helps to augment → *'quality of services (9)'* → ensures coverage → 'electricity demand	Electricity supports health improvements in Amazon communities (Kuang-Yao Pan et al. 2010), at the household level (Figure 3.11) through the substitution of diesel lamps that lead to indoor air pollution, or mitigation of vector diseases like human rabies (section 3.3.5; and Mendes et al. 2009), which positively influences home comfort benefiting women and children who are those mainly responsible for housework (Figure 3.11). It enhances gender equity by distributing electricity benefits (Smith 2000; Szoleczky 2012; UNWOMEN 2013). Women satisfaction was believed to be able to encourage their participation as technical staff, which is a driver (Table 3.7) to enhance maintenance services and quality of services (e.g. shorten repair times and restore electricity services) influencing positively the coverage of electricity demand.
4	*Electricity outcomes on house comfort, culture preservation and economic growth reinforcements:*	Improvements in home comfort through electricity increase social gatherings (Figure 3.11), reinforcing social cohesion, a very important cultural aspect in Amazon communities (Perreault 2003). However, if

No	Feedback loop as perceived by workshop participants	Explanation and discussion
	'Electricity demand (1)' → improves → 'house comfort and social resources (5)' → tackles → *'acculturation (7)'* → encourage practices that diminish → 'health (16)' → *increases capacity to enhance* → 'household economy (6)' → helps to enhance → *'financial equilibrium (13)'* → supports investments to cover → *'electricity demand (1)'*	cultural values are negatively influenced by electricity access (e.g. watching TV), a process of acculturation could be observed on a longer time scale (Pace 1993). Acculturation is a driver that jeopardizes people's health by inducing alcoholism and unhealthy eating habits (Wirsing 1985; Schnettler et al. 2013). A decline in health influence people's capacity to work, and hence household economy (to be continued in feedback loop 1 from *'financial equilibrium (13)'*).
5	*Electricity outcomes on youth participation and economic growth reinforcements:* *'Electricity demand (1)'* → improves → *'education (17)'* → increases → *'youth involvement (12)'* → contributes to increasing → *'household economy (6)'* → helps to enhance → *'financial equilibrium (13)'* → supports investments to cover → *'electricity demand (1)'*	Improvement of education through electricity influences mainly the young population by distributing electricity benefits, e.g. through electricity in schools or children's education at night (Figure 3.8) (Daka and Ballet 2011). By enhancing their knowledge and skills, their chances to get jobs increases. Since the young population is the working force and key actors for welfare of Amazon communities (Espinosa 2012), household and community's economy is also benefited (to be continued in feedback loop 1 from *'household economy(6)'*)
6	*Electricity outcomes on the environment and economic growth reinforcements:* *'Electricity demand (1)'* -> influences -> *'environmental quality (4)'* -> influence -> *'health (17)'* -> increases capacity to enhance -> *'household economy (6)'* -> helps to enhance -> *financial equilibrium of DRE* -> supports investments to cover -> *'electricity demand (1)'*	The process of DRE could negatively influence the Amazonian environment, e.g. through the production of electronic waste from worn-out batteries (Zhang et al. 2016), or artificial light pollution (Castro et al. 2010). But it also could have positive effects, e.g. by replacing polluting sources of energy (Figure 3.10) (Schmid and Hoffmann 2004). Environmental conditions have a strong effect on the health of indigenous Amazon people because their livelihoods are obtained directly from nature (Lu et al. 2010) (to be continued in feedback loop 4 from 'health (16)'.

A system model of DRE in the Ecuadorian Amazon is proposed (Figure 4.12) as a graphic representation of selected feedback loops incorporating the active variables that were not integrated in any feedback loop but are relevant leverages for the system, i.e. *'accessibility(3), 'funding and investment(10)', 'energy governance(11)' and 'appropriate technology(8)'*. Also, as the Sensitivity Model method (Vester 2007) suggests that some variables were subdivided (see boxes in Figure 4.12) using their associated indicators (Appendix 2-1) in order to describe better and in greater detail the regulatory mechanisms that depict the selected feedback loops.

The imbalance between *'electricity demand (1)'* and *'electricity generation (ED-1)'* results in an *'electricity deficit (ED-2)'* which, if positive (e.g. higher electricity demand than generation), calls for an increase or update in '*DRE installations (ED-2)*'. Hence, more *'funding and investment (10)'* is needed for an initial investment of new installations, or the *'subsidy for maintenance (FI-1)´* of DRE. *'Energy governance (11)'* is a strong leverage that rule *'funding and investment (13)'*, the regulations for a high *'quality of electricity service (9)';* and, the institutional and stakeholder arrangements needed for a *'management effectiveness (15)'* of DRE. The latter also has an effect on reducing the '*subsidy for maintenance (FI-1)'* of DRE, e.g. local technicians restore the electricity services reducing the cost of having a constant external assistance. The use of *'appropriate technology (8)'* that is robust and reliable improves the *'quality of electricity service (9)'* (low failure rates), which ensures long-term reliability of the *'electricity generation (ED-1)'.*

The fulfillment of *'electricity demand (1)'* (or zero *'electricity deficit (ED-2)'*) is expected to improve in the long term all variables related to people's welfare (see box productive uses of electricity in Figure 4.12). If welfare improves, it will have a feedback effect on increasing *'electricity demand (1)'* and on the overall process of DRE. An improvement on *'household economy (6)'* will increase *'fee payments (FE-1)',* which will reduce the need for *'subsidy for maintenance (FI-1)'* and hence increase *'financial equilibrium (13)'* of DRE. Also, improvements in *'education (17)'* will enhance *‘communication effectiveness (2)’* between, for example, electricity supplier and beneficiary for a correct use of the technology, and hence improve *'management* *effectiveness (15)'.* Improvements on *'home comfort and social resources (5)'* increase *'gender equity (14)'* and women participation, e.g. as technical staff, which has a positive feedback effect on *'quality of services (9)'*.

Moreover, *'electricity generation (ED-1)'* and *'electricity demand (1)'* will influence the *'environmental quality (4)'*, which have a feedback effect on vital indigenous livelihoods and hence on indigenous people's welfare (see box productive uses of electricity in Figure 4.12). *'Accessibility (3)'* acts as the strongest leverage on the system, influencing *'environmental quality (4)'*, *'maintenance effectiveness (15)'* and also people's welfare variables.

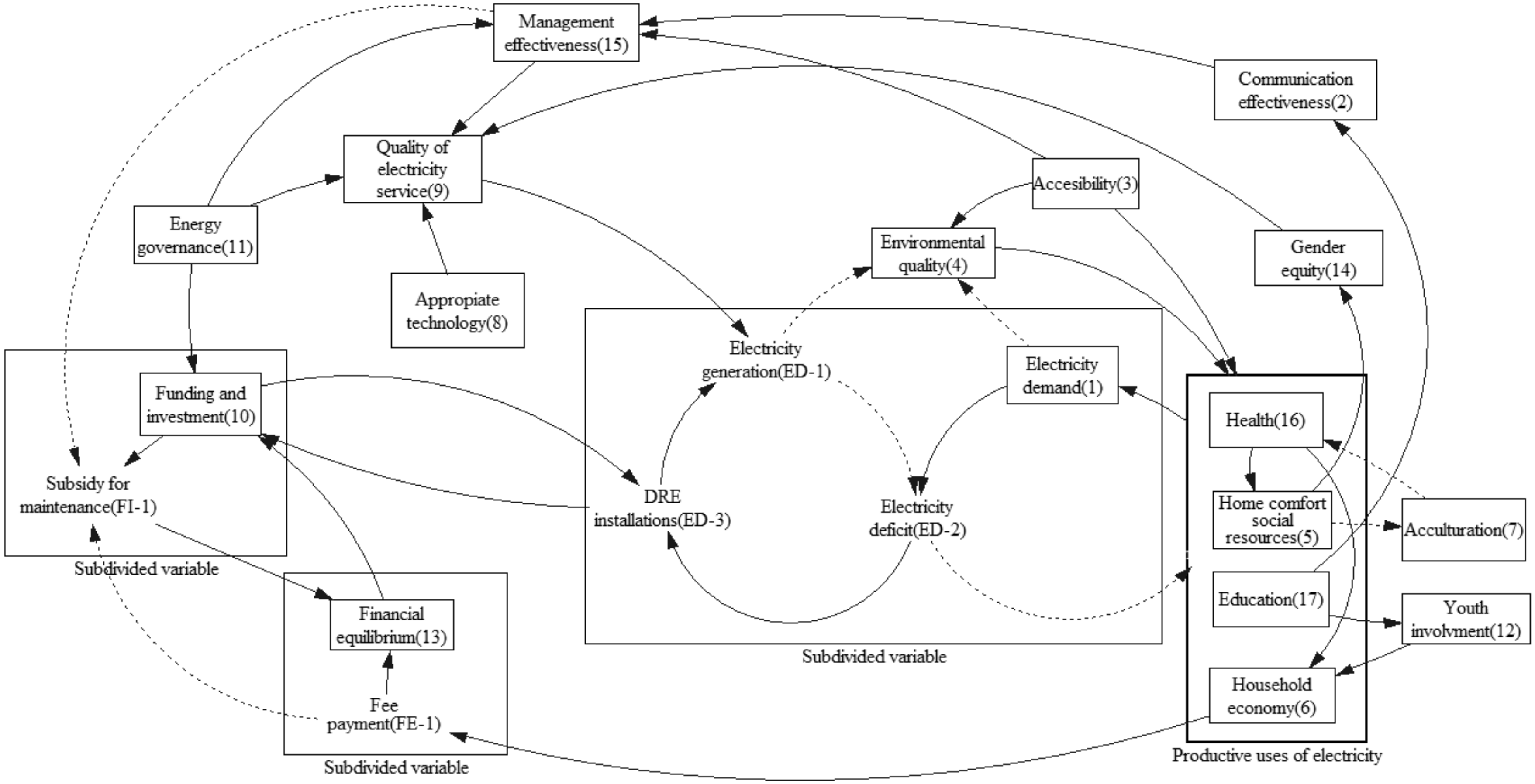


Figure 4.12 System model of DRE in the Ecuadorian Amazon

Continuous lines: balancing (positive) effects, dotted lines: reinforcing (negative) effects.

4.4 Conclusions

Through a participatory, iterative and flexible process, the complexity of DRE establishment in the Ecuadorian Amazon was captured and evaluated. This complements the findings presented in Chapter 3 by structuring and integrating stakeholder viewpoints into a set of variables with their cause-effects (Figure 4.8), thus providing arguments for a definition and representation of sustainable DRE as a system (Figure 4.12).

Different variables were identified and by the description and evaluation of their interlinkages, their systemic roles in the sustainability of DRE were evaluated (Figure 4.9). It is extensively recognized that 'energy governance', 'funding and investment' are strong leverages for sustainable DRE. However, increasing 'accessibility' without threatening the environment, promoting the use of 'appropriate technology', and an active 'youth involvement' were seen as specific and instrumental leverages for sustainable energy policy designs in the Ecuadorian Amazon. Other variables such as 'financial equilibrium' of DRE, 'communication effectiveness' between stakeholders, 'environmental quality' and 'health' are strongly influenced by the whole system and are thus best suited as summary proxies to gauge rather than control the system development of sustainable DRE. Conversely, variables with a potential role to correct undesirable system developments are 'quality of electricity service', 'management effectiveness', 'gender equity', and the avoidance of 'acculturation'. Regarding the last two, women and young people are crucial for bringing well-being and cultural preservation into Amazon communities. Variables important for sustainable development in indigenous communities are 'household economy', 'home comfort and social resources', and 'education' because these stand out as being well integrated into the system, and in most of the balancing feedback loops.

Overall, DRE was perceived as a system composed of highly interconnected variables related to environmental, economic, social, institutional and technological variables forming mostly reinforcing feedback loops without self-regulation to maintain the equilibrium of the system. Thus, the provision of electricity in the Ecuadorian Amazon is perceived as an unstable system, not self-sufficient, politically, technically and financially dependent on external inputs. Thus, in order to ensure the sustainable success of DRE, it should be carefully monitored and integrated into the development process. This demands pro-active stakeholder collaboration.

Few research efforts have selected and prioritized variables based on such a participatory and systems thinking approach. Most existing models rely on pre-defined lists of variables that can lead to incorrect definitions of system boundaries and principles, potentially excluding critical relevant stakeholder interests. Thus, the results presented in this chapter provide a holistic basis that can be further investigated for the construction of sound decision support tools for the study of sustainability of DRE.

5 DEVELOPMENT OF A SPATIALLY EXPLICIT AND PARTICIPATORY APPROACH FOR THE ASSESSMENT AND SIMULATION OF SUSTAINABILITY OF DECENTRALIZED RURAL ELECTRIFICATION

5.1 Introduction

As detailed in the previous chapters, a key challenge is how DRE should be managed to be sustainable in order to ensure electricity availability, reliability and affordability while supporting local development, environment and culture preservation of Amazon people. This implies complex multi-criteria decisions that usually are addressed emphasizing and isolating either economic, technical or environmental criteria of DRE (Bhattacharyya 2011), leading to misinformed decisions and subsequently unrealistic solutions and frequent failures (Brent and Rogers 2010). Thus, it is recognized that decision support tools are needed to focus the analysis on the overall sustainability of DRE and hence better decisions can be taken (Cherni et al. 2007; Ilskog and Kjellström 2008; Tiba et al. 2010).

There is a diverse type of tools to deal with complexity in energy systems (Table 2.4) and with reference to DRE it is arguable that such decision support tools must have interdisciplinary capacities, manage uncertainties, enable stakeholder participation, and capture various time spans and multiple level of spatial scales to disclose system dynamics (Boulanger and Brechet 2005). Other than technical criteria, the success of DRE and its implications for rural development are influenced by multiple and generally difficult to quantify criteria (Cherni et al. 2007; Ilskog 2008; Brent and Rogers 2010). Neglecting uncertainty of unforeseeable consequences resulting from the complex technology-society-environment interaction increases the risk of DRE failure (Bekker and Gaunt 2006; Bhattacharyya and Dey 2007). Moreover, participation is widely encouraged (Cherni et al. 2007; Brent and Rogers 2010; Holtorf et al. 2015). It reduces knowledge gaps surrounding complex and difficult to quantify problems (Ozesmi and Ozesmi 2004), thereby addressing uncertainty in DRE plans (Brent and Rogers 2010). But perhaps most importantly, people's expectations are acknowledged and valued by being placed in the center of decision making, supporting an equitable DRE process (Brent and Kruger 2009; Hirmer and Cruickshank 2014). Finally, spatial and integrated planning is needed for sustainable energy transitions (Stoeglehner et al. 2011). The level of accessibility influences electricity costs (Szabó et al. 2011), maintenance services (Tiba et al. 2010), socio-economic development (Hansen 1959; Ahlstrom et al. 2011). Also, the spatiotemporal dependency of renewable energy sources influences rural electrification master plans and technology choices for DRE (Amador and Dominguez 2006; Levin and Thomas 2012). Thus, there exists a need for spatially explicit methodological approaches to support stakeholders in a bottom-up decision-making process for the management of DRE under high uncertainty and inevitably even higher amounts of multi-sectoral data.

Following this argumentation, a decision support tool was conceived and tested by combining geographical information systems (GIS), multi-criteria decision analysis (MCA) and fuzzy cognitive mapping (FCM) with the purpose of providing a participatory and practical approach for the assessment as well as a simulation of sustainability of DRE. It does not aim to provide a precise forecast, but rather broad perspectives to encourage stakeholder discussions and thus enhance the quality of the knowledge base for an effective management of DRE.

5.2 Materials and methods

To support a participatory, spatially explicit and holistic assessment and simulation of sustainable DRE it is proposed to combine fuzzy cognitive mapping (Kosko 1986) and multi-criteria decision analysis (Malczewski and Rinner 2015) in a GIS framework (Figure 5.1). Fuzzy cognitive mapping will capture and integrate stakeholder knowledge, i.e. system model, and simulate the emergent behavior of that system to infer future states of sustainable DRE for policy design. Furthermore, multi-criteria decision analysis will portray sustainability in different levels of aggregation, i.e. indicators, variable and sustainability index (SI), and in a spatially explicit manner through maps to complement scenario development and analysis.

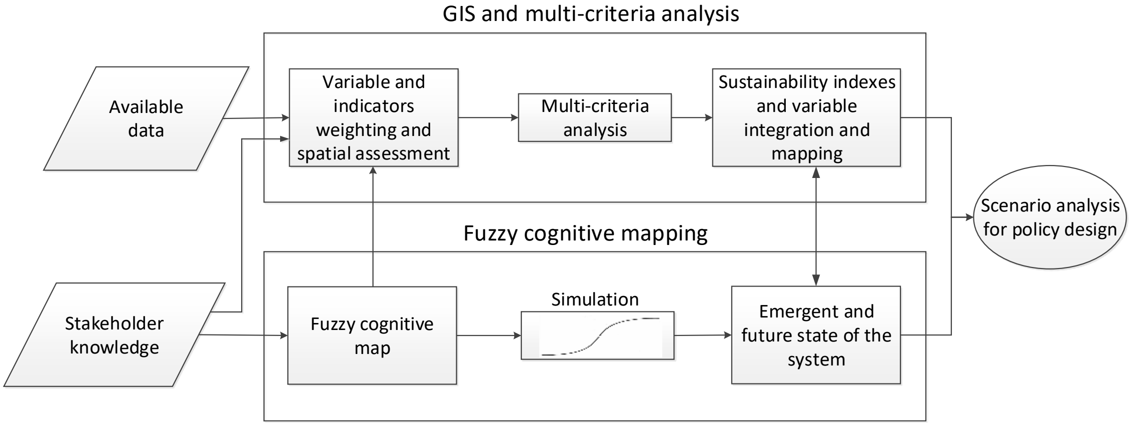


Figure 5.1 Conceptual model to integrate fuzzy cognitive mapping and multi-criteria decision analysis into geographic information system for participatory assessment and simulation of the sustainability of decentralized rural electrification to support policy design.

Fuzzy cognitive mapping is an extension of cognitive mapping (Eden 1988), which encodes accumulated experiences and knowledge of experts who operate and know how a system behaves (Kosko 1986). Network diagrams that portray concepts or ideas (in this case sustainability variables) and their causal relationships emerge from group discussions (Ozesmi and Ozesmi 2004). For instance, in the feedback loop 4 (Table 4.4), the causal relationships *electricity→ cause → house comfort → cause → social gathering →cause →acculturation* suggest the importance *of electricity* for sustainable DRE from a sociocultural viewpoint. Most expert knowledge crucial for sustainable DRE is expressed in this kind of mingled and qualitative terminology (Sovacool 2009), characterized by high uncertainty and imprecision that are difficult to capture and simulate in quantitative models, but appropriate in FCM (Mendoza and Prabhu 2006). Integrating qualitative and partial knowledge of different stakeholders through the application of FCM has been useful for scenario analysis of complex energy problems overcoming the lack of information and facilitate policy and decision making (Jetter and Schweinfort 2011).

Multi-criteria decision analysis is a method useful for decision making in rural electrification that allows integrating competing criteria in participatory approaches (Pohekar and Ramachandran 2004; Cherni et al. 2007; Wang et al. 2009; Rojas-Zerpa and Yusta 2015). Multi-criteria decision analysis integrated into GIS (Malczewski and

Rinner 2015) can be used to compute comparative sustainability levels for spatial assessment of sustainability at a regional scale and at different levels of aggregation (Alshuwaikhat and Aina 2006; Graymore et al. 2009; Xu and Coors 2011). Thus, it provides a comprehensive, visual and practical tool for sustainability assessment of DRE.

5.2.1 Constructing a spatially explicit decision support tool

Fuzzy cognitive mapping and multi-criteria decision analysis were coupled over three iterative steps (Figure 5.2), through a workshop, household survey and deskwork.

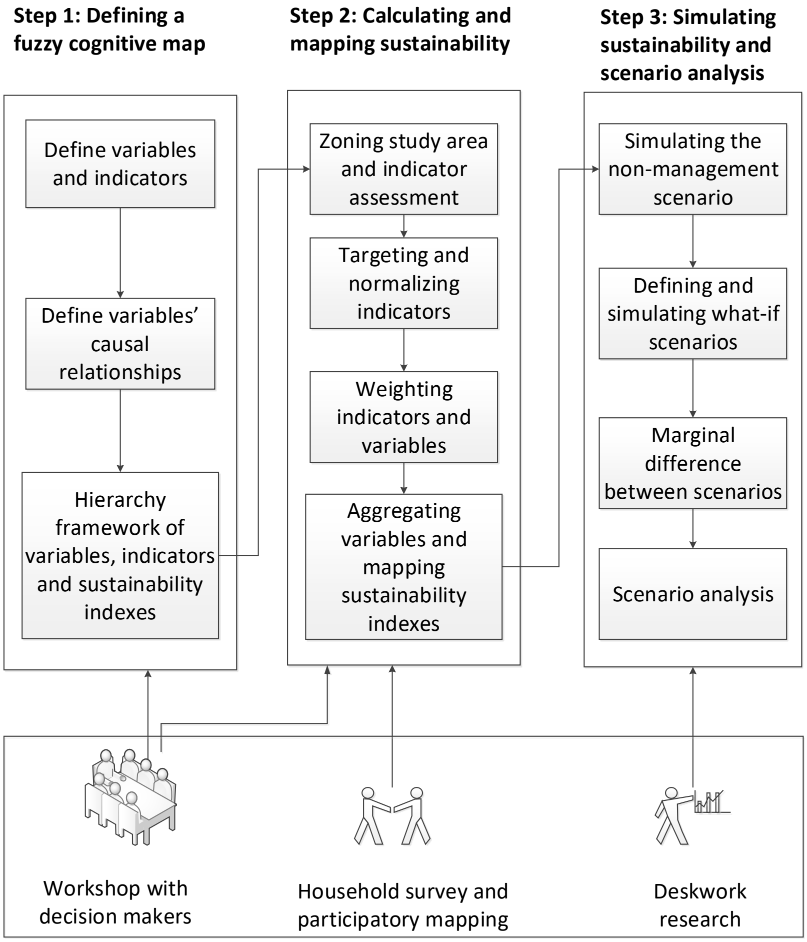


Figure 5.2 Analysis steps and research approach for a participatory sustainability assessment and simulation of decentralized rural electrification via fuzzy cognitive mapping, multi-criteria decision analysis and geographical information system

Step I: Defining a fuzzy cognitive map

A fuzzy cognitive map was constructed from the aggregated knowledge of experts who defined a set of variables and their causal relationships. It was the most important step to sufficiently capture the normative and guiding concepts of sustainable DRE. The greater the number and diversity of experts, the greater the knowledge base to ensure plausible results in the simulation phase (step III) (van Vliet et al. 2010), so stakeholders with different viewpoints participated. Fuzzy cognitive maps can be constructed from interviews or workshops. The latter was preferred because participants can check or balance on each other false or extreme viewpoints providing a greater opportunity for consensus and an integrated inquiry (Flick 2009).

Different variables that express essential elements of sustainable DRE were defined by workshop participants including a set of relevant indicators to provide measurable information for the variable assessment. Variables and their corresponding indicators were grouped under different sustainability dimensions (environmental, institutional, social, economic and technological) creating a hierarchy framework for sustainability assessment of DRE (step II).

The strength of causal relationships among variables was described by a fuzzy degree of causation (S_{ij}) between the values -1 and 1. This is the degree to which a variable V_i causes the variable V_j to happen (Ozesmi and Ozesmi 2004). There are three types of causal relationships (Yaman and Polat 2009): (i) $S_{ij} > 0$ when an increase (decrease) in V_i causes an increase (decrease) in V_j, (ii) $s_{ij} < 0$ when an increase (decrease) in V_i causes a decrease (increase) in V_j, and (iii) $s_{ij} = 0$ for no causal relationship. For example, using increments of 0.2 if 'electricity' increases causes a very small increase in 'household income', so causal strength is positive and equals 0.2. If 'pollution' increases, it causes a significant decrease in 'water quality', so causal strength is negative and set at -1. The fuzzy degrees of causation are approximations based on direct observation and experts' knowledge, which have demonstrated valid results in simulating complex problems, e.g. lake pollution (Ozesmi and Ozesmi 2004), deforestation (Kok 2009), and predicting plant species richness (Skov and Svenning 2003). The causal strengths were coded in an 'adjacency matrix' of the form $A(D) = [S_{i,j}]$ arranging variable V_i in the vertical axis, and variable V_j in the horizontal axis (Figure 5.3).

$$A = \begin{vmatrix} 0 & S_{1,2} & S_{1,3} & 0 & S_{1,5} \\ 0 & 0 & S_{2,3} & 0 & S_{2,5} \\ 0 & 0 & 0 & S_{3,4} & 0 \\ 0 & S_{4,2} & 0 & 0 & S_{4,5} \\ 0 & S_{5,2} & 0 & 0 & 0 \end{vmatrix} \; where -1 \leq \; S_{i,j} \leq 1$$

Figure 5.3 Example of an adjacency matrix representing the causal relationships between variables of a fuzzy cognitive map. Source: Yaman & Polat (2009)

The variables and indicators of the fuzzy cognitive map were organized in a hierarchy framework to allow the sustainability assessment of DRE in step II.

Step II: Calculating and mapping sustainability levels

The sustainability of DRE was calculated and mapped via a multi-criteria decision analysis that included four steps: (i) zoning the study area, (ii) normalizing indicators, (iii) weighting indicators and variables, and (iv) aggregating and mapping variables and sustainability indexes (SI).

First, a spatial scale needs to be defined for the assessment of complex problems (Meentemeyer 1989; Gibson et al. 2000; Fekete et al. 2010). In sustainability studies, a spatial scale defined by trans-boundary phenomena is recommended instead of administrative boundaries because the former integrates multiple scales of socio-economic and ecological imperatives (Graymore et al. 2009; Mascarenhas et al. 2015). In this case, the level of accessibility was considered an appropriate parameter, as it is a determinant for rural development (Yoshida and Deichmann 2009; Ahlstrom et al. 2011) and deforestation in the Amazon region (Mena et al. 2006; Scouvart et al. 2008), and is a critical variable for sustainable DRE (Figure 4.6). Thus, the study area was subdivided into different zones q_i where i=1,…,p=number of accessibility levels.

Second, indicators of variables were calculated for each zone q_i using primary data, e.g. from the household survey. Sustainability targets for each indicator were defined using appropriate reference values such as legal thresholds, normative standards, and expert inputs from the workshop. Subsequently, indicators were normalized using equation 5-1 when a maximum target was desirable, and equation 5-2 when a minimum target was desirable (Manzini et al. 2011). For example, for the latter case, if a given indicator was above the target, a value of 1 was given for indicator sustainability, if not it was calculated with equation 5-2. For the former case, if a given indicator was below the target, then a value of 1 was given, if not, equation 5-1 was applied:

$$In_i^q = \frac{Iref_i}{I_i^q} \leq 1 \tag{5-1}$$

$$In_i^q = \frac{I_i^q}{Iref_i} \leq 1 \tag{5-2}$$

where In_i^q is the normalized indicator i in zone q, I_i^q is the value of indicator i, and $Iref_i$ is the sustainability target of indicator i homogenous for the study area.

Third, indicators and variables were weighted using a rating method to assess their relative importance during aggregation (Malczewski and Rinner 2015). The weighting of indicators was done via public consultation with the double purpose of also reviewing variable definition (feedback for step I). The weights of the indicators associated to a given variable were calculated using equation 5-3:

$$W_i = \frac{\overline{r_i}}{\sum_{k=1}^{M} r_k} \tag{5-3}$$

where W_i is the weight of indicator i, $\overline{r_i}$ is the average rate calculated from experts' assessment of the indicator i against five criteria using a qualitative scoring scale between 1 and 5 (1 being the lowest score): (i) transparency to convey a simple and unambiguous message, (ii) facilitates communication and interpretation, (iii) provides an integral measurement, (iv) captures trend and spatial range of changes, and (v) its priority does not change despite changes in administrations and policies (Mendoza and

Prabhu 2000; Callo-Concha 2009; Mascarenhas et al. 2015). M is the number of indicators associated to the same variable.

In contrast to indicators, the rate for weighting a variable was equivalent to its centrality degree, which is a measure of the variable´s level of interconnectedness within the fuzzy cognitive map (sum of outdegree and indegree, explained below) (Ozesmi and Ozesmi 2004). Weights that account for variable interconnectedness are appropriately metric for sustainability assessment (Graymore et al. 2009; Mainali et al. 2014). The weighting of variables associated to a given sustainability index (SI) were calculated using equation 5-4:

$$Y_j = \frac{od(V_j) + id(V_j)}{\sum_{k=1}^{Q} od(V_k) + id(V_k)} \tag{5-4}$$

$$od(V_j) = \sum_{k=1}^{N} S_{j,k} \tag{5-5}$$

$$id(V_j) = \sum_{k=1}^{N} S_{k,j} \tag{5-6}$$

where Y_j is the weight of variable j, Q is the number of variables associated to the same SI, od(V_j) is the outdegree of variable j (equation 5-5) that is the cumulative strengths of connections ($S_{j,k}$) exiting the variable j (the row sum of absolute values of adjacency matrix; Figure 5.3), id(V_j) is the indegree of variable j (equation 5-6) that is the cumulative strengths of connections ($S_{i,k}$) entering the variable j (the column sum of absolute values of a variable in the adjacency matrix; Figure 5.3), and N is the total number of variables.

Fourth, a linear weight sum was applied to aggregate indicators into variables (equation 5-7) and variables into SI (equation 5-8) for its simplicity and intuitive nature to be applied in GIS (Malczewski and Rinner 2015):

$$V_j^q = \sum_{k=1}^{M} w_k In_k^q \quad \leq 1 \tag{5-7}$$

$$CSI_m^q = \sum_{k=1}^{N} Y_k V_k^q \quad \leq 1 \tag{5-8}$$

where, V_j^q is the value of variable j in zone q, w_k is the corresponding weight of the normalized indicator In_k (M=1,…,n=number of indicators associated to variable j), CSI_i^q is the value of sustainability sustainability index m (m=1,2,3,4,5) in zone q, Y_k is the corresponding weight of the variable V_k (N=1,…,p=number of variables associated to SI).

Sustainability indexes were intended to be aggregated metrics that summarized the five sustainability dimensions of DRE that stakeholders can understand and handle more easily for assessment and decision-making of rural electrification (Neves and Leal 2010; Sharma and Balachandra 2015).

Variable and SI were spatialized and ´argument maps´ were produced. Each pixel in a map represents comparative levels of DRE sustainability in different locations. As mentioned above, the aggregation of variables and SI was repeated during the simulation phase to analyze sustainability trends in different and hypothetical scenarios (step III).

Step III: Simulating sustainability and scenario analysis

To grasp an idea of the emergent system's behavior, i.e. sustainability trend, that might result from the complex dynamics among variables, an FCM simulation was adopted by applying iteratively equation 5-9 (Reimann 1998; Ozesmi and Ozesmi 2004):

$$I^{t+1} = f\left(I^t + I^t A\right) \tag{5-9}$$

where, I^{t+1} is the row vector that contains the variables sustainability values at simulation step t+1, I^t is the row vector at simulation step t, A is the adjacency matrix of the concerning fuzzy cognitive map, and f is a monotonic increasing function:

$$f = \left(\frac{1}{1+e^{-x}}\right) \tag{5-10}$$

A monotonic increasing function was used because the sustainability variables were between 0 and 1 (Knight et al. 2014), and quantitative or qualitative variables for strategic planning scenarios were introduced (Tsadiras 2008).

The previous equations were solved by a vector-matrix algorithm implemented in MS Excel (Ozesmi and Ozesmi 2004; Papageorgiou et al. 2010): (i) Give the row vector I^t that contains variable values, i.e. sustainability levels, between 0 and 1, setting the initial condition for simulation, (ii) calculate a row vector adding the effects of the cumulative strength of causal relationships among variables $(I^t + I^t A)$, (iii) the elements of the resulting vector are transformed (equation 5-10) to ensure variable values always stay within the bounds of a non-negative interval of sustainability (between 0 and 1), (iv) the resulting non-negative row vector is compared with the row vector of step (i), and if they are equal stop the iteration, if not the iteration continues until the row vector converges to a steady state (or not).

The simulation output called the ‘row vector in steady state’ provides an approximation of whether the values of the variables will increase or decrease as a result of their complex dynamics. This was the basis to evaluate relative changes, e.g. how strong a variable changed compared with others, rather than absolute values of variables (van Vliet et al. 2010) and used for scenario development and analysis (van Vliet et al. 2010; Jetter and Schweinfort 2011; Lopolito et al. 2015).

For scenario development and analyses, the clamping method for FCM simulation was applied (Kosko 1986; Ozesmi and Ozesmi 2004). This has two aims: (i) make inferences about sustainability trends without external intervention in the system, and (ii) evaluate the effect of different interventions in the system (policies experimentations) on the sustainability of DRE.

First, the fuzzy cognitive map as perceived by experts was simulated. This is called the “non-management scenario”. The simulation output (row vector in steady state) allowed making inferences about variable changes without external interventions and setting the baseline for scenario analysis.

Second, a simulation of one or more ‘what-if scenarios’ was applied to mimic external interventions in the system by keeping one or more variables constant (between 0 or 1) over the whole simulation process. Variables equal to one (1) express that it is constantly taking place at its highest sustainability. The output row vector expresses the future conditions that might result from a hypothetical intervention in the system, e.g. what will happen with the sustainability of DRE if the variable ´X’ is always high (1).

Third, the variables in steady state were aggregated into SI and the marginal difference between simulation outputs of the ‘non-management scenario’ and ‘what-if scenario’ was calculated. The marginal differences allowed making inferences of the effect of different interventions in the system at different dimensions (environmental, institutional, social, economic and technological) and levels (variable, sustainability indexes) for scenario analysis of sustainability trends of DRE.

All fuzzy cognitive maps have ‘meta-rules’ that need to be taken into account (Jetter and Kok 2014). Several input row vectors lead to the same final steady state. The steady state is typically reached in less than 30 iterations and depends on the transformation function, initial conditions and adjacency matrix. The number of iterations needed to reach a steady state cannot be interpreted as the time the real-world system represented by the FCM needs to reach stability. The steady states of variables must be interpreted in relative but not in absolute terms.

5.2.2 Case study, data and processing collection

The solar program 'Yatsa Ii Etsari' (section 3.3.5) was used to assess the usefulness of the proposed methodology explained above.

Data was collected from a workshop (Figure 5.4) consisting of six (6) participants who had knowledge and experience of DRE in the Amazon region context including all the administrative and technical staff (4) responsible for the solar program 'Yatsa Ii Etsari' (one technician was an indigenous person with a deep understanding of the study area), one researcher with more than 15 years’ experience in renewable energy in Ecuador, one consultant, also a researcher, who had installed solar home systems in Amazon communities for more than 15 years, and one practitioner from the main hospital in the study area. The results of the participatory system analysis (section 4.3) were reviewed and analyzed by the workshop participants, who were also part of the participatory system analysis.

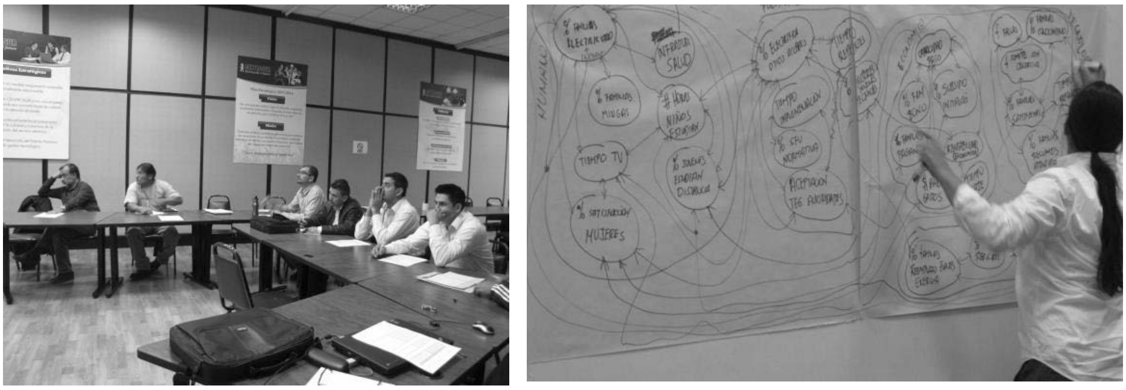
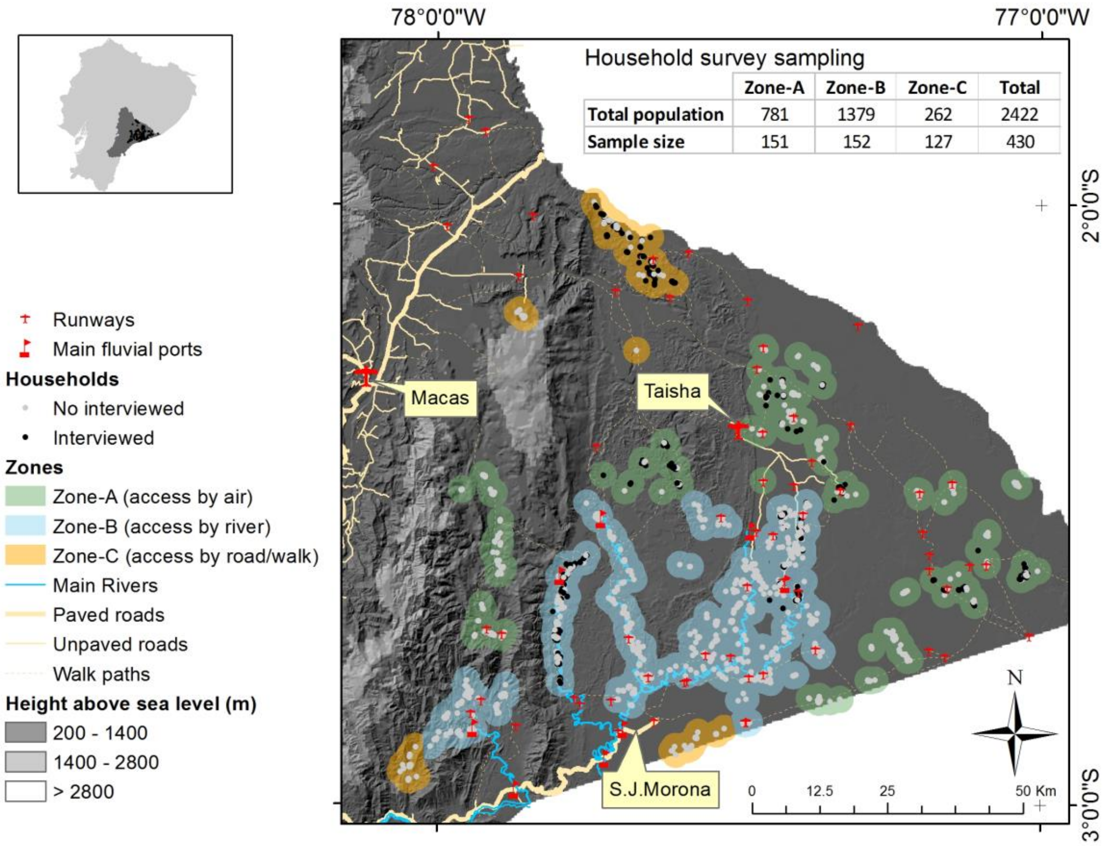


Figure 5.4 Participants of the workshop (left), building a fuzzy cognitive map with participants (right)

Workshop data was complemented by an extensive household survey, maintenance reports of the solar program 'Yatsa Ii Etsari' (Centrosur 2014), and national census (INEC 2010). For household survey and data analysis, the study area was subdivided into zones based on accessibility criteria (section 5.2.1, Step II). Via a participatory mapping with local experts three zones were defined (Figure 5.5): (i) Zone A: accessible by air from main local airports (i.e. Macas or Taisha), travel time 15-60 minutes, and travel cost USD 25-400. (ii) Zone-B: accessible by river from the main fluvial port (S.J. Morona), travel time 3-20 hours, and travel cost USD 2-20. (iii) Zone-C: accessible by road or walking paths, travel time 3-48 hours, and travel cost USD 0-10.



	Zone-A	Zone-B	Zone-C	Total
Total population	781	1379	262	2422
Sample size	151	152	127	430

Figure 5.5 Demarcation zones in study area for sampling and analysis

For data inquiry, ESRI ArcGIS-10® was used for spatial analysis and construction of maps, 'R' for descriptive statistics, and MS Excel for the analysis and simulation of the fuzzy cognitive map. Formal validation of simulations is not possible (Ozesmi and Ozesmi 2004), thus a qualitative validation reflecting on literature and previous research results (Chapter 3 and 4) was applied.

5.3 Results and discussion

5.3.1 Fuzzy cognitive map

The knowledge and experience of workshop participants were captured via a fuzzy cognitive map (section 5.2.1 methodological background) and coded in the adjacency matrix (Figure 5.6) that contains 17 variables and their 55 causal relationships. The workshop participants reviewed and discussed the 'effect-matrix' (Figure 4.8) and 'cause-effect diagram' (Figure 4.10) constructed in a previous workshop (participatory system analysis, Chapter 4) in which they had also participated. The ‘effect-matrix’ was used to confirm the strength of causal relationships in a scale between 0 and 1, while the ‘cause-effect’ was used to confirm the direction of causal relationships (positive or negative). Each cell in the resulting adjacency matrix (a_{ij}) portrays the alleged causal relationships between variables. A cell´s value aij > 0 means the variable in row i when increases/decreases, causes the variable in column j to increase/decrease, aij < 0 means the variable in row i when increases/decreases, causes the variable in column j to decrease/increase, and aij = 0 (empty) means there is no causal relationship. The adjacency matrix depicts the perceived complex structure of the developing system (DRE) for a further inquiry.

The contribution of each variable to the entangled dynamics of the resulting fuzzy cognitive map was calculated by the centrality degree (last column Figure 5.6) which does not depend solely on the number of causal relationships but on the absolute sum of causal relationships exiting (outdegree, equation 5-5) and entering (indegree, equation 5-6) a variable. For example, ‘accessibility (AC)’ is interconnected with more variables (7) than ‘household economy (HE)’ (5); however, the latter has tougher causal relationships so the resulting centrality degree is more than twice (12) the centrality degree of the former (5.6). Thus, the higher the centrality degree the higher a variable contributes to the dynamics of the fuzzy cognitive map. Ranking the variables by their centrality degree allowed identifying those belonging to the third quartile (centrality degree≥8.7, Figure 5.6), which are a selected number of social (3), technological (2) and economic (1) variables suggested as the stronger drivers for the sustainability of DRE as perceived by workshop participants.

The variables and indicators of the fuzzy cognitive map were organized in a hierarchy framework to allow the sustainability assessment of DRE. The allocation of each variable to a sustainability dimension (environmental, institutional, social, economic, and technological) was confirmed by the workshop participants, who also selected a final set of indicators for each variable from a comprehensive list presented during the workshop (see Appendix 2-1).

			Environm		Institutional			Social						Economic			Technological			outdegree	indegree	centrality degree
			Accessibility	Environmental benefits	Energy policy implementation	Management effectiveness	Communication effectiveness	Household comfort	Culture preservation	Gender equity	Youth involvement	Health	Education	Funding availability	Tariff adequacy	Household economy	Electricity self-sufficiency	Appropriate technology	Quality of service			
Sustainability Index	Variable	ID	AC	EN	EG	ME	CE	HH	CU	GE	YI	HL	ED	FA	TA	HE	EL	AT	QS			
Environmental	Accessibility	AC						1	-1			0.7	0.7	0.7		1			0.6	5.6	0.0	5.6
	Environmental benefits	EN						0.7	0.7			1				0.7				3.0	1.0	4.0
Institutional	Energy policy implementation	EG										0.7	1	1			1			3.7	0.0	3.7
	Management effectiveness	ME												1	0.5				0.7	2.2	1.7	3.9
	Communication effectiveness	CE													0.3				0.6	0.9	1.4	2.3
Social	Household comfort	HH							0.7	0.6		0.6	0.6							2.5	5.5	8.0
	Culture preservation	CU						1		-1						-1				2.4	6.3	8.7*
	Gender equity	GE					0.7	1	1			0.6	0.6			1			0.6	5.5	1.8	7.3
	Youth involvement	YI							1			1	0.6			1				3.6	0.3	3.9
	Health	HL							1				0.5			1	0.3			2.8	6.9	9.7*
	Education	ED					0.7		0.6			0.5				1	0.3			3.1	5.8	8.9*
Economic	Funding availability	FA				1											1		1	3.0	4.2	7.2
	Tariff adequacy	TA												-1		1			1	3.0	1.9	4.9
	Household economy	HE						1		0.5		0.6	0.6		0.6					3.3	8.6	11.9*
Technological	Electricity self-sufficiency	EL		1				0.5	-0.3		0.3	0.7	0.7			0.7				4.1	4.6	8.7*
	Appropriate technology	AT				0.7								0.5			1		1	3.2	0.0	3.2
	Quality of service	QS						0.3				0.6	0.6		0.5	0.6	1			3.6	5.5	9.1*

Figure 5.6 Adjacency matrix of the fuzzy cognitive map extracted from workshop representing variable strength and direction of causal relationships, outdegree, indegree and centrality degree.

The matrix must be read as a variable in rows influences a variable in columns. Matrix cell values express the strength and direction of causal relationship (positive or negative). Variables were clustered by workshop participants according to relevance for different sustainability dimensions.

**variables located in the third quartile of the centrality degree range of values. The higher the centrality degree the more interconnected the variable is.*

5.3.2 Sustainability assessment of the solar program 'Yatsa Ii Etsari'

Indicator and variable spatial assessment and weighting

Table 5.1 shows the targets, weights and values of indicators and variables resulting from the analysis of workshop and household survey. Selected indicators were rated by workshop participants against five criteria and the resulting average was applied for weighting them (equation 5-3). Also, indicator targets were extracted from workshop information and literature, which set the benchmarks for sustainable DRE in the study area (target justification Appendix 3-1). The values of indicators for each zone (A, B and C) were calculated using data from the household survey and complemented with a spatial analysis in GIS to confirm travel distances (AC-1, FI-2), calculate solar radiation and electricity generation (AT-2, EB-1), and calculate distances to educational and health centers (ED2, HE2). Descriptive statistics of indicators are given in Appendix 3-2.

The value of each variable was calculated by combining normalized indicators (equation 5-1 or 5-2) and their corresponding weights (equation 5-7). The weight for each variable was calculated by relating their outdegree and indegree (Figure 5.6) according to equation 5-4. These weights consider the level of variable interconnectedness within the system, so the higher it is, the higher is the variable's contribution to the complex dynamic of system behavior and sustainability assessments.

Variable values express the sustainability level of a certain phenomenon, e.g. gender equity that, via its weighted aggregation, assesses the level of sustainability for different dimensions presented in the next section.

Table 5.1 Targets, weights and values of indicators and variables, extracted from workshops and household survey

Sustainability dimension, variables and indicators[a]	**Average rate of indicator (scale 1-5)**[b]	**Weight**	**Target for indicator (unit)**	**Value of variable and indicator for**		
				Zone-A	**Zone-B**	**Zone-C**
Environmental dimension						
Accessibility (AC)		0.58		0.56	0.48	0.64
Annual household travel expenses (AC-1)	3.81	0.37	<12 USD/y	60 USD/y	96 USD/y	30 USD/y
Annual household travel frequency (AC-2)	3.53	0.35	<12 times/y	6 times/y	14 times/y	10 times/y
Household perception on accessibility improvement (AC-3)	2.89	0.28	High (1)[c]	Few (2)	Few (2)	Few (2)
Environmental benefits (EN)		0.42		0.92	0.97	0.98
Share of renewable energy for electricity generation (EN-1)	4.03	0.27	>90%	100%	100%	100%
Household’s fuel consumption reduced (EN-2)	3.92	0.26	>95%	100%	100%	100%
Household’s battery consumption reduced (EN-3)	3.72	0.25	>75%	50%	67%	68%
Waste properly disposed (EN-4)	3.47	0.23	>90%	100%	100%	100%
Institutional dimension						
Energy policy implementation (EG)		0.4		0.03	0.08	0.11
Annual growth rate of rural electrification (EG-1)	3.86	0.49	>15 %/y	0.9%/y	2.4%/y	3.5%/y
Households received other basic service (EG-2)	3.94	0.51	>50%	0%	0%	0%
Management effectiveness (ME)		0.4		1.00	0.86	1.00
Household satisfaction with electricity service (ME-1)	4.22	0.38	>90%	95%	91%	94%
Rate of maintenance reports submitted (ME-2)	3.89	0.35	100%	100%	100%	100%
Level of staff's skills (ME-3)	3.14	0.28	High[d]	High	Average	High
Communication effectiveness (CE)		0.2		0.85	0.76	0.92
Household knowledge on technology (CE-1)	3.81	0.55	>0.7 u[d]	1u	0.8u	1u
Households can communicate in their own language (CE-2)	3.14	0.45	100%	66%	46%	81%
Social dimension						

Sustainability dimension, variables and indicators[a]	**Average rate of indicator (scale 1-5)**[b]	**Weight**	**Target for indicator (unit)**	**Value of variable and indicator for**		
				Zone-A	**Zone-B**	**Zone-C**
Household comfort (HH)		0.17		1.00	0.67	1.00
Level of improvement on ability to do housework (HH-1)	3.56	0.33	High (1)[c]	High (1)	Few (2)	High (1)
Level of improvement social gathering (HH-2)	3.56	0.33	High (1)[c]	High (1)	Few (2)	High (1)
Level of improvement on home entertainment (HH-3)	3.56	0.33	High (1)[c]	High (1)	High (1)	High (1)
Culture preservation		0.19		0.82	0.82	1
Level of improvement communal work (CU-1)	3.67	0.36	High (1)[c]	Few (2)	Few (2)	High (1)
Language preference to speak (CU-2)	3.42	0.34	Native (1)	Native	Native	Native
Preference to build houses (CU-3)	3.06	0.30	Traditional (1)	Traditional	Traditional	Traditional
Gender equity		0.16		0.24	0.48	0.16
Staff's gender ratio women/men (GE-1)	3.75	0.52	0.5/0.5	0/1	0/1	0/1
Level of improvement women's life (GE-2)	3.47	0.48	High (1)[c]	Few (2)	High (1)	Same (3)
Youth involvement		0.08		0.56	0.53	0.53
Household's youth with job (YI-1)	3.42	0.52	>95%	14%	10%	10%
Household's youth who migrated (YI-2)	3.14	0.48	<20%	9%	8%	5%
Health (HE)		0.21		0.79	0.98	0.89
Level of improvement health conditions (HE-1)	3.67	0.50	High (1)[c]	High (1)	High (1)	High (1)
Distance to nearest health post with electricity (HE-2)	3.67	0.50	<5km	8.6 km	5.2 km	6.5 km
Education		0.19		0.49	0.74	1.00
Children's study time at night (ED-1)	3.89	0.51	>0.5 h/d	0h/d	0.25h/d	1h/d
Distance to nearest school with electricity (ED-2)	3.67	0.49	<8km	7.5 km	3.5 km	2.0 km
Economic dimension						
Fund availability (FI)		0.30		0.90	0.90	0.90
Installation cost (FI-1)	3.17	0.53	<10 USD/Wp	12.4 USD/Wp	12.4 USD/Wp	12.4 USD/Wp

Sustainability dimension, variables and indicators[a]	**Average rate of indicator (scale 1-5)**[b]	**Weight**	**Target for indicator (unit)**	**Value of variable and indicator for**		
				Zone-A	**Zone-B**	**Zone-C**
Maintenance cost (FI-2)	2.81	0.47	<0.6 USD/Wp/y	0.28 USD/Wp/y	0.11 USD/Wp/y	0.05 USD/Wp/y
Tariff adequacy (TA)		0.20		0.73	0.65	0.86
Number of pending bills (TA-1)	4.17	0.52	<3 pay.	6 pay.	9 pay.	4 pay.
Household’s affordability of energy expenses (TA-2)	3.83	0.48	1 u[d]	0.9 u	1.0 u	0.9 u
Household economy (HC)		0.50		0.66	0.62	0.64
Households use electricity for income generation (HC-1)	3.56	0.35	>75%	25%	9%	13%
Reduction of energy expenses (HC-2)	2.94	0.29	>95%	63%	74%	73%
Household access credits or other incomes (HC-3)	3.53	0.35	>50%	58%	62%	53%
Technological dimension						
Electricity self-sufficiency (EB)		0.416		1	1	1
Daily energy reserve (EB-1)	2.97	0.46	>20%	39%	34%	33%
Ability to cover electricity demand in next five years (EB-2)	3.56	0.54	Yes	Yes	Yes	Yes
Appropriate technology (AT)		0.15		0.53	0.51	0.54
Time needed to get spare parts (AT-1)	3.28	0.51	<90 day	208	227	200
Capacity factor of electricity generator (AT-2)	3.11	0.49	>20%	12.6%	12.6%	12.5%
Quality of service		0.43		0.95	0.94	1.00
Availability of electricity service, annual basis (QS-1)	4.22	0.51	>95%	85%	84%	100%
Frequency electricity service is lost, annual basis (QS-2)	4.00	0.49	<12 times/y	0.5 times/y	0.5 times/y	0 times/y

[a] *Detailed description of indicator and corresponding formulas in Appendix 2-1*

[a] *Average rate calculated from the assessment of each indicator by workshop participants (6) against five criteria. 1 is the lowest score and 5 the highest*

[c] *Qualitative scale: 1=high, 2=few, 3=same, 4=worse.*

[d] *Scale between 0 and 1, 1 is the highest score.*

Sustainability of solar program 'Yatsa Ii Etsari'

Figure 5.7 shows the comparative levels of environmental, institutional, social, economic and technological sustainability of the solar program ‘Yatsa Ii Etsari’. Five sustainability indexes (SI) were calculated (equation 5-8) and mapped using a scale of equal intervals (very high, high, average, low, very low).

An examination of this map shows that the sustainability in all dimensions is high or very high. The technological dimension has the highest sustainability, while the institutional dimension has the lowest. There is a low variation of sustainability between dimensions and across geographical zones. The number of SI that score very high, suggest that Zone-C (restricted access) has the highest sustainability and zone B (access by river) the lowest.

To understand what is causing these differences, an analysis of specific sustainability dimensions and assessment of variable values (Figure 5.8) are discussed below.

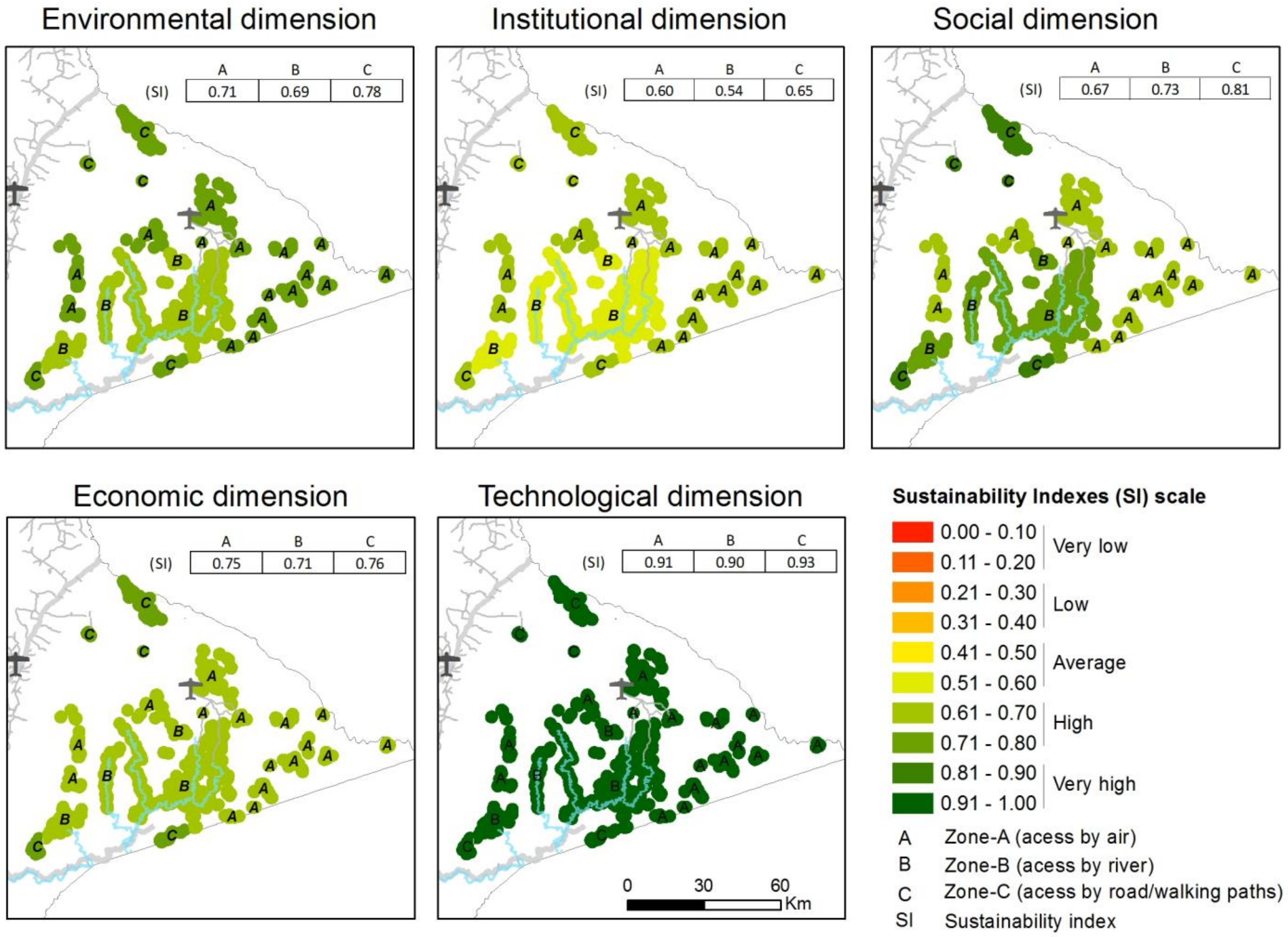


Figure 5.7 Sustainability indexes representing the level of five sustainability dimensions of the solar program 'Yatsa Ii Etsari', extracted from household survey and workshop.

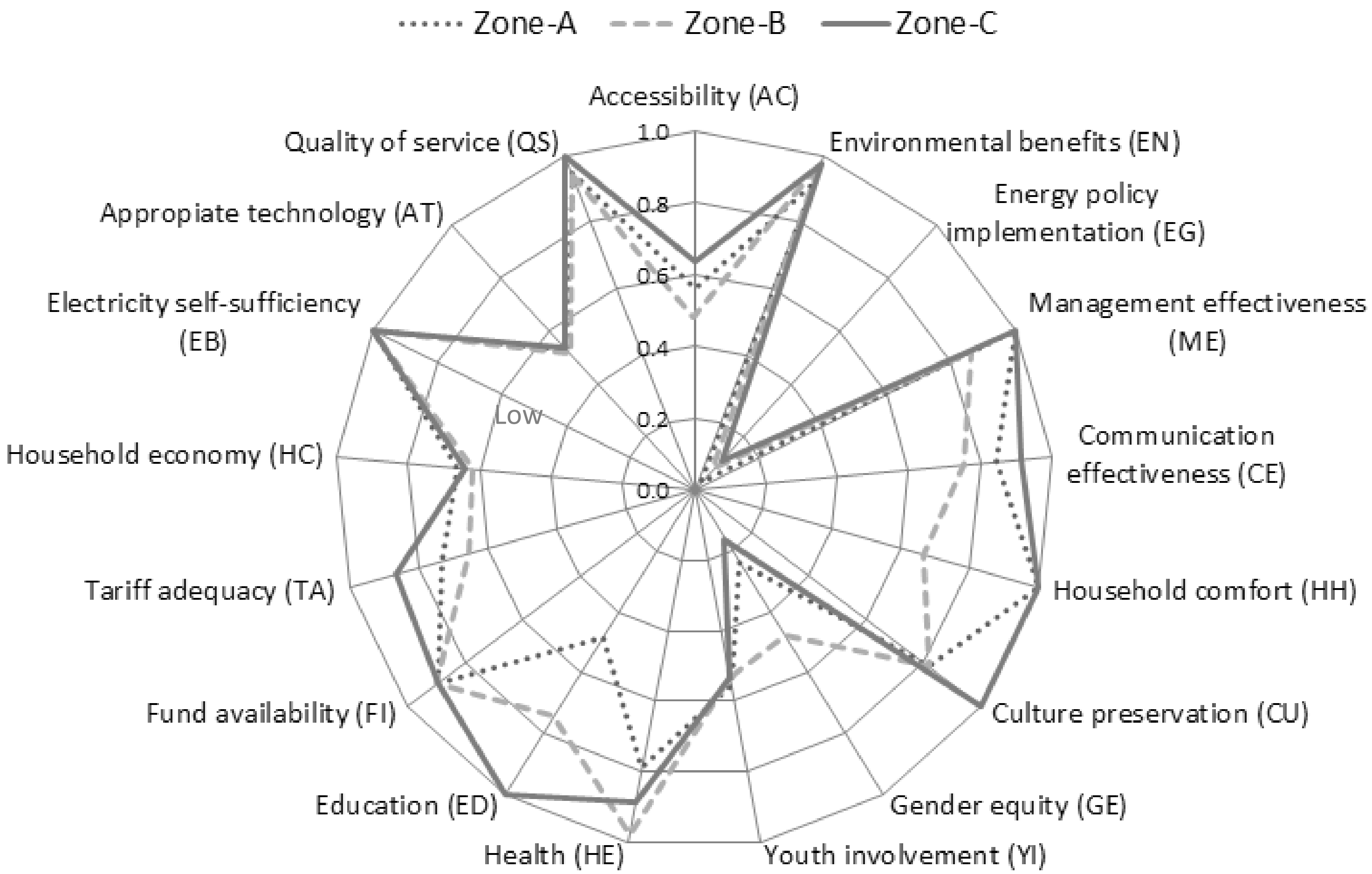


Figure 5.8 Spider graph representing variable scores of each zone for sustainability assessment

Note: sustainability scale (range of values): Very Low (0-0.2), low (0.2-0.4), average (0,4-0,6), high (0,6-0,8) and very high (0,8-1)

The environmental dimension relates to the effects of DRE on the environment and people's accessibility. The environmental SI is high (0.71-0.78) across the study area because *'environmental benefits (EN)'* is very high (0.92-0.98) since fossil fuels (diesel, gasoline) used for lighting were entirely replaced (EN-2), renewable energy generation avoided greenhouse gas emissions of approximately 85 tons CO_2/year[11] (EN-1), all worn-out equipment (100%) was properly disposed (EN-4) thanks to the environmental management adopted by the electricity company (Centrosur 2014; Urdiales 2014), and battery consumption was reduced (EN-3). The latter though was below the expected target (75%). Zone-A has the lowest reduction in batteries (50%) used for flashlights in the frequent hunting and fishing activities. *'Accessibility (AC)'* scores high only in Zone C (relative easy access, roads/walking paths), most households perceived few improvements on accessibility after electrification (AC-3). Households still travel 6-14 times per year to buy food, medicine and other essential needs (AC-2), so reducing the need to purchase energy sources in distance cities had a small impact. Those living along rivers (Zone B) travel more often and therefore have the highest travel expenditures (USD 96/year) (AC-1).

The institutional dimension relates to cross-cutting aspects linked with policies, stakeholder interactions and institutional arrangements to ease technology deployment and electricity services. The institutional SI scores high across the study area (0.6-0.65) except for Zone B (0.54). *'Energy policy implementation (EG)'* scores low (0.02-0.11), since existing low growth rates of rural electrification (0.9-3.4 %/year) (INEC 2001; INEC 2010) threaten the aim of universal access by 2030 in the study area (EG-1), and no household received other basic services after electrification (EG-2). The latter suggests a low coordination between public institutions that are responsible for other basic services such as telephone, the internet, water, and waste management. However *'communication effectiveness (CE)'* between electricity supplier and households scores very high (0.85-0.92) but with a lower score in Zone B (0.76), since 56% of households

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[11] Greenhouse emissions calculated by assuming the reduction in diesel consumption (1 l/month/household in all three zones) and a emission factor of 2.97 kg CO_2/l (Kaufman et al. 2000; Zhang 2014).

prefer to communicate in their native language, but maintenance service and training were delivered in Spanish (CE-2). Overall, the continued training about every 3 months ensured that on average 76% of households knew how to use SHS (CE-1 > 0.7). *'Management effectiveness (ME)'* scores very high (0.8-1) because most households (>90%) were satisfied with the electricity service (ME-1), all maintenance reports were submitted (ME-2), and the capacity of staff included technical and intercultural skills (ME-3); regarding the latter, Zone B is an exception as staff skills rate average there.

Social sustainability is perhaps the most complex dimension and relates to the effects of electricity on the well-being of the Amazonian communities. The score of social SI is high (0.67-0.73) and increases as zones become remote (0.81) suggesting that electricity has a greater effect in zones with restricted access such as Zone C than in those with easy access (Zone A). *'Culture preservation (CU)'* scores very high across the study area (0.8-1), because all households prefer to speak their native language (CU-2), construct and use their own traditional house (CU-3), and periodically participate in communal work reinforcing reciprocity activities (CU-1) suggesting a low acculturation during the time of this study. *'Health (HE)'*, scores higher and with less variation across the study area than *'education (ED)'* because households perceived high improvement in health conditions (HE-1), that lighting helped to see dangerous animals such as snakes and vampire bats in the dark, and most people could reach a health post (HE-2). In terms of education, children's study time at night (ED-1) was high (1 h/day) in zones with relatively easy access (Zone C) but zero in other areas. 'Household comfort' (HE) scores very high (1), except for Zone B (0.67), because households perceived electricity had a lower effect on improving social gatherings (HH-2) and housework (HH-1). *'Gender equity (GE)'* scores from very low to average across the study area (0.16-0.48), because all staff of the solar program were men (GE-1), and there was a variable and low perception concerning women's life improvement (GE-2) across the study area. *'Youth involvement (YI)'* scores average (0.4) suggesting electricity had a low effect on job generation for the young population (YI-1). Nevertheless, it was compensated by a low migration rate (YI-2), which is important for the well-being of the community. The two latter variables (GE and YI) have the lowest values suggesting an improvement in this direction will increase the social sustainability.

Economic sustainability relates to the ability of DRE to survive with existing public resources (subsidies, social investments, etc.) and does not stem from a profitability standpoint. The economic SI scores high and increases as zones become remote (0.71-0.76), suggesting zones with relatively easy access (Zone C) perform better in economic terms. *'Funding availability (FI)'* scores high (0.89) because both installation cost (FI-1) and maintenance cost (FI-2) were always available and subsidized by the government and electricity company. However, maintenance cost was below the expected target (0.6 USD/Wp/y) and could increase considerably by the time the batteries complete their life-cycle in the next 1-2 years following this research. *'Tariff adequacy (TA)'* scores very high (0.86) in Zone C. Most households (93%-96%) consider energy expenditures ($3.2-$6.6/month) affordable (TA-2). The existing tariff is highly suitable for remote and low-income communities but less appreciated by zones with relative easy access (Zone B), which has the higher lag of payments (9) (TA-1). *'Household economy (HC)'* scores average (0.54-0.57) because most households (15%-25%) did not use electricity for income generation activities (HC-1), and the average household's energy expenditures (HC-2) were not reduced (62%-74%) to the expected target (95%). However, more than 50% of the households across the study area received a human development bond (HC-3) of USD 50/month (MIES 2014), which ensured a periodic income enhancing the household economy.

Technological sustainability relates to available, reliable and efficient electricity services. The technological SI scores very high across the study area because of *'electricity self-sufficiency (EB)'* and *‘quality of service (QS)’* scores very high. The adopted design of SHS fully covers the existing household electricity demand (EB-1) and will cover the expected future demand in the next five years (EB-2). It is also assumed that this will incorporate electrical appliances that households will acquire (calculated from the survey). Electricity availability (QS-1) was high but below the target for zones with restricted access (Zone B and C). However, this was compensated by a very low frequency of electricity service lost (0.5 times/y) (QS-2). *'Appropriate technology (AT)'*, has the lowest score (0.51-0.53) because the efficiency to produce electricity (capacity factor) (AT-2) was 12% below the expected target (20%), and more than 200 days on average was needed to restore the service (AT-1) after a failure, which was longer than the target of 90 days.

This assessment provides a comprehensive but static overview of the sustainability of DRE. It does not incorporate the interaction among variables that can fire causation chains and alter sustainability levels. Thus, the emergent system's behavior and how it might influence sustainability was simulated.

5.3.3 Simulations and scenario analysis

Non-management scenario and baseline

The non-management scenario aims to reflect the system behavior as perceived by workshop participants and to elucidate how it will evolve if the status quo is maintained. The row vector input for simulation (variable values Figure 5.8), was iteratively multiplied by the adjacency matrix and transformed until it reached a steady-state (equation 5-9), which took place in less than 24 iterations for all zones and variables (Appendix 3-3). Therefore, oscillating or chaotic behavior is excluded (Dickerson and Kosko 1994; Ozesmi and Ozesmi 2004).

The resulting variables were aggregated (equation 5-8) so five SI were subsequently calculated (Figure 5.9). The steady-state of the variables allows inferring their relative importance in the system. For example, 'household economy', 'education' and 'health' are relatively higher than 'environmental benefits' suggesting that electricity will have a higher effect on these three variables. Concerning SI and compared with initial conditions (Figure 5.7), social and technological sustainability remains high. However, institutional and social dimension have the highest change from current sustainability because their associated variables (high centrality degree) strongly contribute to the dynamics of the system. This simulation results are steady-state of the system and set the baseline to evaluate the effect of different interventions.

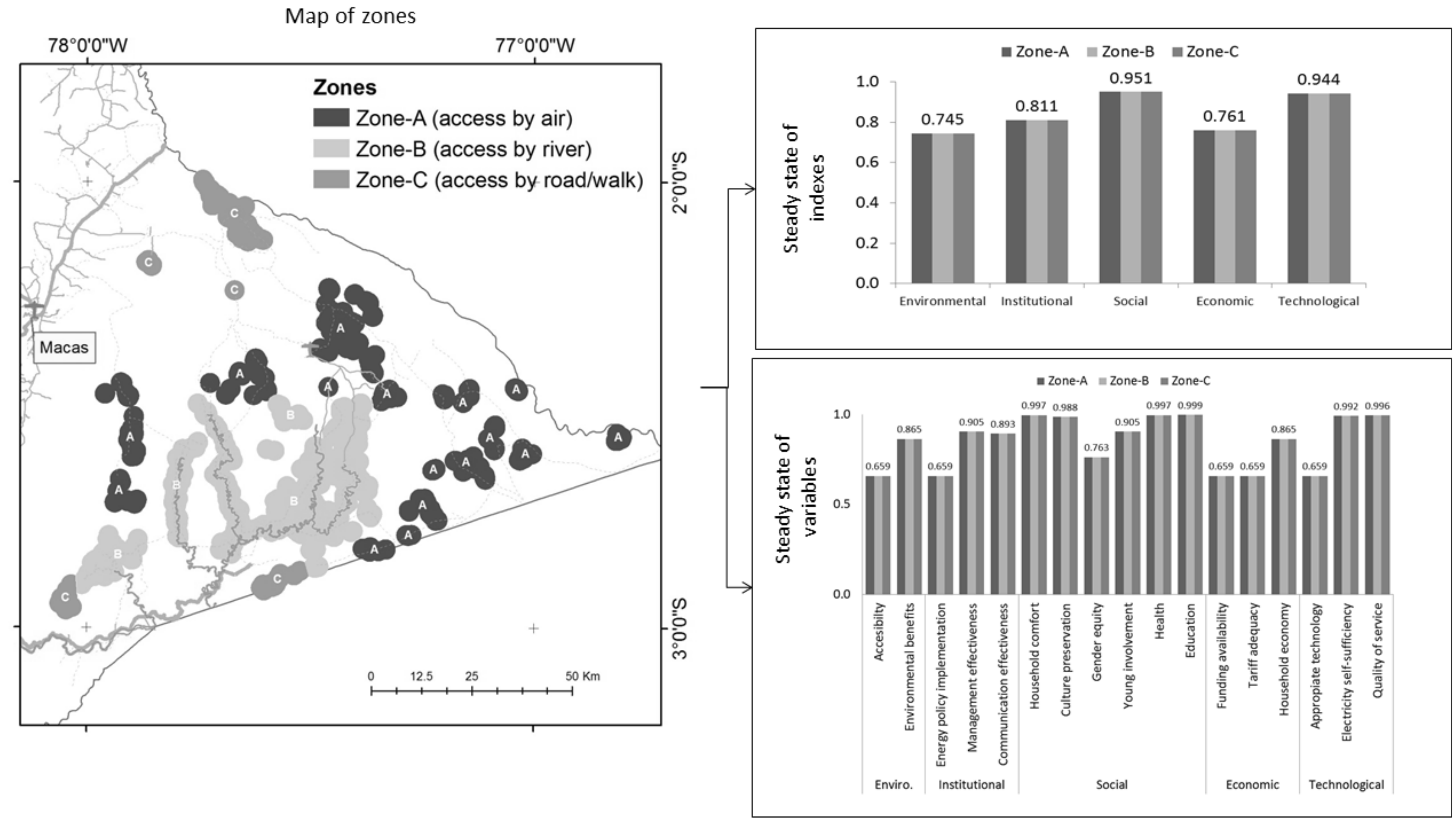


Figure 5.9 Diagrams representing non-management scenarios steady-state of sustainability indexes (top), and steady-state of variables (below).

What-if scenarios

Three ‘what-if scenarios’ were simulated and analyzed: (1) environment and culture preservation, (2) stakeholder communication, and (3) local economic growth.

Scenario 1: Environment and culture preservation

Environment and culture preservation were seen throughout the entire study as important sustainability goals (Table 3.7 and Figure 4.9), which are represented by *'culture preservation (CU)'* and *'environment benefits (EN)'*. The former has a high centrality degree (Figure 5.7) suggesting it is a powerful leverage in the system, also it is arguable that cultural values promote Amazon region conservation (Lu et al. 2010). Therefore, both variables reinforce each other to potentiality drive sustainable DRE. Keeping both variables at their maximum sustainability level (1) during the whole simulation will signify their role in the developing system behavior implying that the targets of the indicators of each variable are always met, so that continuous electricity is generated with renewable energy (EN-1), polluting sources of energy are reduced (EN-2, EN-3), and waste from DRE is properly disposed (EN-4). Also, indigenous people always are always attached to their culture in terms of their preference to speak native languages (CU-3), build and live in traditional houses (CU-3), and communal and reciprocity activities are always present (CU-1).

After the simulation (Appendix 3-4), the resulting variables were aggregated into SI and the marginal differences with the non-management scenario were calculated (Figure 5.10). Environmental and economic sustainability exhibit the highest change, while institutional, technological and social sustainability show a relatively low and negative change suggesting that the supposed interventions in the system such as culture environment preservation will have the highest positive effect on economic sustainability but the lowest and negative effect on social sustainability. The reasons for these differences can be interpreted by looking at changes of specific dimensions and associated variables.

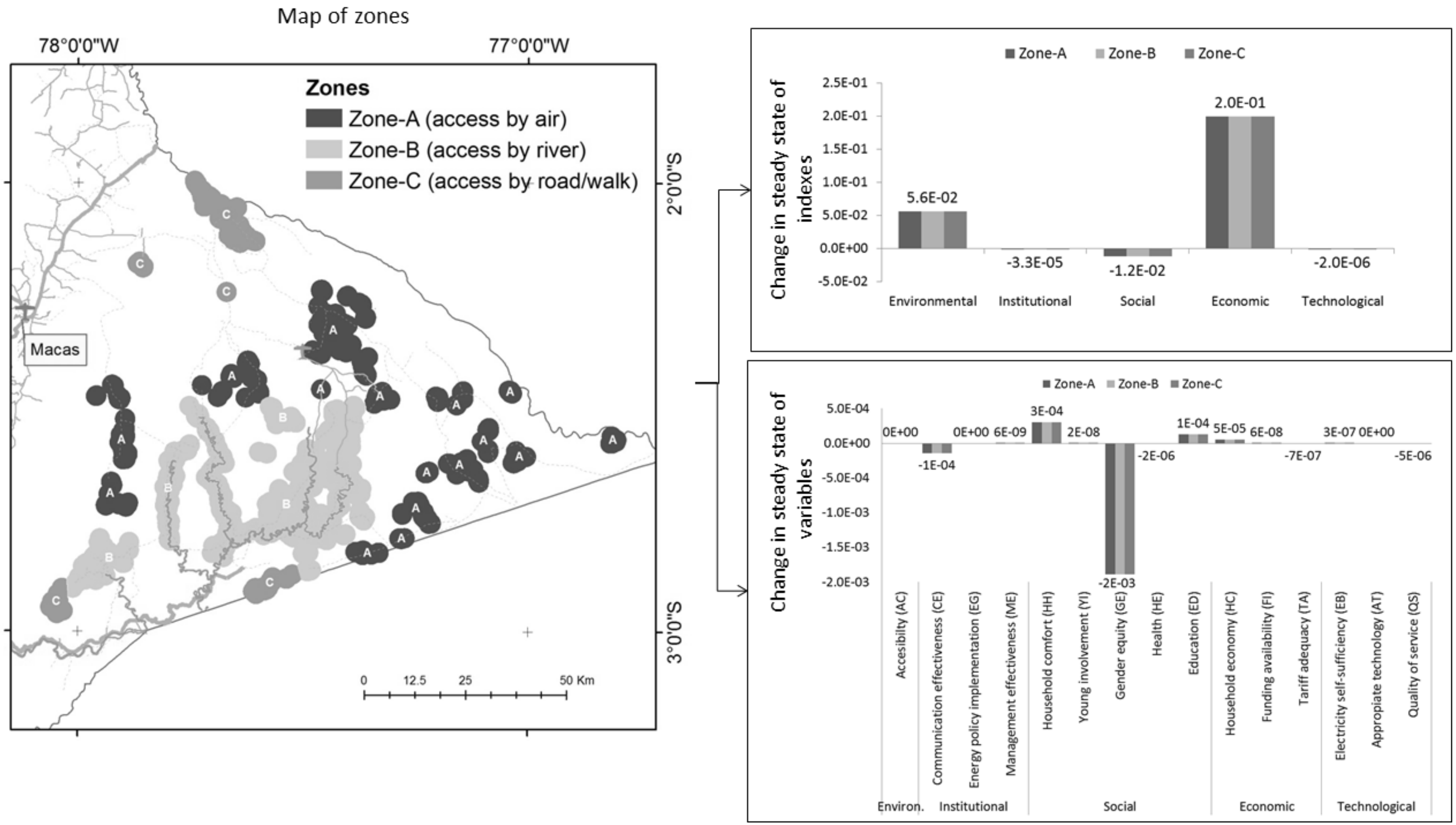


Figure 5.10 Change in steady state of sustainability indexes and variables from non-management scenario under constant environment and culture preservation (scenario 1).

Economic and environmental sustainability have the highest positive changes because *'household economy (HC)'* is impacted positively due to the replacement of expensive and polluting sources of energy (EN-2, EN-3), a change that will always occur in this scenario. Social sustainability has the lowest and negative change because *'gender equity (GE)'* exhibits the highest negative change. From field observations, cultural norms in Amazonian communities considered always high in this scenario, limited the participation of women in DRE. Institutional sustainability also has a negative change but this is relatively low, because *'communication effectiveness (CE)'* between electricity suppliers and households exhibits a negative change influenced by language differences, a phenomenon which will always persist, since indigenous people are attached to their local languages to preserve their culture (CU-2), and managers, engineers, and technical staff of the electricity companies are more versatile in Spanish. Technological dimension shows the lowest change but also negative because *'quality of service (QS)'* is impacted negatively. Cultural differences create language barriers always occurring in this scenario, which provoke a low knowledge of the households on how to use technology (SHS) resulting in frequent failures (Table 3.5) and consequently a lower availability (QS-1) and higher frequency of electricity service lost (QS-2)

Scenario 2: Stakeholder communication

Communication was perceived as an important driver of DRE that ensures technology and knowledge transfer and also limits misunderstandings between electricity suppliers and indigenous people (Table 3.7). Based on this argument and the previous scenario (low institutional sustainability), this motivated the simulation of a continuous *'communication effectiveness (CE)'* maintaining its maximum sustainability level (1) during the whole simulation process, implying that indicator targets are always met so that household's knowledge on technology use (CE-1) and their ability to communication in their own language (CE-2) always takes place in this scenario.

After the simulation (Appendix 3-5), the resulting variables were aggregated into SI, and the marginal differences with the non-management scenario were calculated (Figure 5.11). As expected, a continuously improved *'communication effectiveness (CE)'* contributes to a positive change in institutional sustainability because knowledge and technology transfer in the native language is ensured. However, this is limited by the negative change of *‘management effectiveness (ME)’* because improving communication implies the need of more skilled staff (ME-3), which is not taking place in this scenario as this staff needs to take over responsibility for the increased training of the households for an improved communication. Economic sustainability shows the highest positive change because *‘tariff adequacy (TA)’* shows the highest positive change. Better communication will reduce the lag of payments (TA-1) contributing to improvement in the financial aspects of DRE (section 3.3.5 maintenance solar home systems). However, improving communication requires increased training to further household knowledge on technology use (CE-1). This implies more visits to the communities so operational costs will increase (FI-2) as expressed by the negative change of *‘funding availability (FI)'*. Technological sustainability also has a positive change but it is low because *'quality of service (QS)'* is impacted positively. Improved communication for technology and knowledge transfer reduces the chances of misuse of technology, i.e. in this case SHS, which is confirmed in the previous scenario. Social sustainability shows a negative and low change, but though there are improvements in all social variables, their aggregated contribution to social sustainability is lower than in the non-management scenario. Environmental sustainability change is zero.

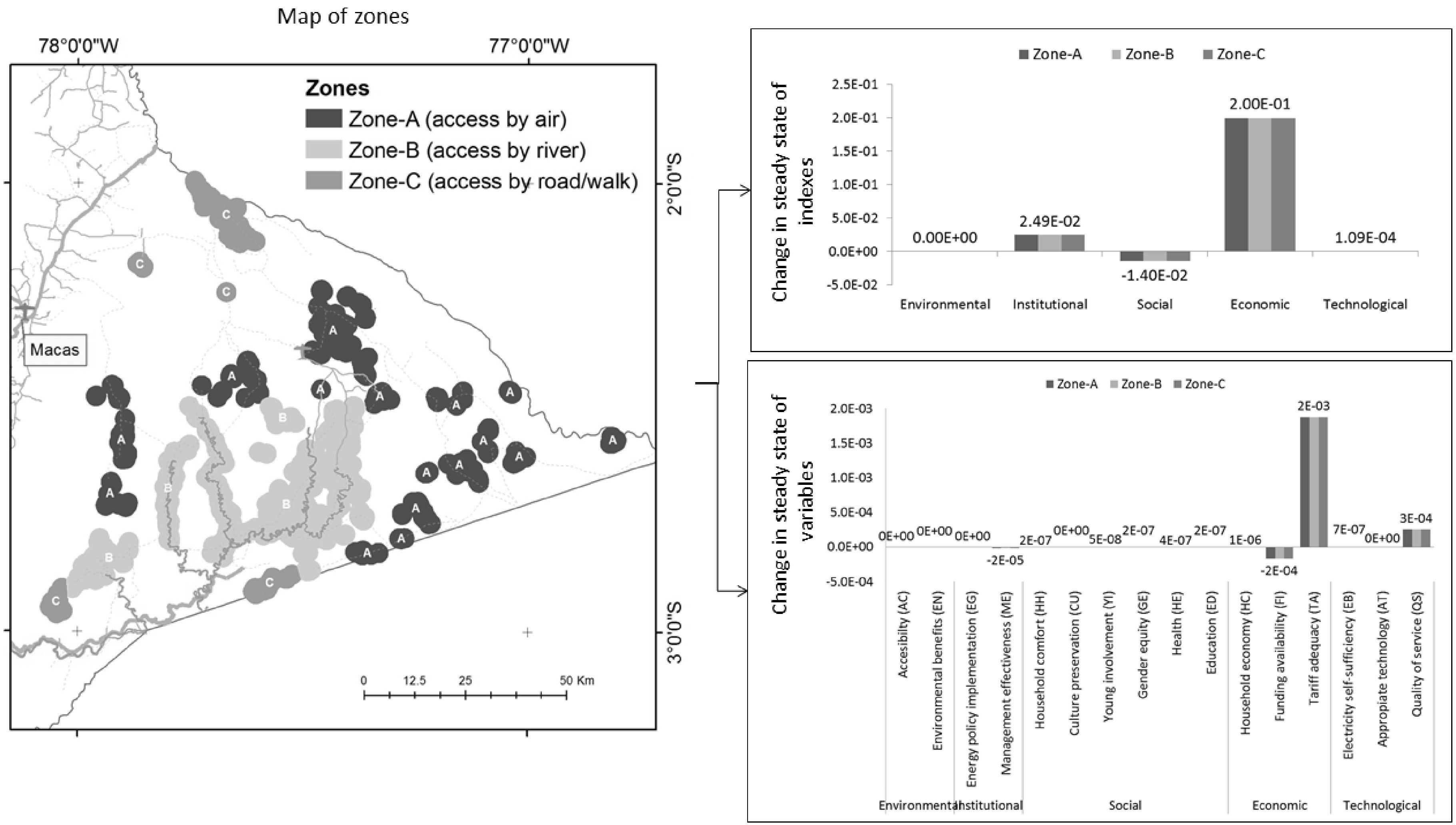


Figure 5.11 Change in steady state of sustainability indexes and variables from non-management scenario under continuous stakeholder communication (scenario 2).

Scenario 3: local economic growth

Local economic growth was seen as a driver of development in the Ecuadorian Amazon (Table 3.7) and as highly critical for the system (Figure 5.6 and Figure 4.6). It could lead to positive, e.g. income generation, or negative, e.g. deforestation, effects (Walsh et al. 2008; Swann et al. 2015). Also, it was found that local economic growth is limited by the level of accessibility to markets (Table 3.6) (Ahlstrom et al. 2011). Thus, these arguments motivated the simulation of a continuously improved *'accessibility (AC)'* and *'household economy (HC)'* by clamping them at their maximum sustainability level (1) during the whole simulation process, implying that indicator targets are always met so that households use electricity for income generation (HC-1), their household energy expenses are reduced (HC-2), and they can access credits ensuring a continuous income (HC-3). Furthermore, household travels expenses (AC-1) and frequency (AC-2) are continuously reduced, so perception on accessibility improvement is always high (AC-3).

After simulation (Appendix 3-6), the marginal differences between variables and SI with respect to the non-management scenario were calculated (Figure 5.12). As expected, environmental sustainability has a relatively high and positive change because of the improvement on *'accessibility (AC)'* always occurs in this scenario. Economic sustainability has the highest positive change because 'funding availability (FI)' is impacted positively. Improvement in *'accessibility (AC)'* reduces transport costs, which have an important share in maintenance costs (Figure 3.6). Institutional and technological sustainability also show positive changes but these are relatively low. Better accessibility implies less difficulty in visiting the communities, so *'management effectiveness (ME)'* and *'quality of service (QS)'* are impacted positively. Social sustainability shows a minor change, but it is negative because *'culture preservation (CU)'* is negatively impacted. A better *'accessibility (AC)'* implies a higher migration to cities but also a more frequent contact with traditional communities with outside society which could drive acculturation (Redfield et al. 1936; Pace 1993).

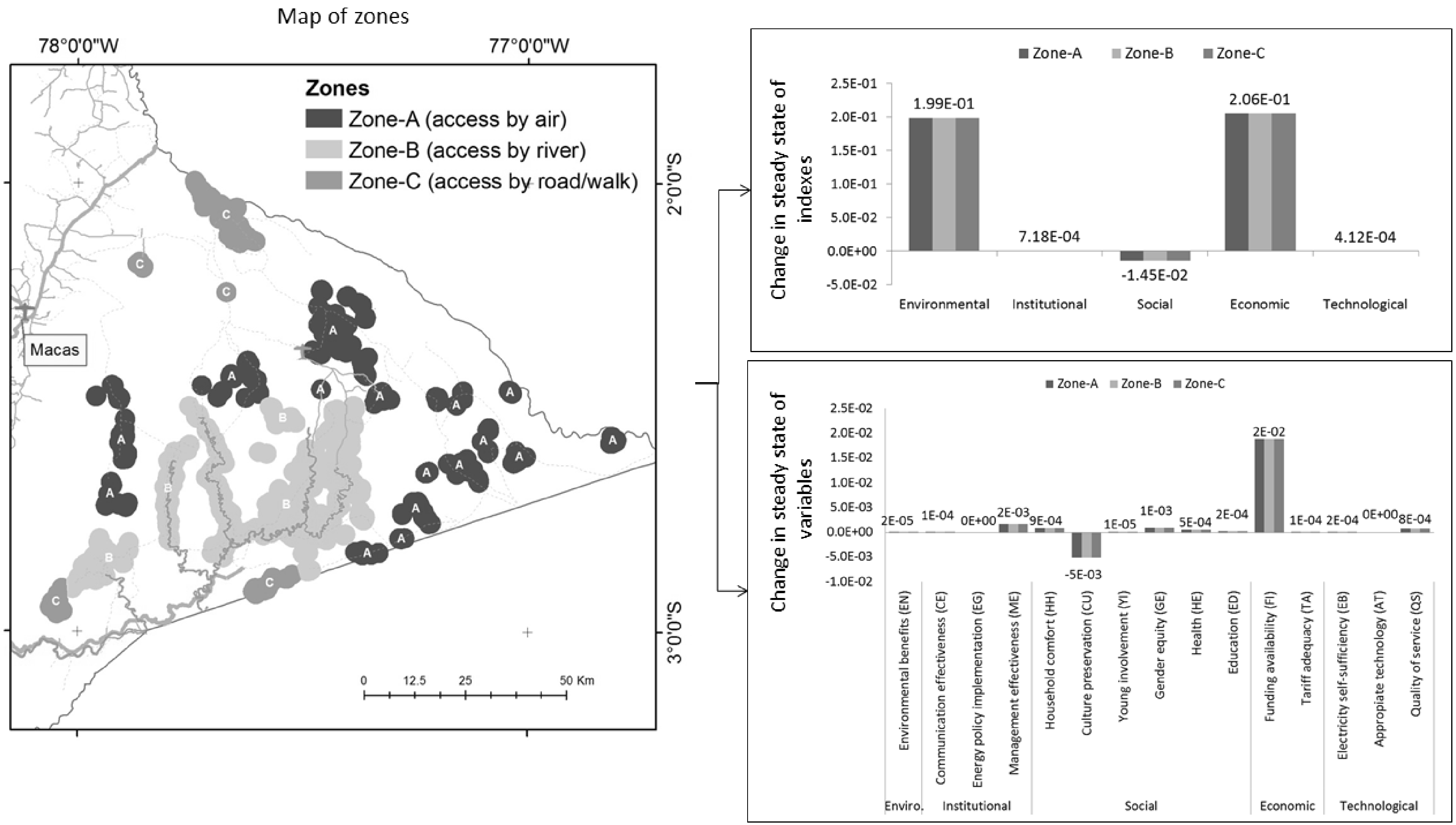
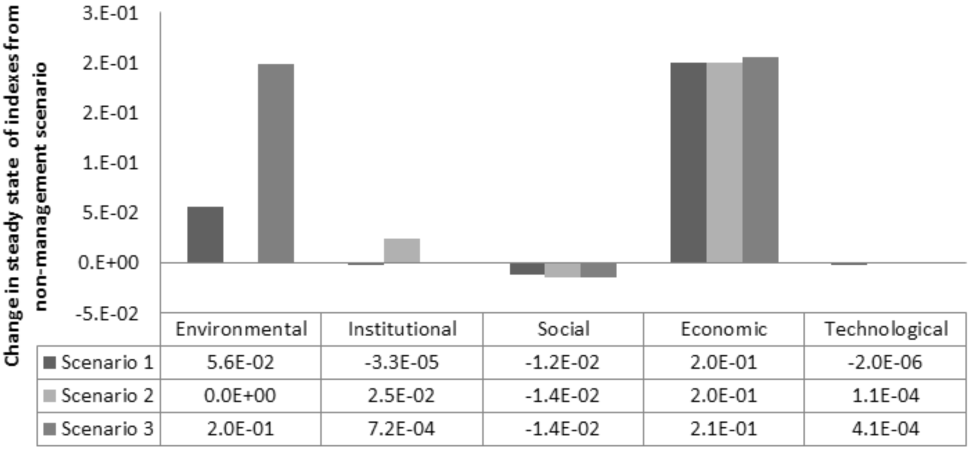


Figure 5.12 Change in steady state of sustainability indexes and variables from non-management scenario under continuous local economic growth (scenario 3).

Contrasting different scenarios

The comparison of the different scenarios is shown in Figure 5.3. Results suggest that any intervention will have a positive and the highest effect on economic sustainability. If environmental sustainability is the main concern, scenario 3 (local growth) shows the biggest positive change. Scenario 1 (environmental and culture preservation) has a lower positive effect on environmental sustainability because *'accessibility (AC)'*, an environmental variable defined by workshop participants, was not changed in this scenario, but it is constantly improved in scenario 3. If institutional sustainability is the main concern, scenario 2 shows the biggest positive change, because of continuous improvement in stakeholder communication that facilitates technology deployment. Technological sustainability will have the lowest change under any intervention in the system. These changes are positive for scenario 2 and 3, but negative for scenario 1, suggesting that technological sustainability was perceived as a top-down managed dimension with high dependence on external inputs such as spare parts. Finally, the social dimension shows negative changes in all scenarios, suggesting that proposed interventions always result in an emergent behavior that does not support for social improvements, which are difficult to predict. Overall, results suggest that the application of FCM simulations has the potential for group discussions and supports policy and decision making.



	Environmental	Institutional	Social	Economic	Technological
■ Scenario 1	5.6E-02	-3.3E-05	-1.2E-02	2.0E-01	-2.0E-06
■ Scenario 2	0.0E+00	2.5E-02	-1.4E-02	2.0E-01	1.1E-04
■ Scenario 3	2.0E-01	7.2E-04	-1.4E-02	2.1E-01	4.1E-04

Figure 5.13 Comparison of the effects of different scenarios on the sustainability of DRE

5.3.4 Evaluation of proposed approach

The development of the fuzzy cognitive map captured and integrated stakeholder knowledge in a transparent and formal way eliciting the complexity of sustainable DRE in a participatory approach. Its implementation was simple and intuitive, thus allowing the participation of diverse stakeholders such as engineers and doctors regardless of their experience. Moreover, FCM was flexible by allowing the incorporation of new variables and causal relationships at any stage, even if initial diagraming of variable interconnections was incorrect or incomplete. Models can be quickly updated, for example in MS Excel, to test the effects of such changes.

Geographic information systems allowed storing, updating and use of an extensive database for multi-criteria decision analysis and the production of maps which were useful to highlight the differences in sustainability across space, and helped to identify environmental, institutional, social and economic conditions that require improvements such as variables or indicators that did not meet the targets. Therefore, local and target-oriented actions can be designed and implemented accordingly. The complementary information between disaggregated variables and indicators and SI facilitated traceability at different scales of sustainability. Thus, this can provide early warning about subtle and negative trends of sustainability across the space helping managers to make timely decisions.

Fuzzy cognitive mapping simulations helped to foresee emergent behavior of the system difficult to predict if a disciplinary or non-participatory approach would have been adopted. The simulation showed plausible results confirming expected but also additional insights on the behavior of the system represented. Therefore, FCM simulation is a powerful discussion tool that can link stakeholder story lines (Chapter 3 and 4) with ‘semi-quantitative’ simulations, and support an investigation on stakeholder’s system perception. Moreover, scenario development and analysis provided arguments useful for policy recommendations and enhancing sustainability of DRE incorporating stakeholder and system thinking perspectives.

Like any decision support tool, it also has limitations. Transforming qualitative variables, e.g. culture preservation, of FCM into numeric data during simulations produces information based on assumptions and not on real estimates. Thus, results can be debatable, and it is impossible to make a quantitative validation of simulations (Ozesmi and Ozesmi 2004; Jetter and Kok 2014). The quantitative evaluation of indicators through an extensive household survey and reflecting on the findings presented in the previous chapters alleviate this problem to some extent. However, this drawback can be seen as an advantage in the sense that it allowed gathering and studying data that otherwise would not be considered in a non-participatory approach, and that information is the information stakeholders use in most of their decision making.

The GIS-based MCA is dependent on the selected spatial scale, in this case, three zones extracted from a participatory mapping was applied. Creating sub-sets within each zone could have resulted in higher resolutions of sustainability. However, it would have increased cost and time for data collection. Access to the study area was a constraint. Selected spatial scales allowed large-scale coverage of the study area appropriate to support analysis for policy and decision making.

Simulations of fuzzy cognitive mapping cannot be used to make precise forecasts, but rather to provide broad perspectives on sustainability changes grounded on local experience, and help to target areas where there is room for improvement. This is of high relevance to bridge scientific knowledge, and policy and decision-making.

The construction of FCM considered variable causal relationships that were linear (between 0 and 1), so the non-linearity of system behavior was not captured during simulation. Also, it was difficult to set a precise time framework for simulation (Park 1995; Yaman and Polat 2009) since variables operate at different scales and can include delays which were not captured. Thus, simulation outputs provide measures of a long-term and 'unknowable' future. Tackling these issues effectively will imply sophisticated simulation approaches, e.g. system dynamics and agent-based modeling, which could limit the inclusive participation of stakeholders from model construction to analysis who are more accustomed to qualitative evaluations and who thus feel more comfortable with the FCM format (Mendoza and Prabhu 2006).

Simulations of fuzzy cognitive maps are fundamentally dependent on the adjacency matrix and transformation function (Jetter and Kok 2014). The selection of the latter (logistic function) was done in the best knowledge from the literature review (Tsadiras 2008; Knight et al. 2014). The fuzzy cognitive map (adjacency matrix) was assumed equal across the study area, but differentiating causal relationships by zones could have resulted in different steady states and consequently better sustainability resolutions across the space. The effects of choosing different transformation functions and building fuzzy cognitive maps for each zone were not incorporated in this study. Accessibility to the study area was a research limitation. Research is ongoing on the utilization of learning methods to adapt causal relationships and overcome incomplete knowledge or bias of stakeholders (Papageorgiou and Groumpos 2004), and on the selection and use of transforming functions (Jetter and Kok 2014; Knight et al. 2014).

5.3.5 Conclusions

This study demonstrates that MCA and FCM can be integrated into a GIS to form a participatory decision support tool for an integrated assessment and management of sustainable DRE. To illustrate this, an empirical application was implemented to assess and simulate the sustainability of DRE based on SHS in the Ecuadorian Amazon. The plausibility of results validates the suitability of the approach. In this study, DRE from perspectives other than traditional methods, i.e. economic or technical, was examined and should serve as a learning tool that opens new avenues of research, but not as a stand-alone means to make decisions. Thus, the results of this study contribute to the progress towards the development of a fully integrated tool to assess and simulate the sustainability of DRE. There are some limitations that need to be addressed in future research (section 5.3.4)

As noted in the literature and along this study, the most important and challenging aspects of succeeding with the management of sustainable DRE are stakeholder participation and incorporating system thinking perspectives during decision making. This approach contributes to progress in this regard. The construction of FCM, the definition of targets and weights with decision makers, and the incorporation of household viewpoints (survey) allowed an active and inclusive participatory and integrated assessment and simulation approach. The practicality of FCM allowed integrating any kind of variable relevant for sustainable DRE, and a diverse group of stakeholders could also participate in the process regardless of their experience in rural electrification, providing an opportunity to bridge the gap between indigenous people, electricity suppliers, engineers, politicians, and scientists. From a system thinking perspective, FCM allowed studying different aspects of sustainable DRE that otherwise would not be considered in a non-participatory approach, ensuring that information generated is relevant for the decision-making needs of stakeholders, but also allowed generating strategic scenarios that can support group discussions for policy design of sustainable DRE in the Amazon region.

The proposed decision support tool is flexible and adaptable for decision making. An extensive database of spatial and non-spatial information can be stored, updated and processed in GIS. Thus, decision-support maps can be produced to study sustainability across space and at different sustainability scales using variables, indicators, and sustainability indexes. Maps can reach a higher audience of stakeholders so this can promote a better communication and participation to target sustainability actions and geographical areas where there is a need for improvement. Simulating sustainability through FCM uses simple vector-matrix operations, so models can be implemented and updated easily by simple tools, e.g. MS Excel. There is no restriction for incorporating variables or connections as needed in FCM, meaning that models are flexible enough to allow continuous modifications. Thus, the proposed decision support tool is an attractive solution for managers who do not deal with complex simulation models.

Research concerning the assessment and simulation of sustainability in energy systems is still a work in progress. This study contributes by proposing an approach for an integrated and participatory management of DRE in the Amazon region which is useful for helping regional managers to make more informed decisions and progress towards sustainability.

6 SUMMARY, MAIN RESEARCH FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The progression on DRE is necessary for electricity supply and improvement of the living conditions of remote and disadvantaged areas in the Amazon region. However, DRE is often challenged by an unfavorable policy environment, limited organizational capacities, restricted financial resources, users' cultural attitudes and values as well as technology and environmental constraints. Therefore, DRE should be monitored to provide a basis for a proactive management towards universal access and sustainability in the Amazon region. The aim of this research is to assess and simulate in a participatory and systemic manner the sustainability of DRE in the Amazon region using Ecuador as a case study. An integrated and participatory decision support tool was developed and tested that enables stakeholders to explore alternative policy scenarios which in the long run can ensure a reliable electricity supply while improving the peoples' wellbeing and protecting the environment, thereby providing stakeholders with a complementary tool to support and make more informed decisions about sustainable DRE. Research objectives were accomplished by applying an interdisciplinary, participatory and multi-method approach.

This study begins with a description of the study area, and an in-depth literature review of DRE in the Amazon region, and existing approaches to study the sustainability of DRE (Chapter 2). The review shows that DRE is influenced by numerous and interlinked environmental, societal, institutional, economic and technological aspects specific for each country in the Amazon region. To disclose this complexity and to effectively assess and model the sustainability of DRE, decision support tools should be interdisciplinary, participatory, able to address uncertainty, have temporal range flexibility and a local-global viewpoint. At present, there is no all-in-one tool that can address all these aspects. A combination of system thinking approaches with GIS was found suitable to integrate systems, stakeholder and spatial perspectives to study the sustainability of DRE.

Stakeholders were identified, characterized and their interaction in relevance to the DRE was disclosed through a stakeholder analysis (interest-influence matrix and social network analysis; Chapter 3). Based on interaction with relevant stakeholders in semi-structured interviews with decision makers and an intensive survey with households using solar home systems (SHS), the aspects that hinder or favor DRE in remote areas of the Ecuadorian Amazon were identified and discussed accordingly. Thus, concepts, values, and perceptions from real life experience about sustainable DRE provided a background for the subsequent research phases.

In Chapter 4, the participatory system analysis applied to integrate stakeholder knowledge using the computerized Sensitivity Model® (SM) is described. Relevant stakeholders identified in the previous research phase discussed and agreed on a set of variables and their cause-effect to assess the sustainability of DRE. A simplified but complete model of DRE as a system was obtained. Most existing models rely on pre-defined lists of variables that can lead to incorrect definitions of system boundaries and principles, potentially excluding critical relevant stakeholder interests. Thus, results provide a holistic basis for the construction of sound decision support tools for the study of sustainability of DRE incorporating system thinking and stakeholder perspectives.

Based on a comprehensive review of DRE in the study area (Chapter 3), and a conceptual system model of sustainable DRE (Chapter 4), a decision support tool was developed and applied (Chapter 5) by combining multi-criteria decision analysis and fuzzy cognitive mapping with GIS. A real case was used to test the tool. The plausibility of results suggests it is suitable for a participatory assessment and simulation of sustainable DRE contributing to the progress of fully integrated and dynamic approaches for sustainability assessment of DRE.

6.2 Main research findings

6.2.1 Stakeholders, barriers, and drivers

- An entangled network of stakeholders with diverse roles and levels of interest and influence (Figure 3.4) is involved in the DRE system. Although DRE is a government-dependent process, informal stakeholder relationships at the local level (e.g. indigenous political organizations, NGOs, teachers, village presidents and electrification committees) are subtle but nevertheless significant to ensure in the long run an electricity supply that contributes to rural development, i.e. productive uses of electricity.

- A catalog of barriers and drivers that hinder or favor DRE as perceived by relevant stakeholders was built (Table 3.6 and Table 3.7). These are mostly related to social and political aspects, and therefore more difficult to address than the technical or economic ones, which are usually addressed by those in charge of the electricity supply such as electricity companies and engineers.
- The resources to overcome existing barriers surpass the scope of electricity suppliers, so a broader cooperation among stakeholders is required, especially at the local level. However, actual legislation restricts non-governmental actors in participating in activities of the electricity sector, thus complicating potential cooperation.

6.2.2 Participatory system analysis

- The developing system of DRE was disentangled by identifying environmental, economic, social, institutional and technological variables (Table 4.3) and their relationships (Figure 4.9) as perceived by the stakeholders. Thus, the holism of sustainable DRE was captured as a simplified but complete system model (Figure 4.12).
- Variables were categorized according to their systemic role within the system as active, reactive, critical or buffering (Figure 4.9). These express the level of variable dependency or driving power within the system, so this can potentially help decision makers to prioritize and target actions for effective interventions and scale-up of sustainable DRE in the Amazon region.
- DRE is a system made up of highly interconnected variables but with limited self-regulation mechanisms. This means that the provision of electricity in the Amazon region can be perceived as an unstable system in environmental, institutional, social, economic and technical terms, not self-sufficient and

dependent on external inputs. This thus confirms the need for monitoring and assessing DRE and safeguarding sustainable development in the Amazon region.

6.2.3 Development of a spatially explicit and participatory approach for the assessment and simulation of sustainability of decentralized rural electrification

- Combining fuzzy cognitive mapping and multi-criteria decision analysis in GIS (Figure 5.1 and 5.2) demonstrated through an empirical application is shown to be a powerful discussion tool that can tackle the complexity of DRE in an integrated, spatially explicit and participatory manner. Fuzzy cognitive mapping incorporated stakeholders' knowledge in a transparent and formal way, and simulated the emergent behavior of the perceived system, resembling existing knowledge but also providing additional insights to foresee sustainability trends of DRE. Multi-criteria decision analysis and GIS helped to portray sustainability in a spatially explicit manner at different dimensions and scales (indicators, variables, and sustainability indexes) thus facilitating traceability and a practical and comprehensive visual analysis.
- The proposed decision support tool cannot be used to make precise forecasts, but rather to link 'semi-quantitative' simulations with stakeholders' storylines, thus, providing a broad perspective of sustainable DRE grounded on local experience and target actions in areas where there is more room for improvement or stakeholder engagement. It is of high relevance to bridge scientific knowledge into policy and decision making.
- The proposed approach incorporates stakeholder and system thinking perspectives, which are recognized as the most challenging aspects of decision making and management of sustainable DRE. Essential configurations and processes of the system, i.e. variables and causal relationships, perceived by experienced stakeholders, overcomes the need for the large amounts of data required by purely quantitative approaches, where the application is restricted by the frequently data-poor conditions in developing countries.

6.3 Conclusions and recommendations

Research findings suggest that DRE in the Amazon region is prone to failure, and to overcome this from a technological viewpoint, appropriate knowledge and skills to locally operate and manage renewable energy including a context-appropriate communication between beneficiaries (indigenous people) and electricity suppliers is required. Also, DRE designs and installations must be simple and resilient to harsh operating conditions. From a social perspective, a high participation of beneficiaries at different levels of decision-making is needed. Allowing key actors of local and social organization structures, e.g. indigenous political organizations, women, village leaders, to support the process of electrification promotes indigenous peoples' ownership and autonomy. From an economic viewpoint, as DRE will remain a public sector investment, investments should be based on social returns of electricity rather than on financial returns. Therefore, funding must be always available through co-funding schemes among government bodies. Also, DRE should promote community-based income generation activities, e.g. tourism or farming, perceived compatible with a sustainable economic growth in the Amazonian communities. From an environmental standpoint, DRE reduces greenhouse gas emissions but must avoid waste generation and deforestation for the conservation of the Amazonian rainforest. From an institutional viewpoint, tailored regulations, standards, and organizational capacities need to be defined and be conducive to a bottom-up and integrated approach of electricity supply.

The participatory system analysis provides insights on key variables (Table 4.3) and their relationships that may help in strategic decision making to attain sustainable DRE. It is common practice that decision makers focus only on the few aspects perceived as the most important for sustainable DRE, e.g. funding availability, neglecting the significance of other variables such as youth involvement and gender equity. Addressing one variable may improve sustainability, but at the same time, it could heighten the negative effects of other variables. The analysis shows that variables can be categorized by their role within the system (Figure 4.9), which can help decision makers to focus on few but relevant aspects to tackle more effectively the complexity of DRE: (i) lever variables suitable for effective control of the system and strategic decisions are *'energy governance', 'funding and investment,' 'accessibility', 'appropriate technology,'* and *'youth involvement'*. The three latter are instrumental for sustainable energy policy designs in the Amazon region; (ii) gauging variables more suitable for monitoring system development and results orientation are *'financial equilibrium', 'communication effectiveness', 'environmental quality'* and *'health'*; (iii) regulating variables suitable to correct undesirable system developments and for adaptive management are *'quality of electricity service', 'management effectiveness', 'gender equity'* and *'culture'*; and (iv) critical variables (highly interconnected with others) suitable to effectively align DRE outcomes with local development needs are *'household economy', 'home comfort and social resources*', and *'education'*.

It is therefore recommended that decision and policy makers should adopt a systemic standpoint for the management of sustainable DRE in the Amazon region, and the proposed decision support tool sets the basis for progress in this endeavor. GIS are extensively used for energy and rural electrification planning, and multi-sectoral data can be integrated and maps produced as effective means of communication. GIS also facilitate information exchange between government bodies and organizations, e.g. health, education, and electricity, thus promoting stakeholder participation. Linking GIS with system-thinking approaches provides a practical and flexible approach to support the elicitation and processing of stakeholder knowledge, as well as the simulation and assessment of sustainability scenarios of DRE. After the empirical application of the proposed decision support tool, some assertions can be highlighted: (i) The approach allows an active participation of stakeholder regardless of their experience in the construction and analysis of simulation models to assess the sustainability of DRE; (ii) the simplicity and intuitive nature of FCM and MCA is an attractive alternative for policy and decision makers with limited time and resources to formulate purely quantitative approaches; and (iii) the use of maps and FCM simulations can provide early warning about subtle trends of sustainability across space, different scales and the long-term future helping managers to make timely decisions.

Research limitations and future research are recommended on the following:

- Stakeholder networks are dynamic and complex. Stakeholders and ways of interaction might change in the future or may have been different in the past. Thus, there is a need to study how stakeholders' relationships, influence and interest in DRE change along the time and in different phases of DRE. This will help to broaden the understanding of stakeholder dynamics and to define strategies for effective engagement.
- The participatory system analysis included stakeholders with a deep involvement in local affairs, i.e. indigenous leaders, a missionary, indigenous technical staff, NGO representatives, etc.. However, there was no explicit participation of community members. Representatives from some communities were invited but they did not attend hindering a broader participation of indigenous people. This should be considered in future research.
- The proposed decision support tool has limitations (section 5.3.4) that require further investigation on: (i) use of finer resolutions for data collection to study the effect of different spatial scales on sustainability levels of DRE; (ii) incorporation of non-linearity and time delays in FCM models; (iii) the effect of different transformation functions during FCM simulations. These are fields of research described in the literature; and (iv) the effect of constructing FCM differentiated by groups of stakeholders and spatial zones to contrast spatial perceptions of the developing system behavior.
- However, the proposed decision support tool shows encouraging results. The quality of simulation outputs and scenario analyses (relevance, credibility, and legitimacy) for its practical application needs to be investigated through consultation with decision makers and stakeholders.

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8 APPENDICES

8.1 Appendix 1: supplementary information chapter 3

Appendix 1-1: Protocol of semi-structured interviews

Topic: General and personal information

1. Presentation of the research and agreement for interview
2. What is your experience with rural electrification in Ecuador or overseas?

Topic: Perceived barriers and drivers of DRE

3. What do you think are the barriers or problems for DRE in isolated regions of Ecuador?
    - *In terms of*
        - *Political aspects*
        - *Institutional aspects*
        - *Project management*
        - *Economic aspects*
        - *Social aspects*
        - *Technological aspects*
        - *Physical and infrastructure*
        - *Others*

4. How do you think DRE can be improved or solved,
5. What are the aspects needed to be addressed?
    - *In terms of*
        - *Political aspects*
        - *Institutional aspects*
        - *Project management*
        - *Economic aspects*
        - *Social aspects*
        - *Technological aspects*
        - *Physical and infrastructure*

Topic: Perceived electricity impacts on sustainability and development of the Ecuadorian Amazon

6. Who or what do you think benefits from DRE in the Ecuadorian Amazon? And how?
7. What do you think are the negative impacts of DRE in the Ecuadorian Amazon? And How?
    - *In terms of*
        - *Environmental aspects*
        - *Socio-economic aspects*
        - *Energy demand*

  - *National and political*
  - *Others*

8. What do you think are the probable productive uses of electricity for the Ecuadorian Amazon?

Topic: Stakeholder identification and analysis

9. Can you explain briefly and assess using a scale of Low, Medium, High,
   - What is your interest in DRE?
   - What is your influence on the success and sustainability of DRE?

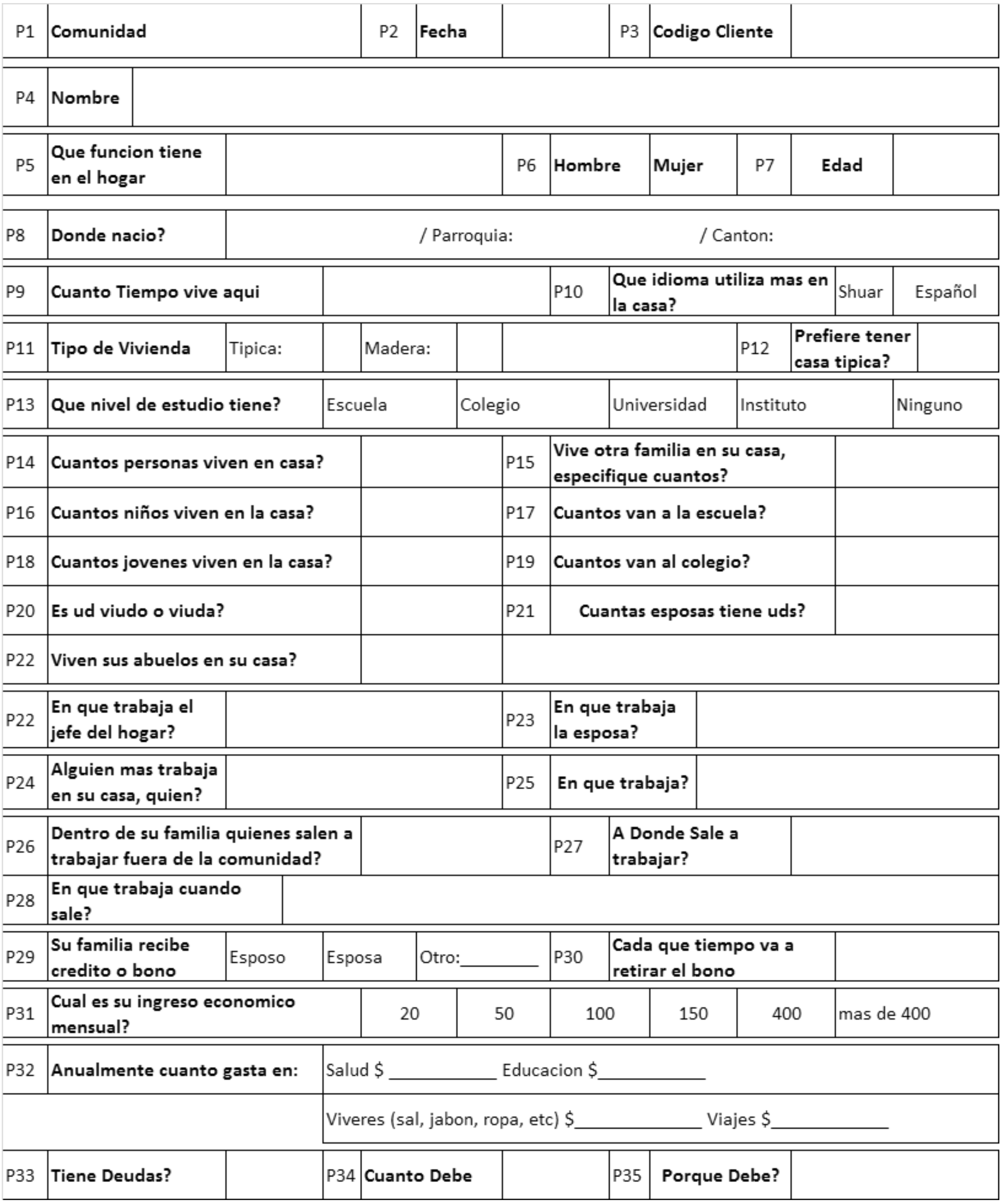
	High (3)	Medium (2)	Low (1)
Interest			
Influence			

10. Who are the stakeholders that you have cooperated with in DRE and how was this cooperation? If not
11. Who do you think are key stakeholders for rural electrification in the Ecuadorian Amazon?
12. Can you assess the interest and influence of the following list of stakeholders (Table 3.1) using the same scale?

Topic: Sustainability normative concepts and ideas

13. How do you define a sustainable DRE project or program?
14. What do you think are the important variables or indicators that should be monitored to measure the sustainability of DRE?

Appendix 1-2: Questionnaire used for household survey



P1	**Comunidad**		P2	**Fecha**		P3	**Codigo Cliente**		
P4	**Nombre**								
P5	**Que funcion tiene en el hogar**		P6	**Hombre**	**Mujer**	P7	**Edad**		
P8	**Donde nacio?**	/ Parroquia: / Canton:							
P9	**Cuanto Tiempo vive aqui**		P10	**Que idioma utiliza mas en la casa?**	Shuar	Español			
P11	**Tipo de Vivienda**	Tipica:		Madera:			P12	**Prefiere tener casa tipica?**	
P13	**Que nivel de estudio tiene?**	Escuela	Colegio	Universidad	Instituto	Ninguno			
P14	**Cuantos personas viven en casa?**		P15	**Vive otra familia en su casa, especifique cuantos?**					
P16	**Cuantos niños viven en la casa?**		P17	**Cuantos van a la escuela?**					
P18	**Cuantos jovenes viven en la casa?**		P19	**Cuantos van al colegio?**					
P20	**Es ud viudo o viuda?**		P21	**Cuantas esposas tiene uds?**					
P22	**Viven sus abuelos en su casa?**								
P22	**En que trabaja el jefe del hogar?**		P23	**En que trabaja la esposa?**					
P24	**Alguien mas trabaja en su casa, quien?**		P25	**En que trabaja?**					
P26	**Dentro de su familia quienes salen a trabajar fuera de la comunidad?**		P27	**A Donde Sale a trabajar?**					
P28	**En que trabaja cuando sale?**								
P29	**Su familia recibe credito o bono**	Esposo	Esposa	Otro:________	P30	**Cada que tiempo va a retirar el bono**			
P31	**Cual es su ingreso economico mensual?**	20	50	100	150	400	mas de 400		
P32	**Anualmente cuanto gasta en:**	Salud $ ___________ Educacion $___________							
		Viveres (sal, jabon, ropa, etc) $_____________ Viajes $____________							
P33	**Tiene Deudas?**		P34	**Cuanto Debe**		P35	**Porque Debe?**		

Seccion II					
P36	**Que necesita mas urgente su familia?**				
P37	**Que necesita mas urgente su comunidad?**				
P38	**Con la electricidad su familia ha mejorado?**	**Mucho**	**Poco**	**Igual**	**Empeoro**
P39	**Explique porque?**				
P40	**Con la electricidad la SALUD ha mejorado?**	**Mucho**	**Poco**	**Igual**	**Empeoro**
P41	**Con la electricidad la EDUCACION ha mejorado?**	**Mucho**	**Poco**	**Igual**	**Empeoro**
P42	**Con la electricidad el TRABAJO ha mejorado?**	**Mucho**	**Poco**	**Igual**	**Empeoro**
P43	**Con la electricidad los INGRESOS ECONOMICOS han mejorado?**	**Mucho**	**Poco**	**Igual**	**Empeoro**
P44	**Con la electricidad el TRABAJO COMUNITARIO (mingas) ha mejorado?**	**Mucho**	**Poco**	**Igual**	**Empeoro**
P45	**Con la electricidad llegan mas VISITAS a su vivienda?**	**Mucho**	**Poco**	**Igual**	**Empeoro**

		Con la Electricidad	**Sin la Electricidad**
P46	**A que hora se levanta de la cama?**		
P47	**A que hora se va a dormir?**		
P48	**A que hora se levanta su MUJER?**		
P49	**A que hora se va a dormir su MUJER?**		
P50	**A que hora se levantan los NIÑOS?**		
P52	**A que hora se van a dormir los NIÑOS?**		
P53	**A que hora se va a la huerta su MUJER?**		
P54	**A que hora vuelve de la huerta su MUJER?**		

P55	**Cual es la enfermedad mas comun en los ninos?**							
P56	**Cual es la enfermedad mas comun en los adultos?**							
P57	**De donde saca el agua**	Pozo	Quebrada	Rio	Entubada	P58	**A cuanto tiempo esta de su casa el agua?**	
P60	**Cuantos veces al dia acarrean agua?**		P61	**Cuantos galones de agua trae en cada viaje?**				
Secccion III								
P62	**Le preguntaron a Usted si queria electricidad?**		P63	**Usted participo en la instalacion, especifique?**				
P64	**Es importante que participen las mujeres en el proyecto de electricidad? Porque?**							
P65	**Es importante que participen los jovenes en el proyecto de electricidad? Porque?**							
	Sistema Economico							
P66	**Utiliza la electricidad para hacer:**	Artesanias	Tienda	Desgranar Productos	Chicha	Otro: ___________		

		Con Electricidad	Sin Electricidad		
P67	Cuantos pares de pilas compra al mes?				
P68	Para que usa las pilas	Radio/Linterna _________	Radio/Linterna _________		
P69	Cuanto cuesta el par?		P70	Donde compraba las pilas?	
		Con Electricidad	Sin Electricidad		
P71	Cuantos paquetes de velas compra al mes?				
P72	Cuanto cuesta el paquete de velas?		P73	Donde compraba las velas?	
		Con Electricidad	Sin Electricidad		
P74	Cuanto diesel compra al mes?				
P75	Cuanto costaba el diesel?		P76	Donde compraba las velas?	
		Con Electricidad	Sin Electricidad		
P77	Cuanta gasolina compra al mes?				
P78	Cuanto cuesta la gasolina?		P79	Donde compraba las velas?	
P80	Para que usa Gasolina?		P81	Para que usaba Gasolina?	

P82	La tarifa de $1,46 le parece?	Muy Caro Normal Barato	P83	Cuanto quisiera pagar?	$

P84	Cuanto le duran los troncos de la cocina y dimensiones?	

P85	Cuantos cilindros de gas utiliza al mes		P86	Cuanto Cuesta:	$	P87	Donde Compra:	

P88	Con la llegada de la electricidad viaja:	Mas	Igual	Menos	No Viajo

P89	A donde viaja con mas mas frecuencia?				
P90	Cuantas veces sale al año				
P91	Para que va a este lugar?				
P92	Cuanto cuesta el viaje de ida				

P93	Que productos compra en la ciudad?	
P94	Que productos trae con mas frecuencia en cada viaje?	
P95	Que productos vende en su comunidad?	
P96	Que productos vende fuera de su comunidad?	

P97	De que tamano es su huerta?		P98	Que cultiva en su huerta?	

P99	Tamaño de su Finca?		P100	A que tiempo esta su finca?		P101	Que cultiva en su finca?	

P102	Cuantos animales	Pollos: ______Cuy: ______Patos: ______Ganado: _______ Caballo: _______ Chancho:_____ Piscina: _____

P103	**Cuantas veces se va de caceria al mes?**		P104	**Que animales caza al mes**	

P105	**Cuantas veces se va de pesca al mes?**		P106	**Que pescado coge en cada pesca?**	

P107	**Ud Vende madera**		P108	**Que tipo de madera vende?**	

P109	**Le gustaria vender madera para mejorar su economia en la familia?**	

Secccion IV

P110		**Cuantos Tiene?**	**A que hora que enciende en la madrugada**	**A que hora enciende en la tarde**	**A que hora apaga en la noche**
	Focos				
	Radio				
	TV/DVD				
	Linterna recargable				
	Celular				
	Computador				

P111	**Piensa comprarse nuevos aparatos electricos? Especifique cuando y cuales**	

P112	**Que equipo del sistema solar se le ha dañado?**	**Panel**	**Regulad**	**Bateria**	**Inversor**	**Fusible Bateria**	**Fusible Focos**	**Focos**	**Otro**
P113	**Hace cuanto tiempo se le daño?**								
P114	**En cuanto tiempo le dieron arreglando?**								

P115	**Usted ha reclamado a Centrosur?**		P116	**Fue atendido su reclamo?**		P117	**Esta Satisfecho con el servicio electrico (S/N)**	

P118	**Que le pediria a la Centrosur para mejorar el servicio?**	

P119	**Le gustaria tener la red electrica o el Panel Solar?**	R	S		P120	**Quien es dueño del sistema solar?**	Empresa	YO
P121	**Puedo conectar una refrigeradora al sistema?**	SI	NO		P122	**Conoce las obligaciones del tecnico de CENTROSUR?**	SI	NO
P123	**Conoce las obligaciones del tecnico comunitario?**	SI	NO		P124	**Conoce usted que tiene que pagar por la electricidad**	SI	NO

Secccion 5

P125	**Los focos quemados fueron retirados**		P126	**El sistema solar ha contaminado la comunidad?**	Mucho Poco Nada
P127	**Donde bota los restos de comida?**		P128	**Donde bota los plasticos, metales, cauchos, etc**	
P129	**Que tipo de letrina tiene?**		P130	**Donde bota las pilas**	

8.2 Appendix 2: supplementary information chapter 4

Appendix 2-1 Variables and keywords extracted from the workshop

Variable	Keywords (i.e. potential indicators)
Electricity demand	Installed capacity Number of installations Electricity generation Demand deficit People with electricity People without electricity
Communication effectiveness	User acknowledges the use of technology and project rules Frequency of communication between service provider and user Share of indigenous staff Communication channel with service provider (ICT) Availability of a communication plan and conflict resolution
Accessibility	Travel expenses Travel time Satisfaction on accessibility Unpredictable weather impacts on access
Environment Quality	% polluting fuel consumption replaced % dry batteries replaced Ratio waste produced (broken equipment) Ratio waste disposed to total produced % of households with access to sanitary services % of renewable energy generation Rate of deforestation attributed to electricity access Artificial light and sound pollution Improvements in hunting conditions Water quality change attributed to electricity access

Variable	**Keywords (i.e. potential indicators)**
Home comfort and social resources	Household perception life improved Increased social gatherings Access to information (TV, radio) Communication with distant family members Less hassle for lighting Less hassle for water collection Feel secure at night Efficiency in performing household tasks (non-income) Change in bedtime Theft and vandalism Increased social status
Household economy	Households started an income generation activity Households improved their income Jobs generation Savings on energy expenditures Savings on travel costs In-debt households
Acculturation	Language use and preference TV and music preferences Participation in community work? Traditional house constructions Households eat traditional food Households practice traditional medicine Participation of indigenous political organizations Household practice cattle ranching Perceived DRE implementation complies with their rules
Appropriate technology	Durability of equipment Time to get a spare part Energy density Power density

Variable	Keywords (i.e. potential indicators)
	Capacity factor Energy reserve
Quality of electricity service	Time to restore service after a failure Frequency electricity service is lost User claims fulfilled Errors in metering Voltage variations % of systems fulfilling standards
Funding and Investment	Number of households benefiting from other social investments Subsidy for installation cost Subsidy for operation and maintenance costs Funding allocation for the next 5 years
Energy Governance	Electrification rate for isolated areas Interest in DRE among decision makers Availability of DRE policies Energy policies with explicit sustainability goals % households receiving another service after electrification
Youth involvement	Youths with jobs Youths that have migrated (work, study) Youths in project staff
Financial equilibrium	User willingness to pay Affordability energy expenses Profitability Cost-benefit rate Availability of financial structures
Gender equity	Women life improvement in domestic tasks Woman satisfaction with electricity service Women in project staff Women are able to generate income Women own a system

Variable	Keywords (i.e. potential indicators)
Management effectiveness	Information reliable for studies and monitoring Expected time for grid advancement % professional staff with intercultural skills Audit reports submitted Time to connect new users Degree of local technical services Level of institutional infrastructure for DRE User satisfaction Level community participation in maintenance activities
Health	Health centers with electricity and equipment Households perceived health improved Nighttime births benefiting from improved lighting Morbidity of water-related diseases Morbidity of vector diseases Alcohol consumption
Education	Students with access to the internet Study hours at home Increased child attendance at schools Increased adult participation in higher education Schools with electricity and equipment

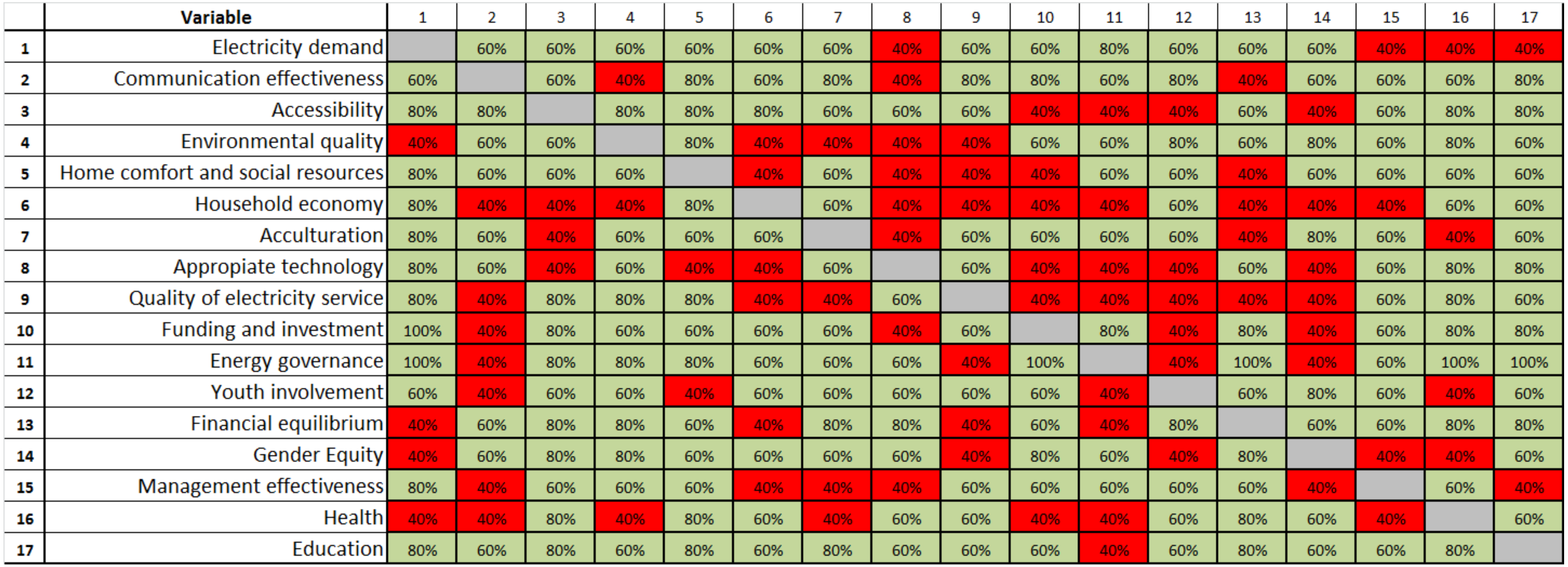
Appendix 2-2: Criteria matrix

The assessment of each variable against each criterion was done by the author and the facilitator team. ´Population´ and ´human ecology´ criteria of the ´sphere of life´ category have the highest scores revealing their importance for participants. ´Information´ has a higher rate than ´matter´ and ´energy´, which indicates that the former, which is related to acculturation, education, and communication effectiveness, is a major component of the system. The high scores of criteria in ´system dynamic´ and ´dynamic category´ suggest that DRE in the Ecuadorian Amazon is an open system and hence external aspects outside the system such as climate change and social conflicts should be taken into account in the process of policy formulation and strategies for sustainable DRE.

	Sphere of Life							**Physical Category**			**Dynamic Category**				**System Relations**			
CRITERIA	Economy	Population	Space utilization	Human ecology	Natural balance	Infrastructure	Rules and Laws	Matter	Energy	Information	Flow Quantity	Structural Quantity	Temporal Dyamics	Spatial Dynamics	Opens through inputs	Opens through output	Influenced from inside	Influenced from outside
Electricity demand	1	0.5	0.5	0.5	0.5	1		1	1		0.5		1	0.5	1	0.5	0.5	1
Communication effectiveness		1		0.5		0.5	0.5	0.5	0.5	1	1		0.5	0.5	1	1	0.5	1
Accessibilty	1	1	1	1	1	1	0.5	1	1	1	0.5	1		1	1	0.5		1
Environmental quality	0.5	0.5	1	1	1		0.5	1	1	0.5	0.5	1	1	1	1	1	1	1
House comfort and social resources	0.5	1	0.5	1		1	0.5	1	1	1	1	1	1	0.5	1	1	0.5	1
Household economy	1	1	0.5	1	1	1	0.5	1	1	1	1		1	0.5	1		0.5	1
Acculturation		1	1	1	0.5		1			1	1		1	0.5	1	0.5	0.5	1
Appropiate technology	1		1	0.5	0.5	1		1	1	1	0.5	1	1		1			1
Quality of electricity services	0.5	0.5	0.5	0.5	0.5	1	1	1	1	0.5	0.5	0.5	1	0.5	1		0.5	1
Funding and investment	1	1	0.5	0.5	0.5	0.5	1	0.5	1	1	1		1		1			1
Energy governance	0.5	0.5		0.5		0.5	1		0.5	1	1	0.5	1		1		0.5	1
Youth involvement	0.5	1	0.5	1			0.5	1		1		1	0.5	0.5	0.5	0.5	1	1
Financial equilibrium	1	0.5					1		1	1	1	0.5	1	0.5	1		1	1
Gender Equity	0.5	1	0.5	1	0.5		1	1	0.5	1		1	0.5	0.5	1	0.5		1
Management effectiveness	0.5	0.5		0.5		1	1	0.5		1	1	1	1		1	0.5	1	1
Health	0.5	1	0.5	1	1	1	0.5	0.5	0.5	1	1	0.5	1	1	1	0.5	0.5	1
Education	0.5	1	0.5	1	1	1	0.5	0.5	0.5	1	1	0.5	1	1	1	0.5	1	1
Degree of criteria representation in the system	**10.5**	**13.0**	**8.5**	**12.5**	**8.0**	**10.5**	**11.0**	**11.5**	**11.5**	**15.0**	**12.5**	**9.5**	**14.5**	**8.5**	**16.5**	**7.0**	**9.0**	**17.0**

Appendix 2-3 Difference between effect matrixes (5 groups)

If the percentage of groups that agree on the strength effect among variables was equal to or more than 60%, i.e. three groups out of five, it was considered as an agreement.



	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Electricity demand		60%	60%	60%	60%	60%	60%	40%	60%	60%	80%	60%	60%	60%	40%	40%	40%
2	Communication effectiveness	60%		60%	40%	80%	60%	80%	40%	80%	80%	60%	80%	40%	60%	60%	60%	80%
3	Accessibility	80%	80%		80%	80%	80%	60%	60%	60%	40%	40%	40%	60%	40%	60%	80%	80%
4	Environmental quality	40%	60%	60%		80%	40%	40%	40%	40%	60%	60%	80%	60%	80%	60%	80%	60%
5	Home comfort and social resources	80%	60%	60%	60%		40%	60%	40%	40%	40%	60%	60%	40%	60%	60%	60%	60%
6	Household economy	80%	40%	40%	40%	80%		60%	40%	40%	40%	40%	60%	40%	40%	40%	60%	60%
7	Acculturation	80%	60%	40%	60%	60%	60%		40%	60%	60%	60%	60%	40%	80%	60%	40%	60%
8	Appropiate technology	80%	60%	40%	60%	40%	40%	60%		60%	40%	40%	40%	60%	40%	60%	80%	80%
9	Quality of electricity service	80%	40%	80%	80%	80%	40%	40%	60%		40%	40%	40%	40%	40%	60%	80%	60%
10	Funding and investment	100%	40%	80%	60%	60%	60%	60%	40%	60%		80%	40%	80%	40%	60%	80%	80%
11	Energy governance	100%	40%	80%	80%	80%	60%	60%	60%	40%	100%		40%	100%	40%	60%	100%	100%
12	Youth involvement	60%	40%	60%	60%	40%	60%	60%	60%	60%	60%	40%		60%	80%	60%	40%	60%
13	Financial equilibrium	40%	60%	80%	80%	60%	40%	80%	80%	40%	60%	40%	80%		60%	60%	80%	80%
14	Gender Equity	40%	60%	80%	80%	60%	60%	60%	60%	40%	80%	60%	40%	80%		40%	40%	60%
15	Management effectiveness	80%	40%	60%	60%	60%	40%	40%	40%	60%	60%	60%	60%	60%	40%		60%	40%
16	Health	40%	40%	80%	40%	80%	60%	40%	60%	60%	40%	40%	60%	80%	60%	40%		60%
17	Education	80%	60%	80%	60%	80%	60%	80%	60%	60%	60%	40%	60%	80%	60%	60%	80%	

8.3 Appendix 3: supplementary information chapter 5

Appendix 3-1 Indicators' formulas and target justification

The formulas were defined based on workshop discussion and literature review (World Bank 2003; IAEA 2005; Ilskog 2008; World Bank 2013; Reddy 2015; Sharma and Balachandra 2015; Purwanto and Afifah 2016). Targets justification was based on workshop discussion, interviews with decision makers, and household survey.

Indicators' formula	**Target justification**
Environmental dimension	
Accessibility (AC)	
AC-1=annual household travel expenses (USD/year)	The prices of road transportation are the cheapest and most affordable for the average income of Amazon people (50 USD/month). Thus, the target was set at 12 USD/year, based on local prices and assuming one trip per month.
AC-2=annual household travel frequency (cities, markets) (travel/year)	From field observation, the target was set in one travel per month (12 times/year) because it suggested people can fulfill most of their living needs locally. The less the household travel to cities (e.g. markets, hospital, and administration issues) the higher people's autonomy and less influenced by isolation.
AC-3(u)= $\begin{cases} 1 & if \quad high \\ 2 & if \quad few \\ 3 & if \quad same \\ 4 & if \quad worsen \end{cases}$ Where, AC-3=household perception on accessibility improvement after electrification	From workshop discussions the target was set at the highest level (1) to show positive results after electrification.
Environmental benefits (EN)	
$EN-1(\%)=\frac{\text{Electricity produced from renewable energy (kWh/yr)}}{\text{Total electricity production (kWh/yr)}}$	The Organic Law of the Electric Service Sector mandates universal access and environmental conservation by promoting the use of renewable energy (Ecuador 2015). Thus, the target was set at the highest level (100%) to show positive results

Indicators' formula	**Target justification**
Where, EN-1=share of renewable energy for electricity generation	
$EN-2(\%)=\frac{F_1-F_2}{F_1}$ Where, EN-2=Household's fuel consumption reduced F1=fuel consumption before DRE (liters/ month) F2= fuel consumption after DRE (liters/ month)	From field survey, households use fuels mainly for lightning (diesel, gasoline or kerex lamps). And only 6% to run electric generators. For the case study, electricity was expected to cover all lighting needs so a reduction of 95% was set as a target.
$EN-3(\%)=\frac{B_1-B_2}{B_1}$ Where, EN-3=household's battery consumption reduced B1= battery consumption before DRE (units/month) B2= battery consumption after DRE (units/month)	From field survey, household use batteries in flashlights for lighting homes, hunting or fishing. The two latter were practiced by 70% of households for fishing and hunting activities. For the case study, electricity was expected to cover all lighting needs in the home so a complete replacement of batteries is not possible and so the target was set at 75%.
$EN-4(\%)=\frac{\text{Waste disposed (units)}}{\text{Total waste (units)}}$ Where, EN-4=waste properly disposed (broken or worn-out equipment)	Environmental management plan of the electricity company decree all broken or worn-out equipment (e.g. batteries, electronic regulators, inverters, solar panels, electric cables) must be retired from the communities and disposed properly (Centrosur 2014; Urdiales 2014). Thus the target was set at 100%.
Institutional dimension	
Energy policy implementation (EG)	
$EG-1(\%)=\frac{\frac{ER2010-ER2001}{9}}{ER2001}$ Where, EG-1=Annual growth rate (linear) of rural electrification ER2010=Rural electrification coverage from national census 2010 ER2001=Rural electrification coverage from national census 2001	To reach universal access in remote areas of the Ecuadorian Amazon by 2030 (ARCONEL 2013) the annual growth rate of rural electrification should be 15% per year. It includes the average population growth (INEC 2001; INEC 2010)

Indicators' formula	**Target justification**
$$EG-2(units)=\frac{number\ of\ household\ with\ "A"}{total\ number\ of\ households}x100$$ Where, EG-2=household received another basic service after electrification A= telephone, internet, water supply, waste management, health, education or any other basic and public service after electrification.	From interviews, it was suggested that electricity sets the basis to provide other basic and public services. Thus, at least half of household (50%) should have received another basic service after two years of electrification.
Management effectiveness (ME)	
$$ME-1(\%)=\frac{number\ of\ household\ satisfied\ with\ electricity}{Total\ number\ of\ households}x100$$ Where, ME-1=household satisfaction with electricity service	The quality of service regulations (CONELEC 2001) instructs that the share of satisfied users must be >90%.
$$ME-2(u)=\frac{\text{Maintenance reports submitted}}{12}x100$$ Where, ME-2=rate of maintenance reports submitted	The electricity company instructed maintenance staff to submit and appraise all maintenance reports on a monthly basis (Centrosur 2014). So target was set at 100%
ME-3= $\begin{cases} 1 & if\quad A \\ 0{,}5 & if\quad B \\ 0 & if\quad C \end{cases}$ Where, ME-3=level of staff's skills A=Staff have technical skills and is bilingual (Spanish and native language) B=Staff have technical skills C=None of the above	As was studied in chapter 3 (section 3.3.7) staff should have technical and intercultural communication skills to ensure knowledge and technology transfer to households. Thus, staff with both skills (1) was set as a target
Communication effectiveness (CE)	
$$CE-1(\%)=\frac{\text{A}+\text{B}+\text{C}+\text{D}+\text{E}+\text{F}}{5}x100$$	Household knowledge is related to the use of technology (i.e. SHS) but also on others issues necessary for technology deployment (see criteria in

Indicators' formula	**Target justification**
where, CE-1=household knowledge on technology A=household acknowledge ownership of the system (Yes=1, No=0) B= household acknowledge how to use the system (Yes=1, No=0) C= household acknowledge electricity company duties (Yes=1, No=0) D= household acknowledge maintenance technician duties (Yes=1, No=0) E= household acknowledge their duties (electricity payments) (Yes=1, No=0)	the formula). The target was set when a household acknowledge three or more criteria (0.7)
$CE-2(\%) = \frac{\text{CC}}{\text{total number of households}}\text{x}100$ Where, CE-2=share of households that can communicate in their own language with electricity supplier, CC=the number of households communicate in their own language	Household should be able to communicate in their own language during maintenance service to ensure their claims or concerns are understood by electricity supplier. Thus the target was set at 100%.
Social dimension	
Household comfort (HH)	
HH-1(u)= $\begin{cases} 1 & if \quad high \\ 2 & if \quad few \\ 3 & if \quad same \\ 4 & if \quad worsen \end{cases}$ Where, HH-1(u)=household's opinion about level of improvements on ability to do housework after electrification	From workshop discussions the target was set at the highest level (1) to show positive results after electrification
HH-2(u)= $\begin{cases} 1 & if \quad high \\ 2 & if \quad few \\ 3 & if \quad same \\ 4 & if \quad worsen \end{cases}$ Where,	Same as above

Indicators' formula	Target justification
HH-2(u)=household's opinion on the level of improvement of social gathering after electrification	
HH-3(u)= $\begin{cases} 1 & if \quad high \\ 2 & if \quad few \\ 3 & if \quad same \\ 4 & if \quad worsen \end{cases}$ Where, HH-3(u)=household's opinion about the level of improvement on home entertainment (TV, radio, the internet, social events) after electrification	Same as above
Culture preservation	
CU-1(u)= $\begin{cases} 1 & if \quad high \\ 2 & if \quad few \\ 3 & if \quad same \\ 4 & if \quad worsen \end{cases}$ Where, CU-1(u)=household's opinion about level of improvements on communal work and reciprocity activities after electrification	Same as above. Collectivism and communal work are a cultural values in Amazonian communities (Erazo 2010)
CU-2(u)= $\begin{cases} 1 & if \quad Native\ language\ is\ the\ most\ used \\ 2 & if \quad Native\ and\ Spanish\ are\ the\ languages\ most\ used \\ 3 & if \quad Spanish\ is\ the\ language\ most\ used \end{cases}$ Where, CU-2(u)=language preference to speak	Language usage is frequently applied to measure acculturation (Hoffman et al. 1985; Ryder et al. 2000). If people prefer to speak their own language suggest a low acculturation. Since all population of the case was indigenous the target was set in 1 when native languages were preferred.
CU-3(u)= $\begin{cases} 1 & if \quad Traditional\ houses \\ 2 & if \quad Traditional\ and\ wooden\ houses \\ 3 & if \quad Wooden\ houses \end{cases}$ Where,	From workshops discussions and field survey, wooden houses are built with imported and expensive materials (iron corrugated). While traditional houses are constructed with local materials (wooden and palms leafs) and traditional techniques. If a household still knows how to build traditional houses was stressed as a proxy to measure people's

Indicators' formula	**Target justification**
CU-3(u)=household preference to build houses	traditional knowledge and low acculturation. Thus the target was set in 1 when household prefers to build and live in traditional houses.
Gender equity	
GE-1= WS : MS Where, GE-1=staff's gender ratio, women/men WS=women staff (%) MS=Men staff (%)	To ensure participation of women in DRE, the staff should have an equal number of men and women. Thus the target was set in a ratio of 0.5:0.5
GE-2(u)= $\begin{cases} 1 & if \quad high \\ 2 & if \quad few \\ 3 & if \quad same \\ 4 & if \quad worsen \end{cases}$ Where, GE-2(u)=household's opinion about level of improvement women's live	From workshop discussions the target was set at the highest level (1) to show positive results after electrification
Youth involvement	
$\mathrm{YI}-1(\%)=\frac{\text{number of youth people with work}}{\text{total number of youth people}}\text{x}100$ Where, YI-1=Youth population with job after electrification	The target (95%) was set based on the national unemployment rate 3.86% (INEC 2015b)
$\mathrm{YI}-2(\%)=\frac{\text{number of youth people who migrated}}{\text{total number of youth people}}\text{x}100$ Where, YI-2=Migration of youth population after electrification	The target (20%) was set based on the average national migration 23.4% (INEC 2012).
Health (HE)	
HE-1(u)= $\begin{cases} 1 & if \quad high \\ 2 & if \quad few \\ 3 & if \quad same \\ 4 & if \quad worsen \end{cases}$	From workshop discussions the target was set at the highest level (1) to show positive results after electrification

Indicators' formula	**Target justification**
Where, HE-1(u)=household's opinion about level of improvement health conditions	
HE-2=Average Euclidean distances of a household to reach the nearest health post with electricity (km) Where, HE-2=distance to the nearest health post with electricity	From field observation and workshop discussion, a health center approachable in less than 1 walking hour was considered optimal. So the target was set at 5km.
Education	
ED-1= Time children study in night (h/day)	Similar studies in rural context suggest that 0.5 hours is the minimum time expected for children study at night after electrification (Daka and Ballet 2011). So it was assumed as a target.
ED-2=Average Euclidean distances to reach the nearest school with electricity (km) Where, ED-2=distance to the nearest school with electricity	From field observation and workshop discussion, a school approachable in less than 1.5 walking hour was considered optimal. So the target was set at 8km.
Economic dimension	
Fund availability (FI)	
$FI - 1(USD/Wp) = \frac{LI + TR + EQ}{PT}$ Where, FI-1=Installation cost LI= Average labor cost (USD) TR= Average transport cost (USD) EQ= Average equipment cost (USD) PT=Total capacity installed (Wp)	Local experiences of DRE in the Ecuadorian Amazon showed that installation cost was between 10-16 USD/Wp (Cajamarca and Montero 2011; Jara-Alvear and Urdiales 2014). The lowest was set as a target.
	Literature suggests that maintenance cost of DRE based on SHS are between 2%-10% of installation cost (Notton et al. 1998; Carrasco et al.

Indicators' formula	**Target justification**
$FI-2(USD/Wp*year\ )=\frac{(LM+TR+SP)-FE}{PT}$ Where, FI-2=maintenance cost LM=Maintenance labor cost (staff's salary, administrative) (USD/year) SP=Spare parts cost (USD/year) FE=Fee collected (USD/year)	2013). Thus the average 6% of installation cost was set as a target (0.6 USD/Wp/year)
Tariff adequacy (TA)	
TA-1=Average number of household's pending payments (quantity)	The feasible time to re-visit communities by the electricity company for fee collection in the study area was 3 months (Centrosur 2014). Thus 3 pending payments were considered as the maximum lag of payment.
$TA-2(units)=1-\frac{EE}{IN}$ Where, TA-2=Household's affordability of energy expense. 1 means completely affordable if value<0 means not affordable at all (Reddy 2015) EE=Energy expenses after electrification (diesel, candles, batteries, electricity fee) (USD/month) IN=Household income (USD/month)	Once electricity is available it must be affordable for household's income. Thus target was set at the maximum target (1) to show positive results.
Household economy (HC)	
HC-1(u)= $\begin{cases}1 & if \quad Yes\\0 & if \quad No\end{cases}$ Where, HC-1=Household use electricity for income generation	From workshop discussions, it was desirable that a high number of household use electricity for income generation to enhance socioeconomic impacts of electricity and ensure electricity fee payments. Thus the target was set at 75%.
$HC-2(\%)=\frac{EE_2-EE_1}{EE_1}$ Where, HC-2=reduction of household's energy expenses	The most expensive energy sources (diesel, gasoline, candles, and batteries) bought in distance markets are used mainly for lighting, which was expected to be totally replaced after DRE. Thus the target was set at 95%.

Indicators' formula	**Target justification**
EE_1=household's energy expenses before DRE (USD/month) EE_2=household's energy expenses after DRE (USD/month)	
$\text{HC-3(u)}=\begin{cases}1 & if \quad Yes\\ 0 & if \quad No\end{cases}$ Where, HC-3=household access credits or others incomes	An existing bond program in the study area demonstrated to be an effective source to ensure a continuous household income(MIES 2014). From interviews with maintenance staff the target was set in 50% of the household receives this bond. It was believed a continuous income will increase the low capacity and willingness to pay for electricity services. Presently, 40% of households do not pay the electricity.
Technological dimension	
Electricity self-sufficiency (EB)	
$\mathrm{EB}-1(\mathrm{units})=1-\frac{\mathrm{DD}}{SP}$ Where, EB-1=daily energy reserve DD=Average household electricity demand (e.g. lightning, radio, TV, others) (kWh/day) SP=Electricity produced by solar home system at household location (kWh/day)	The target was set in 0.2 to ensure there is always energy storage in the lead-acid batteries of SHS. It will avoid over-discharging batteries (more than 80% of its nominal capacity) and avoid premature damages in the system (Carrasco et al. 2014)
$\text{EB-2(u)}=\begin{cases}Yes & if \quad A<0{,}400\\ No & if \quad A>0{,}400\end{cases}$ Where, EB-2=ability to cover demand in next five years $\mathrm{A}=\mathrm{DD}*\mathrm{e}^{5*\mathrm{r}}$ r=growth rate=3%	SHS used in the case study were designed to supply 400kWh/day (Figure 3.8). From survey, future electric appliance that a household will acquire and connect to the SHS were identified. The analysis shows that it is expected an average annual growth demand of 3%. So, if calculated household future demand is below the maximum capacity of the SHS, the target was attained.
Appropriate technology (AT)	

Indicators' formula	**Target justification**
AT-1=reported time to change a broken part in the system (days)	The feasible time to re-visit communities by the electricity company for replacement a defect part or component of the SHS was 3 months (Centrosur 2014). Thus 90 days were considered as the maximum time
$\mathrm{AT}-2(\%)=\frac{\mathrm{SP}}{8760*\mathrm{PT}}x100$ Where, AT-2=capacity factor of the power system SP=gross electricity produced at household meter (kWh/day) PT=Total capacity installed (kWp)	Literature suggests that a capacity factor of 20% for photovoltaic is an optimal target considering the existing technology (Nemet and Husmann 2012)
Quality of service (QS)	
$\mathrm{QS}-1(\%)=\frac{\mathrm{T}\ -\ \mathrm{DT}}{\mathrm{T}}$ Where, QS-1=availability of electricity service on an annual basis T=time of analysis (365 days) DT=Dow-time household electricity service (days)	Existing regulations rule that 18 days per year is the maximum time a user can be without electricity in rural areas (CONELEC 2001). Thus the target was set at 95%
QS-2=number of times a household lost the electricity service (times/year)	Existing regulations decree that 12 times per year is the maximum frequency of electricity lost a user can have in rural areas (CONELEC 2001). Thus the target was set at 95%

Appendix 3-2: Descriptive statistics of indicators

Descriptive statistics of indicators from the household survey for the three zones of the study area: Zone-A (access by air), total population=781, Zone-B (access by boat), total population=1379, Zone-C (access by car), total population=262.

Indicator Code	Zone	Mean	Standard deviation	Standard error mean	Skewness	Q-0%	Q-25%	Q-50%	Q-75%	Q-100%	Number of data	Source
AC-1	A	259.884	491.828	40.024	3.14	0	0	60	240	2640	151	Survey
	B	181.967	258.237	20.946	3.00	0	48	96	198.5	1410	152	Survey
	C	47.207	91.178	8.091	7.44	0	12	30	49	912	127	Survey
AC-2	A	15.642	25.155	2.047	3.05	0	2	6	16.5	158	151	Survey
	B	31.664	47.624	3.863	3.90	0	7	14	38.25	365	152	Survey
	C	11.709	11.942	1.060	2.45	1	4	10	12	64	127	Survey
AC-3	A	1.762	0.538	0.044	-0.13	1	1	2	2	3	151	Survey
	B	1.730	0.619	0.050	0.25	1	1	2	2	3	152	Survey
	C	1.827	0.505	0.045	-0.29	1	2	2	2	3	127	Survey
EN-1	A	1.000	0.000	0.000	-	1	1	1	1	1	829	Survey
	B	1.000	0.000	0.000	-	1	1	1	1	1	1457	Survey
	C	1.000	0.000	0.000	-	1	1	1	1	1	285	Survey
EN-2	A	0.604	0.483	0.039	-0.426	0	0	1	1	1	151	Survey
	B	0.840	0.409	0.033	-3.330	-2	1	1	1	1	152	Survey
	C	0.740	0.438	0.039	-1.408	-1	0.58	1	1	1	127	Survey
EN-3	A	0.454	0.386	0.031	-0.368	-1	0	0.50	0.75	1	151	Survey
	B	0.570	0.396	0.032	-0.378	0	0	0.67	1	1	152	Survey
	C	0.583	0.321	0.028	-0.750	0	0.50	0.68	0.83	1	127	Survey
EN-4	A	0.946	0.214	0.007	-3.94	0	1	1	1	1	829	Survey
	B	0.978	0.134	0.004	-6.61	0	1	1	1	1	1457	Survey
	C	0.936	0.236	0.014	-3.60	0	1	1	1	1	285	Survey
EG-1	A	0.0151	0.0162	0.0006	-0.6383	-0.051	-0.026	-0.009	-0.009	0.005	829	Census
	B	0.0279	0.0134	0.0004	-0.8032	-0.051	-0.026	-0.024	-0.024	-0.009	1460	Census
	C	0.0325	0.0078	0.0005	-0.0150	-0.051	-0.035	-0.035	-0.024	-0.016	282	Census

Indicator Code	Zone	Mean	Standard deviation	Standard error mean	Skewness	Q-0%	Q-25%	Q-50%	Q-75%	Q-100%	Number of data	Source
EG-2	A	0.000	0.000	0.000	0	0	0	0	0	0	151	Survey
	B	0.000	0.000	0.000	0	0	0	0	0	0	152	Survey
	C	0.000	0.000	0.000	0	0	0	0	0	0	127	Survey
ME-1	A	0.947	0.225	0.018	-4.032	0	1	1	1	1	151	Survey
	B	0.914	0.281	0.023	-2.994	0	1	1	1	1	152	Survey
	C	0.937	0.244	0.022	-3.641	0	1	1	1	1	127	Survey
ME-2	A	1.000	0.000	0.000	-	1	1	1	1	1	829	Reports
	B	1.000	0.000	0.000	-	1	1	1	1	1	1457	Reports
	C	1.000	0.000	0.000	-	1	1	1	1	1	285	Reports
ME-3	A	0.783	0.248	0.009	-0.264	0.5	0.5	1	1	1	826	Reports
	B	0.680	0.304	0.008	-0.377	0	0.5	0.5	1	1	1431	Reports
	C	0.837	0.235	0.014	-0.746	0.5	0.5	1	1	1	279	Reports
CE-1	A	0.821	0.240	0.020	-1.424	0	0.8	1	1	1	151	Survey
	B	0.671	0.269	0.022	-0.690	0	0.6	0.8	0.8	1	152	Survey
	C	0.915	0.146	0.013	-1.636	0.4	0.8	1	1	1	127	Survey
CE-2	A	0.662	0.473	0.016	-0.687	0	0	1	1	1	826	Reports
	B	0.459	0.499	0.013	0.164	0	0	0	1	1	1431	Reports
	C	0.814	0.390	0.023	-1.619	0	1	1	1	1	279	Reports
HH-1	A	1.483	0.710	0.058	1.246	1	1	1	2	4	151	Survey
	B	1.816	0.809	0.066	0.425	1	1	2	2	4	152	Survey
	C	1.409	0.596	0.053	1.158	1	1	1	2	3	127	Survey
HH-2	A	1.430	0.698	0.057	1.326	1	1	1	2	3	151	Survey
	B	1.743	0.826	0.067	0.582	1	1	2	2	4	152	Survey
	C	1.402	0.581	0.052	1.133	1	1	1	2	3	127	Survey
HH-3	A	1.331	0.500	0.041	1.047	1	1	1	2	3	151	Survey
	B	1.513	0.737	0.060	1.162	1	1	1	2	4	152	Survey
	C	1.213	0.430	0.038	1.723	1	1	1	1	3	127	Survey
GE-1	A	0.005	0.069	0.002	14.318	0	0	0	0	1	829	Reports
	B	0.023	0.149	0.004	6.423	0	0	0	0	1	1457	Reports

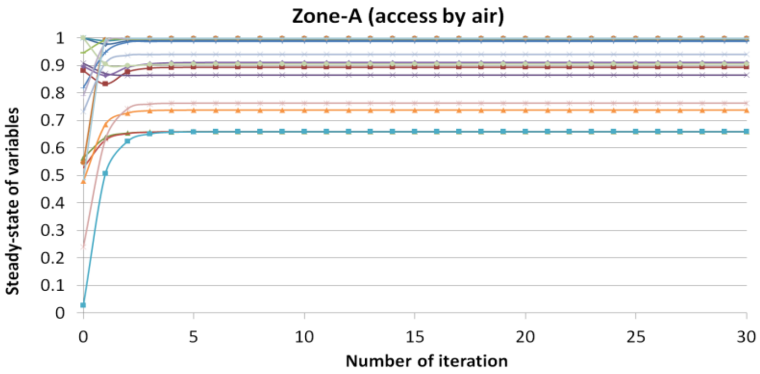
Indicator Code	Zone	Mean	Standard deviation	Standard error mean	Skewness	Q-0%	Q-25%	Q-50%	Q-75%	Q-100%	Number of data	Source
	C	0.000	0.000	0.000	-	0	0	0	0	0	285	Reports
GE-2	A	1.980	0.948	0.077	0.040	1	1	2	3	3	151	Survey
	B	1.434	0.697	0.057	1.428	1	1	1	2	4	152	Survey
	C	2.512	0.825	0.073	-1.202	1	2	3	3	3	127	Survey
YI-1	A	0.143	0.312	0.025	2.103	0	0	0	0	1	151	Survey
	B	0.097	0.254	0.021	2.831	0	0	0	0	1	152	Survey
	C	0.098	0.244	0.022	2.708	0	0	0	0	1	127	Survey
YI-2	A	0.094	0.242	0.020	2.775	0	0	0	0	1	151	Survey
	B	0.083	0.195	0.016	2.465	0	0	0	0	1	152	Survey
	C	0.049	0.184	0.016	4.057	0	0	0	0	1	127	Survey
CU-1	A	1.967	0.787	0.064	0.059	1	1	2	3	3	151	Survey
	B	1.901	0.779	0.063	0.345	1	1	2	2	4	152	Survey
	C	1.638	0.794	0.070	0.843	1	1	1	2	4	127	Survey
CU-2	A	1.126	0.352	0.029	2.733	1	1	1	1	3	151	Survey
	B	1.263	0.537	0.044	1.951	1	1	1	1	3	152	Survey
	C	1.142	0.372	0.033	2.538	1	1	1	1	3	127	Survey
CU-3	A	1.245	0.611	0.050	2.304	1	1	1	1	3	151	Survey
	B	1.776	0.971	0.079	0.464	1	1	1	3	3	152	Survey
	C	1.315	0.698	0.062	1.897	1	1	1	1	3	127	Survey
ED-1	A	1.013	1.463	0.119	1.584	0	0	0	1.5	6	151	Survey
	B	1.158	1.455	0.118	1.105	0	0	0.25	2	6.5	152	Survey
	C	1.740	1.668	0.148	0.781	0	0	1	3	7	127	Survey
ED-2	A	8760.293	7073.139	245.660	0.629	0	3235.23	7533.71	12576.3	23477.4	829	GIS
	B	4372.122	4002.629	104.861	0.656	0	482.486	3509.12	7112.18	15934.5	1457	GIS
	C	2107.904	2306.986	136.654	2.730	0	229.781	2020.7	3213	16532.2	285	GIS
HE1	A	1.331	0.500	0.041	1.047	1	1	1	2	3	151	Survey
	B	1.572	0.751	0.061	0.985	1	1	1	2	4	152	Survey
	C	1.213	0.430	0.038	1.723	1	1	1	1	3	127	Survey
HE2	A	8014.600	5855.203	203.360	0.406	0	2608.19	8610.72	12027.9	24782.3	829	GIS

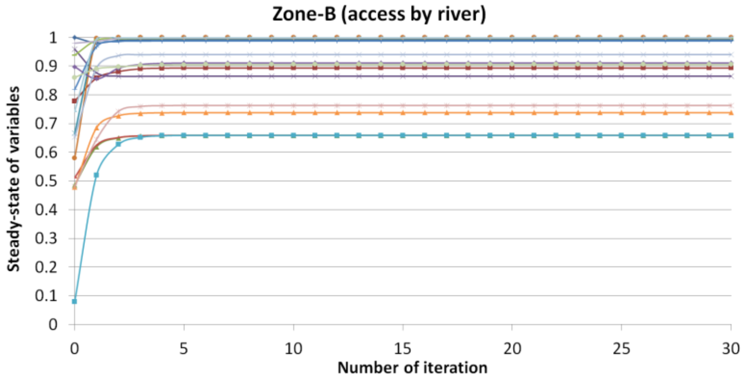
Indicator Code	Zone	Mean	Standard deviation	Standard error mean	Skewness	Q-0%	Q-25%	Q-50%	Q-75%	Q-100%	Number of data	Source
	B	6175.417	4245.425	111.222	0.464	0	2814.52	5209.72	8893.96	19473.6	1457	GIS
	C	7268.604	5429.466	321.614	0.910	0	3327.85	6465.22	10888.8	22197.4	285	GIS
FI-1	A	1852.211	83.613	2.909	-3.827	1446.94	1845.35	1863.24	1878.83	1968.94	826	Reports
	B	1872.569	41.920	1.107	0.949	1826.83	1840.31	1858.41	1893	1957.51	1433	Reports
	C	1744.246	189.037	11.317	-0.941	1446.94	1446.94	1862.09	1862.09	1893	279	Reports
FI-2	A	70.367	140.698	4.896	6.369	2.27624	16.7386	41.2831	78.3981	1415.9	826	Reports
	B	20.572	17.952	0.475	2.582	-2.9444	10.0934	16.6742	25.9582	144.101	1431	Reports
	C	22.917	59.629	3.570	3.867	-8.0911	-0.9507	6.86245	19.4503	276.457	279	Reports
FE-1	A	7.726	6.002	0.209	0.637	0	3	6	12	22	826	Reports
	B	10.414	7.354	0.194	0.774	0	4	9	15	34	1431	Reports
	C	6.061	4.633	0.277	1.275	0	3	4	8	22	279	Reports
FE-2	A	0.897	0.108	0.009	-2.650	0.35047	0.864	0.935	0.968	0.999	151	Reports
	B	0.937	0.066	0.005	-2.663	0.54176	0.934	0.967	0.971	0.996	152	Reports
	C	0.889	0.200	0.018	-8.733	-1.164	0.842	0.935	0.966	0.996	127	Reports
HC-1	A	0.252	0.435	0.035	1.156	0	0	0	0.5	1	151	Survey
	B	0.086	0.281	0.023	2.994	0	0	0	0	1	152	Survey
	C	0.134	0.342	0.030	2.176	0	0	0	0	1	127	Survey
HC-2	A	-0.471	0.467	0.038	1.904	-0.9736	-0.770	-0.627	-0.307	1.817	151	Survey
	B	-0.657	0.355	0.029	5.426	-0.9612	-0.862	-0.736	-0.544	2.557	152	Survey
	C	-0.649	0.280	0.025	2.172	-0.9789	-0.845	-0.731	-0.532	0.817	127	Survey
HC-3	A	0.581	0.495	0.040	-0.330	0	0	1	1	1	155	Survey
	B	0.618	0.487	0.040	-0.492	0	0	1	1	1	152	Survey
	C	0.527	0.501	0.044	-0.110	0	0	1	1	1	129	Survey
QS-1	A	0.828	0.182	0.015	-1.410	0	0.753	0.849	1	1	151	Survey
	B	0.803	0.214	0.017	-1.343	0	0.712	0.836	1	1	152	Survey
	C	0.913	0.171	0.015	-2.552	0	0.877	1	1	1	127	Survey
QS-2	A	0.788	0.578	0.038	0.213	0	0.5	0.5	1.5	1.5	236	Reports
	B	0.606	0.363	0.014	1.703	0	0.5	0.5	0.5	1.5	643	Reports
	C	0.486	0.656	0.054	0.811	0	0	0	1.5	1.5	146	Reports

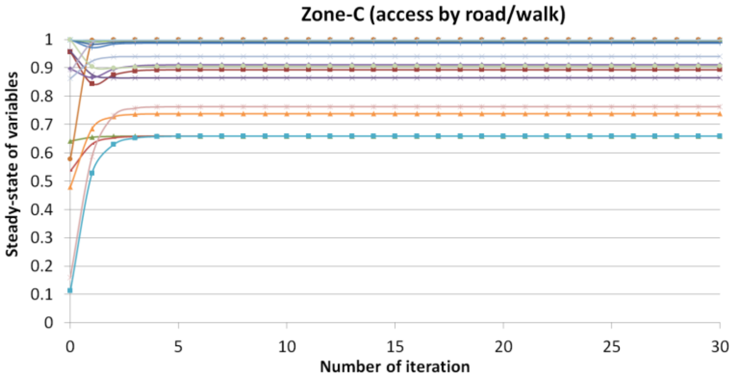
Indicator Code	Zone	Mean	Standard deviation	Standard error mean	Skewness	Q-0%	Q-25%	Q-50%	Q-75%	Q-100%	Number of data	Source
AT-1	A	208.088	105.665	8.599	2.727	30	150	208.088	210	810	151	Reports
	B	226.743	123.852	10.046	1.639	7.5	150	226.743	230.057	810	152	Reports
	C	199.573	86.142	7.644	3.111	30	199.573	199.573	199.573	810	127	Reports
AT-2	A	0.126	0.002	0.000	-0.634	0.12067	0.124	0.126	0.127	0.128	829	GIS
	B	0.126	0.001	0.000	-1.603	0.12223	0.126	0.126	0.127	0.128	1460	GIS
	C	0.125	0.001	0.000	-1.831	0.12079	0.125	0.125	0.125	0.126	282	GIS
EB -1	A	0.335	0.325	0.026	-1.246	-1.0329	0.199	0.394	0.569	0.865	151	Survey
	B	0.347	0.294	0.024	-0.786	-0.5024	0.210	0.343	0.538	0.912	152	Survey
	C	0.329	0.331	0.029	-0.936	-0.9253	0.170	0.334	0.555	0.911	127	Survey
EB-2	A	0.350	0.171	0.014	1.256	0.070	0.228	0.316	0.421	1.064	151	Survey
	B	0.345	0.156	0.013	0.784	0.046	0.244	0.349	0.418	0.795	152	Survey
	C	0.351	0.173	0.015	0.939	0.046	0.232	0.349	0.433	1.011	127	Survey

Appendix 3-3: Simulation results of the non-management scenario

In figures, *s(value)* is the resulting steady-state of variables and *i(value)* is the iteration in which the steady-state was reached, i.e., when the variable's value in iteration *t+1* is equal to the value in iteration *t* (see section 5.2.1, equation 5-9)



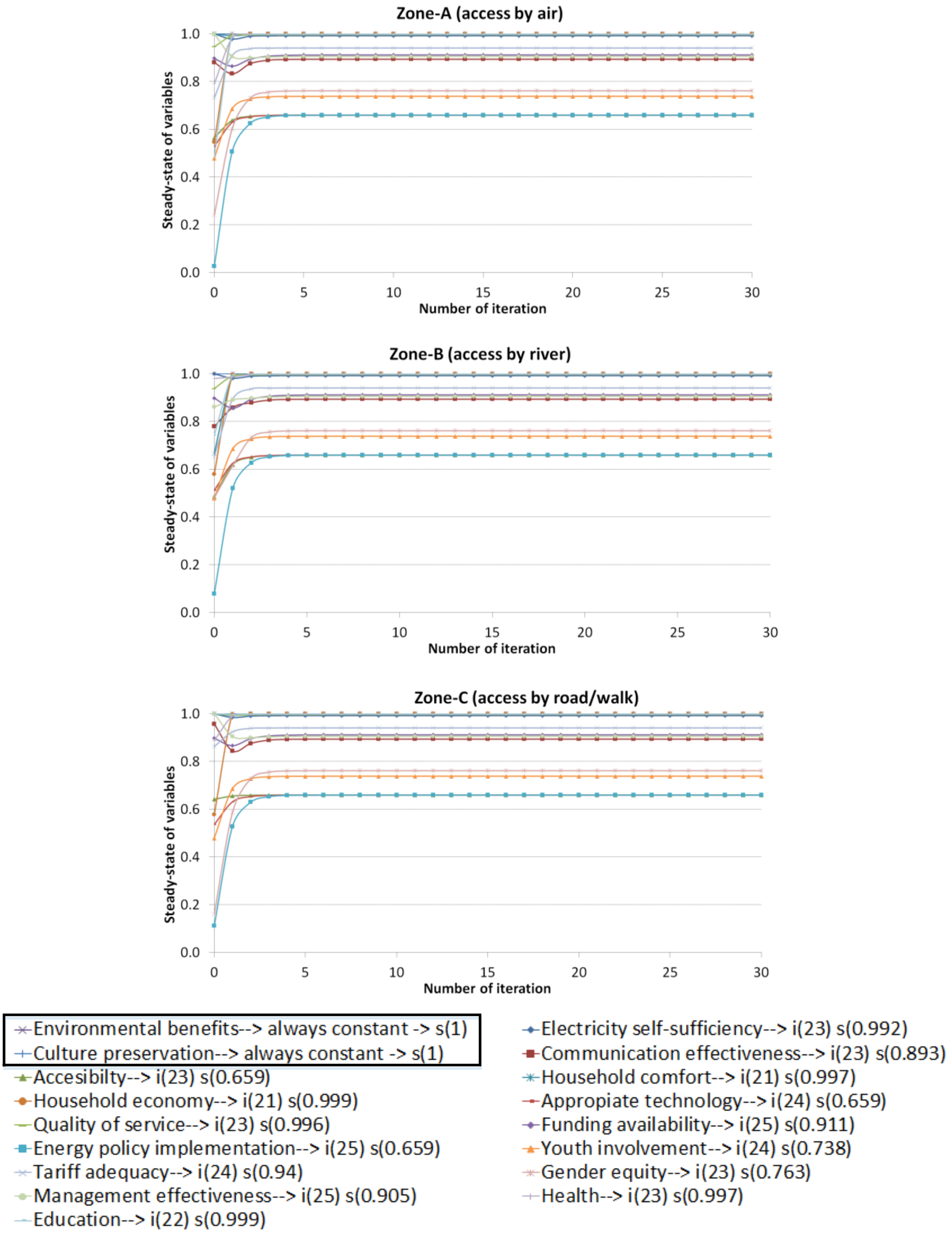




Electricity self-sufficiency--> i(23) s(0.992)
Accesibilty--> i(22) s(0.659)
Household comfort--> i(20) s(0.997)
Culture preservation--> i(21) s(0.988)
Quality of service--> i(22) s(0.996)
Energy policy implementation--> i(24) s(0.659)
Tariff adequacy--> i(23) s(0.94)
Management effectiveness--> i(24) s(0.905)
Education--> i(21) s(0.999)
Communication effectiveness--> i(21) s(0.893)
Environmental benefits--> i(23) s(0.865)
Household economy--> i(20) s(0.999)
Appropiate technology--> i(23) s(0.659)
Funding availability--> i(24) s(0.911)
Youth involvement--> i(23) s(0.738)
Gender equity--> i(21) s(0.763)
Health--> i(21) s(0.997)

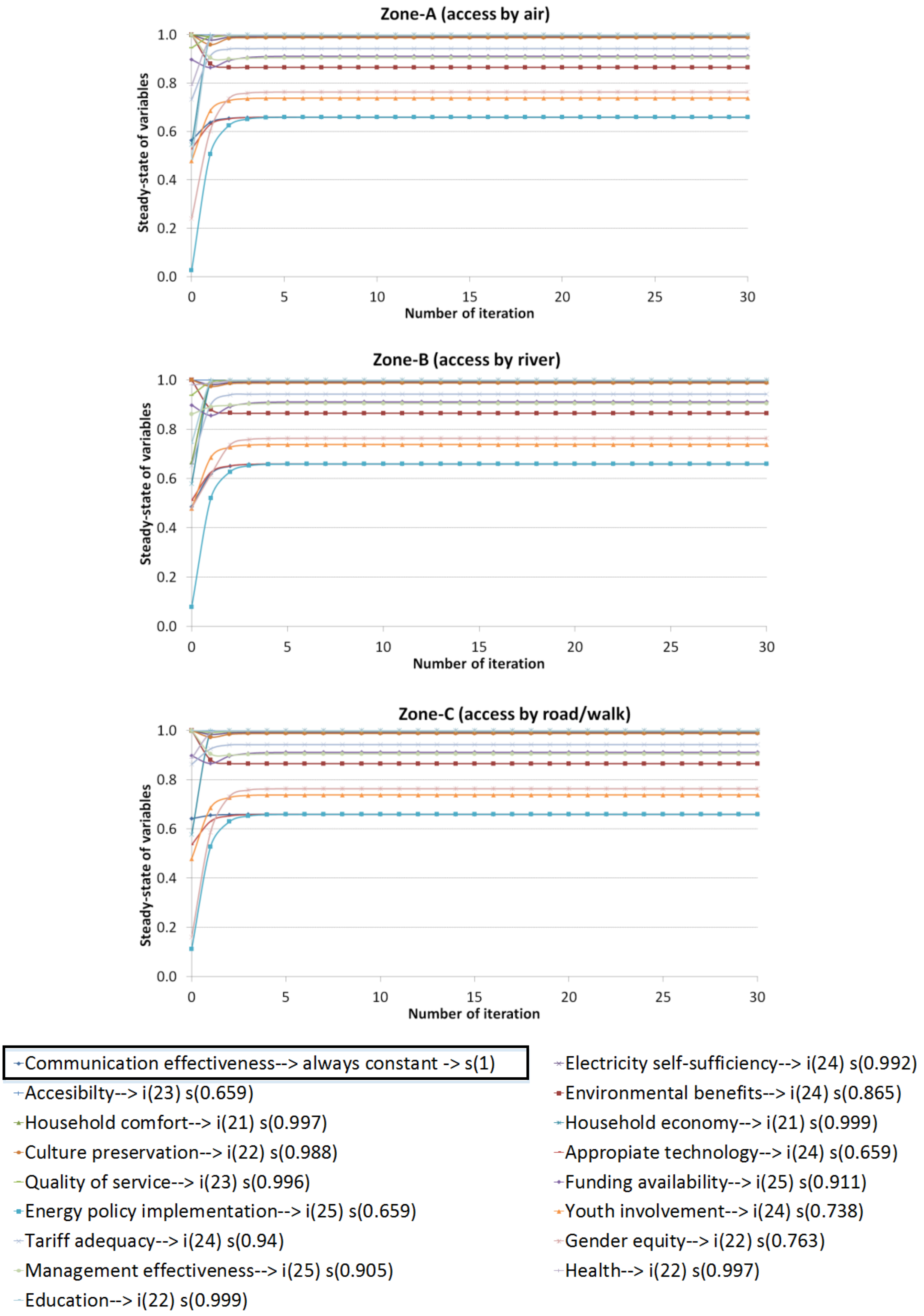
Appendix 3-4: Simulation results of the scenario 1

During the whole simulation the variables ‘environmental benefits’ and ‘culture preservation’ were clamped at 1 to signify their role in the developing system behavior. In figures, *s(value)* is the resulting steady-state of variables and *i(value)* is the iteration in which the steady-state was reached.



Appendix 3-5: Simulation results of the scenario 2

The variable 'communication effectiveness' was clamped at 1 to signify its role in the developing system behavior. In figures, *s(value)* is the resulting steady-state of variables and *i(value)* is the iteration in which the steady-state was reached.



Appendix 3-4: Simulation results of the scenario 3

The variables ‘accessibility’ and ‘household economy’ were clamped at 1 to signify their role in the developing system behavior. In figures, *s(value)* is the resulting steady-state of variables and *i(value)* is the iteration in which the steady-state was reached.