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Fostering rural electrification – the case of renewable energy-based village grids in South East Asia

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Abstract

Providing the rural poor with access to modern energy services is a major challenge in developing countries striving for economic growth, social development and environmental integrity. Socially, developing countries suffer from higher poverty levels accompanied by greater inequality, faster-growing populations, more unsolved health issues and lower educational levels than developed countries. Economically, they struggle with a largely untrained workforce and a lack of public and private financial resources. Environmentally, developing countries have to juggle new industrial development with environmental precaution. A major environmental threat is climate change. Developing countries are often disproportionately affected by it, which poses challenges in terms of adaptation and mitigation. In an attempt to address these challenges in a concerted international effort, the United Nations defined the Millennium Development Goals (MDGs) in 2001. Currently the follow-up goals, the so called Sustainable Development Goals (SDGs), are under discussion.

An important lever to address the MDGs and SDGs is the provision of (renewable energy-based) electricity to a wider population. As of today, more than 1 billion people worldwide still lack access to electricity. Most of them are poor and live in rural areas in Africa and Asia. Access to electricity is a prerequisite for industrial progress and an increased standard of living for these people. Additionally, if the electricity is produced by means of renewable energies, it contributes to the reduction of CO₂ emissions, which is a global concern in the context of mitigating climate change.

Compared to the alternative rural electrification approaches (e.g., solar lanterns, stand-alone systems, diesel-based village grids and grid extension), renewable energy based village grids (RVGs) are - in light of the MDGs and SGDs - the most appropriate solution to provide rural poor with access to electricity. RVGs are decentralized electricity systems which power a rural village with electricity produced by renewable energy technologies. They are environmentally-friendly and allow for social infrastructure and productive use of electricity, in addition to electricity for household purposes. Despite the advantages of RVGs as a rural electrification approach, large-scale diffusion of RVGs has not yet taken place. So far literature has not provided sufficient and diversified insights on the reasons for the low diffusion rates. In this thesis I address this gap by considering the question: **“why is the diffusion of RVGs in developing countries low and how can it be advanced?”** for the case of Indonesia and Laos. The target of the thesis is to provide insights for practitioners such as investors, development specialists, and policy makers, as well as to improve existing theory and empirical data on the diffusion of (renewable energy) technology.

The question is tackled from three complementary perspectives: a techno-economic, investor's, and innovation systems perspective. While the techno-economic literature examines how diffusion of technology depends on relative prices, in the investor's perspective, individual firms are regarded as the central drivers of diffusion. Innovation systems literature, alternatively, understands diffusion as an

evolutionary process, where different actors are involved and decisions depend on additional variables apart from relative prices. These different perspectives complement each other and allow for practical (investor and policy) implications.

This dissertation makes three scientific contributions. First, as suggested by different scholars, the thesis applies different concepts and methods. The different concepts are reflected in the three applied perspectives. Depending on the perspective, I employ quantitative or qualitative methods. The second contribution is in terms of new, empirical data. New data on costs of RVGs and villager's willingness-to-pay in Indonesia is gained. National and international revenue sources for owners of RVGs in Indonesia are introduced and quantified. Additionally, it is the first research effort that models a village's electricity demand and the needed supply on an hourly base. The third contribution lies in enriching the *Technological Innovation System and functions* framework theoretically by applying the framework to a new, "extreme" case which significantly differs from analyzed cases. The thesis thereby contributes to the ongoing debates on the set and definition of *functions*, the *functions'* role in the system, the role of institutions, the role of geographical aspects, and the derivation of policy recommendations from a *TIS and functions* analysis.

From the combined insights of the four papers presented in this dissertation follows; first, the techno-economic argument – that RVGs do not diffuse because they are more expensive than alternative solutions – does not hold true. Second, by combining this insight with the contributions from the investor's and innovation systems perspective, I find that a major reason for the low diffusion of RVGs is their high complexity in technological and non-technological terms. For investors, development specialists and policy makers, this implies that managing this complexity is key to advancing the diffusion of RVGs. Investors, for example, can take measures such as managing stakeholders and their cultural diversity actively in order to reduce complexity. However, while some challenges can be addressed by the investors, in other areas policy intervention is required. For example, policy makers can consider a removal or redistribution of fuel and electricity subsidies, define and implement a stringent rural electrification strategy, fulfill a connector and translator role between their rural population and international actors and institutions, and invest in the country's educational system. The thesis then concludes with proposals for future research.

Zusammenfassung

Die ärmere Landbevölkerung mit Strom zu versorgen ist eine der grossen Herausforderungen, die sich Entwicklungsländern momentan stellt. Diese Länder streben nach Wirtschaftswachstum und sozialer Entwicklung bei kleinstmöglichem negativen Einfluss auf die Umwelt. In sozialer Hinsicht leiden Entwicklungsländer unter hoher Armut, grossen Einkommensschere, grossem Bevölkerungswachstum und tiefen Standards im Gesundheits- und Bildungsbereich. Aus ökonomischer Sicht sind die tiefen Ausbildungsniveaus von Arbeitskräften und der Mangel an öffentlichen und privaten finanziellen Mitteln ein Hindernis. Entwicklungsländer müssen ökonomisches Wachstum und Umweltfreundlichkeit unter einen Hut bringen. Eine grosse Herausforderung bezüglich letzterem ist der Klimawandel. Üblicherweise sind Entwicklungsländer stärker vom Klimawandel betroffen als Industrieländer, was sie dazu zwingt sich anzupassen und ihren eigenen Klimaeinfluss zu minimieren. Um die sozialen, wirtschaftlichen und umweltbezogenen Herausforderungen in Entwicklungsländern anzugehen, hat die UN im Jahr 2010 die Millennium-Entwicklungsziele formuliert. Momentan werden die Nachfolgeziele (nachhaltige Entwicklungsziele genannt) der im 2015 auslaufenden Millennium-Entwicklungsziele diskutiert.

Ein wichtiger Hebel, um die Millennium- und nachhaltigen Entwicklungsziele für die Landbevölkerung in Entwicklungsländern zu erreichen, ist der Zugang zu Elektrizität, welche auf erneuerbaren Energien basiert. Heute lebt weltweit immer noch mehr als 1 Milliarde dieser Landbevölkerung ohne Stromzugang, die meisten von ihnen in Asien und Afrika. Für sie ist Zugang zu Strom die Voraussetzung für industrielle und wirtschaftliche Tätigkeiten und damit auch für die Verbesserung ihres Lebensstandards. Zusätzlich hat Strom, der durch erneuerbare Energien produziert wird, den Vorteil, dass er kein CO₂ emittiert. Damit trägt er dazu bei, dass ein Land seinen negativen Klimaeinfluss limitieren kann.

Unter dem Aspekt der Millennium- und nachhaltigen Entwicklungsziele sind Dorfstromnetze, die auf erneuerbaren Energien beruhen, die geeignetste Technologie, um ländliche Gebiete mit Elektrizität zu versorgen. Zu den weniger geeigneten Alternativen zählen Solarlaternen, Systeme für den einzelnen Haushalt, auf Diesel basierende Dorfstromnetze oder der Ausbau des nationalen Stromnetzes. Dorfstromnetze sind dezentrale, kleine Systeme, die ein Dorf mit erneuerbarem Strom versorgen. Sie sind umweltfreundlich und produzieren genügend Strom für gesellschaftliche und industrielle Bedürfnisse sowie für Haushalte. Trotz der Vorzüge von Dorfstromnetzen als Elektrifizierungslösung hat ihre grossflächige Verbreitung noch nicht stattgefunden. Auch in der Literatur wird das Thema nur unzureichend und zu wenig differenziert beleuchtet. In meiner Dissertation widme ich mich deswegen am Beispiel von Indonesien und Laos der Frage: **“Wieso ist die Verbreitung von Dorfstromnetzen in Entwicklungsländern so tief und wie kann sie erhöht werden?”** Das Ziel der Dissertation ist es, einerseits Praktikern wie zum Beispiel Investorinnen, Investoren, Personen aus dem Bereich der

Entwicklungszusammenarbeit sowie Politikerinnen und Politikern einen Einblick in die Problematik zu ermöglichen, und andererseits bestehende Theorien und empirische Daten zum Thema der Diffusion von erneuerbaren Energie-Technologien zu erweitern.

Die Frage wird aus drei komplementären Perspektiven beleuchtet: einer technologisch-ökonomischen Perspektive, einer Investoren- und einer Innovationssystem-Perspektive. Während die technologisch-ökonomische Perspektive untersucht, wie die Verbreitung einer Technologie von unterschiedlichen Technologiekosten abhängt, betrachtet die Investoren-Perspektive die Verbreitung aus Firmensicht. Im Gegensatz dazu versteht die Innovationssystem-Perspektive die Verbreitung einer Technologie als evolutionären Prozess, bei dem verschiedene Akteure involviert und wo Entscheidungen nicht nur auf Grund von Kostenoptimierungen gefällt werden. Die verschiedenen Perspektiven ergänzen sich gegenseitig und ermöglichen Schlussfolgerungen für Praktiker.

Die Dissertation umfasst drei wissenschaftliche Beiträge. Erstens, wie von verschiedenen Wissenschaftlern vorgeschlagen, wendet die Arbeit unterschiedliche Methoden und theoretische Konzepte an, um die Verbreitung einer Technologie zu untersuchen. Die unterschiedlichen Konzepte spiegeln sich in den drei Perspektiven. Die Wahl der Methoden richtet sich nach der jeweiligen Perspektive, wobei quantitative und qualitative Forschungsmethoden zur Anwendung kommen. Der zweite Beitrag liegt in der Bereitstellung von neuen, empirischen Daten: Daten für die Kosten von Dorfstromnetzen sowie Daten über die Zahlungsbereitschaft von Dorfbewohnern. Zusätzlich wurden nationale und internationale Einkommensquellen für Dorfstromnetzbetreiber identifiziert und quantifiziert. Weiter wurden zum ersten Mal die Stromnachfrage und Stromproduktion in einem Dorf stundengenau simuliert. Der dritte wissenschaftliche Beitrag der Dissertation bezieht sich auf die konzeptionelle Weiterentwicklung des *Technological Innovation System and functions*-Konzepts. Dies geschieht, indem das Konzept auf einen neuen, "extremen" Fall, der sich stark von bisherigen Anwendungsbeispielen unterscheidet, angewendet wird. Die Schlussfolgerungen daraus tragen zur aktuellen theoretischen Debatte über die Auswahl und die Definitionen der *functions*, ihre Rolle im System, die Rolle von Institutionen und geographischen Aspekten, sowie zur Verbesserung der aus einer *Technological Innovation System and functions*-Analyse abgeleiteten Empfehlungen für Politikerinnen und Politiker bei.

Aus den kombinierten Erkenntnissen der vier in dieser Dissertation präsentierten wissenschaftlichen Artikeln kann man Folgendes für die Praxis schliessen: Erstens, das technologisch-ökonomische Argument – dass Dorfstromnetze sich nicht verbreiten, weil sie teurer als alternative Lösungen sind – bestätigt sich nicht. Indem man in einem nächsten Schritt die Erkenntnisse der Investoren- und Innovationssystemperspektiven einbezieht, findet man heraus, dass ein Hauptgrund für die schlechte Verbreitung von Dorfstromnetzen ihre hohe technologische und nicht-technologischer Komplexität ist. Für InvestorInnen, Investoren, Personen aus dem Bereich der Entwicklungszusammenarbeit sowie Politikerinnen und Politiker bedeutet dies, dass die Bewältigung dieser Komplexität der Schlüssel zur

Verbreitung von Dorfstromnetzen ist. Investorinnen und Investoren beispielsweise können durch die aktive Kommunikation mit den verschiedenen Akteuren – unter Berücksichtigung der kulturellen Hintergründe – die Komplexität der Probleme reduzieren. Während gewisse Herausforderungen von Investorinnen und Investoren selbst bewältigt werden können, braucht es in anderen Bereichen regulatorische Änderungen. So können politische Entscheidungsträgerinnen und -träger die Komplexität reduzieren, indem sie Diesel- und Stromsubventionen entfernen oder umverteilen, eine stringente Elektrifizierungsstrategie definieren und implementieren, zwischen ihrer Bevölkerung und internationalen Akteuren als Bindeglied und Übersetzer tätig sind und indem sie das Bildungssystem ausbauen. Die Dissertation endet mit Vorschlägen für weiterführende Forschung.

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Annex I (Individual Papers)

1 Introduction

Providing the rural poor with access to modern energy services is a major challenge in developing countries¹ striving for economic growth, social development and environmental integrity. Renewable energy based-village grids (RVGs)² are an appropriate means of accomplishing this goal (Kanagawa and Nakata, 2007; Takada and Charles, 2007; Legros et al., 2009; Cook, 2011). A RVG is defined as an isolated, small (sizes vary between 5kW and 500kW) grid which powers a rural village with renewable energy-based electricity (ESMAP, 2007; Bardouille et al., 2012). Despite the applicability, the diffusion rate of RVGs is low and only picking up slowly. This dissertation provides insights into the reasons for this paradox by taking three perspectives: a techno-economic, an investor's, and an innovation systems perspective. Understanding the causes behind the slow diffusion of RVGs is valuable for international and national policy makers, development specialists and investors, and at the same time it can contribute to furthering theories on the innovation and diffusion of renewable energy-based technologies. In this introduction, developing countries' challenges in terms of rural electrification along with different rural electrification approaches (among them RVGs) are discussed, and the research question is derived.

Social, economic and environmental challenges specific to developing countries

Developing countries have to address manifold economic, social and environmental challenges to improve livelihoods and catch up with developed countries. Socially³, developing countries suffer from higher poverty levels accompanied by greater inequality (e.g. measured by the GINI coefficient), faster-growing populations, more unsolved health issues and lower educational levels than developed countries. Economically (often measured by the GDP), they struggle with a largely untrained workforce and a lack of public financial resources. Private investors also generally refrain from investing in developing countries due to higher investment risks and weak institutional structures (The

¹ In this frame chapter I use the terms: countries in transition, developing and developed countries based on the World Economic Situation and Prospects' classification, which is based on the countries' economic situation (WESP, 2012). However, countries can be classified in many different ways along different indicators. While the World Bank refers to low-income, lower-middle-income, upper-middle-income, higher-income economies, and high-income OECD members according to the country's Gross National Income (GNI, which equals the GDP in developing countries) per capita per year (The World Bank, 2013c), the United Nations classifies very poor countries with respect to their HDI as least developed countries (UN-OHRLLS, 2013).

² RVGs are decentralized systems which power a village with electricity produced by renewable energy technologies. There also exist such systems powered by diesel. In this case I refer to them as diesel-based village grids. While RVGs are the focus of this dissertation, I occasionally refer to the diesel-based solution as a reference.

³ An indicator that incorporates economic as well as social aspects is the Human Development Index (HDI (Perkins et al., 2013; UNDP, 2013d)).

World Bank, 2013a; Transparency International, 2013). Environmentally, developing countries have to juggle new industrial development with environmental precaution. Issues such as resource depletion and waste management are pressing. Additionally, developing countries are often disproportionately affected by climate change compared to developed countries, which poses challenges in terms of adaptation and mitigation.

In an attempt to address these challenges in a concerted international effort, the United Nations defined the Millennium Development Goals (MDGs) in 2001 (UNDP, 2013a), which initially were set to be met by 2015. Among the eight goals, two are specifically relevant for the diffusion rate of RVGs: the first, aimed at *eradicating poverty*, and the seventh, aimed at ensuring environmental sustainability. The goals are intended to work as "worldwide guidance" in international and, most notably, development cooperation.

Even though much has been achieved since 2001 (see e.g. country specific MDG indicators in UN, 2013a), poverty, and environmental challenges remain widespread. Therefore – and as the MDG timeline is approaching – the targets are currently being renewed and adapted. In the context of the Rio+20 conference, the discussion around post-2015 goals, also referred to as Sustainable Development Goals (SDGs), was launched (UNDP, 2013b). A prominent proposition for new targets was recently presented by the Asian Development Bank (Brooks et al., 2013). The Bank suggests a trio of targets: (1) achieving zero extreme poverty, (2) tackling country-specific socioeconomic challenges beyond extreme poverty, and (3) addressing the environmental imperatives that underpin long term development. As in the MDGs, poverty reduction and environmental sustainability are key elements of these SDGs (UN, 2013b).

Rural electrification based on renewable energy as an opportunity

An important lever to address the MDGs and SDGs is the provision of (renewable energy-based) electricity to more people⁴ (UNDP, 2011; Johnson, 2013). The United Nations declared the year 2012 as the International Year of Sustainable Energy for All, and the UN General Assembly recognized that "*...access to modern affordable energy services in developing countries is essential for the achievement of the internationally agreed development goals, including the Millennium Development Goals, and sustainable development, which would help to reduce poverty and to improve the conditions and standard of living for the majority of the world's population.*" (UN, 2013c). Today, more than 1 billion people worldwide still lack access to electricity, most of them impoverished⁵ and

⁴ Often international organizations refer to the need for providing „modern energy services [...] [which encompass] lighting, refrigeration, mechanical power for grinding and milling, heat, cooking fuels, etc.“ (UNDP 2009, p.9). However, in this thesis the scope is set on the provision of electricity only.

⁵ Referring to people living below or close to the national poverty lines (UNDP, 2010a; UN, 2013a).

living in rural areas in Africa and Asia (Figure 1) (Casillas and Kammen, 2010; UN AGECC, 2010; IEA, 2011; OECD/IEA, 2011).

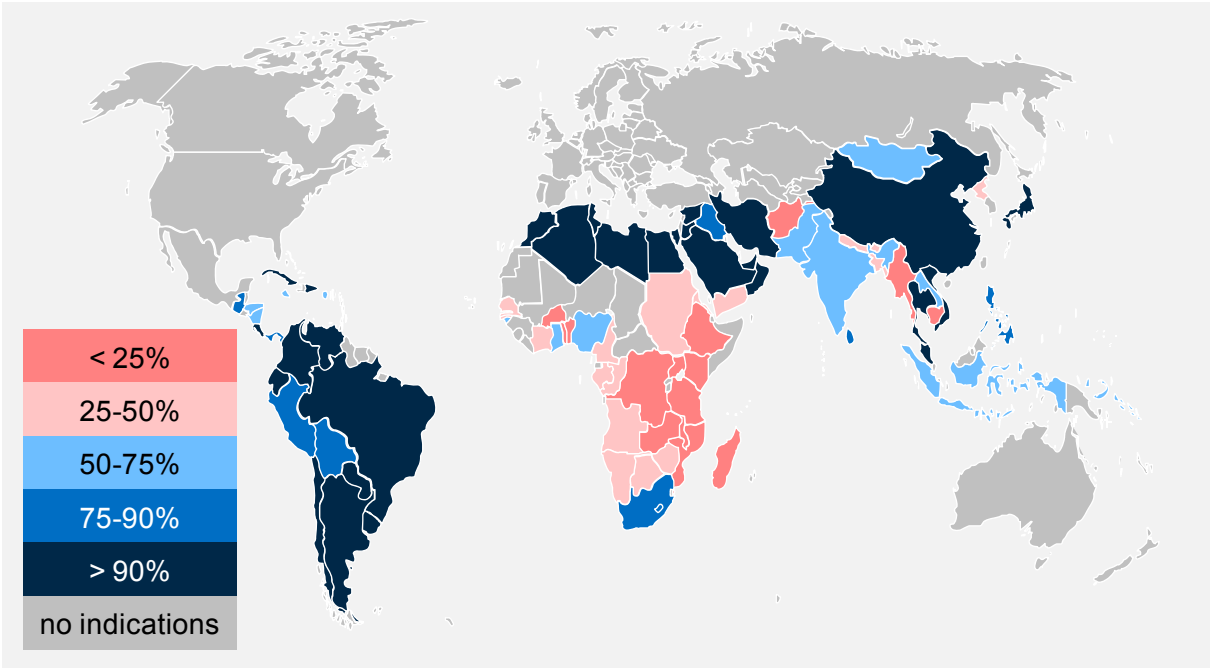


Figure 1 – Percentages of people with access to electricity in 2009 (own graph based on data by the IEA, (2013) and The World Bank (2013b))

Access to electricity for the rural poor (often referred to as rural electrification) – especially if based on renewable energy sources – contributes to the fulfillment of the MDGs and SDGs by enabling sustainable⁶ development (Modi et al., 2006; Cook, 2011). Economically, electricity is a prerequisite and incubator for industrial progress and, therefore, economic growth and development. Socially, the poor benefit from better livelihoods and increased standards of living if industrial progress is not only fostered in cities, but also in rural areas (Perkins et al., 2013)⁷. Consequently rural depopulation, along with the emergence of urban slums and uncultivated farm land in the countryside, can be prevented. Environmentally, thanks to modern renewable energy technologies (RET), electricity can be produced with minimal negative impact on the environment while at the same time reducing the dependence on fossil fuels (critical access in remote areas) and firewood (scarce in arid regions).

In addition to these national and regional benefits, rural electrification based on renewable energy sources contributes to the reduction of CO₂ emissions, which is a global concern in the context of climate change (IPPC, 2012). While industrialized countries are locked into a centralized electricity generation system and have installed capacities that are mainly based on non-renewable energy such as coal, fuel or nuclear energy (IEA, 2012a), developing countries can focus on renewable energy

⁶ In this context, sustainable refers to the combination of economic, social and environmental aspects.

⁷ Another frequently mentioned advantage of rural electrification through renewable energy sources is the improved health conditions (i.e. if kerosene lanterns and indoor fireplaces are replaced by electric solutions) (UN AGECC, 2010).

sources earlier on in their development path and thereby leapfrog non-renewable electricity (Unruh, 2000, 2002). In a recent publication, Rogelj and colleagues (2013) showed that it is feasible to ensure access to electricity for all within the planetary warming limit of 2° C, given that this development is based on renewable energy sources.

Rural electrification approaches

Even if economically viable, socially beneficial and environmentally unproblematic, the provision of (renewable energy-based) electricity to the rural poor remains a challenge in developing countries. The lack of diffusion of RETs, especially in rural areas, is due to financial, political, and technological challenges which have yet to be met. In terms of finances, national and international policy makers aim to invest public money efficiently and to tap additional financial sources from the private sector. Both are challenging tasks for governments with scarce budgets and a list of competing issues, such as health improvements or education (Perkins et al. 2013, p. 105). In terms of political challenges, policy makers have to evaluate what type of investment, in which projects, most effectively and efficiently promotes access to electricity through RET. The answers are influenced by factors such as the country's electricity needs today and in the future, the current and future desired design of the electricity sector⁸, the costs of the different approaches⁹ and their environmental impact. From a technological point of view, there are competing rural electrification approaches (see Table 1) which have, so far, partially diffused within and between developing countries. The extent of diffusion differs between approaches and depends, among others, on the countries' public support in terms of subsidies, taxes and the like for RET, and the competing non-renewable solutions. The involvement of the private sector also varies between countries as well as between electrification approaches (Bardouille et al., 2012).

In the following, I provide an overview of rural electrification approaches, with a focus on their environmental and socio-economic implications. RET¹⁰ are in general considered to be environmentally friendly, as fossil fuel-based solutions contribute to climate change, among other negative impacts. In socio-economic terms, electricity has the biggest effect if it is used for productive activities (e.g. the processing of rice or coffee, agricultural purposes) and social infrastructure (e.g.

⁸ Current electricity sector structures in developing countries range from centralistic state-owned to decentralized private market-based structures, and from a central grid to several non-integrated regional grids.

⁹ Since costs between different electricity productions technologies differ and change over time, this is a long-term versus short-term decision. In the long-term, RET are becoming cheaper due to innovation and oil prices are increasing. However, short-term the initial investment cost for diesel engines is cheaper.

¹⁰ Keeping in mind that most RET also have their environmental shortcomings in terms of resource use for production or environmental effects during usage (e.g. environmental debate about influence of hydro power on a rivers ecosystem or the influence of wind turbines on bird migration, etc.).

health clinics, schools and information and communication technologies (ICT)¹¹) and not solely for consumption in the household (e.g. for light, cooking and entertainment). When used productively, electricity increases people’s chances to perform income-generating activities, which improves their economic situation and, in the long run, their living conditions.

Table 1 – Rural electrification approaches and their environmental and socio-economic dimensions in terms of energy source (non-renewable energy in grey) and potential for use of electricity

Electrification approach	(Non)- renewable energy source	Potential for use of electricity	
Solar lanterns	Solar PV	Household purposes	Light and mobile phone charging
Household-based system	Solar PV (mostly)	Household purposes	Light and mobile phone charging
	Wind		Cooking, cooling and entertainment for a single household
	Pico hydro		
Village grids	Diesel	Household purposes	Light and mobile phone charging
	Solar PV		Cooking, cooling and entertainment
	Wind	Productive use	Machinery (e.g. coffee or rice proceeding machines, carpenter tools)
	Micro hydro		
	Biomass	Social infrastructure	Health clinic
	Hybrids (combinations of the above often in combination with batteries or diesel)		School
			ICT
Grid extension	Mixed, depending on national electricity mix	Same as village grids, however depending on the grid’s reliability	

In order to improve the socio-economic situation of the rural poor in developing countries at low (or no) environmental cost, RVGs are the best fit (compare Table 1). Compared to solar lanterns and household-based system, RVGs offer more electricity and therefore allow for productive use and social infrastructure in addition to household purposes (Takada and Charles, 2007; Legros et al., 2009; UN AGECC, 2010; Cook, 2011; Bhattacharyya, 2013; Practical Action, 2013). Compared to grid extension, RVGs are often more cost-effective in inaccessible, mountainous regions or on islands in developing countries since extending the grid to such regions is costly (Roland and Glania, 2011). Additionally, national grids in developing countries are often unreliable due to outdated equipment and a lack of generation capacity; if designed well, RVGs can achieve better reliabilities (IEA, 2010; Dean et al., 2012). Furthermore, national grids can be problematic in terms of environmental impact as they typically rely to a large extent on non-renewable energies for electricity production (IEA, 2012b). In conclusion, RVGs best fit the purpose of rural electrification in light of the MDGs and SDGs – they are environmentally compatible and potentially contribute more to poverty reduction than the available

¹¹ In rural villages, ICT (such as telephones and computers) is often organized in a centralized manner.

alternatives (Kanagawa and Nakata, 2007; Takada and Charles, 2007; Legros et al., 2009; Cook, 2011).

Village grids (based on renewable energy)

The village grid concept and technology evolved in the 1980s in developing countries when public energy authorities realized that a centralized electrification approach, which until then was the dominant strategy (in both industrialized and developing countries), is often not the most economic option for remote areas in developing countries (Peskett, 2011). In this thesis, a village grid¹² is defined as an isolated (i.e. off-grid), small (sizes vary between 5kW and 500kW) grid which powers a rural village (ESMAP, 2007; Bardouille et al., 2012). A village grid's purpose is to connect one or more power sources to the households and other consumers (such as workshops or medical centers) of a village and balance the load with the supply. The core components of a village grid are synchronizers, transformer(s), potentially a battery back-up to address intermittency of the sources, switchgears and the respective software to balance the load with the supply from the power plant(s), and the wiring (see Figure 2). In the case of a power source which produces direct current (DC)¹³, additional inverters are needed to feed the alternating current (AC) village network. Power sources can be both non- and renewable energies (see Table 1). The choice depends on the availability of (natural) resources and influences the system's design since renewable energy sources such as solar PV or wind are intermittent and require storage and balancing components. The load is determined by the electricity demand of the village, which depends on the number of households, their electric appliances (such as lamps, rice cookers, TVs and radios), the requisites of the social infrastructure (e.g. schools and medical centers) and businesses (e.g. small grocery shops, coffee processing plants and rice mills), and their respective consumption patterns (Saengprajak, 2006; Terrado et al., 2008; Raharjo, 2009). While village grids typically serve one common purpose, no single standard design exists because each village grid has to be adjusted to the context where it is implemented. The final design thus heavily depends on factors such as the amount and variability of supply and demand, and the availability and cost of materials and power sources (Inversin, 2000).

¹² Sometimes also referred to as a micro/mini-grid or mini-utility.

¹³ Micro hydro, biomass gasifier and wind power plants typically produce AC, while solar PV and batteries' output is DC (Roland and Glania, 2011).

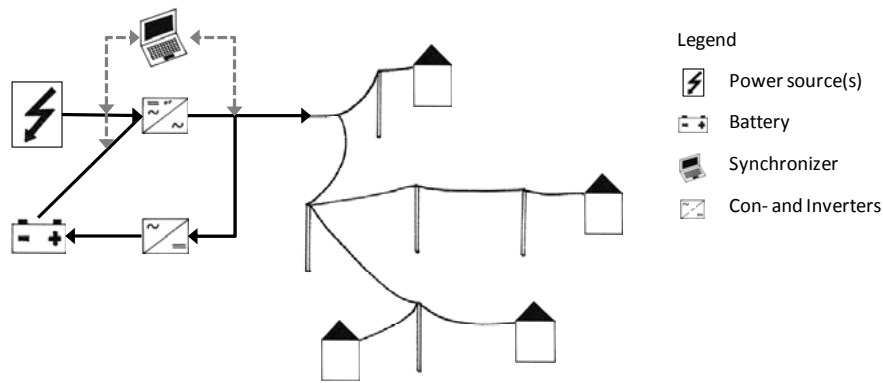


Figure 2 – Basic design of a village grid based on Roland and Glania (2011), Lopes et al. (2012) and Suwannakum (2007)

At this point, a differentiation between renewable energy-based and diesel-based village grids is necessary. A diesel generator’s electricity production can more easily be adjusted to loads and is only limited by its capacity and the availability of fuel. Additionally, the technology of diesel generators is, thanks to products such as motorcycles, already known in rural areas of developing countries, whereas renewable energy technologies are rather new. However, as diesel generators do not address the MDGs and SDGs, this dissertation focuses on village grids which are (to a bigger share) powered by renewable energy (i.e. RVGs).

Despite the advantages of renewable energy-based village grids (RVGs) as a rural electrification approach, large-scale diffusion of RVGs has not yet taken place. This is in spite of an estimated market potential of 28 million households (an equivalent of 3.1 billion EUR, with a forecasted annually growth rate of 13% from 2012 to 2020 (Bardouille et al., 2012)), successful examples on all continents (e.g., in Bolivia, Cambodia, India, Indonesia, Mali, Nepal, Nigeria, and the Philippines) and promotion by development agencies and international organizations (Roland and Glania, 2011; Bardouille et al., 2012).

Research question, case and structure of the dissertation

RVGs are an appropriate area to investigate promoters and obstacles of technology diffusion because they are desirable in terms of the MDGs and SDGs but have not readily spread. Conducting a literature review on RVGs¹⁴ reveals 38 scientific articles (referring to peer-reviewed articles, conference proceedings and PhD theses) and 21 reports and books (excluding purely technical work). While more than half of all publications addressed techno-economic aspects of RVGs, only a smaller fraction (around 15%, most of them reports) address managerial questions. The rest deal with social and

¹⁴ The literature review is based on a search on Google and Google scholar for the following search words: “village grid”, “renewable energy-based village grid”, “mini grid”, “micro grid”, and “micro utility”, “village electrification”. 40% of all reviewed literature referred to RVGs only, the other 60% also addressed hybrid village grids. Articles published between 2001 and 2013 were considered.

development oriented topics. Geographically, the majority of scientific articles draw upon cases in Africa and South Asia, leaving a gap in Latin America (where, due to advanced electrification rates, off-grid applications play a less prominent role, compare Figure 1) and the rest of Asia. This literature review on RVGs and a special issue by the journal of *Energy for Sustainable Development* (Bhattacharyya, 2011) highlight that, besides preliminary efforts, the subject in general is still under-investigated. To summarize, in terms of empirical data, predominantly village grids (often hybrid village grids) in South Asia (mainly India and Nepal) and Africa are described, while empirical data of other countries and on RVGs is missing. In terms of a theoretical approach, older scientific and practical publications address purely technical engineering issues, while more recent publications either perform techno-economic analyses, take a sociological perspective or have a strong practical focus (the latter are mostly published by development agencies or international organizations). More holistic scientific approaches which integrate different perspectives (economic, technical, social and political) to explain the low diffusion rate of RVGs are rare and, if existent, have a strong practical focus.

In this thesis, I address the gap in research on the diffusion of RVGs by considering the following question: **Why is the diffusion of RVGs in developing countries low and how can it be advanced?** The question is tackled from three complementary perspectives: a techno-economic, investor's, and innovation systems perspective. The target of the thesis is to provide insights for practitioners such as investors, development specialists, and policy makers¹⁵ as well as to improve existing theory and empirical data on the diffusion of (renewable energy) technology. To this end, I will investigate the diffusion of RVGs from a techno-economic and investor's perspective in Indonesia and from an innovation systems perspective in Laos¹⁶.

This research subject – RVGs in Laos and Indonesia – is interesting for several reasons. Laos and Indonesia both face a geographically challenging situation in terms of electrification. Indonesia consist of about 17'508 islands, out of which around 6'000 are inhabited (The CIA World Factbook, 2013). Laos is characterized by very remote, mountainous areas. Additionally, both countries have high renewable energy potentials in terms of solar radiation, hydro potentials, and biomass (e.g. rice husks) (ADB, 2010; Ölz and Beerepoot, 2010). At the same time, electrification rates are rather low in both countries and a large share of the countries' population are poor (compare Figure 3) and live in rural areas. However, the countries differ in several ways: in terms of population, culture (e.g. religion), landscape, development status, and most important for this research, in terms of business as usual in rural electrification. While in Indonesia diesel generators are a common rural electrification option, they are barely used in Laos, the main reason being that Indonesia has access to fossil fuel resources

¹⁵ The central questions that are relevant for policy makers are: (1) How much financial support should policy makers grant to RVGs? (2) How else can policy intervene?

¹⁶ Also referred to as Lao People's Democratic Republic (Lao PDR).

while Laos does not. While several RVG pilot projects exist in both countries, practitioners from both countries claim that scaling them up is difficult.

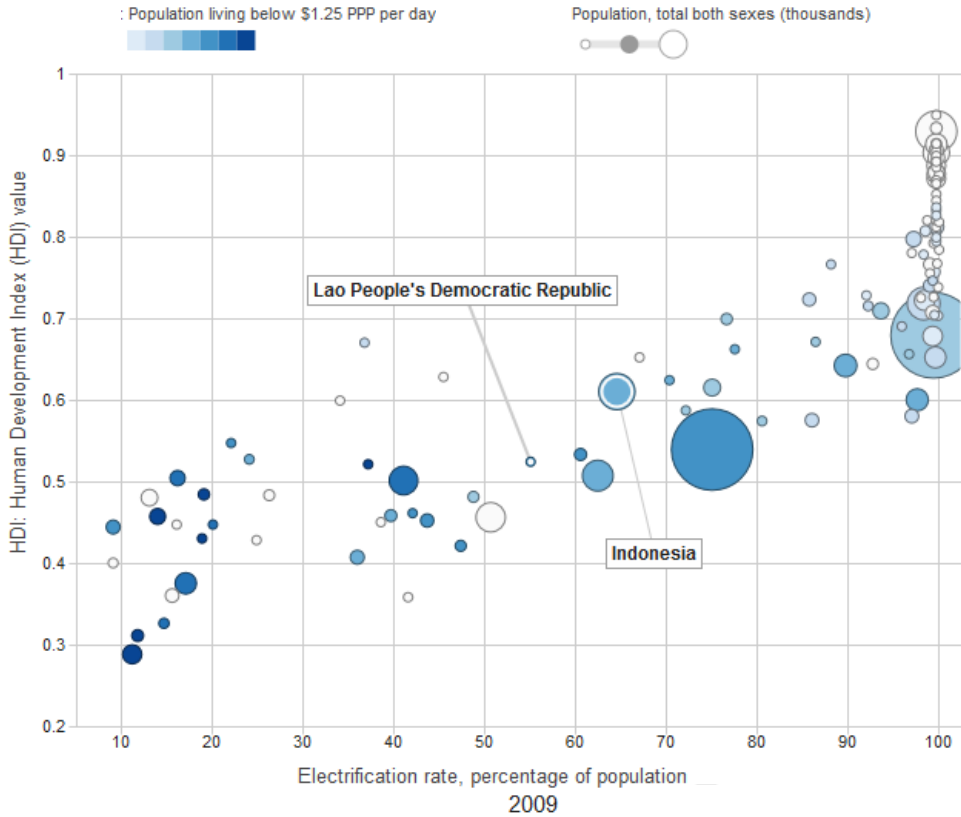


Figure 3 – Countries and their HDI, electrification rate and population living below 1.25USD per day in 2009 (UNDP, 2013c). The focal countries of this dissertation – Laos (Lao People’s Democratic Republic) and Indonesia – are marked.

The following section lays out the overall objective of the dissertation and how it relates to existing theory (as described in Section 2). The methods and data used are explained in Section 3, while each paper and its findings are summarized in Section 4. The dissertation concludes in Section 5 by describing its methodological, empirical and theoretical contributions, proposing implications for investors and policy makers and listing areas for future research. Section 6 provides an overview of the four papers and Annex I contains the full version of each paper.

2 Research framework and theoretical background

This dissertation investigates the diffusion of renewable energy technologies in a particular context – RVGs in developing countries – by embracing different perspectives. Such an approach is helpful to “overcome inherent limitations of single [theories and] methods, helping the researcher to see ‘the whole elephant’ and not just a part of it” (Kemp & Pontoglio 2011, p.33; Norgaard, 1989; Little, 1999) – in this case, the low diffusion of RVGs in developing countries. Economic, financial/management and innovation systems literature provide suitable approaches to investigate the diffusion of infrastructure¹⁷ – such as RET – and to derive implications for policy makers (Jacobsson and Johnson, 2000; Bhattacharyya, 2012; Truffer et al., 2012). While the economic literature examines how diffusion of technology depends on relative prices, financial/management literature regards individual firms as the central drivers of diffusion. Innovation systems literature, alternatively, understands diffusion as an evolutionary process, where different actors are involved and decisions depend on additional variables apart from relative prices. These three literature streams lead to three different perspectives from which I investigate the diffusion of RVGs; a techno-economic, investor’s and innovation systems perspective. The perspectives complement each other in describing ‘the elephant’ and allow for practical (investor and policy) implications.

2.1 Introducing the three perspectives

In the following subsections I discuss each perspective along its conceptual roots and assumptions, derive the sub-research questions for the four papers and additionally highlight the perspective’s strengths and shortcomings.

Techno-economic perspective

The techno-economic perspective comprises approaches that compare costs of different technologies. Today, such techno-economic modeling is frequently used to derive the cost of renewable energy. Out of the many existing modeling approaches¹⁸ for calculating generation costs of electricity, I chose to

¹⁷ Roger’s (2003) famous framework on the ‘diffusion of innovation’ is more suited to analysing the diffusion of consumer products (Lundblad, 2003).

¹⁸ In Europe, the leading models to simulate electricity markets and calculate electricity costs, among other things, and the related institutions are: the MARKAL and TIMES models (e.g. used at the PSI Energy economics group in Switzerland), the UCL Energy Institute in the UK, the Osemosys model (an open source model used e.g. at KTH in Sweden), the MESSAGE model (e.g. used by the IIASA in Austria), and the EXPANSE model (focused on RET and used at ETH Zurich in Switzerland).

apply a levelized cost of electricity (LCOE) calculation. The LCOE¹⁹ allows for the comparison of alternative energy technologies as it pays tribute to the different investment and running costs, as well as to the life span of the technologies. Despite its wide acceptance in the scientific community and in the political arena, there is methodological criticism. For example, Joskow (2011) criticizes the application of LCOE for intermittent technologies (such as solar PV) in regions with fluctuating electricity sale prices. The use of LCOE for the purposes of this dissertation is still valid since the logic of varying electricity prices applies to powerful, liberalized electricity markets which barely exist in most developing countries (including the here analyzed country, Indonesia) and per definition do not apply to the “monopoly status” of RVGs in villages (supplementary information in Schmidt et al., 2012). The basic assumption when interpreting LCOE analyses is that the diffusion of the lowest cost technology is most likely and that policy can therefore intervene by adjusting the cost differences (e.g. by introducing subsidies to lower the cost of renewable or by putting a price on external costs, such as CO₂ emissions). Therefore the techno-economic perspective stands in the tradition of least cost techno-economic modeling. The question to be addressed in light of this thesis is: “In terms of cost²⁰, how competitive are RVGs compared to the standard conventional village grid solution?”

Least cost modeling and LCOE in particular are valuable in identifying the amount of financial support needed to foster RETs²¹. The strengths of LCOE modeling are its wide acceptance and dissemination in the political arena²² –especially in the context of developing countries (Waissbein et al., 2013) – along with its persuasive power. The relevance of LCOE literature within the policy process has several reasons: the single cost indicator is easy to understand, though still able to incorporate – to a certain extent – dynamics (e.g. future cost projections such as learning curves or fuel prices) and is very helpful in quantifying necessary policy support levels (e.g. the amount of needed subsidies (Peters et al., 2011)). Nevertheless, the perspective’s strongest advantage – its focus on a single indicator – is also its biggest shortcoming. It omits barriers and risks which do not affect costs, as well as revenues, necessary technological capabilities and actors involved in the diffusion of technologies.

¹⁹ LCOE takes into account all discounted costs accrued throughout the system lifetime (n) including investment expenditure (It), operations and maintenance expenditure (Mt), and fuel expenditures (Ft), divided by the discounted value of electricity sold during the lifetime (Et).

²⁰ This research aims at describing the economics of RVGs in Indonesia today. As of today, Indonesian regulations do not put a price on external costs such as CO₂ emissions. Therefore, external costs are also not incorporated in the LCOE analysis. However, I acknowledge that pricing them would be in favor of RVGs.

²¹ E.g. often used to determine the height of feed-in tariffs for RET (Peters et al., 2011).

²² Well-respected organizations such as the International Energy Agency (IEA), the International Institute for Applied Systems Analysis (IIASA), the International Renewable Energy Agency (IRENA), the Energy Information Administration (EIA) and the United Nations’ Intergovernmental Panel on Climate Change (IPCC) regularly use it to derive policy recommendations.

Investor's perspective

The investor's perspective partly addresses these shortcomings since it takes the viewpoint of a central actor in the diffusion of technologies; namely the investor who builds, owns and operates a RVG²³. In corporate finance literature, a standard assumption is that investors base their investment decisions on the risk/return profiles of investment options (see e.g. Brealey et al., 2008). The interplay of risks and returns is regarded as a central aspect when understanding whether or not an investor will invest despite existing risks. The underlying assumption is that favorable risk/return profiles, and thus positive returns and manageable risks, trigger private investments. Further, it is assumed that risks and returns are positively interrelated (see e.g. Lundblad, 2007; Brealey et al., 2008)). Barriers – created by all kinds of stakeholders – increase the probability of negative events in the future (Waissbein et al., 2013). Thereby they impose risks for the investors. These risks are only accepted by investors if compensated by 'sufficient'²⁴ returns (DB Climate Change Advisors, 2011; Davies et al., 2012; Glemarec et al., 2012; Waissbein et al., 2013). For policy making, this has the following implications: if policy makers aim to attract private investments in a specific technology, they can, first, influence returns²⁵ through instruments such as subsidies, and, second, identify and address barriers in order to reduce risks. Ideally such interventions result in a favorable investment environment for the respective technology. From the investor's perspective, the question "what do the current risk/return profiles of RVGs look like and how can they be improved in order to attract private investments?" is addressed²⁶.

This perspective is gaining acceptance in the policy arena (DB Climate Change Advisors, 2011; Glemarec et al., 2012; Waissbein et al., 2013) because its investor-oriented, market-based approach is in line with the current efforts in international development cooperation. The World's Bank's president, Jim Yong Kim, states that market-based growth is a priority in developing countries (BBC, 2012). Supporting developing countries in creating markets and thereby leveraging private capital is a central focus in development cooperation programs of today's main international actors, such as the UN or the World Bank (Roberson, 1999). Despite having a strong and beneficial focus on investors, the perspective neglects other actors, fully omits social aspects of technologies and also ignores dynamics, as well as geographical issues.

²³ In this perspective I focus on build-own-operate-type of investors only and do not consider other investors, such as e.g. venture capitalists, who purely do financial investments and are not involved in the building and operating of RVGs.

²⁴ What qualifies as "sufficient" is subjective to each investor.

²⁵ In calculating returns, I do not include external costs and thereby reflect the current regulatory and investment environment in Indonesia.

²⁶ Since risks and returns both appear on different geographical levels, the analysis is divided into local, national and international levels.

Innovation systems perspective

In the innovation systems perspective, I rely on the literature concerning systems of innovations (for an overview see Edquist, 1997). *Innovation systems (IS)* literature has its roots in evolutionary economics and theories of interactive learning (Nelson and Winter, 1982; Rosenberg, 1982; Edquist, 1997; McKelvey, 1997). It gained relevance in innovation research in the late 1980s (for an overview see e.g. Edquist, 1997; Edquist et al., 2007). The *IS* literature defines the innovation and diffusion of technologies as an evolutionary, systemic process. Hence, the approach goes beyond mere cost-competitiveness, as in the techno-economic perspective, and beyond analyzing a single organization, as in the investor's perspective (Jacobsson and Johnson, 2000). Depending on the object under investigation, researchers have distinguished between national/regional, sectoral, and technological innovation systems (Carlsson et al. 2002; Malerba 2002). Of these different levels of analysis, a *Technological Innovation System (TIS)* focuses on a specific technology and is defined by Carlsson and Stankiewicz (1991, p.93) as a “dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology“. The practical purpose of innovation systems is to derive policies which foster technological change (Edquist, 1997). To this end, *TIS* researchers developed the concept of *functions* (Carlsson and Jacobsson, 2004; Bergek et al., 2005), which make the system's performance ‘measurable’ and provide a tool to derive policy recommendations to foster specific technologies (Hekkert et al., 2007; Bergek et al., 2008). The *(technological) innovation systems* literature assumes that technological change results from the interplay of different actors in a certain institutional environment. It involves reinforcing processes in, for example, knowledge development and diffusion or resource mobilization. It also assumes that policy makers can intervene in these processes in order to support the diffusion of a favored technology. From this innovation systems perspective, first, I address the question “to which extent is the *TIS and functions* framework generalizable to ‘extreme’ cases?” Applying the framework to an “extreme” case, that differs strongly from cases analyzed thus far, can demonstrate the general validity of the concept in such cases and can help to identify weaknesses and potential improvements. The chosen “extreme” case consists of the (thus far in the *TIS* community not investigated) relatively complex technology of RVGs in rural Laos (a least developed country). I thereby aim at contributing to the current debates on (a) the set of *functions*, their role in the system and their individual definitions; and (b) the role of *spatial aspects* and their integration into the *TIS and functions* framework. Focusing more on practical aspects, the second question asks “how the low diffusion of RVGs in a least developed country can be explained using the *TIS and functions* framework.”

The advantages of this approach are, first, that the *TIS and functions* framework has proven to deliver valuable insights into the development and diffusion processes of infrastructure technologies (Bergek,

2012; Truffer et al., 2012)²⁷ and therefore fits the empirical focus of this thesis. Second, by mapping only those aspects relevant for the studied *TIS*, it simplifies a complex real-life situation while still integrating dynamic aspects of diffusion (Hekkert et al., 2007). Finally, it is empirically proven to be successful in identifying bottlenecks in the process of the diffusion of a technology, which provides the basis for informed, holistic policy making (Johnson, 2001; Smits and Kuhlmann, 2004; Bergek et al., 2008; Markard and Truffer, 2008; Jacobsson and Bergek, 2011). However, this perspective also has its limitations. Probably its biggest limitation is that the *TIS* approach is a rather young framework which is not yet fully established and is currently mainly applied by research groups in Europe. Because of this, the approach (explicitly not referred to as a theory (Edquist, 1997)), being young (see e.g., Bergek 2012; Truffer et al. 2012), comprises a set of issues under debate; amongst others, the stability of implications for policy makers. While many researchers formulate policy recommendations from empirical research, others claim that such recommendations remain unspecific and purely qualitative (Jacobsson and Karltorp, 2012). Other disciplines might claim that factors such as competition between firms are under-established and that the approach – even if first attempts to develop quantitative measures for *TIS and functions* have been made (Negro et al., 2007; Bergek et al., 2008; Suurs and Hekkert, 2009) – remains qualitative.

Figure 4 provides an overview of the perspectives and the respective sub-research questions. Together with co-authors I addressed each sub-research question in a paper²⁸. While the first three papers directly relate to one perspective and its respective interaction with the case of RVGs in South East Asia, the fourth paper is a purely conceptual viewpoint on the *TIS and functions* framework without relation to the empirical case of RVGs in developing countries. The integration of Paper 4 into the thesis strengthens the thesis' general aim to derive recommendations for national and international policy makers. It does this in a conceptual, theory-oriented way by addressing the question: “How to improve the relevance and applicability of *TIS and functions* in research findings for the political forum?”

²⁷ In fact the *TIS and functions* framework was empirically driven by infrastructure – more specifically RET.

²⁸ While the entire papers are provided in Annex I, a summary of the results of each paper can be found in Section 4.

Perspectives	Research questions		
Techno-economic perspective LCOE of RVGs	In terms of cost, how competitive are RVGs compared to the standard conventional village grid solution?	Paper 1	Why is the diffusion of RVGs in developing countries low and how can it be advanced?
Investor's perspective Risk/return profile of RVGs	What do the current risk/return profiles of RVGs look like and how can they be improved in order to attract private investments?	Paper 2	
Innovation systems perspective A) <i>TIS and functions</i> framework applied to an „extreme“ case	To which extent is the <i>TIS and functions</i> framework generalizable to “extreme” cases? How can the low diffusion of RVGs in an LDC be explained using the <i>TIS and functions</i> framework?	Paper 3	
B) Improvement of policy recommendations of <i>TIS and functions</i> framework	How to improve the relevance and applicability of <i>TIS and functions</i> in research findings for the political forum?	Paper 4	

LCOE = Levelized Cost of Electricity, RVG= renewable energy-based village grid, TIS = Technological Innovation System, LDC = Least Developed Country

Figure 4 – The overall framework of the PhD thesis, an overview of the papers and their research questions

2.2 How the three perspectives complement each other

Having discussed the rationales behind the use of each perspective above, this section concludes with the contributions of each to the explanation of **why the diffusion of RVGs in developing countries is low and how it can be advanced**. It thereby provides insights for practitioners, such as investors and policy makers and the improvement of existing theoretical concepts and empirical data on the diffusion of (renewable energy) technology.

Implications for investors can be derived from all three perspectives. Costs, returns, and risks, as well as systemic barriers, are all relevant information for investors. Understanding potential risks and returns provides investors with a good starting point to base their investment decisions on. However, before making a final investment decision, investment barriers have to be understood in order to evaluate potential risks.

Providing policy makers with recommendations on how to foster the diffusion of a specific technology is the second aim of this thesis. In this regard, policy makers in developing countries need to understand that there are different dimensions to evaluate when determining whether it is desirable to foster the diffusion of a specific technology. One of these is cost and, another, how well a technology contributes to the fulfillment of development goals such as poverty reduction. If after such an

assessment²⁹ a technology (e.g. RVG) is considered worthwhile for diffusion, two important policy questions have to be asked: (1) How much financial support should policy makers grant to RVGs? (2) How else can policy intervene? While the techno-economic perspective provides insights on costs of technologies, only together with the return calculation and the risks aspects from the investor's perspective can policy makers come to conclusions about the amount of financial support needed in order to turn RVGs into an investment with positive returns. The second question can be answered by combining the investor's and the innovation systems perspectives. While the investor's perspective specifically points to investment barriers, the innovation systems perspective helps identify barriers (which are labeled as bottlenecks or weaknesses by the *TIS and functions* framework) and their systemic roots in the overall system. It includes all kinds of relevant actors, their interrelations, as well as the institutional factors that shape their decisions. Conducting the barrier analysis and the *TIS and functions* analysis by applying different geographical levels reveals whether policy makers should intervene locally, nationally or internationally. To summarize, in order to answer both questions, the combination of the perspectives is essential. Or, in other words: "policy impacts depend on the design of the policies and context in which they are used", "in limiting oneself to one [theory and] method there is a danger of coming up with partial truths, and mak[ing] unjustified generalizations" (Kemp & Pontoglio 2011, p.33), whereas the multi-perspective approach applied here allows us (and policy makers) to see more of 'the whole elephant'.

This thesis also adds empirical data on renewable energy-based technologies in developing countries and contributes to existing theoretical concepts. Whereas in all three perspectives new empirical data is gained, only the *TIS and functions* framework (in the innovation systems perspective) is conceptually enriched by this dissertation. In other words, the "extreme" research case, which is new to the *TIS and functions* framework, allowed for testing of this tool 'to make the elephant visible'. The framework was then enriched to make it more effective in investigating other *TIS* ('other animals') as well.

²⁹ Sometimes referred to as technology needs assessment (UNDP, 2010b).

3 Methods and Data

Researchers in economics and social sciences recognize that methodological pluralism is the most appropriate approach when dealing with complex questions (e.g., Norgaard, 1989; Little, 1999). Kemp and Pontoglio (2011) suggest looking at a research subject (the ‘elephant’) from different angles and embracing different methods, and researchers that focus specifically on rural electrification topics suggest integration of the expertise of practitioners with the knowledge of different academic disciplines (Schäfer et al., 2011). Therefore, in researching the different perspectives, this thesis employs methodological pluralism and multiple data sources. While Paper 4 is theoretically driven and develops a new conceptual approach to derive policy recommendations from a *TIS and functions* analysis, Papers 1-3 are methodologically based on quantitative and qualitative methods and rely on both primary and secondary data (compare Table 2). A sound literature review is the basis of all scientific work, and therefore also of all four papers in this thesis³⁰. However, this will not be described in this section (please refer to the respective papers in Annex I).

Table 2 – Methods and data used in the four papers

Perspectives		Method	Data source	Regional Scope	Technological Scope
Techno-economic perspective LCOE of RVGs	1	Quantitative: cost modelling	Secondary data: information on village development, energy resource, and cost of technology	Indonesia	Diesel-, solar PV/battery-, and microhydro-based village grids
Investor’s perspective Risk/return profile of RVGs	2	Quantitative: revenue modelling Qualitative: interview-based case study	Secondary data: Business model documents, and policy reports Primary data: 31 interviews, 4 RVG visits	Indonesia	Solar PV/battery-, and microhydro-based village grids
Innovation systems perspective A) <i>TIS and functions</i> framework applied to an „extreme“ case	3	Qualitative: interview-based case study	Primary data: 17 interviews, RVG visit	Laos	All types of renewable energy-based village grids
B) Improvement of policy recommendations of <i>TIS and functions</i> framework	4	Conceptual	Secondary data: empirical <i>TIS and functions</i> papers	n/a	n/a

RVG= renewable energy-based village grid, TIS = Technological Innovation System

³⁰ The focus of the reviewed literature is different in each paper and includes: costs of RVGs in Indonesia (Paper 1), barriers to RVGs and corporate measures to address the barriers (Paper 2), empirical (focusing on developing countries) and conceptual *TIS and functions* studies as well as documents on rural electrification/RVGs in Laos (Paper 3), and empirical work applying the *TIS and functions* framework (Paper 4).

3.1 Quantitative: Modeling of electricity generation costs, CO₂ abatement costs, and revenues (Paper 1 and 2)

In Paper 1 and 2, quantitative modeling is applied in order to determine electricity generation costs (LCOE), CO₂ abatement costs and (potential) revenues of RVGs in Indonesia.

3.1.1 Electricity generation costs

In Paper 1, the life-cycle costs of electricity generation in RVGs (and the conventional solution) are modelled. Figure 5 provides an overview of the procedure and the following subsections describe each step in more detail (for the full analysis, please see Paper 1 in Annex I).

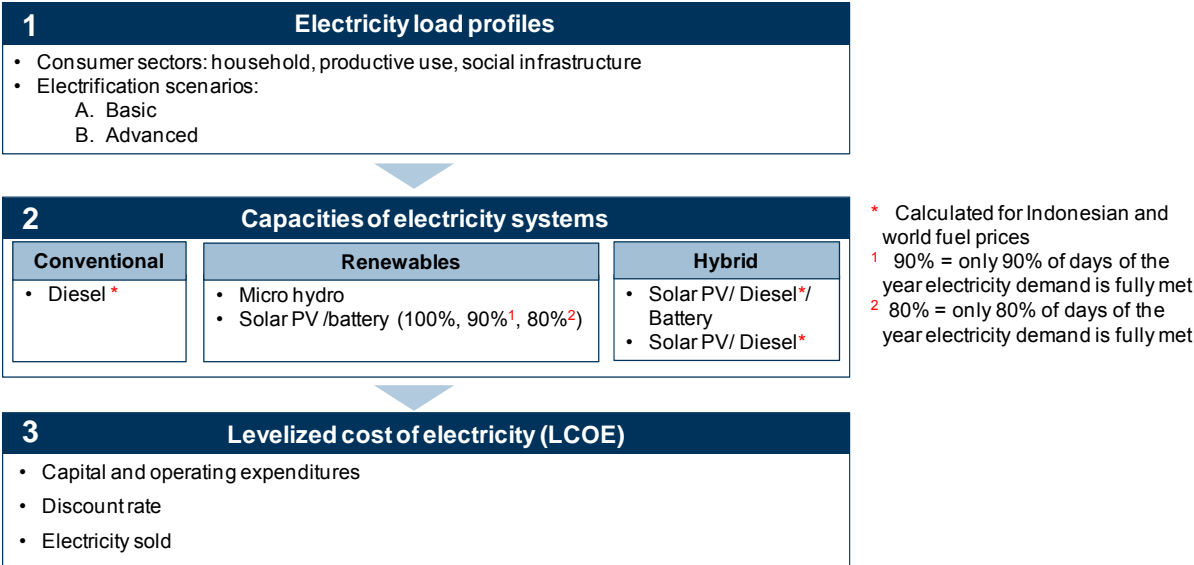


Figure 5 – Three step approach to model electricity generation costs

Electricity Load Profiles

In the first step, the village electricity demand was estimated. To this end, I, together with my co-authors, defined the size of a generic village, two electrification strategies (to account for different socio-economic development stages of villages), and the corresponding village load profiles, including electricity consumption for households, productive use and social infrastructure. Previous studies and our own field investigations and interviews were used as input data.

Capacities of electricity systems

Having determined the demand for electricity in the generic Indonesian village, in the second step the required capacities of each system in order to meet the electricity demand levels for each scenario as defined in the hourly load profiles were determined. While the diesel and micro hydro-based systems were sized according to the peak demand, all mixed systems (where solar PV plus at least one

additional electricity generation technology is employed) were sized by minimizing the LCOE of the system and accounting for variations in the solar radiation throughout the year.

Levelized cost of electricity

For each electricity generation system and both electrification scenarios, the LCOE was calculated via a non-linear, dynamic cash-flow model. It allows for the comparison of alternative technologies even if system sizes, investments and operating times differ (Campbell et al., 2009). The LCOE equation (below) takes into account all discounted costs accrued throughout the system lifetime (n), including investment expenditure (I_t), operations and maintenance expenditure (M_t), and fuel expenditures (F_t), divided by the discounted value of electricity sold during the lifetime (E_t). r is the assumed discount and inflation rate.

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad [€/kWh]$$

3.1.2 CO₂ abatement costs

Implementation of a RVG reduces greenhouse gas emissions that would otherwise have been caused by a conventional diesel-based village grid. In Paper 1, the emissions abatement costs were defined using the difference in LCOE between the diesel and renewable energy-based solutions, as well as the associated emissions displaced relative to the diesel system. This relationship is defined by the following formula:

$$Abatement\ cost\ (AC) = \frac{LCOE_{renewable\ based} - LCOE_{diesel}}{Emissions_{diesel} - Emissions_{renewable\ based}} \quad [€/tCO_2]$$

We also calculated the savings in CO₂ emissions made by opting for a RVG as opposed to diesel, given by the formula:

$$CO_2\ emissions\ savings = \frac{Yearly\ fuel\ input_{diesel} - Yearly\ fuel\ input_{renewable\ based\ alternative}}{Diesel\ fuel\ specific\ CO_2\ emission} \quad [tCO_2/year]$$

3.1.3 Revenues

In Paper 2, potential local, national and international revenues of RVGs were calculated. Local revenues were assumed to equal electricity sales prices. Since real electricity tariffs are fixed in Indonesia, and therefore do not reflect the whole local revenue potential, I used the villagers' willingness-to-pay as a proxy. The data used was based on a mini-survey with 9 implementers and

operators of RVGs, as well as villagers. National revenues are reflected by a potential redistribution of fuel and electricity subsidies. The actual value of diesel subsidies (in €/kWh) in currently operating diesel-based village grids was determined using the difference between the LCOE of diesel-based village grids considering Indonesian and international diesel prices (following IEA’s opportunity cost approach). The difference between the LCOE of diesel-based village grids (at Indonesian diesel prices) and the Indonesian national electricity tariff (charged by the Indonesian electricity utility and paid by already electrified rural poor households) yielded current electricity subsidies. To determine potential revenues from international sources, I considered revenues obtained through the sale of carbon credits, which I calculated based on the CO₂ emission savings obtained in Paper 1 (Section 3.1.2):

$$\text{Carbon revenues} = \frac{\text{CO}_2 \text{ emissions savings}}{\text{Yearly electricity production}} * \text{carbon price} \quad [€/t\text{CO}_2]$$

3.2 Qualitative: Interview-based case studies (Paper 2 and 3)

For the barrier analysis in Paper 2 and the *TIS and functions* analysis in Paper 3, I followed Yin (2003) ’s approach and applied a qualitative, single case study design. This is appropriate for explanatory and exploratory purposes in a complex, contemporary, social context which has not been previously explored in depth (Eisenhardt, 1989; Gibbert et al., 2008). In the following subsections I describe the sampling, data collection and analysis.

Sampling of cases and interview partners

By applying theoretical sampling (following Eisenhardt, 1989), I chose Indonesia and Laos as case studies to investigate the diffusion of RVGs. While the diffusion of RVGs is considered beneficial to both countries³¹ and there are RVG pilots in both of these countries, the scale-up is very slow. The investor’s perspective is best investigated in Indonesia, one of the countries with the largest potentials for RVGs worldwide. Here the “ease of doing business” is more attractive to private investors than in Laos (The World Bank, 2013a) and several partly privately funded RVGs have already been built. For developing the *TIS and functions* framework in the innovation systems’ perspective, choosing “cases such as extreme situations and polar types in which the process of interest is ‘transparently observable’” makes sense (Eisenhardt, 1989, p.537). Laos presents such an “extreme” case to the *TIS and functions* literature. Laos is “extreme” in terms of, for example, its development status as a least developed country³², with limited resources and (technological) capabilities (UN-OHRLLS, 2013).

³¹ Both countries have high renewable energy resources, low electrification rates, challenging terrain in remote areas (islands or mountains), as well as poverty reduction and environmental goals.

³² The United Nations’ Human Development Index (HDI) classifies Laos as a least developed country (UN-OHRLLS, 2013).

In Paper 2, interview partners were sampled to fill three categories relevant to an investor's perspective: customers (villagers), professionals (involved in the building, owning and operating of RVGs in Indonesia) and representatives from the government. In Paper 3 I sampled interview partners to fill four categories of actors in a *TIS*: villagers, governmental units, development specialists (from international organizations, nongovernmental organizations and development agencies) and private sector representatives.

Data collection

As suggested by Yin (2003) for 'explanation building', I followed an iterative process in collecting and analyzing data. For the analysis, I drew on primary data sources, such as semi-structured interviews and on-site observations of RVGs, which I conducted during two several week-long stays in South East Asia in 2010 and 2011, as well as from secondary data sources such as reports, policy documentation, websites, and other documentation (Eisenhardt & Graebner 2007). The procedure was as follows:

- (1) Through a web search, I identified a preliminary list of potential interview partners.
- (2) To complete the list and to refine the semi-structured interview guidelines, I followed Yin (2003)'s suggestion to conduct a pilot interview and visited Laos in 2010 for an exploratory face-to-face interview. For this interview, I selected, based on a web search, a prominent actor in rural electrification who would be helpful in challenging the interview guideline and identifying additional interview partners.
- (3) After obtaining an extended list of potential interviewees, I requested interviews for mid-2011 through phone calls and emails.
- (4) In preparation for the interviews I scanned related documentation and tailored the interview guidelines to each interviewee.
- (5) I then conducted the arranged interviews and arranged additional ones once in South East Asia. Among the 42 interviews used for this thesis, twelve were conducted in Laos, 26 in Indonesia, two in Cambodia, one in Thailand, and one in Switzerland. While eleven of the interviewees are non-South East Asians, 7 are Laotian and 14 are Indonesian citizens. Surprisingly, most interviews could only be arranged once in South East Asia. This highlights the importance of on-site research, especially if interviewees are not easily accessible by email or phone or have no English language skills, such as most Indonesian and Laotian villagers. Each interview lasted between 30 and 120 minutes. When the interviewee agreed, interviews were recorded; otherwise the interviewer took detailed notes.
- (6) To triangulate information provided by the different interviewees, I included observations of visits to four different RVGs and additional written information obtained from interviewees. The visits to the RVGs included visits to the power plants, inspection of the civil construction

and visits to the villages and grid networks. The observations were documented on videotapes and through the researcher's notes. The additional written data provided by interviewees was of special value, as many country specific documents are not available online. Interviewees therefore represent an important source for presentations, non-public policy documentations and drafts of reports.

- (7) Finally, interviews were transcribed and together with the other documents (videotapes from RVG visits and written secondary data) saved in a central, standardized electronic case study database, which facilitates the repetition of the analysis.

Data analysis

To analyze the collected data, I structured the information using coding. Throughout this process, I followed an explanation building logic which is applicable to both explanatory and exploratory contexts (Yin, 2003). The beneficial attribute of such logic is its iterative character. It allows the consideration of rival explanations and the opportunity to examine the evidence from perspectives other than the one initially defined (Yin, 2003). To this end, I applied categorical aggregation “of instances until something can be said about them as a class” (Stake, 1995, p.74) to the data. For the analysis, I used the software Atlas.ti. I applied a code list including barriers and measures that investors can take (from interviews for Paper 2(Indonesia)), as well as all structural and dynamic elements of the *TIS* and the three *geographical* levels (from interviews for Paper 3(Laos)). The list of codes was extended along the coding process whenever a peculiarity arose that was not covered by the codes. By applying a reduction process (Marshall and Rossman, 1989) for additionally identified codes, I ensured that no important aspects were neglected. After coding all interview transcripts, I identified the most important barriers (from interviews for Paper 2 (Indonesia)) and bottlenecks in the *TIS* (from interviews for Paper 3 (Laos)).

4 Summary of the Results

While Section 2 outlined the dissertation’s objectives, and Section 3 the methods and data used, this section highlights the main findings of each paper.

4.1 Paper 1: Rural electrification through village grids – Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia

As discussed in Section 2, Paper 1 investigates how competitive, in terms of costs, RVGs in Indonesia are compared to the standard conventional village grid solution. To this end, we calculated the LCOE of micro hydro, solar PV/battery³³ and diesel-based village grids for a generic Indonesian village and two electrification scenarios (A and B). Figure 6 shows our main results.

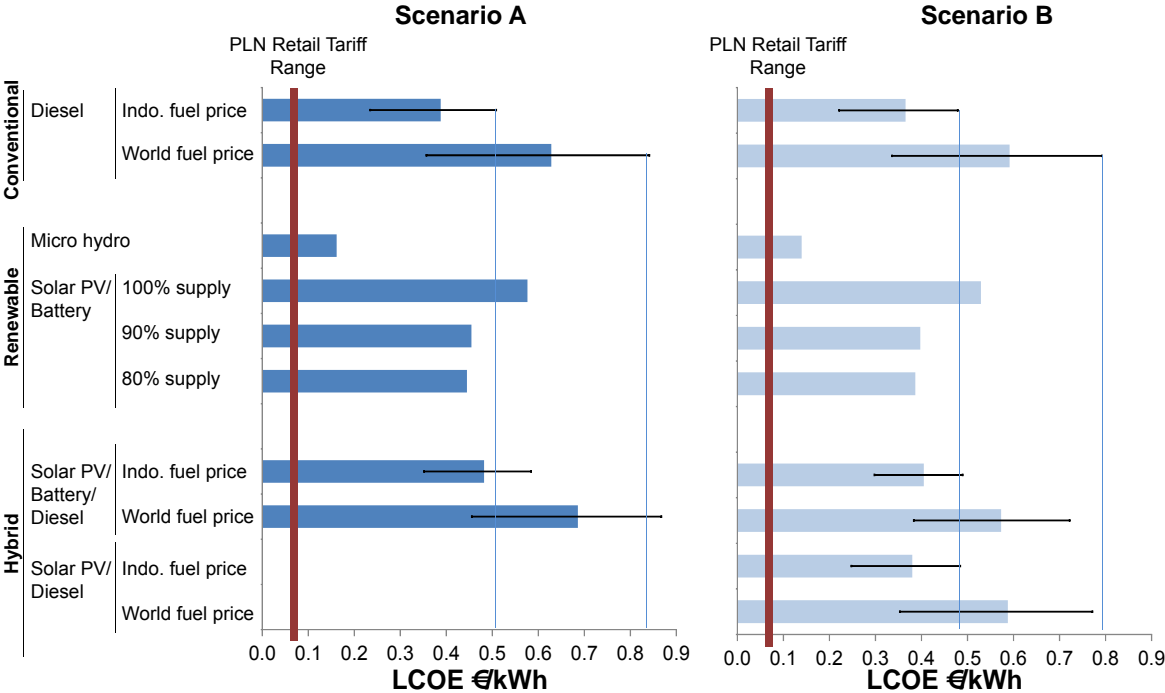


Figure 6 – LCOE for generic Indonesian village grid with various power generation configurations and applying basic (A) and advanced (B) electrification scenario. For each technological option, the LCOE are quantified on the horizontal axis in €/kWh. The black lines represent the range of LCOE for any village grid configuration with diesel components, demonstrating the influence of fuel costs due to the remoteness of the village. The furthest left (smallest) LCOE within a variation represents locations close to distribution centres. The furthest right (highest) represents the most remote locations. Additionally, we compared the LCOE results to the Indonesian, state-owned electricity utility’s retail tariff range depicted by the red vertical bars. A range of tariffs exist since retail prices differ for household, productive use and social infrastructure consumers.

³³ To investigate ways to reduce the costs of solar PV/battery-based village grids, we additionally calculated the LCOE for different system configurations, including a reduced supply contingency and a hybridization approach. Under a 90% reduced supply contingency, the RVG is able to supply sufficient electricity to fully meet the village’s demand during 90% of the days throughout a year. For the remaining 10%, a shortage of electricity supply may be expected

Figure 6 shows that the cost of all technologies decreases when the advanced electrification scenario is applied instead of basic electrification. This is driven by a higher capacity factor in scenario B, achieved through daytime utilization of electricity for productive use and social infrastructure.

Through our analysis, we find large differences in the LCOE of the various solutions. Starting from the conventional solution, we observe that the diesel powered village grid option has the second lowest LCOE (at low and medium remoteness) when considering the Indonesian diesel fuel prices. However, when we consider world diesel fuel prices, the LCOE are 62% higher³⁴. Additionally, due to transportation costs of diesel, particularly in more remote areas, diesel prices can be much higher than in distribution centres. In the set of results for renewable energy-based village grid solutions, we observe that micro hydro consistently has the lowest LCOE compared to other technologies for both scenarios, at 0.16€/kWh (A) and 0.14€/kWh (B). Our analysis also demonstrates that solar PV is still the most expensive technological option to power village grids. For scenario A, a LCOE of 0.58 €/kWh was obtained, and for scenario B, a LCOE of 0.53€/kWh. However, for solar PV in scenario B, we observe that the solar PV/battery LCOE is already lower than a diesel engine at world fuel prices, even at medium remoteness. In evaluating the effects of alternative configurations to solar PV/battery-based village grids, first, we observe that the reduced supply contingency strategy proves to be successful in reducing LCOE. Secondly, hybrid technologies which combine diesel and solar PV are only cheaper than pure solar PV/battery options if diesel subsidies are assumed and/or the village location is not remote. Their application might be interesting in places where diesel generators already exist but more generation capacity is needed due to the development of the village.

By law, all end-users to the state-owned Indonesian electricity utility (Perusahaan Listrik Negara PLN) are entitled to the official PLN tariffs. For completeness, we compared the LCOE of the village grids to PLN retail tariffs (red band in Figure 6). PLN tariffs differ according to the end-use category as determined by Ministerial Decree 4/2010 (Ministry of Energy & Mineral Resources Indonesia, 2010) and range from 0.06 - 0.08€/kWh. This retail tariff band is thus far lower than any of the LCOE for the analysed village grid options.

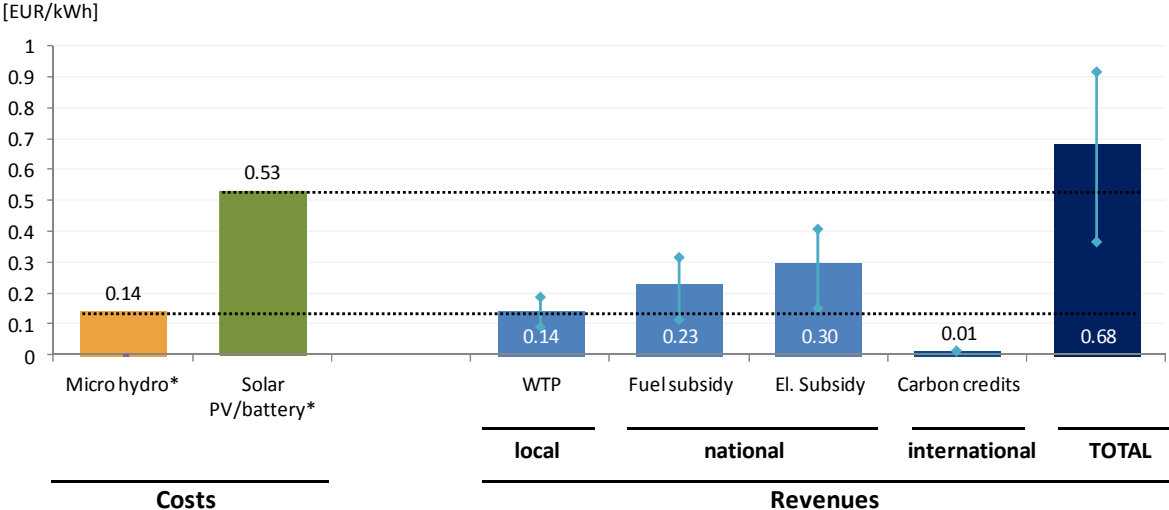
Looking at the solutions from an environmental perspective, in our CO₂ abatement cost calculation (compare Paper 1 in Annex I) we also find that, micro hydro-based village grid solutions have negative CO₂ abatement costs with significant potential to reduce emissions. The results also show that a certain part of the additional costs of solar PV/battery-based systems could be covered by carbon credits.

³⁴ If external costs such as e.g. CO₂ emissions were priced, the cost of diesel-based village grids would increase even more.

4.2 Paper 2: Attracting private investments into rural electrification – A case study on renewable energy-based village grids in Indonesia

Taking the investor’s perspective, Paper 2 answers the question “What do the current risk/return profiles of RVGs look like and how can they be improved in order to attract private investments?” The paper investigates the risk and return aspects of RVGs for the case of Indonesia.

The return analysis (see Figure 7) shows that potential local and national revenue streams are able to cover costs³⁵. This builds the base for a profitable business case, at least in the case of micro hydro-based village grids. While local revenue estimates are based on the villagers’ willingness-to-pay for electricity, national revenues are based on potentially redistributed subsidies. Both revenue streams are substantial and, in contrast, the role of international revenues in the form of carbon credits turns out to be limited.



* Source: Paper 1

Figure 7 – Cost and revenue estimates for micro hydro and solar PV/battery-based RVGs³⁶

Next, in order to understand the risk aspect, the paper analyzes investment barriers on a local, national and an international level and matches them with measures that build-own-operate investors can take to address these barriers. We find a wide range of barriers as well as measures for investors (see Table 3).

³⁵ As this paper takes a business perspective, the here presented costs reflect current production costs (calculated as LCOE) and do not incorporate external costs.

³⁶ Even if the submitted article (see Paper 2 in Annex I) depicts values in USD/kWh and IDR/kWh, here the values are shown in EUR/kWh to ease comparison with Figure 6.

Table 3 – Barriers (in Indonesia) and measures for investors to address them

	Barriers (based on <i>interviews</i>)	Measures for investors to address the respective barrier (based on literature review and <i>interviews</i>)
Local	Lack of understanding the customers' needs	Conduct market research to understand village specifics Introduce customer service Involve the community
	Lack of decentralized operation, maintenance and administration	Implement a decentralized organizational structure Employ locals
	Unsteady electricity demand and uncertain forecasts	Do scenarios for the demand forecast of each village Increase modularity and flexibility of design of the RVG Educate customers on efficient electricity use Agree with local businesses on fixed and regular electricity purchases
	Lack of local human resources	Train and up-skill own, local staff Retain trained and skilled staff
	Lack of local financial resources	Design a locally adapted tariff and payment scheme Foster local productive use and entrepreneurship Provide customers with access to loans
National	Lack of standards and knowledge transfer on best practices	Draw from and advocate for existing best practice examples and standards Conduct pilot projects, then scale up
	Lack of information and data	Collect and share information and data
	Lack of national network of investors	Attend and conduct workshops, seminars and conferences Build strategic partnerships
	Lack of national technology supplier network	Buy from local suppliers whenever possible Buy from international suppliers where necessary
	Strongly regulated electricity market	Advocate for market liberalization
	Ineffective governmental structures	Maintain professional contacts to governmental units in order to gain trust Decentralized operation, maintenance and administration
International	Lack of national financial resources (debt and equity)	Reduce business risk Employ new financing schemes
	Lack of international financial resources (debt, equity, carbon)	Reduce business risk Employ new financing schemes Loan from impact investors Apply for carbon credits
	Negative externalities caused by international donors	Strengthen NGOs, governmental agencies and other non-private actors in their understanding of free market mechanisms

This list of measures is extensive. As an example, I summarize two representative measures. First, to address the local barrier “lack of understanding the customers’ needs”, investors need to “involve the community”. Concrete activities that prevent negative investor and consumer experiences include stakeholder meetings (Bardouille et al., 2012; Rickerson et al., 2012), in-kind support for villagers (Sovacool and Valentine, 2011; Rickerson et al., 2012), co-operation with existing income-generating organizations (e.g., coffee or rice farmers) (Aron et al., 2009), and community ownership³⁷ and management³⁸ (Aron et al., 2009; Glemarec, 2012; Yadoo, 2012). Such community activities are time-

³⁷ Perceived community ownership (or sometimes also referred to as cooperative approach) is more important than actual legal ownership (Yadoo, 2012).

³⁸ Possible disadvantages of community-centered models can be the time intensity to establish the cooperative, as well as the risk of technical and financial failure over time and the dependence on the community members (Glemarec, 2012). Yadoo and Cruickshank (2010), and Cook (2011) on the other side, stress that operation and management costs are lower in

consuming, yet as experts from other NGOs state, a prerequisite for customer acceptance (Alvial-Palavicino et al., 2011). Second, to address the barrier of the “strongly regulated electricity market” in Indonesia, investors can advocate for market liberalization, for example by networking with other investors and lobbying for regulations in favour of RVGs. However, such efforts are challenging and resource intensive.

Despite the variety of measures that build-own-operate investors can take to address barriers, we argue that investors cannot solve the low diffusion of RVGs by themselves and that policy reforms are needed. The two most important governmental activities in this regard are the re-distribution of fossil fuel subsidies towards RVGs and the implementation of public de-risking measures. These include actions such as reforming the national renewable and electrification policies, reducing overlapping functionalities, introducing technology standards for RVGs, and improving access to finance.

4.3 Paper 3: Applying the *Technological Innovation System and functions* framework to a complex technology in a Least Developed Country – Implications from an extreme case

As discussed in Section 2, Paper 3 investigates “to which extent the *TIS and functions* framework is generalizable to ‘extreme’ cases” and “how the low diffusion of RVGs in a least developed country can be explained using the *TIS and functions* framework.” The purpose of the paper is twofold: first, to enhance the ongoing debate on how to advance the *TIS and functions* framework (Bergek, 2012; Truffer et al., 2012). To this end, we contribute to the discussion on (a) the set of *functions*, their role in the system and their individual definitions; and (b) the role of *geographical aspects* and their integration into the *TIS and functions* framework via the distinction of *geographical levels*. We apply the framework to an “extreme” case that has not been previously investigated in the *TIS* community and differs strongly from cases analyzed thus far: RVGs in Laos. To account for *geographical aspects* we conduct our analysis along the *local*, *national* and *international* level. Second, we provide new empirical insights into the reasons for the low diffusion rate of the RVG technology in Laos.

Throughout our analysis, we identified a large array of bottlenecks in the diffusion of RVGs in Laos. Other than a barrier analysis, the *TIS and functions* framework encompasses the capability to identify systemic roots of these bottlenecks and to derive systemic policy recommendations (Smits and Kuhlmann, 2004; Wieczorek and Hekkert, 2012).

To this end, one of the most important overarching empirical observations is that the institutional settings (such as dominant paradigms, expectations or beliefs) of the RVG *TIS* differ strongly across the three *geographical* levels. On the *national* level, the most influential institutions are arguably regulatory ones. While the government aims at economic growth and development, it is hesitant to implement and support stringent market-based approaches. Furthermore, the regulatory actors display

cooperatives and Palit and Chaurey (2011) explain that, “due to equity, commitment and transparency”, cooperatives are successful. They also show that this holds true particularly if there is a productive use of electricity.

low technological capabilities and a reluctance to choose RVGs as the appropriate technology for the electrification of the (at least) 10% non-electrified population outside of the grid range. Despite RVGs' advantages over alternative technologies, national regulators indiscriminately support technologies of all kinds. Hence, regulatory institutions on the *national* level remain weak. On the *international* level, the paradigm that least developed countries need external support to induce economic growth and development, and that such support should foster private sector involvement, is consistent across most actor groups. However, international actors' choice of appropriate technologies, the amount and means of resource transfer and the time horizons and scale of support differ widely. This results in technology plans and offers of support that are inconsistent and sometimes even contradictory. At the *local* level as well, some institutional settings are homogeneous and others heterogeneous. Across the country, villagers believe the central state should provide the infrastructure. They are also rather skeptical of entrepreneurship. Additionally, the general level of education and professional training is low, often leading to unrealistic expectations vis-à-vis electrification on the part of the villagers. The heterogeneity of the institutional settings is of a cultural nature: the many ethnicities, languages, and dialects make each village *sui generis*.

Additionally, the cultural heterogeneity of villages hampers knowledge flow on the *local* level, i.e. between villages, as well as from the *international* to the *local* levels and vice versa. As information related to RVGs comes predominantly from the *international* level and is mostly coded in English, it is not well received and is often not retained. For their part, villagers are unable to make their needs heard, which can result in a mismatch between local needs and international supply of resources.

These different institutional settings and lacking flows of knowledge result in low flows of tangible and intangible resources between the three *geographical* levels and, as a result, dampen network building dynamics.

4.4 Paper 4: Unlocking the full potential of *Technological Innovation System and its functions* framework – A viewpoint

The emergence of the *TIS* (Carlsson & Stankiewicz 1991) and *functions* (Hekkert et al., 2007; Bergek et al., 2008) framework has been interdisciplinary since its outset (Johnson, 2001; Fagerberg et al., 2006). The beauty of the analytical framework provided by the *functions* approach is its applicability to a single technology (Carlsson, 1995). This in turn results in high policy relevance when it comes to the question of how policy could incentivize the diffusion of this specific technology. Additionally, the framework reduces the complexity of the considered case while at the same time providing a systemic view of it. Analyzing the existing literature in this field shows that the *functions* approach is well suited to identify bottlenecks and pinpoint systemic problems in *TIS*. But, so far, conclusions on policy recommendations have not often been linked to the *TIS and functions* analysis and remain rather generic and broad (Jacobsson and Karltorp, 2012). A short survey of the existing empirical papers

applying the *functions* approach, listed in two recent reviews (Bergek, 2012; Truffer et al., 2012), shows that most empirical *TIS and functions* studies (a) focus on issues of sustainability (out of 50 papers, 45 are (renewable) energy-related) and (b) formulate policy recommendations to foster sustainable transition. However, less than half formulate concrete policy recommendations based on the identified bottlenecks and even less formulate these in a very specific, directly applicable way (Bergek, 2012). Because of this, the analyses remain underexploited for policy making.

This viewpoint paper contributes to the ongoing debate about how to translate *TIS and functions* research findings for policy makers. We address the question “how to improve the relevance and applicability of *TIS and functions* in research findings for the political forum?” To this end, we suggest to build bridges to established strands of research outside the innovation systems literature. The underlying assumption is that knowledge from related disciplines can enrich findings from a *TIS and functions* analysis. We see room for making policy recommendations more specific and relevant by linking the *functions*, and thereby the identified bottlenecks, to existing theories from related fields, such as economics, organizational studies, and/or political science. Like political science, economic theories are a classical domain to formulate policy recommendations concerned with the diffusion of technologies. Organizational studies can also help us to understand the inner logic of those actors in the innovation system that play a crucial role in inducing technological change (Utterback, 1971; Hekkert et al., 2007; Bergek et al., 2008). Furthermore, the *functions* approach emerged from an actor-based evolutionary perspective (Carlsson and Stankiewicz, 1991; Edquist et al., 2007).

As procedure we suggest to first conduct a *TIS and functions* analysis as proposed in step 1 - 6 in Bergek et al. (2008). This yields a set of bottlenecks and general policy issues (each associated to specific *functions*). We suggest to then introducing a seventh step, where for each identified bottleneck (and the related policy issue) literature from, e.g., political, economic or organizational science which is well suited to addresses the specific bottleneck is chosen. By applying this theory to the bottleneck, specific policy recommendation can be (re-)formulate. We exemplary apply this seventh step to two characteristic bottlenecks which were identified in two recent papers (Negro et al., 2007; Schmidt and Dabur, 2013). Thereby we stress how economic theories could improve their policy recommendations. The paper ends with suggestions for future research.

5 Discussion and Conclusions

In the following section, I discuss first the methodological, empirical and theoretical contributions. Then I provide implications of the thesis (in general and for investors and policy makers) and propose areas for future research.

5.1 Contributions

This dissertation applies methodological pluralism, provides new empirical data and contributes to current debates in the *TIS and functions* literature.

Methodological Contribution

This dissertation applies analytical and methodological pluralism. Scholars from different theoretical fields have stressed that the investigation of complex problems benefits from embracing different methods (Norgaard, 1989; Little, 1999; Kemp and Pontoglio, 2011; Schäfer et al., 2011). The complexity of the phenomenon analyzed in the dissertation lies in the various factors (e.g. technical, business, social, environmental and political) that influence the (lack of) diffusion of RVGs. While, to date, most studies of RVGs focus solely on technical details, costs or social aspects, this thesis takes an integrative approach in order to address the complexity of the issue. To this end, three analytical perspectives were introduced: the techno-economic, investor's, and innovation systems perspective (see Section 2). To address the three perspectives, quantitative and qualitative methods and different primary and secondary data sources were used. With my diversified results I prove that analytical and methodological pluralism indeed is beneficial for investigating complex problems in the field of technology diffusion.

Empirical Contribution

The empirical contribution of the dissertation is based on the provision of new (quantitative and qualitative) data on RVGs in South East Asia. As discussed in the introduction, there is a very limited amount of scientific data on RVGs so far. The quantitative data provided in literature is mostly limited to technological data and cost analyses of electricity. This dissertation provides new quantitative data, firstly, on costs of RVGs in Indonesia, and thereby extends and updates existing, outdated, cost data (Paper 1). Second, so far the role of variable demand and fluctuating supply over the day or the season (which is typical for intermittent renewable energy sources) is under-researched for RVGs. The model in Paper 1 addresses this gap by scheduling an hourly-based electricity demand of a village and the needed supply to meet it. Third, this dissertation provides new data on villagers' willingness-to-pay in rural Indonesia and thereby replaces earlier, outdated data, or that which has been indicated by interviewees to be unrealistic (Paper 2). Fourth, until this point, only local revenues (sales of

electricity) have been considered in RVG research. This dissertation additionally introduces and quantifies national and international revenue sources (Paper 2).

On the qualitative side, so far research on RVGs has strongly focused on case studies of single projects. For RVGs in South East Asia only a small amount of scientifically collected qualitative data exists³⁹. The data collected through the interviews conducted for the data gathering portion of this thesis and the accessed written data (such as reports, policy documentations, presentations on RVGs in Laos and Indonesia) address this gap and provide a new qualitative data base for two developing countries (Paper 2 and 3).

Contributions to theory

The thesis also contributes to conceptual enhancements in the framework of *TIS and functions*. From its inception, the *TIS and functions* framework has been strongly informed by empirical analyses (see e.g., Johnson & Jacobsson 2001; Bergek & Jacobsson 2003). Hence, this thesis follows the idea that applying the framework to a new empirical case – which significantly differs from analyzed cases – is useful for challenging the potential to generalize the existing theoretical framework, thereby providing insights in the ongoing debate on how to improve it (Bergek, 2012; Truffer et al., 2012; IST, 2013). This thesis addresses five aspects of the ongoing debate by applying the framework to an “extreme” case (RVGs in Laos): the set and definition of *functions*, the *functions*’ role in the system (are they processes or are they activities?), the role of institutions, the role of geographical aspects, and the derivation of policy recommendations from a *TIS and functions* analysis. The following paragraphs relate each to one aspect.

Relating to aspect one (the set and definitions of *functions*), the analysis shows, first, that in the “extreme” empirical case applied, the definition of the *function knowledge diffusion* falls short in explaining badly-absorbed and retained knowledge. Drawing from organizational science literature and its concept of absorptive capacity (see e.g. Cohen & Levinthal 1990; Zhara & George 2002; Todorova & Durisin 2007), I suggest adapting the *function* into *knowledge absorption* and defining it as all processes which influence information flows in networks, including the *acquisition*, *assimilation* (storage and distribution), *transformation* and *exploitation* of knowledge (also in terms of learning by doing, using and interacting). Second, the empirical case highlights that the *functions* bear cultural components. Understanding culture as part of institutions, I suggest reconsidering cultural (institutional) aspects in the definition of each *function* as well as taking them into account during empirical analysis.

³⁹ However, there are a number of reports and case studies conducted by development agencies and international organizations on the topic.

To the debate on the *functions*' role in the system, I add the following thought: The suggestion of extending the *function knowledge diffusion* to *knowledge absorption* was inspired by the concept of *dynamic capability* in the management literature. In that literature, *dynamic capabilities* are defined on the firm level as the ability to “integrate, build, and reconfigure internal and external competencies to address rapidly changing environments” and thereby become a source of competitive advantage (Teece et al. 1999, p.516). Gavetti and colleagues (2007)⁴⁰ define firms as complex “systems of coordinated action” (March and Simon, 1993, p.2). The similarity of this definition to the definition of *TIS* as “dynamic network of agents interacting” (Carlsson & Stankiewicz 1991, p.93) raises the question of whether the *functions*' role can be understood as *dynamic capabilities at the system level*⁴¹.

Adding to the discussion of the role of institutions in the *TIS and functions* framework, I recommend strengthening the cultural aspects in the definition of the structural element *institutions*. Conceptually, so far no consensus on the definition of *institutions* has been reached in the *TIS* community. Hence, the cultural aspect of institutions, especially, is neglected in the *TIS and functions* framework, but also in studies applying it⁴².

So far in empirical research, the choice of *geographical* levels has been guided by the location of the technology source and use (Binz et al., 2012; Schmidt and Dabur, 2013). I recommend, however, considering all relevant institutions (including cultural aspects, see above), along with the value chain of the technology and the location of actors and networks, in the choice of *geographical* levels. With this I support earlier claims by *TIS* scholars who conceptually (Coenen et al., 2012) and empirically (Binz et al., 2012; Schmidt and Dabur, 2013) suggest that *spatial/geographical* aspects in the *TIS* framework should be considered more explicitly.

Regarding the fifth aspect, I found, in Paper 4, that as good as the framework is to identify bottlenecks in the system; it remains unspecific in providing guidance to derive specific implications for policy making. A review of recent empirical work shows that so far conclusions on policy recommendations are rather generic and too broad, if existing at all (see also Bélis-Bergouignan and Levy, 2010; Jacobsson and Karltorp, 2012). Therefore my last conceptual contribution (presented in Paper 4 in Annex I) addresses this gap⁴³. I suggest to add a seventh step to Bergek (2008)'s scheme of analysis. In this step I propose – instead of directly deriving policy recommendations from identified bottlenecks – to draw from further literature that specifically addresses each identified bottleneck and

⁴⁰ The authors belong to the so-called Carnegie school, which was highly influential in the development of the concept of dynamic capabilities.

⁴¹ First attempts in a similar direction, for example by defining system resources (Markard and Worch, 2009), have been made and suggest that this may indeed be possible.

⁴² So far, hardly any empirical studies make cultural aspects explicit – for an overview of these studies see Bergek (2012) and Truffer et al. (2012).

⁴³ In this gap I refer to step six in Bergek et al. (2008)'s scheme of analysis.

to combine the findings from the *TIS and functions* analysis with these insights. This can either directly result in more specific policy recommendations or lead to questions, which – in a second iterative step – could then be addressed via interviews with actors in the *TIS*.

5.2 Implications of dissertation

Although the findings of this dissertation are based on Indonesia and Laos, some general implications and recommendations for investors, and policymakers⁴⁴ can be derived. In the next sections I discuss, first, **why the diffusion rates of RVGs in developing countries are low**, and second, **how the diffusion of RVGs in developing countries can be advanced** by investors and policy makers.

General reasons for the low diffusion of renewable energy-based village grids

As discussed in the introduction, RVGs are considered the best off-grid solution to contribute to poverty reduction among rural poor in developing countries at low (or no) environmental cost, and thereby contribute to the fulfillment of the MDGs and SDGs (Takada and Charles, 2007; Legros et al., 2009; UNDP, 2011). Despite this strong argument in favor of RVGs, they have barely diffused.

Techno-economic theory states that the diffusion of the lowest cost technology is most likely. Taking a techno-economic perspective to explain this lack of diffusion, the assumption is made that RVGs do not diffuse because they are not the lowest cost alternative for rural electrification. The comparison of RVGs and alternative rural electrification approaches in terms of costs in Figure 8 shows, however, that RVGs can be the most cost-competitive solution (when not considering solar lanterns which have a different value proposition by providing light only instead of electricity). RVGs' competitiveness strongly depends on country specific data (e.g. its renewable energy resources) and the remoteness of the to-be-electrified village (Roland and Glania, 2011; Paper 1), which is indicated by the heights of the columns in Figure 8. While grid extension can offer a very low cost solution in areas close to the grid, for more remote villages, prices for grid extension rise quickly. In these regions, other options are more likely to diffuse (at least from a techno-economic perspective). While grid extension and diesel-based village grid costs heavily depend on distance; the cost of household-based systems and RVGs mostly depends on the used RET. Therefore, there is no single technology which has an absolute cost advantage over the others at every location (except for solar lanterns which are limited in their use). Hence, costs alone do not explain the low diffusion of RVGs in developing countries.

⁴⁴ Depending on their field of expertise, development specialists can be informed by both implications for investors and/or policy makers.

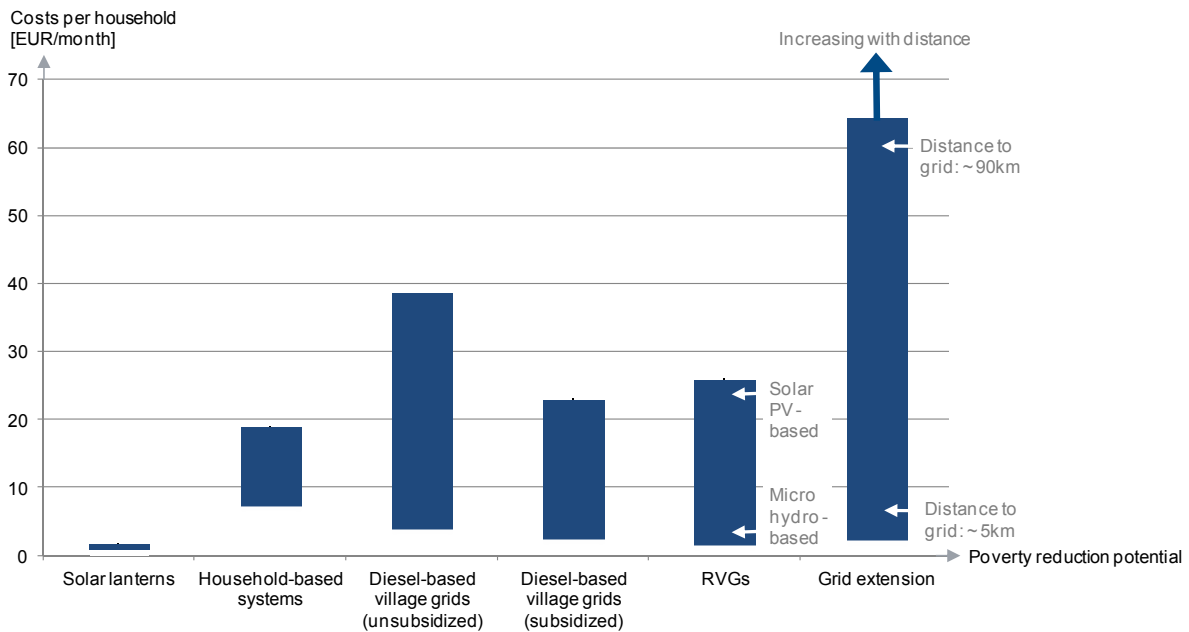


Figure 8 – Illustrative⁴⁵ comparison of cost ranges for different rural electrification approaches, indicated in EUR/month/household (own graph based on Terrado et al., 2008; Holland and Derbyshire, 2009; LIRE and Helvetas Laos, 2011; OECD/IEA, 2011; van Mansvelt, 2011; Bardouille et al., 2012; Susanto, 2012, Paper 1).

Despite competitive prices in remote areas, the diffusion rates of RVGs remain low, which indicates that there are other factors that hinder their diffusion. Combining findings from the investor’s perspective and the innovation systems perspective, I conclude that one important aspect seems to be complexity. This complexity is composed of technical and non-technical factors. First, the technical complexity influences a technology’s diffusion, especially in developing countries where knowledge on complex technologies is limited. RVG-related knowledge is limited in developing countries as it barely diffuses into the country, and even less into the rural areas, and is – if diffused – not retained. This (local) technological complexity of RVGs is driven by the fact that RVGs are not a simple stand-alone product (such as solar lanterns), with few or no interfaces with other technologies. RVGs belong to the category of complex products and systems (Hobday, 1998), because they require a fair amount of customized and high-tech components (which distinguishes them from diesel-based village grids) and certain knowledge and skills. Additionally, they are typically implemented in “small batches” in a project-based form for a single village. Using the classification by Tushman and Rosenkopf (1992), a RVG therefore can be regarded as a small open assembled system . Figure 9 compares RVGs’ (local) technological complexity to the complexity of alternative rural electrification approaches. To classify a technology’s complexity, Tushman and Rosenkopf (1992)’s definitions of closed and open assembled systems are used.

⁴⁵ Comparing costs between the approaches is challenging since, as in the case of solar lanterns and household-based systems, often only initial costs are indicated, whereas village grids and grid costs are usually calculated on a USD/kWh basis. Therefore this Figure is illustrative.

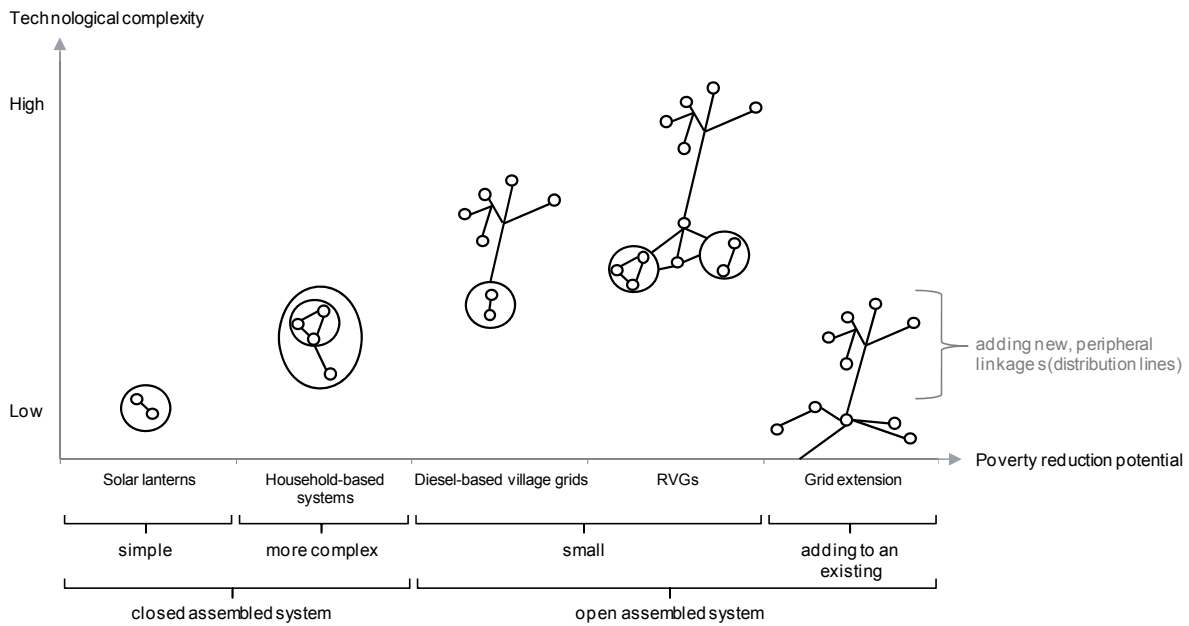


Figure 9 – (Local) technological complexity of different rural electrification approaches

following Tushman and Rosenkopf (1992)

Solar lanterns⁴⁶ have the lowest (local) technological complexity, and are therefore likely to diffuse quickly. This prediction is confirmed by the increasing number of solar lantern entrepreneurs in developing countries around the world (Aron et al., 2009; Bardouille et al., 2012). However, their contribution to the *MDGs* and *SDGs* is limited (Adkins et al., 2010; Hong and Abe, 2012). They also cannot grant access to electricity⁴⁷ to their users. Therefore there is also a high probability that they will soon be replaced or updated by one of the other rural electrification approaches. Grid extension too has relatively low complexity since it basically adds a “simple electricity line” to an already existing grid. This explains why governments and organizations such as e.g. the World Bank often prefer extending the grid to other options; it keeps complexity (and therefore risks) low. However, as seen in Figure 8, depending on the remoteness of the village to-be-electrified, costs are immense. In such areas, it is probable that household-based system (such as solar home systems) would diffuse first, followed by diesel-based village grids and RVGs. This explains the high numbers of social entrepreneurs in the household-based system business (Aron et al., 2009; Bardouille et al., 2012) and the lack of such entrepreneurs in the RVG sector.

Non-technological factors add to this technological complexity. For example, cultural factors have a pervasive influence on the diffusion of RVGs as shown in Paper 3. Tushman and Rosenkopf (1992, p.331) state that it is “the interaction of technical options with organizations and interorganizations dynamics that shapes the actual path of technological progress” and that “the greater a product’s

⁴⁶ Another common rural electrification approach is (more efficient) cook stoves. They are also classified as simple closed assembled systems and therefore can be similarly interpreted as solar lanterns in terms of complexity and diffusion.

⁴⁷ Some solar lanterns have a mobile charging feature, but do not provide additional electricity for other household purposes.

technical uncertainty [shaped by a technology’s evolutionary cycle and technological complexity] the greater the intrusion of non-technical factors in the product’s evolution.” In the case of RVGs the non-technical factors are manifold and include, e.g., high cultural diversity among end-consumers, community decision models in villages and uncertain legal frameworks⁴⁸.

Therefore, even if RVGs’ contribution to poverty reduction is bigger than the contribution of solar lanterns’ and household-based systems, due to their high technological and non-technological complexity RVGs are the least probable of all rural electrification approaches to diffuse.

At this point, allow me to reflect on the original assumption of this thesis, namely that RVGs are the most appropriate rural electrification approach. When looking at the different rural electrification approaches in terms of poverty reduction, RVGs, together with diesel-based village grids and grid extension, offer the highest potential for productive use at low environmental cost. Combining this fact with the finding from Paper 1 and 2, I find that RVGs are the most cost-efficient rural electrification approach, meaning that they offer the highest potential for productive use (and thereby poverty reduction) per cost (see Figure 10). Thereby I agree that RVGs are desirable in terms of the MDGs and SDGs. However, these are not the only factors which influence RVGs’ diffusion. Paper 3 indicates that the (local) technological complexity of RVGs requires villagers to absorb a lot of technical knowledge. Passing technical knowledge from the international (and national) level to the local level remains a challenge. Other rural electrification approaches require less technical knowledge by the villagers, and are therefore often more easily diffused as qualitatively shown in Figure 10.

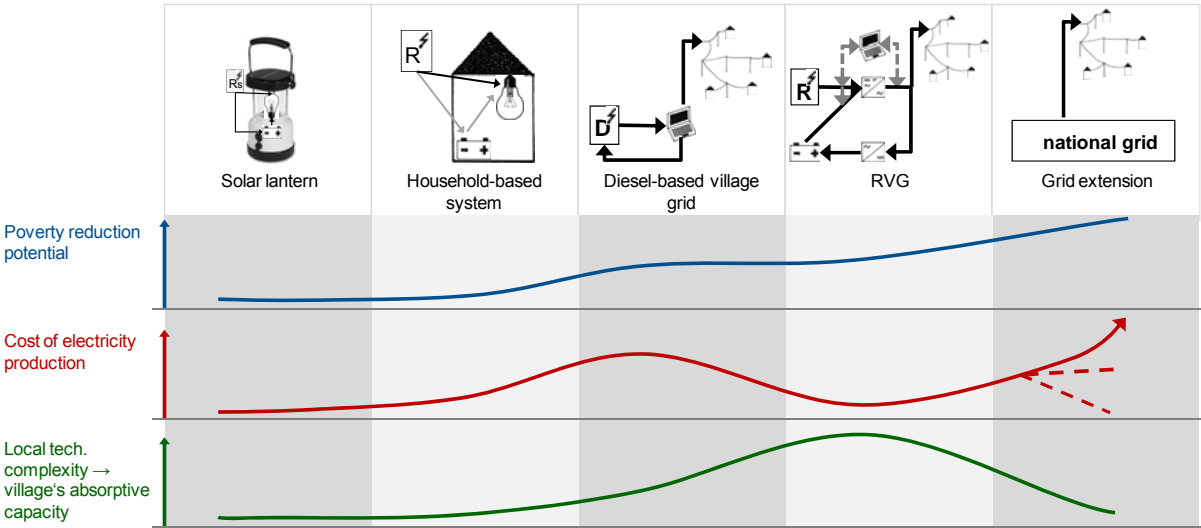


Figure 10 – Qualitative comparison of different rural electrification approaches in terms of poverty reduction potential, cost of electricity production, and local technological complexity (resp. the required absorptive capacity by the village).

⁴⁸ The non-technological factors apply to different extents to other rural electrification approaches too.

With regards to the thesis' original assumption, I conclude that the choice of the appropriate technology remains a trade-off between socio-economic development goals of the country (e.g. poverty reduction), environmental considerations, the cost of electricity production, and the local technological and non- technological complexity (e.g. the educational, cultural and social situation in the respective village). Therefore, a sound assessment of the situation of the village-to-be-electrified is the first step. If RVGs are identified as the most appropriate technology, special attention has to be paid to technical and non-technical complexity aspects⁴⁹. The next section provides an overview of what the complexity issue implies for practitioners.

Implications for investors

Even if the profitability of RVGs is given, investors refrain from getting involved. The underlying reason lies in the technological and non-technological⁵⁰ complexity of RVGs. This complexity leads to various barriers. The barriers increase the probability of negative events in the future and thus imply various risks for investors.

Besides the technological complexity of the RVGs, an important aspect of non-technological complexity from an investor's viewpoint is the wide array of involved stakeholders, potentially villagers, governments, development cooperation organizations and private sector actors. These stakeholders have different ambitions and cultural backgrounds. For investors it raises the probability that a negative event will occur: For example when an investor does not meet villagers' expectations regarding electricity supply and costs, development cooperation organizations become competitors (e.g. by employing sponsored RVGs), or when the already uncertain legal framework is changed (The World Bank, 2013a). Investors are therefore challenged to manage resulting risks by addressing the underlying barriers. In the case of RVGs, barriers occur on different *geographical* levels and affect different parts of an investor's business model (see Paper 2 in Annex I). Two potential solutions for investors are as follows.

First, investors can address stakeholder-based barriers by managing their stakeholders actively. This requires, among others, local language and cultural capabilities in order to understand stakeholders' (e.g. villagers') points of view in the first place, and then to deal with potential barriers accordingly. The challenge is that acquiring these capabilities is costly (transaction costs may rise).

⁴⁹ One option to reduce (local) technological complexity, might be to introduce RVGs in stages; First, rural electrification starts by introducing means of less complex technologies such as household-based system. Then, these household-based systems are slowly clustered to smaller, independent and more complex RVGs.

⁵⁰ Non-technological complexity, from an investor's viewpoint, refers, for example, to the various stakeholders, and institutional (cultural) settings that an investor has to deal with.

Second, due to the high cultural diversity, differences in the availability of renewable energy resources and the political uniqueness of each country and within countries (compare the case of Laos in Paper 3 in Annex I), there is no single standard design for RVGs which can be scaled up with low efforts. Spillover effects are small since each RVG has to be designed for the individual village and this design ideally incorporates cultural aspects and not purely technological ones. Investors can increase spillover effects by translating between cultures and by making the technology and associated knowledge accessible to more cultures (e.g. by providing information documents for villagers in pictures instead of texts).

This highly complex situation, which requires active stakeholder management and limits spillover effects, explains the reluctant involvement of the private sector in the diffusion of RVGs. While some challenges still can be addressed by the investors themselves, in other areas policy intervention is required.

Implications for policy makers

If policy makers wish to attract engagement of private actors in rural electrification (and especially RVGs), the consideration of different perspectives, as Kemp and Pontoglio (2011) suggest, allows for “rounder” policy implications. In this thesis therefore, the techno-economic⁵¹ perspective, and partly also the investor’s perspective, inform policy makers on the effects of monetary support or incentives for a technology. The innovation systems perspective and parts of the barrier analysis (investor’s perspective) paint a more colorful picture of policy issues than the techno-economic perspective, especially by pointing at non-monetary hurdles for the diffusion of RVGs.

Most importantly, the reduction of complexity is a main issue in the diffusion of RVGs as they do poorly in this area compared to alternative rural electrification approaches. Therefore, ideally, policy intervention should not add to the already existing complexity, but reduce complexity. Two central questions to this end are: first, how much financial support should policy makers grant to RVGs and, second, how can policy intervene to reduce complexity in other ways? I address these two questions by referring to the *geographical* levels (*international*, *national*, and *local*) where support can come from, and where it intervenes.

Regarding the question of how much financial support policy makers should grant to RVGs, the following factors come into play. Today, diesel and electricity subsidies are widely spread in developing countries and hinder the diffusion of RETs (OECD/IEA, 2011; Schmidt et al., 2012). As shown for the case of Indonesia, the competitiveness of RVG’s is reduced by these high diesel and

⁵¹ In terms of concrete policy recommendations, the most concrete results are obtained from the techno-economic perspective since, especially in the innovation systems perspective, deriving concrete policy recommendations is subject to current studies.

electricity subsidies. National policy making can balance this uneven situation by, for example, providing additional subsidies for RETs, or removing or redistributing current diesel and electricity subsidies⁵². While the specific recommendations, which can be derived in this regard from the results of Paper 1, apply to Indonesia, recommendations for other countries should be based on a country- and location-specific analysis.

Regarding the question of other potential methods of policy intervention besides financial support, there are alternative ways for policy makers to reduce complexity and increase the diffusion of RVGs. First, *national* policy makers should reduce the complexity in governmental structures. Today, different governmental departments are often responsible for rural electrification, e.g. the energy department and the social development department, which both conduct independent programs. This recommendation goes hand in hand with the suggestion to develop a stringent national strategy to foster rural electrification which is aligned with the country's environmental, social and economic development strategy. Such a strategy ensures purposeful spending of public financial resources. Second, to connect villages and international actors (in other words, to link the *local* and the *international* level), national governments could act as translators (of languages but also cultural customs) and thereby help investors scaling up their businesses within the country. Third, in even more general terms, a good national educational system, including professional training (often also refer to as capability building), incubation of industrial development in terms of entrepreneurship and productive activities in villages (local level) (Perkins et al., 2013) and facilitated local banking and access to micro finance for villagers (see also Zerriffi, 2011; Bhattacharyya, 2013) are measures that support the above mentioned efforts and contribute in the long-term to self-dependent rural areas in developing countries. Fourth and finally, *international* policy makers can also contribute to the diffusion of RVGs by fostering knowledge sharing and technology transfer with developing countries and support the creation of a carbon market (CDM/PoA) in the long-term.

To summarize, national policy makers should consider removing or redistributing fuel and electricity subsidies, define and implement a stringent rural electrification strategy, take on a translator role between their rural population and international actors by being aware of the different cultural backgrounds and other institutions, and invest in the country's educational system. By these means a government can reduce barriers which will reduce complexity.

5.3 Limitations and future research

Five fields of future research are proposed. The two first are informed by limitations of the dissertation, whereas the others are based on findings of the dissertation.

⁵² For an overview of different types of subsidies in rural electrification see Zerriffi (2011).

First, while in the techno-economic perspective end-consumers are represented by their electricity demand, in the investor's perspective they are seen as a revenue source and potential risk (e.g. if they are not able to pay their electricity bills), and in the innovation systems perspective they, so far, have been viewed from a producer perspective only (Dewald and Truffer, 2011). None of the perspectives investigated in this dissertation has a strong end-consumer focus. However, diffusion of technologies, especially those with social aspects (such as providing rural poor with electricity in order to ameliorate their living standards), heavily depends on end-consumer acceptance (see e.g., Rogers, 2003). I therefore suggest investigating the role of end-consumers in the *TIS and functions* framework.

Another limitation of this thesis is that the techno-economic and investor's perspective are researched in Indonesia and the innovation systems perspective in Laos. While this provided insights into country differences, it is as if 'sibling elephants' were researched, and therefore we do not "see the whole elephant". To provide more consistent and specific recommendations I recommend applying these (or slightly different) perspectives to the diffusion of a technology in a single country (the 'elephant' as in Kemp and Pontoglio; 2011).

Third, in the innovation systems literature, the National/Regional Innovation System investigates innovation in an entire country/region. When conducting the analysis on RVGs in Laos, I observed that remote villages work as, to some extent, de-coupled sub-systems of a country. Especially when it comes to questions on how to socially and economically develop such a village (typical questions in development cooperation), researching a village as a Village Innovation System could be productive. From there, specific development and policy recommendations could be derived and allow for more holistic, purposeful driven development programs.

Fourth, following our suggestions in Paper 4, the analysis in Paper 3 could be extended by an additional step. In this step the specific bottlenecks would be re-investigated by applying strands of knowledge from related disciplines. Depending on the bottleneck, economics, organizational, and/or political science would be applied. Through this procedure, more specific policy recommendations could be derived.

Finally, diffusion rates of RVGs might increase when less complex technologies such as household-based systems (e.g. solar home systems) are gradually clustered to slowly create larger, more complex systems, RVGs. Understanding if such an approach leads to higher diffusion rates of complex systems, than if complex systems are diffused directly, would confirm the dissertations finding that technological and non-technological complexity hinders the diffusion of a RVGs and provide new insights into diffusion processes.

6 Overview of the Papers

All four papers are included in Annex I. The provided versions are current as of April 28, 2013, as published or as submitted to the respective journal or conference (in case of Paper 4). Table 4 provides an overview.

Table 4 – Overview over the four papers

Perspectives		Title	Authors	Journal (Status)
Techno-economic perspective LCOE of RVGs	1	Rural electrification through village grids - Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia	Blum, N.U. Sryantoro Wakeling, R. Schmidt, T.S.	Renewable & Sustainable Energy Reviews (published)
Investor's perspective Risk/return profile of RVGs	2	Attracting private investments into rural electrification – A case study on renewable energy based village grids in Indonesia	Schmidt, T.S. Blum, N.U. Sryantoro Wakeling, R.	Energy for Sustainable Development (re-submitted, April 2013)
Innovation systems perspective A) <i>TIS and functions</i> framework applied to an „extreme“ case	3	Applying the Technological Innovation System and functions framework to a complex technology in a Least Developed Country – Implications from an extreme case	Blum, N.U. Bening-Bach, C. Schmidt, T.S.	Technological Forecasting and Social Change (to be submitted, September 2013)
B) Improvement of policy recommendations of <i>TIS and functions</i> framework	4	Unlocking the full potential of <i>Technological Innovation System and its functions</i> framework – A viewpoint	Blum, N.U. Bening-Bach, C. Schmidt, T.S.	Environmental Innovation and Societal Transitions (to be submitted, October 2013)

RVG= renewable energy-based village grid, TIS = Technological Innovation System

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Annex I

Paper 1

Rural electrification through village grids - Assessing the cost competitiveness of isolated renewable energy technologies in Indonesia

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Abstract

Isolated grids in rural areas powered by independent renewable energy sources ('renewable energy based village grids') are widely considered a clean and sustainable solution for Indonesia's rural electrification challenge. Despite the advantages of renewable energy based village grids, the number of conventional rural electrification solutions – such as costly grid extension (on-grid) or diesel powered village grids (off-grid) which are characterized by high operating costs and high greenhouse gas emissions – is much larger. One reason for the low diffusion of renewable energy based village grids can be attributed to the lack of private sector investments, leaving the responsibility of rural electrification predominantly on the shoulders of the government who often prefer the centralized and conventional solutions. To better understand this situation in this paper we perform a literature review on the economics of renewable energy based village grids in Indonesia, which reveals a gap in terms of cost data. Therefore, we calculate the levelized cost of electricity (LCOE) of solar photovoltaic (solar PV) and micro hydro powered village grids, and compare them to the conventional diesel solution. For solar PV, we additionally investigate different system configurations including a reduced supply contingency and a hybridization approach. Finally, we determine the CO₂ emission abatement costs and reduction potentials. Our results show that micro hydro powered village grids are more competitive than diesel powered solutions (at least when taking out Diesel and other subsidies). Solar PV powered solutions increase their competitiveness with the remoteness of the village grid is and when reduced supply contingency is applied. From an environmental perspective, micro hydro powered village grid solutions are found to have negative abatement costs with significant potential to reduce emissions. We conclude by discussing our results addressing the question which measures could support private investments into renewable energy-based village grids.

1 Introduction

As an emerging economy Indonesia needs to respond to multi-faceted challenges in its growing energy sector. This includes providing modern energy services to the poor, reducing oil dependency, and decoupling economic growth from greenhouse gas emissions [1–3]. Today Indonesia’s electrification rate is 71%¹ [4]. Of the remaining 29%, about 80% reside in rural areas and almost all outside of the most populated islands, Java and Bali [3, 5]. Most of Indonesia’s poor are living in regions which are difficult to access; either located in the countryside or on small islands, and therefore they have limited access to reliable and affordable electricity services. At the same time, rural electricity demand is rapidly growing².

Currently, the responsibilities for electrification are borne almost solely by the state-owned utility Perusahaan Listrik Negara (PLN), which owns and operates the country’s entire transmission and distribution network, as well as a large proportion of the generation plants. PLN itself has long faced many challenges associated with being the dominant actor in the monopolized electricity sector. First, the expansion of the electricity network is very capital-intensive due to the geographically challenging nature of the archipelagos of Indonesia. Options for grid extension to remote areas or deployment of submarine cables into remote islands are typically very expensive [6]. Second, a large proportion of PLN’s budget is dedicated to relieving the pressure of aging infrastructure, leaving little allowance for access expansion³. Despite these facts, some remote rural areas are already being electrified by the PLN, yet these electrification attempts are mainly based on diesel generators. Third, the Indonesian low grid electricity tariff is set by the government, in a bid to provide affordable electricity to the general population. This eventually caps PLN’s revenue from electricity sales, making it difficult to recover the high production and distribution costs [7, 8].

Recognizing the urge for electricity access in remote areas and for replacing conventional by renewable energy sources, the Government of Indonesia recently set the target of 90% electrification by 2020, as a subset of its “Vision 2025: Building New Indonesia strategy”⁴ and aims at implementing policies which foster renewable energy technologies. In recent years, a number of promising reforms have taken place designed to invite the participation of local government and the private sector in renewable energy based rural electrification efforts. This includes amongst regulations on small scale power purchase agreements [9], proposed US\$43m program to increase renewable-based rural electrification and reduce diesel content⁵, a framework which coordinates budgetary contribution of central and local governments to rural electrification advancement [3, 10, 11], and a 1000 remote island PV electrification program [10].

¹ This number reflects general access to electricity, but does not reflect the quantity and quality of the accessed electricity.

² PLN’s projections and findings from our own in-depth interviews with a number of Indonesian renewable-energy based rural electrification project developers suggest that demand growth is expected to be 10% per year until 2018 [72].

³ PLN’s 2009 – 2018 supply plan outlines a proposed spending of \$32b in generation, \$14b in transmission and \$13b in distribution [72].

⁴ Vision 2025 Building New Indonesia lists a set of targets to achieve by 2025 focusing in the areas of economics, poverty eradication, and equal access to vital utilities across the nation [73].

⁵ Diesel currently serves as the conventional solution for remote rural electrification due to its perceived low cost, scalability and accessibility. PLN statistics show that they operate 936 decentralized diesel power plants (50kW – 500kW) with a total capacity of 987MW across Indonesia [74].

Due to its geography, most non-electrified villages in Indonesia are too remote, complex and expensive for grid extension to take place⁶. Hence, off-grid solutions (predominantly diesel) become the basic electrification solution for these areas. As an alternative to diesel, renewable energy based village grids are widely considered as a feasible solution to improve rural electrification access which provides a platform to encourage rural economic growth [11–14] and do not result in additional greenhouse gas emissions [15]. However, despite the aforementioned efforts in improving rural electrification access and the benefits of renewable energy based village grids, only a small number have been realized. Efforts are still needed to scale up the diffusion of these solutions.

According to Indonesian rural electricity practitioners (who we interviewed during our study), investments in remote, renewable energy based rural electrification are almost entirely dependent from grants or charities from socially-inclined private organizations, aside from PLN. The literature review we perform (see Section 2) reveals a lack of data on the economics of renewable energy based village grids in Indonesia, making it difficult for decision makers to implement measures that foster their diffusion and attract private investments. In this study, we therefore address this data gap by tackling the following main research question: How competitive are isolated renewable energy based village grid solutions compared to the standard conventional solution? Specifically, we analyze two sub-research questions; first, what are the levelized costs of electricity generation (LCOE) of various solutions? and second, what are the costs and potentials of CO₂ emission abatement of these solutions?

To this end, first, we develop two electricity demand scenarios for a generic Indonesian village, reflected through daily load profiles. Second, we design standalone conventional, renewable and hybrid power generation systems to supply the village grid. Third, we calculate the LCOE for the baseline (conventional diesel powered village grid) and compare it to different micro hydro powered and solar PV powered solutions. Fourth, we calculate the abatement cost (AC) and emission reduction potentials of the renewable energy based and the hybrid solutions, compared to the diesel baseline.

The paper is structured as follows. While Section 2 reviews recent literature on the economics of RVGs in Indonesia. Section 3 describes the method applied in the study. This includes the quantitative approach to estimating Indonesian village electricity demand estimation, generation plant technical parameter sizing, and the calculation of LCOE, AC and emission reduction potentials. Section 4 outlines the results of our techno-economic model, followed by a discussion and conclusion in Section 5.

2 Literature review on the economics of RVGs in Indonesia

A review of literature published in the past five years on the economics of RVGs (or micro-/mini-/island-grids) in Indonesia resulted in eight documents (including scientific articles, reports and a presentation). The overview

⁶ Based on our Indonesian field interviews with practitioners, the ideal distance between independent power plants and PLN's grid needs to be between 5 – 10km to guarantee project profitability.

given in Table 1 shows that the eight papers differ regarding several aspects, e.g., in terms of technologies considered or economic indicator(s) provided.

Table 1 | Overview of studies investigating the economics of RVGs in Indonesia

Authors (Year)	Model (Generic vs. Specific)	Renewable Energy source to power village grids	Conventional power village grids	Economic indicator(s)	Details of calculation provided
USAID (2007) [16]	Generic	– Solar PV – Micro hydro – Biomass	– Diesel	Estimated generation costs	No
Holland & Derbyshire (2009) [6]	Specific	– Solar PV – Micro hydro – Biomass – Wind – Geothermal – Hybrid: Diesel/wind/battery	– Diesel	LCOE	Yes
Feibel (2010) [17]	no Model	– Micro hydro	– none	Cash flow	No calculation, but primary data of real projects
Tumiwa and Rambitan (2010) [18]	no Model	– Micro hydro	– none	Investment costs and real net profit	No calculation, but primary data of real projects
van der Veen (2011) [19]	Specific	– Solar PV – Hydro – Biomass – Wind	– Diesel	Generation cost	Yes
Abraham et al. (2012) [20]	No Model (LCOE) Specific (IRR, NPV)	– Solar PV – Micro hydro – Biomass – Wind	– Diesel (un- and subsidized)	LCOE Internal Rate of Return (IRR), Net Present Value (NPV)	LCOE: No IRR, NPV: Yes
Hivos (2012) [21]	no Model	– Micro hydro	– Diesel	Generation costs	No calculation, but secondary data
van Ruijven et al. (2012) [22]	Generic	– Hybrid: Wind/diesel		Generation costs	Yes

Out of the eight studies, Feibel [17] and Tumiwa and Rambitan [18] provide cost performance data on five real-life micro hydro based village grids in Indonesia. Both studies do not compare RVG cost to the conventional diesel based solution. Contrarily, Abraham and colleagues [20] and Hivos [21], while also referring to real project data, perform comparisons of RVGs and conventional village grid solutions (diesel-based), sourced from primary and secondary data. The remaining four studies are based on techno-economic models. USAID [16] lists in-house estimates of generation costs for different rural electrification options. In a report from 2009 Holland and Derbyshire [6] calculate the LCOE for different electrification options, among them RVGs, and compare

them to the LCOE of grid extension. However, as both reports were written in 2007 and 2009 respectively, cost data might be outdated due to fast cost reductions of renewable energy technologies in recent years. Van der Veen [19] investigates the least-cost investment options to electrify the island of Sumba based on 100% renewable energy sources. While the study focuses on a larger island grid and does not explicitly calculate generation costs for village grids, some results are still comparable to village grids as the sizes of single installed plants partly match village grid requirements. Finally, van Ruijven and colleagues [22] model global rural electrification trends and investment requirements and also apply their model to several regions and countries—including Indonesia. To do so, they calculate (amongst others) the generation cost of wind/diesel based village grids and compare it to grid-based electricity in a generic model.

While the above literature is very valuable for understanding the economics of rural electrification in Indonesia, we see four reasons why further work is required: First, the role of variable demand and fluctuating supply over the day or the season (which is typical for intermittent renewable energy sources) is under-researched. Of the eight studies, only van der Veen [19] matches hourly demand curves with hourly supply – however on a larger island grid level. Second, the role of different electrification scenarios reflecting different economic developments, which is especially important from a policy perspective, needs more attention. Only van Ruijven and colleagues [22] (but only for a wind/diesel hybrid system) and van der Veen [19] (again for the island) look into different demand developments. Third, the competitiveness of RVGs compared to diesel generators is strongly influenced by the distance of the village to the diesel source and the electricity grid. Only Holland & Derbyshire [6] include the distance aspect explicitly (however, their cost assumptions might be outdated). Fourth, the role of subsidies for diesel, which is crucial when comparing RVGs to the conventional diesel based solution, has to be scrutinized in more detail. Only Abraham and colleagues [20] in their presentation provide numbers on the role of subsidies but do not provide a model. Therefore, in the remainder of the paper we will calculate the LCOE of different RVGs considering all four aspects simultaneously. In Section 4 we will compare our modelling results with the data provided by the above studies.

3 Method and Data

We answer the research question in a four step approach (see Figure 1), based on the principals of matching the demand side to the supply side model of a rural electricity sector in a generic Indonesian village. In step one, we estimate the electricity demand of the generic Indonesian village. For this village two electrification scenarios and different end-user consumer sectors are considered. In steps 2-4, we model the three supply side variables (power generation system capacities, LCOE and abatement costs) for conventional, renewable energy based and hybrid village grids. In step two, we model the capacities of conventional (baseline), renewable and hybrid electricity systems such that they meet the demands modelled in step one. In step three, we perform a cost analysis in which we consider capital expenditures (equipment investment, engineering, civil, construction and physical contingency), operating and maintenance expenditures (fixed and variable) of each system [17, 23], and appropriate discount and inflation rates. This step results in LCOE for each demand scenario and each power generation system and with this addresses the sub-research question 1. In step four, we calculate the abatement cost of the renewable and hybrid options compared to the conventional baseline and with this target sub-research question 2. The method and data section is structured along these four steps.

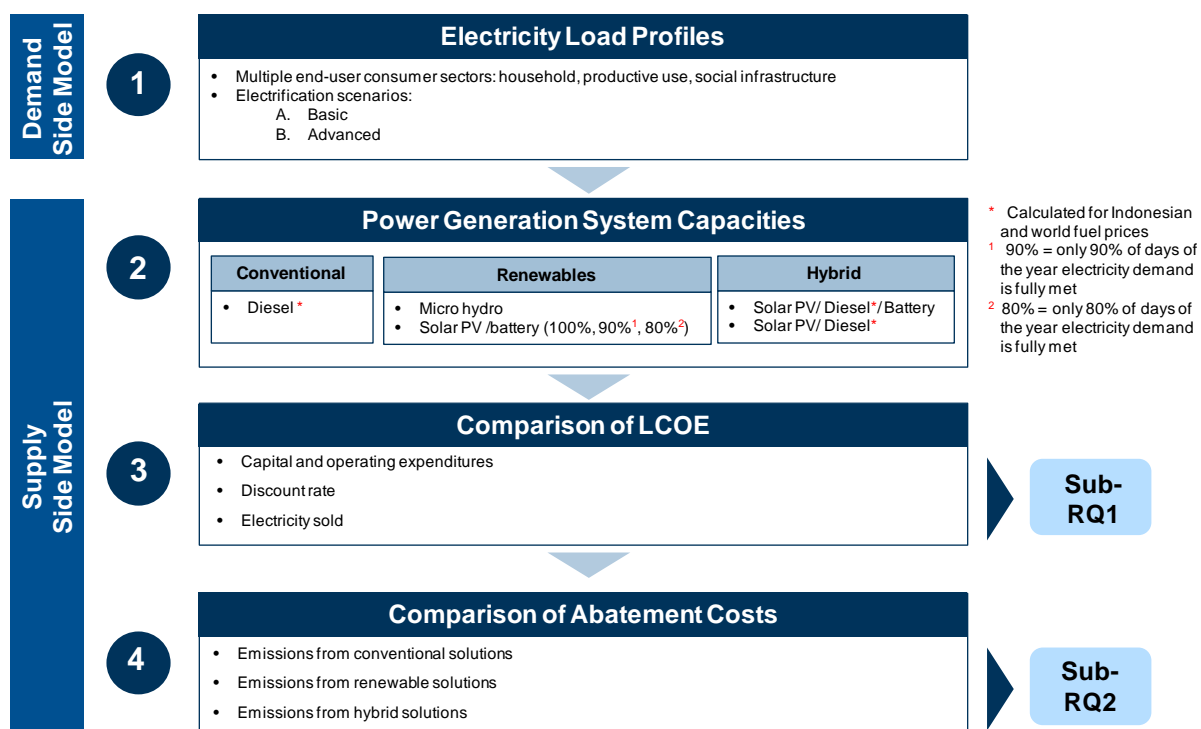


Figure 1 | Overview of research outline. Step 1. Demand model which calculates the village electricity load profile, based on a basic and an advanced electrification scenarios Step 2. Determination of required power generation system capacities to meet village electricity demand according to the load profiles and scenarios. We consider conventional (baseline), renewable energy based and hybrid village grids. Step 3. Calculation of LCOE for both electrification scenarios for all power generation options. This step answers to sub-research question 1. Step 4. Calculation of emissions abatement costs from implementation of renewable energy based and hybrid village grids. This step answers to sub-research question 2.

3.1 Electricity Load Profiles

In the first step we estimate the village electricity demand by defining the size of a generic Indonesian village, two electrification strategies, and the corresponding village load profiles. Based on a study of 10 remote, un-electrified villages in Sulawesi and Sumatra [17] and our own investigations during field visits, the size of a generic village is estimated to establish a baseline of a typical Indonesian village. Our generic village consists of 1475 people in 350 households, with 4.5 people per household on average.

While previous rural electrification studies have typically only considered household electricity demand [13, 14], to reflect the variability of villages across Indonesia and incorporate potential demand growth for rural electricity (compare van der Veen [19]), we define two types of electrification scenarios as classified in Table 2, considering three categories of end-user consumers: household, productive use and social infrastructure.

Table 2 | Two types of rural village electrification scenarios are considered in this study to reflect the variability of villages across Indonesia.

	Scenario A Basic Electrification	Scenario B Advanced Electrification
Overview of village	Remote rural village, with agriculture as the main economic activity.	Rural village with established or growing economic activities, beyond agriculture.
Power availability and end-consumer sectors	Electricity is available 18:00 – 06:00 for: <ul style="list-style-type: none"> Household sector (night) 	Electricity is available 24 hours for: <ul style="list-style-type: none"> Household sector (day and night) Productive use (majority during daytime) Social infrastructure (majority during daytime)

Based on the proposed electrification scenarios for the generic village, in the next step we determine the load profile for both scenarios. As meters are often not employed in small off-grid electricity networks there is a lack of empirical data on electricity consumption from Indonesian villages [24]. Therefore, the load profile is estimated by determining the demand for electricity for each end-user category at hourly intervals during a typical day. The demand for electricity is estimated by identifying the electricity appliances required by consumers in each end-user category and the times of usage⁷. All assumptions to the demand model side are outlined in [Appendix B](#), based on previous studies and our own Indonesian field investigations and interviews.

For scenario A, which is intended to serve remote rural villages with only the household sector as the end-users, the electricity demand per household is outlined in [Appendix B](#). The village’s total daily electricity consumption accounts to 162.5 kWh under this scenario. The peak demand periods for this strategy occur between 18:00 – 23:00 when villagers are home and use electricity for lighting and recreational purposes. During the day no electricity demand is generated as villagers perform their farming activities (see Figure a).

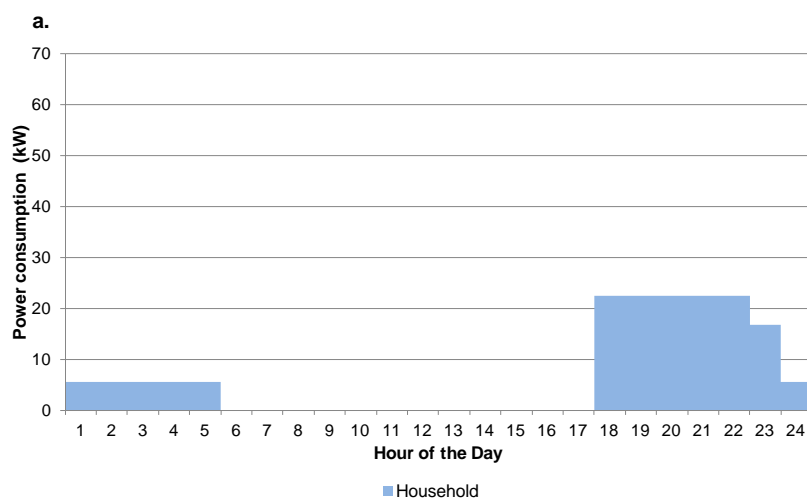


Figure 2a | Total village hourly load profile for end-user sector under Scenario A (basic electrification scenario) where demand is requested during 15 hours per day.

⁷ Due to the geographical location of Indonesia, we assume no seasonality effect on the demand.

For scenario B, the household, productive use and social infrastructure sectors are considered as end-users. The total village daily electricity demand under this strategy for the generic village is 558.5 kWh. A breakdown of electrical appliances and power consumption for each sector is given in [Appendix B](#). The resulting hourly load profile for both electrification strategies applied to our generic village is given in Figure 2b.

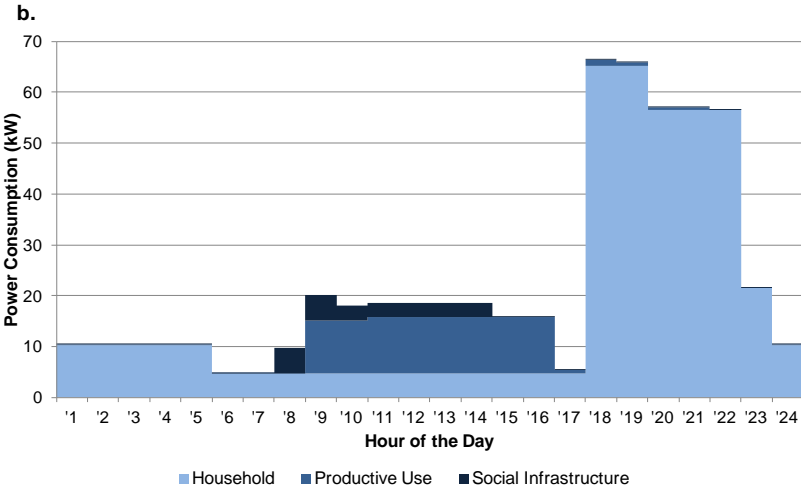


Figure 2b | Total village hourly load profiles for each end-user sector under Scenario B (advanced electrification scenario) where electricity is requested during 24 hours per day.

3.2 Power Generation System Capacities

Having determined the demand for electricity in the generic Indonesian village, in the second step, we calculate the required capacities of power generation systems to meet the electricity demand levels for each scenario as defined in the hourly load profiles. As the village grid in question is assumed to be an isolated network, electricity is produced independently by the power generation systems and distributed through the grid to the end-use consumers. The results of this sizing process can be found in Table 3. Assumptions relevant to the modelling of power generation system capacities are outlined in [Appendix A](#).

3.2.1 Conventional (diesel powered) village grid

The required diesel engine capacity is determined by matching the peak demand of the village for both electrification scenarios, including the distribution losses and diesel generator system efficiency. The system’s load factor adjusted efficiency is dependent on the capacity factor, which is deduced from our load profile⁸.

The most important drawback of diesel generators is its high operating costs due to dependence to diesel fuel. In Indonesia, this effect is even more prominent in rural areas and remote islands where fuel prices increase with transportation costs and distance to distribution centers. This location-dependence factor is reflected by three diesel retail price categories determined by the Indonesian Oil and Gas Distribution Agency (BHP Migas)⁹

⁸ We calculate the hourly capacity factors based on the estimated load profile and take a daily average to obtain the overall capacity factor. By utilising a diesel engine efficiency-load map we obtain the load factor adjusted engine efficiency [66].

⁹ BHP Migas official prices show Sumatra and Nusa Tenggara prices as being the lowest (1x), compared to Java-Bali (1.04x) and Borneo-Sulawesi-Papua (1.06x) [26]. In practice, the accessible retail prices can reach up to 3.3 times official prices [75].

Therefore, as a fair proxy to reflect this location-dependence variability, we assume three categories of transport cost variation of low (1.0x lowest official diesel price), medium (2.0x) and high (2.73x)¹⁰.

Furthermore, we differentiate the subsidized and unsubsidized diesel prices in Indonesia (compare Abraham et al. [20]). First, we consider the discrepancy between the Indonesian diesel fuel oil prices which has remained since 15 March 2009 at 3,578 IDR/liter (0.29€₂₀₁₂/liter) [25] with the global price of 0.61€/liter in 2012 [26]. To both prices, we also apply a diesel fuel price growth projection over the lifetime of the diesel power system [27, 28] ([Appendix D](#)).

3.2.2 Renewable energy based village grids

As a first alternative to conventional diesel powered village grids, we consider micro hydro and solar PV/battery based solutions.

Micro hydro

In areas with sufficient natural resources (flow rate, water availability and head), micro hydro is a proven reliable and low-maintenance technological option to address rural electrification access [10, 15]. Through our interviews with industry practitioners, we discover that micro hydro popularity in Indonesia is also underpinned by the strong local technical knowledge base, mature domestic micro hydro industry and manufacturing capability. However, currently only 19% capacity of Indonesian estimated 450MW micro hydro potential have been tapped [29]¹¹. Similarly to the estimation method for diesel, the micro hydro power plant capacity in this study is sized such that it matches the peak load of the village, including distribution losses.

Solar PV/battery

Solar PV systems, which directly convert solar energy into electricity, offer a number of additional benefits; including high modularity, zero noise, and particularly the availability of high solar resources in almost all developing countries [12]. Previous studies have concluded that standalone solar PV off-grid networks are still less competitive when compared to other more mature renewable energy technologies, driven by high investment costs [12, 22]. The main challenge concerning the use of an intermittent power generation source such as solar PV/battery is that all electricity can only be produced during day time, leaving night time or cloudy day consumption reliant on battery storage. However, this peak production pattern does not match the demand curve, where peak demand occurs at night time, where the solar PV panels do not produce electricity (compare van der Veen [19]). For an isolated network, this significantly raises the need for battery storage to meet electricity demand during non-daylight hours. We assume a solar PV system configuration which consists of crystalline silicon (cSi) based solar PV power plant connected to advanced lead-acid battery storage. The electricity produced by solar PV panels is used directly to satisfy demanded levels of electricity at that point in time. Excess electricity production during daylight-hours will be stored, and discharged at night or during cloudy days to meet the requested demand.

¹⁰ Multipliers obtained on the basis of analysis of PLN's official cost of electricity supply across the entire network [38].

¹¹ Due to the location-dependence nature of micro hydro, the overall investment and O&M costs are not as scalable as diesel power plants. As practitioners suggest from interviews we conducted, the main cost drivers are either construction cost (for low head situations) or generator cost (for high head situations). However, for modeling purposes this effect is assumed negligible.

To determine the appropriate solar PV and battery system sizes, data of the solar irradiation potential for the target location is required. Hourly solar irradiation data from a Typical Meteorological Year (TMY) derived from multi-year measurements is used as it provides a more robust overview of solar energy potential corrected for a standard year [30]¹². Our analysis based on the data set results in an average global horizontal irradiation of 4214 Wh/m²¹³. We calculate the solar PV and battery system size through an optimization approach. To this end, the sizes of the solar PV field and battery capacity are optimized to reduce the LCOE of the entire system. Complete details on the formulation of this optimization process are outlined in [Appendix E](#).

Solar PV/battery with 90% and 80% reduced supply contingencies

To reduce the LCOE of the higher renewable energy based village grid solution, the solar PV/battery (see results on Figure 4); we consider an alternative solution with reduced supply contingencies. We argue that since the SAIDI (System Average Duration Interruption Index) of PLN is 6.96¹⁴ [31] and based on practitioners' advice from our own field interviews, an isolated village grid with sub-100% availability can be acceptable, provided that it is explicitly covered in a community agreement approved by the villagers. We therefore consider two levels of reduced supply contingency approach to the solar PV configuration. First, under a 90% reduced supply contingency the power generation system configuration is able to supply sufficient electricity to fully meet the demanded levels as reflected by the load profiles. In the remaining 36 days (10% of the days in the year), a shortage of electricity supply may be expected. Second, under the 80% configuration, there are 72 days (20% of the days in the year) where electricity supply shortage may be expected.

To estimate the 90% configuration, using TMY data we rank and omit the worst 36 days of irradiation (below 3633 Wh/m²). From the reduced data set, we select the four worst irradiation days as a basis to determine the appropriate solar PV and battery capacities to fulfil electricity demand for 329 days in the year (see Figure 3). For the 80% configuration, we take a similar approach to the 90% reduced supply contingency approach. However, in this case we omit worst 73 days of irradiation (below 3741 Wh/m²) from the data set. Subsequently, we size the solar PV/battery system to fully satisfy electricity demand for 292 days in the year (see Figure 3).

¹² Since no TMY data exists yet for any location in Indonesia, as a proxy we utilize TMY data for Kuching (Malaysia) which shares the region of north-western Borneo island with Indonesia, located at 01°33'N and 110°25'E [34].

¹³ This figure is only slightly lower compared to results of a simulation study for Samarinda (East Borneo) of 4830 Wh/m² [76], which makes our assumption conservative.

¹⁴ In comparison, according to IEEE Standard 1366 – 1998 the median value for North American utilities SAIDI is 1.5 hours per customer per year.

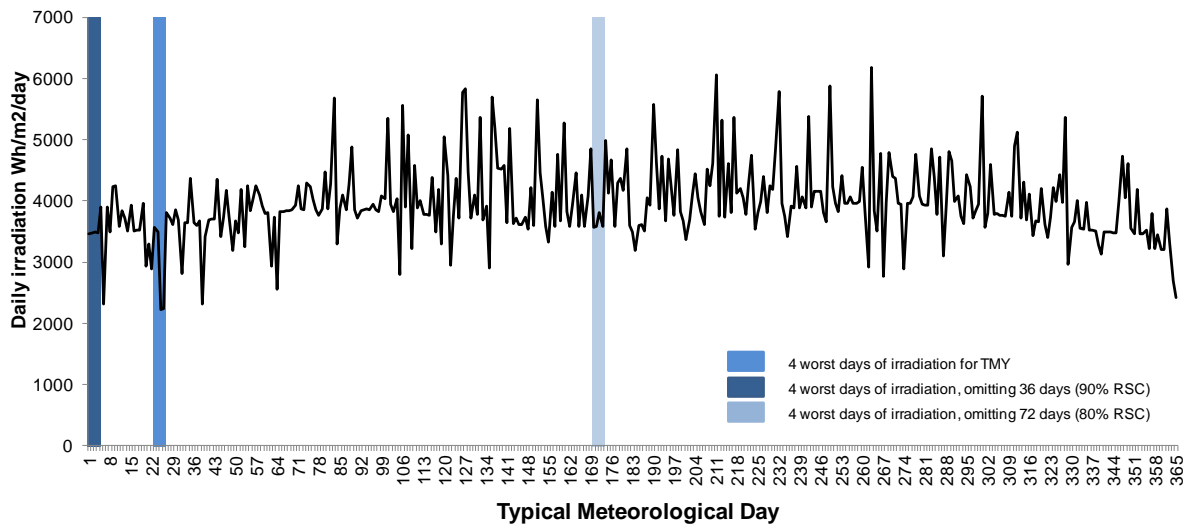


Figure 3 | TMY data [34] showing daily irradiation (Wh/m²) representing the solar potential for electricity generation. The highlighted areas show four consecutive worst days under three system configurations (100% availability, 90% and 80% reduced supply contingencies). The solar PV and battery system capacities are determined through an optimization process such that using available irradiation from these sets of four consecutive days, village electricity demand will always be satisfied.

3.2.3 Hybrid village grid

As a second alternative to conventional diesel powered village grids, we model two hybrid options combining both conventional and renewable energy based village grid solutions. As our results (Figure 4) suggest that micro hydro already has the lowest LCOE compared to the conventional diesel powered village grid solution, we apply the hybridization strategy only for solar PV powered solutions.

Solar PV / battery / diesel hybrid

In this configuration, we utilize a 50% solar PV to 50% diesel electricity production mix, complemented by battery backup. During the day solar PV panels produce electricity for immediate consumption. Whenever excess electricity production occurs it is stored in the battery and discharged when required. A diesel generator is available for use at any time of the day to cover shortages in electricity supply which cannot be provided through solar PV production or discharging the battery.

Solar PV / diesel hybrid

In this configuration, battery backup is eliminated and any shortage of power not supplied by solar PV field is covered by diesel generator. In this configuration, we utilize a 30% solar PV to 70% diesel mix for electricity production [32]. Day time demand is supplied by solar PV production and supplemented by diesel generator. Due to absence of battery, the diesel generator produces electricity to fully supply night time electricity demand. This hybridisation strategy is applicable only for the scenario B, as scenario A does not demand electricity during the day. This configuration was planned to be installed in some PLN owned and operated village grid networks through the 1000 island program.

For all power generation systems, the results for the required capacities are outlined in Table 3.

Table 3 | Resulting power generation system sizes for scenarios A and B under various configurations (conventional, renewable energy based and hybrid village grids).

Power generation type		Capacity for scenario A	Capacity for scenario B
Conventional	Diesel	23.4 kW	69.6 kW
	Micro hydro	23.4 kW	69.6 kW
Renewable	Solar PV	62.3 kWp	232.5 kWp
	Battery	300 kWh	716 kWh
	Solar PV at 90%	52.0 kWp	177.6 kWp
	Battery	219 kWh	517 kWh
	Solar PV at 90%	50.4 kWp	170.8 kWp
	Battery	216 kWh	516 kWh
	Solar PV	8.9 kWp	32.4 kWp
	Battery	118.8 kWh	260.4 kWh
Hybrid	Diesel	8.9 kW	32.4 kW
	Solar PV	-	29.8 kWp
	Diesel	-	69.6 kW
	Diesel	-	69.6 kW

3.3 LCOE calculation

To answer the sub-research question 1, we calculate the LCOE for all power generation system which had been sized above and both electrification scenarios via a non-linear dynamic cash-flow model. To assess the generation cost of the conventional, renewable and hybrid electrification technologies, the LCOE are calculated. Taking into account all discounted costs accrued throughout the system lifetime (n) including investment expenditure (I_t), operations and maintenance expenditure (M_t), and fuel expenditures (F_t), divided by the discounted value of electricity sold during the lifetime (E_t). We assume that the demand is always met by the generation. This approach is valid as the grid is isolated and electricity which is not consumed is also not sold and therefore presents no benefit from an economic point of view. The cost assumptions for all technological options are available in [Appendix C](#). LCOE is defined as:

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad [€/kWh]^{15}$$

3.4 Calculation of abatement costs and savings of CO₂ emissions

To answer sub-research question 2, we calculate the emissions abatement costs for all renewable energy based and hybrid village grid options and for both electrification scenarios. Implementation of an alternative renewable energy based power generation system reduces greenhouse gas emissions that would otherwise have been caused by a conventional diesel generation system to power the village grid. The emissions abatement costs from these

¹⁵ Calculated in €/kWh instead of USD/kWh as carbon markets are more proliferated in Europe .

alternative technologies are defined by the difference in LCOE between diesel and renewable-based technologies and the associated emissions relative to the diesel plant that it would displace [33]. This formula is defined as:

$$Abatement\ cost\ (AC) = \frac{LCOE_{renewable\ based} - LCOE_{diesel}}{Emissions_{diesel} - Emissions_{renewable\ based}} \quad [€tCO_2]$$

Subsequently, we also calculate the savings in CO₂ emissions from opting for renewable energy based village grid solutions as opposed to diesel, given by the formula:

$$CO_2\ emissions\ savings = \frac{Yearly\ fuel\ input_{diesel} - Yearly\ fuel\ input_{renewable\ based\ alternative}}{Diesel\ fuel\ specific\ CO_2\ emission} \quad [tCO_2/year]$$

4 Results

In this section, we present the results for the LCOE and abatement costs and potentials for the two proposed electrification scenarios and the different technological solutions. The LCOE results are depicted in Figure 4, and the abatement costs and emission reduction potentials results in Figure 5.

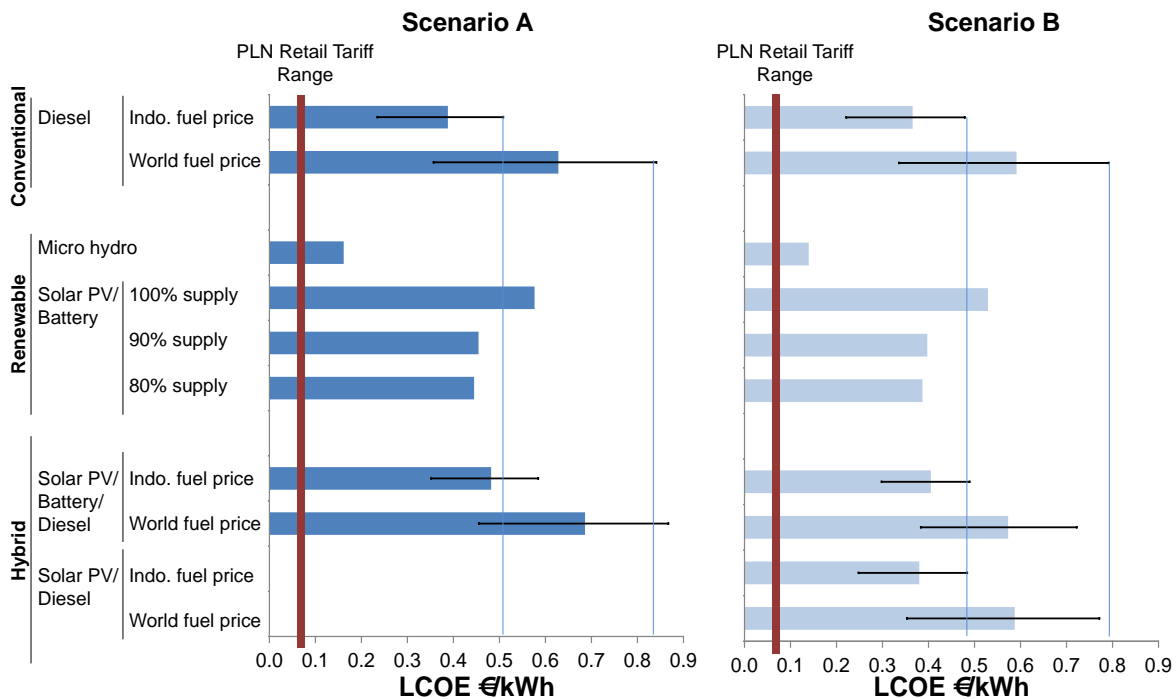


Figure 4 | LCOE for generic Indonesian village grid with various power generation configurations, applying a basic (A) and advanced (B) electrification scenario. For each technological option, the LCOE are quantified in by the horizontal axis in €/kWh. The black lines represent the range of LCOE for any village grid configuration with diesel components, demonstrating the influence of fuel costs due to remoteness of the village. The most left (smallest) LCOE within a variation represent locations close to distribution centres, the most right (highest) represent the furthest locations. Additionally, we compare the LCOE results to the PLN retail tariff range depicted by the red vertical bars. A range of tariff exists as retail prices differ for household, productive use and social infrastructure consumers [35].

The first observation from Figure 4 is that the cost of all technologies decreases when advanced electrification scenarios are applied instead of basic electrification. This is driven by a higher capacity factor, achieved through daytime utilization of electricity for productive use and social infrastructure. In the basic scenario (Scenario A), as electricity is demanded only at night time during which villagers return home, the power generation systems are idle throughout the day and therefore no electricity can be sold. In the advanced scenario (Scenario B), during the day the demand pattern is smoother, the power generation system never reduces to an idle state and proportionately more electricity can be sold to multiple end-user sectors. During the day electricity demand predominantly comes from social infrastructure and productive use, while at night time demand stems from household sector.

Second, we find strong differences for the LCOE of the various solutions. Starting from the conventional solution, we observe that the diesel powered village grid option has the second lowest LCOE (at low and medium remoteness) when considering the Indonesian diesel fuel prices. However, when we consider world diesel fuel prices, the LCOE are 62% higher. The dependence of diesel powered village grids on an external factor – the transportation of diesel from a distribution centre to the generation site – affects the operating cost throughout its lifetime strongly. Particularly in more remote areas diesel prices can be much higher than in distribution centres. When considering this sensitivity to location we observe a large range of variation in LCOE. For scenario A we observe LCOE between 0.23 – 0.51 €/kWh (at Indonesian diesel prices) and 0.36 – 0.84 €/kWh (at world diesel prices). For scenario B we observe LCOE between 0.22 – 0.48 €/kWh (Indonesian fuel prices) and 0.34 – 0.79 €/kWh (world fuel prices). This is in a similar range to the findings of Holland & Derbyshire [6] and shows that diesel powered village grid is the most expensive option for very remote area application, particularly when no subsidies are assumed. However, results by van der Veen [19] and real project data by Hivos [21] and Abraham et al. [20] show lower figures, which can be explained by the fact that the studies neglect future diesel price development in the case of Hivos [21] and Abraham et al. [20] and lower investment and operational cost assumptions in combination with a longer lifetime for the diesel generator in the case of van der Veen [19]. Furthermore, we observe no significant difference in LCOE with change in electrification strategies. This demonstrates the scalability of the diesel generation system, where costs are driven primarily by purchase of diesel fuel and its expected price growth throughout the asset lifetime.

In the set of results for renewable energy based village grid solutions, we observe that micro hydro consistently has the lowest LCOE compared to other technologies, for both scenarios at 0.16 €/kWh (A) and 0.14 €/kWh (B). However, these results, which are also very comparable to those by Holland & Derbyshire [6], are only valid when sufficient hydro resources are available. USAID [16], van der Veen [19], Hivos [21] and Abraham et al. [20] report lower generation cost, which stems from higher capacities, favourable local specifics and lower discount rates. Solar PV/battery is considered to have the least restrictions for application and can be placed almost anywhere in Indonesia due to the abundance of solar potential [29, 34]. In alignment with results of previous studies in other countries [10, 22, 32, 33], our analysis demonstrates that solar PV is however still the most expensive technological option to power village grids. For scenario A we obtain LCOE of 0.58 €/kWh and for scenario B 0.53 €/kWh. However, for solar PV in scenario B we observe that the solar PV battery LCOE is already lower than a diesel engine at world fuel prices, even at medium remote places. Interestingly, these results are higher than those obtained by Holland & Derbyshire [6] four years ago, despite the fact that PV cells

experienced strong cost reductions, and also higher than newer results by van der Veen [19]. The reason for this is that we assume a higher discount rate and that we size the system so that it can provide electricity even in the least sunny period of the year and therefore include large battery storage investments. In evaluating the effects of alternative configurations to solar PV powered village grids, first, we observe the reduced supply contingency strategy, which proves to be successful in reducing LCOE. At 90% configuration the LCOE of a solar PV/battery powered village grid is reduced to 0.45€/kWh (A) and 0.40€/kWh (B), indicating a total reduction between 21% - 25%. Furthermore, at 80% configuration the LCOE is reduced to 0.44€/kWh (A) and 0.39€/kWh (B), indicating a reduction between 22% - 27%. The LCOE reduction between 100% to 90% configuration is more effective than the step between 90% to 80%, as the worst irradiation days (mostly outliers) are already eliminated from the calculation in the first reduced supply contingency step.

In the hybridisation strategy, firstly, for solar PV/battery/diesel hybrid configuration, scenario A results in LCOE ranging from 0.35 – 0.58 €/kWh (at Indonesian diesel prices) indicating an average reduction of 17% compared to the original solar PV/battery configuration and only 4% higher than diesel (similar to Holland & Derbyshire's results [6]). At world prices the LCOE of this configuration is 0.46 – 0.87€/kWh. This demonstrates that in locations close to diesel distribution centres, such configuration may increase the competitiveness of solar PV powered village grids compared to a solar PV/battery configuration. However it is not ideal and relatively more expensive for application in more remote areas due to increased transportation cost of diesel. For scenario B, the solar PV/battery/diesel hybrid proves to be even more expensive than standalone solar PV/battery with relatively higher LCOE of 0.30 – 0.49€/kWh (Indonesian fuel prices) and 0.38 – 0.72€/kWh (world fuel prices). Secondly, the results for the solar PV/diesel hybrid village grid (30% solar PV and 70% diesel), the results for advanced electrification strategy are slightly more competitive than solar PV/battery/diesel. We observe LCOE between 0.25 – 0.48 €/kWh (Indonesian fuel prices) and 0.35 – 0.77 (world fuel prices). Hybrid technologies which combine diesel and solar PV are only cheaper than pure solar PV/battery options, if diesel subsidies are assumed and/or the village location is not remote. Their application might be interesting in places where diesel generators already exist but more generation capacity is needed due to the development of the village.

By law, all end-users to the PLN grid are entitled to the official PLN tariffs. For completeness, we compare the LCOE of the village grids to PLN retail tariffs (red band in Figure 4). PLN tariffs differ according to the end-use category as determined by Ministerial Decree 4/2010 [35]. On average the lowest tariff is for consumers in the social sector (0.06€/kWh). This is followed by household (0.07€/kWh) and industrial consumers who use for productive use (0.08€/kWh). The PLN retail tariff band is thus far lower than all the LCOE of the analysed village grid options.

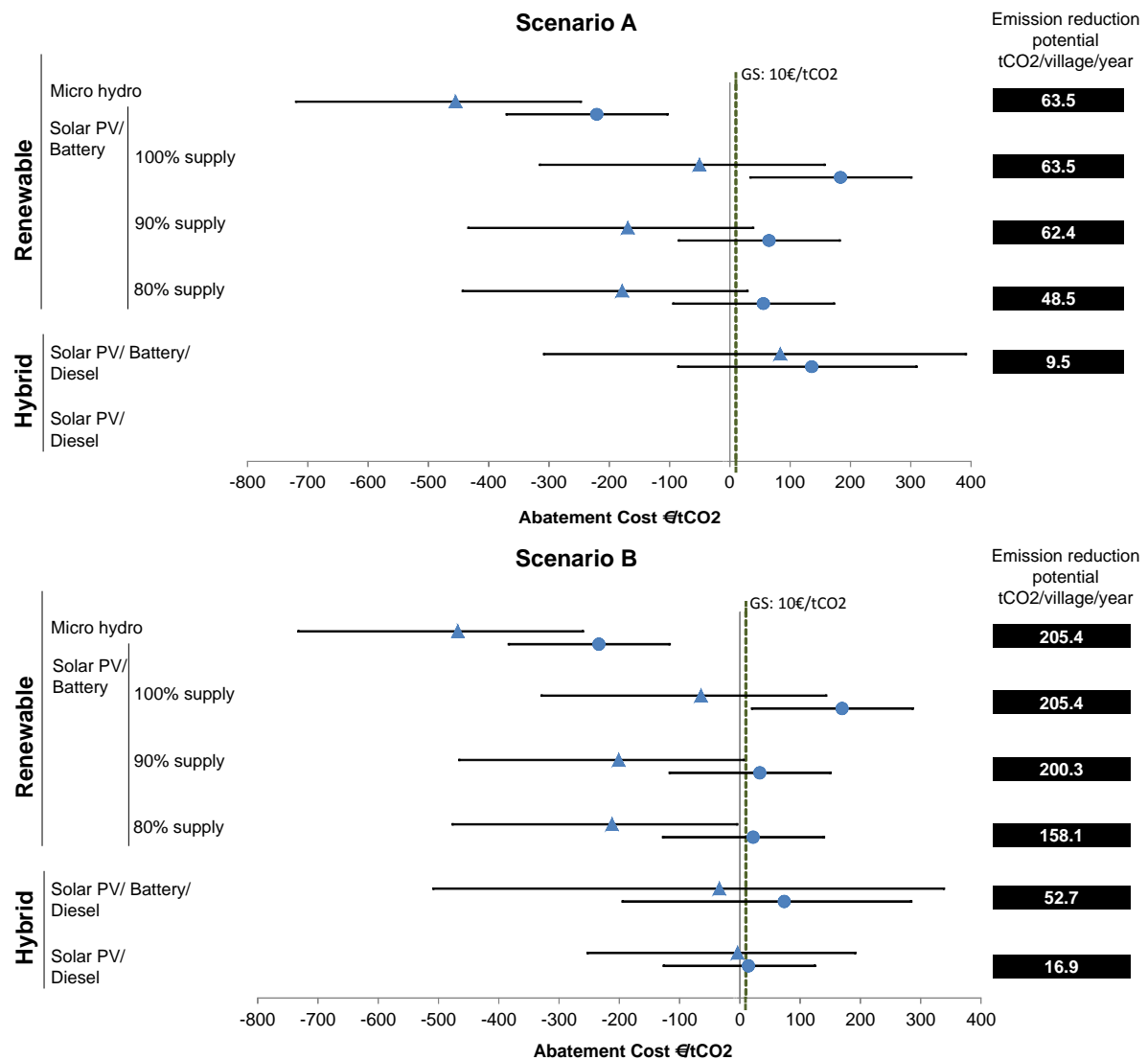


Figure 5 | Abatement costs and emission reduction potentials of renewable energy based and hybrid village grids compared to the conventional diesel baseline. The abatement costs are quantified by the horizontal axis, measured in €/tCO₂. For each technological option, we calculate the abatement costs considering world unsubsidized prices (symbolized by the triangle symbol) and Indonesian subsidized prices (symbolized by the circle symbol). We also consider a range (black lines) of abatement costs to differing remoteness levels of the village. We compare these abatement costs to the current Gold Standard (GS) carbon price of 10€/tCO₂, depicted by the dotted line¹⁶. For each technological option, we also calculate the emissions reduction potential by choosing a renewable energy based or hybrid village grid as an alternative to the conventional diesel solution (black boxes).

The abatement cost analysis shows a wide range of emission abatements and costs. Generally, the influence of fuel subsidies is quite high. We observe that abatement costs for micro hydro solutions are in any case negative, when compared to diesel solutions. This implies that savings can actually incur by choosing micro hydro over diesel powered village grid option while at the same time emissions can be reduced by 63.5 tCO₂/year/village (scenario A) respective 205.4 tCO₂/year/village (scenario B). The abatement costs for all power systems which contain solar PV components are higher. However, we observe in all cases (except for solar PV/battery/diesel in

¹⁶ While the retail price for GS projects is above these 10€/tCO₂, interviews we conducted with carbon market actors indicate that 10€/tCO₂ is the maximum that is passed through to the project.

scenario A), when considering unsubsidized world diesel fuel prices, abatement costs are negative. In terms of emissions reductions, as expected the renewable energy only solutions (micro hydro and solar PV/battery at different configurations) yield the highest volume of CO₂ emission avoided. The hybrid solutions result in 75%-84% (solar PV/battery/diesel/) and 91% (solar PV/diesel) less emission reductions due to the presence of the diesel content. Finally, the Gold standard carbon price of 10€/tCO₂ is small compared to the wide range of abatement costs. However, it becomes obvious that for several options a carbon price could (partially) financially support the diffusion of renewable energy based village grids sufficiently.

5 Discussion and conclusion

In order to reach Indonesia's 90% electrification target, high investments are needed. The US\$43m provided by the government and the grants from international organizations will not be sufficient. Additional resources stemming from private investors are urgently required [36]. In this section we discuss why only little private investment into village grids takes place and how the diffusion of renewable energy based village grids can be ramped up strongly by providing incentives for private investors. We commence our discussions from micro hydro and then solar PV powered solutions.

Our results highlight that micro hydro powered village grid is the solution with the lowest generation costs and negative abatement costs in all cases (even when assuming subsidized non-remote diesel prices). Despite this fact and many studies identifying locations with sufficient natural resources [7, 37] the diffusion of micro hydro village grids is still low. This is related to the extremely low electricity retail tariff determined by the government. While PLN's average network costs of electricity supply at €0.16/kWh [38] also exceed this range of tariff, the resulting gap is covered by the government. This represents a second, indirect, form of subsidy (additional to the direct fuel price subsidies), which becomes a hindrance to private investments (unless private investors would be bailed out by the Indonesian government like PLN – a rather unrealistic and socially doubtful scenario)¹⁷. Previous studies suggest that the deterrent of private investors in rural electrification projects may be caused by a number of reasons, including national electricity tariffs that are lower than the cost of decentralized-produced electricity [6] and from the high (transaction) cost associated with rural electrification projects [11] and regulatory, technological and counterparty uncertainty [37]. Therefore, it's essential to create an investment environment that is conducive to increase village grid private investment; one option is for the government to remove the electricity "price cap". With this retail tariffs would reflect cost of electricity supply more closely and fairly. While this first option may result in higher prices for consumers and potentially a significant burden to the lower income earners, studies show that in other countries rural poor are willing to pay higher electricity prices [13, 20]: e.g., in Cambodia rural electricity prices are much more flexible and reach from 37 to 74 €/kWh [39]. The second option to increase private investments is to remove the electricity price cap, and concurrently re-distribute fuel subsidies. In case the Indonesian government wants to keep end-user prices very low, one option is to shift current fuel subsidies in such way that micro hydro solutions get subsidized. Electricity subsidies in Indonesia, when measured by price-gap methodology¹⁸ are among the highest in non-

¹⁷ These indirect subsidies of course also impede private investments in fossil fuel-based rural electrification.

¹⁸ Price-gap methodology calculates the gap between regulated retail tariffs and regulated benchmark price [40].

OECD countries, in particular for oil [40]. These subsidies have increased significantly from 2005 (€0.7b) to 2008 (€6.3b) driven by increase of international oil prices and high dependence on diesel based generation systems [41]. Gradually lowering the subsidies from emission intensive technologies and increasing those for hydro would be a feasible solution¹⁹. Additionally, when the electricity subsidy removal is implemented simultaneously with fuel subsidy redistribution, the adverse effects on household levels may be dampened, compared to an electricity subsidy removal alone [42]. In the case of village grids, the LCOE of diesel is much higher than the retail price when compared to micro hydro. Hence, if hydro is installed instead of diesel, the total amount of required subsidies is reduced, resulting in savings for the government. Another consideration is that micro hydro capacity and capabilities are already advanced in Indonesia, with a number of manufacturing centers across the country²⁰ [42, 43]. This is in contrast with solar PV technology, where manufacturing takes place mainly in industrialized or threshold countries. Hence, strengthening this technology could also create jobs and economic development in the country (additional to the development that can be expected due to the existence of power in the villages) and thereby be a contribution to an Indonesian green growth strategy.

While micro hydro is the cheapest option and should be chosen where the natural potential is available, solar PV based options are much more expensive but nevertheless can be interesting for villages where the hydro potential is lacking. For an overview on different electrification options for different remote environments, see a recent IEA-RETD report [44]. Solar PV technology has very high technical potential and is expected to experience rapid reduction in costs [14, 42, 43]. Especially in very remote villages, solar PV/battery options can be cheaper than diesel. This trend will reinforce itself with raising diesel prices [45]. Hence, the same reasons for non-investments from the private sector as discussed for micro hydro hold for solar PV options. However, the role of diesel subsidies is even more precarious. Without diesel subsidies, solar PV based options are also attractive in medium remote villages. A gradual phase-out of subsidies could be coupled with a gradual build-up of solar PV/battery powered village grids. In order to limit additional costs during this transition phase, the solar PV/battery solutions can be designed in a way that they do not aim at 24 hour power delivery over 365 days. Smaller configurations can limit costs significantly (while still delivering major amounts of electricity; compare the LCOE results of our 90% configuration) and be installed in the beginning. The high modularity of solar PV and batteries allows a subsequent addition of generation and storage capacity (which will be even cheaper at the time of installation due to the learning curve of both solar PV and battery technologies [23]). Similarly to hydro, fuel and electricity “price cap” subsidies should be re-distributed to also support solar PV in places without hydro potential.

The findings underline renewable options can be cheaper than their fossil alternatives that typically represent the baseline. The public perception is often still dominated by idea that renewable-based options are far off from competitiveness with conventional generation options [46]. Schmidt et al. [27] show that for grid-connected large scale wind, abatement costs can be negative if the baseline is largely based on oil products. They, in line with other recent studies [46, 47], conclude that subsidies are a major issue. Our study confirms this for the case

¹⁹ In a promising step, the government has already announced plans for subsidy reforms between September 2012 – April 2013, following a failed attempt in April 2012 [42].

²⁰ The same holds true for several other developing countries, such as Nepal, Kenya or Nigeria.

of village grids in Indonesia. Fuel subsidies can strongly deteriorate the competitiveness of renewables. Energy prices have been subsidized in Indonesia since 1967 and are determined through a government decree. Subsidies in diesel oil result in official retail prices which are 33% lower than the world market prices [41]. In the case of solar PV, these subsidies push the abatement cost from negative to as high as almost 200€/tCO₂. Additionally we find, that indirect subsidies, which allow for extremely low retail prices make private investments totally unattractive.

The results on the abatement cost show that a certain part of the additional costs of solar PV could be covered by carbon credits. While the United Nations Framework Convention on Climate Change talks are currently at a time of uncertainty, new market mechanisms, e.g., Nationally Appropriate Mitigation Actions (NAMAs), are looming, which can partially also be financed via carbon credits²¹ [48]. For more details on the potential of new carbon finance mechanisms, see e.g., a series of recent UNDP papers [46, 47, 49, 50].

Overall it seems that rural electrification through renewable energy based village grids is hardly an issue of high additional costs of renewables but rather of the political economy of the country's energy sector. In order to remove the barriers for renewable electrification, political work is required. Agencies for technical and political assistance are required to support the Indonesian government in building an electrification strategy that targets five areas of development relevant to the Indonesian energy sector. First, such strategy must support the 90% electrification rate target at low or even zero emission growth. Second, such strategy can be created in a way that improves economic development through national value creation and capacity building in the village grid technology sector (e.g. scalable and high quality hydro manufacturing, installation and assembling of switch gears and solar PV panel production). Third, the strategy can also be geared towards establishing electricity as a basic commodity for rural economies; such that it stimulates productive use and subsequently boost rural economic development. This stimulation of electricity demand is akin to shifting from a basic electrification (scenario A) to advanced electrification (scenario B) in our study, which proved to be beneficial in lowering LCOE and making village grid electricity more affordable. An important issue is of course the phase out of fuel subsidies, which can be intricate²². Fourth, such strategy must attract private equity and debt sponsors (beyond purely concessional finance). An analysis of the risks involved in rural electrification [49] and their transfer and reduction can lower the cost of renewables more than of conventional technologies. Their high capital intensity makes them more sensitive towards high discount rates (which are found in investment environments with high risks). Last but not least, such strategy has to involve stakeholders – from village residents, via potential investors, the financial sector, technology providers to PLN – in order to manage counterbalance interests.

Finally, we conclude with a statement of our main contributions and some limitations which call for further research. This study enriches the literature in rural electrification – with particular focus to Indonesia – in three ways. First, in contrast to previous studies, our analysis considers a holistic view of rural end-user consumer market including household, productive use and social infrastructure. This serves as a first valuation base for

²¹ As our results show, NAMAs for different technologies have different financial needs.

²² The issue of Indonesian fuel subsidy is very sensitive. Adjustments of fuel prices seldom take place as the political impact and community backlash can be severe [42].

private sector when considering village grid investments. Second, we analyze the issues that are directly relevant in encouraging private sector investment in rural electrification sector. Third, our results contribute towards proposals for policy makers by showing the actual economic barriers (often the high costs of renewables are perceived as the main barrier – something, we clearly disprove).

Our study is clearly limited to techno-economic calculations. However, literature on the diffusion of renewable energies in developing countries has shown that further financial and non-financial barriers are highly relevant [10, 39, 40, 49]. Hence, we suggest four areas for future research: analyze the risks for private investors in order to derive appropriate de-risking strategies; analyze the socio-techno-economic barriers of village grid diffusion which goes beyond the pure cost calculations presented in this study; research on potential business models for renewable energy based village grids in Indonesia; and analyze on a country level to calculate the economic costs and benefits of the proposed rural electrification strategy.

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Appendix A

Assumptions for Power Generation System Capacities

Table A.1 | Assumptions relevant to the modelling of power generation system capacities

Section of Model - Technology		Technical assumptions			Economic assumptions			
		Factor	Assumed value	Source	Factor	Assumed value	Source	
Demand model			Distribution losses	4%	[51]	Population	1497 people	[17]
			Voltage level	Low (under 1 kV)	[52–54]	Number of household	350 households	[17]
			Electrification scenarios	See Table	[14, 43, 55, 56] Supplemented by Indonesia in-field interviews			
			Demand by end-user sector	See Appendix B	[14, 43, 48, 49, 55, 57] Supplemented by Indonesia in-field interviews			
			Operating hours (scenario A)	18:00 – 06:00	Own assump.			
			Operating hours (scenario B)	00:00 – 00:00	Own assump.			
		Operating days	365 days (no seasonality)	Own assump.				
LCOE model					Discount rate	12.5%	[58]	
					Inflation rate	2.1%	[59]	
					Exchange rate USD/EUR	1.31269	[60]	
					Exchange rate IDR/EUR	11779.8	[60]	
Conventional generation model	Diesel	Efficiency (scenario A)		26%	[51, 52]	Diesel price (Indonesia)	0.29€ ₂₀₁₂ /litre See Appendix D	[25]
		Efficiency (scenario B)		27.64%	[51, 52]	Diesel price (World)	0.61€ ₂₀₁₂ /litre See Appendix D	[26]
		Diesel oil density		0.832 kg/litre	[61]	Diesel retail price multiplier, based on transport cost effect	Low: 1.0x, Medium: 2.0x, High: 2.7x	[24, 33, 54]
		Diesel oil calorific value		11.94 MWh/tonne	[62]	Investment cost	See Appendix C	[12]
		Diesel plant lifetime		20 years	[12]	O&M cost	See Appendix C	[12]
		Specific CO ₂ emission		0.26674 tCO ₂ /MWh	[63]			
Renewable energy generation model	Micro hydro		Overall efficiency	85%	Based on an interview with a micro hydro power implementer	Investment cost	See Appendix C	[12]
	Solar PV/ Battery	Solar PV Battery	Location	Kuching, Malaysia as proxy	[34]	O&M cost	See Appendix C	[12]
			Temperature factor	0.932	[17, 64, 65]	Investment cost	See Appendix C	[12]
	Tilt angle		20°	Own assump.	O&M cost	See Appendix C	[12]	
	Nominal Operating Cell Temperature (NOCT)		45°C	[17, 58]				
	Maximum temperature coefficient		-0.38%	[17, 59]				
	Inverter efficiency		95%	[60, 66]				
	Lifetime		25 years	[12]				
	Battery efficiency		90%	[66, 67]	Investment cost	See Appendix C	[12]	
	Overall charging efficiency		81.23%	By calculation	O&M cost	See Appendix C	[12]	
	Depth of discharge		20%	Own assump.				
	Initial rest capacity at start of optimization		10%	Own assump.				
	Lifetime		5 years	[61, 67]				
	Hybrid generation model		Solar PV / Battery / Diesel	Diesel efficiency (scenario A)		35%	[51, 52]	Same Investment cost and O&M cost assumptions as above
Diesel efficiency (scenario B)				35%	[51, 52]			
Other assumptions as above								
Solar PV / Diesel		Diesel efficiency (scenario B)		26%	[51, 52]	Same Investment cost and O&M cost assumptions as above		
Other assumptions as above								

Appendix B

Electric Appliances

Table B.1 | Typical electrical appliances for household sector under Scenario A [11]. Data also supplemented by findings from Indonesian field trip.

Electrical Appliance	Power Consumption (W)	Quantity per household	Usage duration per day
Light bulb (indoor)	16	2	18:00 – 00:00
Light bulb (outdoor)	16	1	18:00 – 06:00
TV 19"	80	0.2 (1 every 5 households)	18:00 – 23:00

Table B.2 | Typical electrical appliances for household sector under Scenario B [14, 43, 55, 56]. Data also supplemented by findings from Indonesian field trip.

Sector	Electrical Appliance	Power Consumption (W)	Quantity per consumer	Usage duration per day
Household	Fluorescent Lamp (inside house)	16	2	18:00 - 0:00
	Fluorescent Lamp (outside house)	16	1	18:00 - 6:00
	Color TV 19"	80	1	18:00 - 23:00
	Stereo (speakers)	20	1	18:00 - 23:00
	Refrigerator	100	4 per 30 household	17:00 - 9:00
	DVD/VCD Player	25	1	18:00 - 20:00
Productive Use	Kiosk (4.5 per village)			
	Light bulb	25	4	18:00 - 22:00
	Coffee milling (2 per village)			
	Coffee Huller	1000	1	9:00 - 17:00
	Coffee Grinder	2000	1	9:00 - 17:00
	Carpenter (1.7 per village)			
	Metal grinder	120	1	9:00 - 17:00
	Drilling machine	350	1	9:00 - 17:00
	Circular saw	1500	1	9:00 - 17:00
	Planer	450	1	9:00 - 17:00
	Tailor (1 per village)			
	Sewing Machine (dynamo)	120	1	9:00 - 17:00
	Restaurant (1 per village)			
	Refrigerator	100	1	0:00 - 0:00
Mixer	100	1	11:00 - 19:00	
Blender	180	1	11:00 - 19:00	
Social Infrastructure	Hospital (1)			
	Vaccine refrigerator	60	1	00:00 - 00:00
	Vaccine refrigerator / freezer	60	1	00:00 - 00:00
	Indoor lights (CFL)	15	10	10:00 - 17:00
	Outdoor lights (CFL)	15	4	10:00 - 17:00
	Microscope	15	1	2 hours per day
	Centrifuge nebulizer	150	1	2 hours per day
	Vaporizer	40	1	2 hours per day
	Oxygen concentrator	300	1	2 hours per day
	Overhead fan	40	4	10:00 - 17:00
	Water pump	100	1	2 hours per day
	Electric steriliser	1500	1	2 hours per day
	Desktop Computer	60	2	10:00 - 17:00
	15" LCD monitors	25	2	10:00 - 17:00
	Multi function scanner/ copier/ printer	17	1	2 hours per da
Satellite phone	5	1	Only in emergencies	
Internet: Cisco Aironet Workgroup	0.05	1	10:00 - 17:00	

Sector	Electrical Appliance	Power Consumption (W)	Quantity per consumer	Usage duration per day
	Internet: 4-port ethernet hub	7.5	1	10:00 - 17:00
	School (1)			
	Internet: Cisco Aironet Workgroup	0.05	1	08:00 - 15:00
	Internet: 4-port ethernet hub	7.5	8	08:00 - 15:00
	Desktop Computer	60	30	08:00 - 15:00
	Indoor lights (CFL)	15	24	08:00 - 15:00
	Outdoor lights (CFL)	15	12	08:00 - 15:00
	Internet: Cisco Aironet Workgroup	0.05	1	08:00 - 15:00
	Common communications infrastructures			
	Payphone	2	3	00:00 - 00:00
	Internet: Cisco Aeronet 350 Access	0.05	1	00:00 - 00:00
	Internet: Digital VSAT receiver	30	1	00:00 - 00:00

Appendix C

Costs of the different generation plants

Table C.1 | Costs of diesel generator plant [12]

Type of Cost	Value
Reference rated output	100 kW
Investment cost	
Engineering	7.62 €/kW
Equipment & material	457.08 €/kW
Civil	10.00 €/kW
Erection	7.62 €/kW
O&M cost	
Fixed O&M cost	0.02 €/kWh
Variable O&M cost	0.03 €/kWh

Table C.2 | Costs of micro hydro power plant [12]

Type of Cost	Value
Reference rated output	25 kW
Investment cost	
Engineering	152.35 €/kW
Equipment & material	3755.64 €/kW
Civil	746.55 €/kW
Erection	533.26 €/kW
Process contingency	533.26 €/kW
O&M cost	
Fixed O&M cost	0.00 €/kWh
Variable O&M cost	0.41 €/kWh

Table C.3 | Costs of solar PV and battery power plant [62, 67]

Type of Cost	Value
Investment cost	
Module sales price	0.87 €/Wp
Inverter sales price	0.21 €/Wp
Remaining balance of plant price	0.64 €/Wp
EPC margin	8%
O&M cost	
Fixed O&M cost	1.5% of total investment cost

Appendix D

Projected development of diesel fuel prices, under world (symbolized by quadrates) and Indonesian (diamonds) prices. These projections are calculated based on multipliers advised by the International Energy Agency [27, 68].

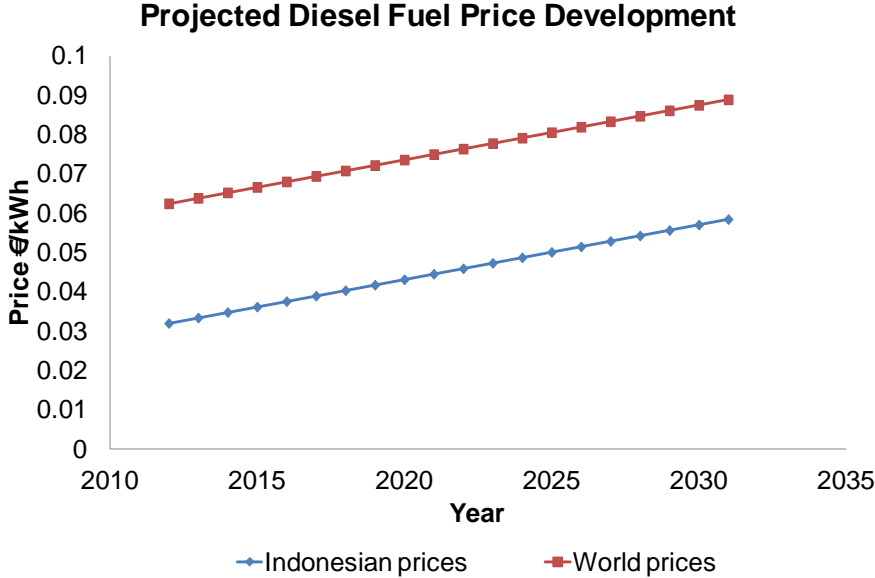


Figure D.1 | Projected Diesel Fuel Price Development

Appendix E

Calculation of solar PV/battery system capacities

First, using the hourly TMY data we calculate the tilt-adjusted global horizontal irradiation (I_{DH}) to obtain the total irradiation (I_{Ct}) by adjusting for the assumed tilt angle ($\theta=20^\circ$), given by the equation

$$\text{Eq. E.1} \quad I_{Ct} = \frac{I_{DH}}{\cos(\theta)} \quad [\text{Wh/m}^2]$$

We then calculate the weighted cell temperature derate factor (Tf) to account for performance variations in case the cell temperature (T_{cell}) differs from the 25°C at standard testing conditions, by incorporating the module Nominal Operating Cell Temperature ($\text{NOCT}=45^\circ\text{C}$) and temperature coefficient ($\nabla=-0.0038/^\circ\text{C}$) [23].

$$\text{Eq. E.2} \quad T_{cell_t} = \frac{\text{NOCT} - 20^\circ\text{C}}{800 \text{ Wh/m}^2} I_{Ct} \quad [^\circ\text{C}]$$

$$\text{Eq. E.3} \quad Tf_t = 1 + [(T_{cell_t} - 25^\circ\text{C})\nabla] \quad [-]$$

$$\text{Eq. E.4} \quad \text{Weighted Tf} = \frac{\sum_{t=1}^{2760} I_{Ct} Tf_t}{I_{C,annual}} \quad [-]$$

$$\text{Eq. E.5} \quad E_{PV_t} = \text{Number of panels} \times \text{Rated power per panel} \quad [\text{W}] \\ \times \text{Weighted Tf} \times \frac{I_{Ct}}{1000}$$

The solar PV/battery system must operate such that the available power for village load consumption (E_{load}) at any time t can either be sourced from solar PV production (E_{PV}) or by discharging battery (E_{batt}).

$$\text{Eq. E.6} \quad E_{Load_t} = E_{PV_t} + E_{Batt_t} \quad [\text{W}]$$

We select the four consecutive days within the TMY with the lowest levels of irradiation as the basis of our model^{23,24} (see Figure 3). A solar PV/battery system that fulfills hourly load consumption during these four ‘worst-case’ days should be able to generate sufficient electricity at 100% availability throughout other days of the year, which have higher solar irradiation levels. At any time t when the power produced from the solar PV panels exceeds the required demand at that time, the excess production can be stored in the battery which has a charging efficiency of 81.23% and 20% rest energy margin [69–71]. Consequently, the battery will be discharged to supply any shortages should the solar PV panels be unable to produce sufficient power to meet demand. These requirements are given by the following formulas.

$$\text{Eq. E.7} \quad E_{Batt_t} = \begin{cases} \text{if } (E_{PV_t} - E_{Load_t}) > 0, \eta_{Batt} [(E_{PV_t} - E_{Load_t}) + E_{Batt_{t-1}}] \\ \text{if } (E_{PV_t} - E_{Load_t}) < 0, E_{Batt_{t-1}} - (E_{Load_t} - E_{PV_t}) \end{cases} \quad [\text{W}]$$

²³ From the IWEC data this was determined to be between January 23rd and 26th 1990 which yielded global horizontal irradiation of 3794, 3712, 2373 and 2376 Wh/m² respectively.

²⁴ Industry practice recommends off-grid small-scale PV generation system ranges from 3 – 6 days [48, 54, 55, 77].

Using a non-linear optimization method we then determine the combination of solar PV and battery capacities, which yields the lowest LCOE (objective function) and meets the demanded levels of power at any time t (constraint).

Eq. E.8

$$\min LCOE_{PV,batt} \quad s. t. \quad E_{PV_t} + E_{Batt_t} \geq E_{Load_t}$$

Annex I

Paper 2

Attracting private investments into rural electrification – a case study on renewable energy based village grids in Indonesia

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– Resubmitted to Energy for Sustainable Development –

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Abstract

Renewable energy based village grids (RVGs) are widely considered to be a sustainable solution for rural electrification in non-OECD countries. However, diffusion rates of RVGs are relatively low. We take the viewpoint that, as public resources are scarce, investments from the private sector are essential to scale-up the diffusion. While existing literature mostly focuses on engineering, development and techno-economic aspects, the private sector's perspective remains under-researched. As investment decisions by private investors are mainly based on the risk/return profile of potential projects we – based on literature reviews and field research – investigate the risk and the return aspects of RVGs in Indonesia, a country with one of the largest potentials for RVGs. We find that considering the potential of local, national and international revenue streams, the returns of RVGs can be positive. Regarding the risk aspect, we see that private investors could address many of the existing barriers through their business model. However, the findings also point to the need for government action in order to further improve the risk/return profile and thereby attract private investments for RVGs.

1 Introduction

Today, about 19% of the global population remain without access to electricity (OECD/IEA 2011). Access to electricity heavily correlates with economic development, and those people lacking access primarily live in rural areas of non-OECD countries (OECD/IEA 2011). Providing these rural poor with electricity is a major challenge. The amount of additional electricity generation capacity needed is enormous when aiming to stimulate rural development (Cook 2011; Bardouille et al. 2012; ESMAP 2008). At the same time, climate change (being a major threat mainly to the poorest countries) needs to be addressed by de-coupling electricity production from CO₂ emissions (Gallagher et al. 2006; UN AGECC 2010; Glemarec et al. 2012; Bhattacharyya 2011). Grid extension – the conventional solution for electrification in most countries – is often not feasible or too expensive, especially in very remote areas such as islands as is the case in Indonesia (Blum et al. 2013; Deichmann et al. 2011; Rickerson et al. 2012). In such cases, off-grid renewable energy technologies which produce electricity with a very low climate impact and that fit the requirements of a decentralized context, can well address the challenge of low-carbon electrification (Zerriffi 2011; Holland & Derbyshire 2009; Sovacool & Valentine 2011). In 2011, the Journal *Energy for Sustainable Development* published a special issue on off-grid electrification in non-OECD countries, which discussed rural electrification through renewable energy in a series of sixteen articles and was specifically valuable for our study (for an overview see Bhattacharyya, 2011). Several authors from this special issue (e.g. Bhattacharyya, 2011; Schäfer et al., 2011) as well as other researchers (e.g. Zerriffi, 2011; Glemarec, 2012) recommend further research with regards to scaling up diffusion through private investments. Even though research on rural electrification through renewable energy is increasing, most studies address the engineering, development and techno-economic aspects. The private sector's investment decisions, remain poorly researched (Bhattacharyya 2011; Kaundinya et al. 2009; Bhattacharyya 2012).

Renewable energy based rural electrification options are diverse and vary greatly regarding the amount of provided electricity and consequently the potential for allowing for the productive use of electricity. While solar lanterns and household-based stand alone systems such as solar home systems offer lighting and limited access to electricity for household purposes respectively, their contribution to the productive use of electricity is low (Macharia et al. 2010; Ölz & Beerepoot 2010). Village grids¹ are widely regarded as more promising in terms of a developmental impact because they allow for the productive use of the generated electricity (Kanagawa & Nakata 2007; Takada & Charles 2007; Legros et al. 2009; Cook 2011). If designed well they can, in terms of reliability, outperform the often unstable national grids in non-OECD countries (Yadoo & Cruickshank 2012; Peskett 2011). If village grids are powered by renewable energy they not only address the poverty, but also the climate change challenge. While the global market for off-grid solutions bringing modern energy to the rural poor has a size of about 35 billion USD p.a., the market potential for RVGs alone is estimated at an annual 4 – 5 billion USD (2012) (or about 28 million households) and growing by 13% p.a. (Bardouille et al. 2012; Dean et al. 2012). However, despite the advantages of RVGs, the existence of pilot projects (e.g., in Bolivia, Cambodia, India, Indonesia, Nepal, Nigeria, or the Philippines) and the heavy promotion by development agencies, large-

¹ Village grids, also referred to as micro- or mini-grids, “provide centralized generation at a local level. They operate at a village or district network level, with loads of up to 500 kW” (OECD/IEA 2011, p.16) and connect a few up to several thousand households (Bardouille et al. 2012).

scale diffusion has not yet taken place (Bardouille et al. 2012; Roland & Glania 2011). In this study we focus on RVGs in Indonesia where they are a very suitable form of rural electrification for three reasons² (see also Section 2). First, the government of Indonesia (GoI) aims to increase the electrification rate from the current 65-70% to beyond 90% by the end of the decade (PT Perusahaan Listrik Negara 2010; Winoto et al. 2012; PWC 2011). Second, Indonesia is an island state, making grid extension complicated and expensive. Third, the country has more than sufficient renewable energy resources, e.g., in forms of solar and hydro power. Theoretically, there are four known sources of finance for RVG projects in Indonesia: First, international grants from nongovernmental organizations (NGOs) and developmental agencies providing initial capital for RVG projects³, second, grants for electrification provided by the federal GoI (Ministry of Energy & Mineral Resources of Indonesia 2009), and fourth, private investors (typically local or regional businesses) and village communities which arrange joint financing agreements. Despite these potential sources of finance, little investments have taken place (Bardouille et al. 2012; OECD/IEA 2011; PWC 2011). While the first two sources of capital are limited by the specific grants, the private capital is abundant. In order to understand private investment – or the lack thereof – the risk/return profile is essential, as for private financiers/investors, “the risk-return profile of a project is the ultimate determinant of whether to finance or not” (UNEP, 2012, p.9).

In this paper, we therefore address the question “**what do the current risk/return profiles of RVGs in Indonesia look like and how can they be improved in order to attract private investments?**” We proceed in two steps. First, we investigate the potential returns of different RVG types by comparing costs with revenues. Second, we turn to risks, by analyzing the barriers that drive investment risks (compare Waissbein et al., 2013) and show how investors could make these risks manageable. Both, positive returns as well as manageable risks are prerequisites for attracting private capital (Glemarec 2012; Waissbein et al. 2013; UNEP 2012). The role of the government in supporting the formation of such a favorable environment for investment is essential (Waissbein et al. 2013; The World Bank 2013).

The paper is structured as follows. Section 2 introduces Indonesia’s electricity sector with an emphasis on rural electrification through renewable energy and RVGs. Section 3 provides an overview of the methods applied. In Section 4 we identify potential returns of RVGs. Section 5 provides the results of a detailed barrier analysis (that is needed to understand risks) as well as a comprehensive selection of multiple measures to assist investors to address these aforementioned barriers. We then turn to the role of regulation and discuss our findings in Section 6 with regards to the role of national policy for improving the risk/return profiles of RVGs. Section 7 concludes with a short summary of our findings.

2 Background on Indonesia’s electricity sector, rural electrification and RVGs

The Indonesian State Constitution from 1945 declares that all vital utilities concerning the greater population must be controlled by the state. Since 1985, the electricity sector in Indonesia has been controlled by the state-

² Another – non-empirically driven – reason for the choice of Indonesia was the fact that one of the authors is an Indonesian native, which strongly improved the accessibility of data gained in literature reviews and during field trips (see Section 3).

³ Additionally, international initial capital can potentially be extended by carbon financing (compare Section 4).

owned power utility Perusahaan Listrik Negara (PLN). After its formation, PLN became the sole body responsible for the provision of electricity across Indonesia. The Ministry of Energy & Mineral Resources serves as the policy making body and regulator for PLN. However, other ministries within the GoI are also stakeholders providing different governing and support functions. In a bid to boost the capacity of electricity generation and keep up with an estimated 9% annual demand growth (Differ Group 2012; Permana et al. 2012), the GoI since 2009 has opened up the market of power generation for competition. Small scale independent power producers (IPPs) can now produce electricity, but are required to sell it to PLN for distribution. Only rural cooperatives are allowed to generate and distribute electricity independently of PLN. Figure 1 shows a schematic of key players in the Indonesian electricity sector and their roles. In order to address climate change and reduce its oil dependency, the GoI has also introduced The Ministerial Decree on Renewable Energy Resources and Conservation (Ministerial Decree No. 002/2004) which aims at increasing the share of renewable energy to 18% by 2025 (Energypedia 2013).

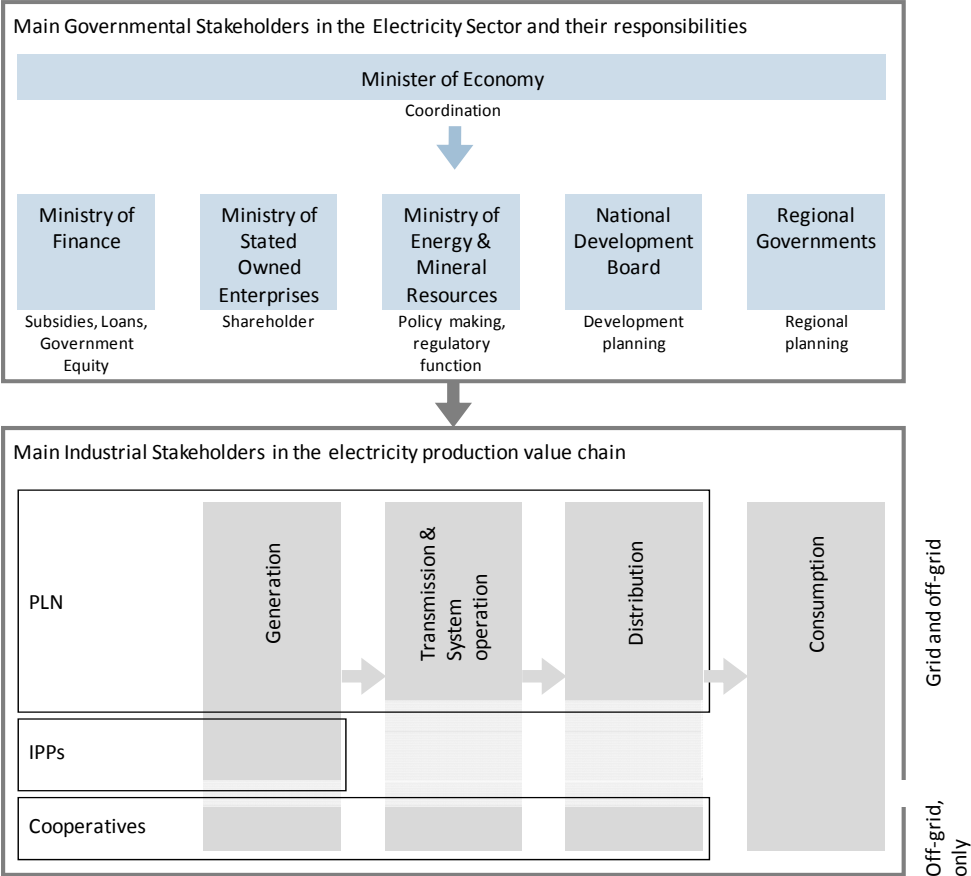


Figure 1 Governmental and industrial stakeholders in the Indonesian Electricity Sector (adapted from Anderson et al., 2011; Purra, 2009)

Despite having significantly developed its generation, transmission and distribution network over the years, the national electricity grid remains significantly strained. The growth in generation capacity has been unable to keep up with the growth in electricity demand. Since 2009, the Java-Bali transmission grid is particularly congested, which has led to “transmission bottlenecks” that often forced PLN to impose rolling blackouts across the two main islands of Java and Sumatra. However, the more remote islands mainly suffer from partial or even

complete lack of electricity. With an electrification ratio of about 65% - 70%⁴, about 72 - 84 million of the 242 million Indonesians still do not have access to reliable and affordable electricity services (PT Perusahaan Listrik Negara 2010; Winoto et al. 2012; Energypedia 2013; Asia Sustainable and Alternative Energy Program 2005; Purwono 2008). Of these 72 – 84 million people the vast majority, about 60 million, reside in rural areas and almost all live outside of the most densely populated islands⁵: Figure 2 shows the electrification ratios per province and clearly indicates that the eastern parts of Indonesia particularly are suffering from a lack of access to electricity. Despite these official figures, it has been very difficult to quantify the real progress at the rural village level.



Figure 2 Indonesian electrification ratios (number of electrified households) per province. Own graph based on data from 2011 from the Indonesian Ministry of Energy and Mineral Resources (Kusdiana 2012; Winoto et al. 2012)

Previous studies suggest that due to the challenging geographical nature of the country, a decentralized off-grid electrification solution is more appropriate than grid extension, in particular for remote and rural villages in mountainous areas and on smaller islands (Blum et al. 2013; Kaundinya et al. 2009; Boedoyo & Sugiyono 2010; Sovacool & Valentine 2011). Currently, most village grids are powered by diesel plants: at the end of 2007, 936 decentralized diesel power plants (50kW – 500kW) with a total capacity of 987MW were operating in Indonesia (Senoaji 2008). Diesel generators are a standard rural electrification solution, due to their long track-record, reliability, scalability, availability and relatively low upfront cost (ESMAP 2007). However, in line with the GoI’s aim to increase the share of renewables in electricity generation, RVGs are largely considered to be a suitable alternative to improve rural electrification while at the same time not increasing greenhouse gas emissions (Beck & Martinot 2004; ESMAP 2007; Terrado et al. 2008; White et al. 2008).

While PLN aims at erecting solar powered village grids on several hundred islands within the next years (through the “1,000 island project”), only on few islands have projects been realized thus far. At the same time,

⁴ Electrification figures diverge depending on the source and the interpretation of electrification; often electrification ratios reflect general access to electricity, but do not reflect the quantity and quality of the accessed electricity (*Interviews*). In Indonesia a village counts as ‘electrified’ if at least one location within the villages is connected to PLN’s low voltage grid – which includes mainly diesel powered village grids. A clearer indication of the true electrification ratio would be the number of electrified households (see Figure 2).

⁵ Indonesia consists of about 17’508 islands, out of which around 6’000 are inhabited (The CIA World Factbook 2013).

only few private sector activities, such as the social business IBEKA, exist. International initiatives include Energizing Development (EnDev) and RewiRE, or UNDP’s support, e.g., for Yayasan Bina Kitorang Mandiri (YBKM).

3 Methods

In terms of methods, the suggestion by Schäfer et al. (2011) was followed to perform research in the field of rural electrification by integrating the expertise of practitioners with the knowledge of different academic disciplines. To this end, quantitative –for the return aspect – and qualitative methods – for the risk aspect – were used in this study. Both, the quantitative and the qualitative parts are based on the field trips and literature. Figure 3 provides an overview of the quantitative and qualitative approach along with the data sources used

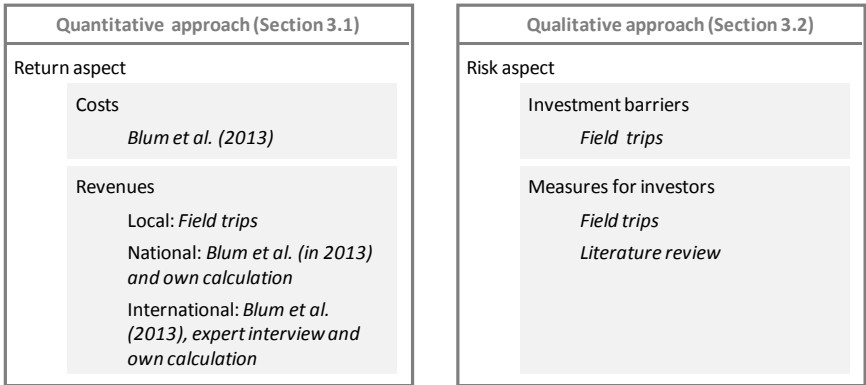


Figure 3 Quantitative and qualitative research approach to determine return and risk aspects (data sources are indicated in italics)

3.1 Quantitative approach

The quantitative methods are used to estimate potential returns, i.e., the revenues minus the costs. Revenues can stem from three different levels: the local (village) level, the national and the international level. The cost and the revenue estimates are based on two main sources first, three field trips (lasting in total 6 weeks) to Indonesia in July 2011 and March 2012; second, literature.

To determine local revenues, we conducted 19 interviews with implementers and operators of RVGs, as well as villagers. As such data on potential revenues through electricity sales (local revenues) has not been thoroughly documented thus far or the appropriate data within literature was insufficient⁶, we gathered own data: In these

⁶ Three literature sources provided data on local revenues through electricity sales in Indonesian, White and colleagues (2008) report a WTP of 0.08 – 0.7 USD/kWh, while Feibel (2010) provides real tariffs of 20 micro hydro power plants (10 in each Sulawesi and Sumatra) of about 0.07 USD/kWh in 2010. Abraham and colleagues (2012) report a WTP of 0.4 USD/kWh. Besides the existence of these studies, we decided to collect new data for three reasons: (a) The first study’s data comes from 2000 and is therefore likely to be outdated; (b) the data from Feibel (2010) refers to real tariffs in micro hydro powered village grids in very specific regions and thus indicates prices which are much lower than the WTP; (c) the WTP provided by Abraham et al. (2012) was regarded as unrealistically high by our interviewees.

interviews build-own-operate (BOO) investors and villagers revealed the current tariffs, which were determined through community agreements and therefore can be assumed to reflect their willingness to pay (WTP)⁷.

To analyze the costs as well as the potential national and international revenues, we draw from literature, mainly from data provided in a paper by Blum et al. (2013). As this paper is such an important source, it is briefly summarized here with a further explanation of which of their cost data we use and how national and international revenue streams were derived from their data: By means of a levelized cost of electricity (LCOE) model, Blum and colleagues (2013) investigate the economics of micro hydro and solar PV/battery powered village grids in Indonesia and compare them to the LCOE of conventional diesel powered village grids. The paper assumes a generic Indonesian village, determines the village's demand curve along with the size of the power plants needed to meet this demand (for assumptions see Table 1). Amongst others, the paper provides results for the LCOE of diesel, micro hydro and solar PV/battery powered village grids. While the latter two results directly inform our cost data, we used the diesel LCOE to estimate national revenues.

Table 1 Selected assumptions from Blum et al. (2013)

Village size	1475 people living in 350 households	
Electricity demand of the village	Electricity is available 24 hours per day for households (day and night), productive use (majority during daytime), and social infrastructure (majority during daytime) – Daily electricity demand of the whole village: 558.5 kWh	
Electricity supply	Diesel system	A diesel system encompasses a diesel generator. – Assumed capacity: 69.6 kW
	Micro hydro system	Micro hydro power describes hydroelectric power up to about 100 kW. A prerequisite for micro hydro systems are rivers with adequate water flow rates, head and water availability. – Assumed capacity: 69.6 kW
	Solar PV/battery system	Solar PV systems, which directly convert solar energy into electricity, combined with battery storage are a usual rural electrification option. A prerequisite for solar PV/battery systems are high irradiation. In our calculations we assume a solar PV system which consists of crystalline silicon (cSi) solar PV panels connected to advanced lead-acid batteries. – Assumed capacity: 232.5 kWp (solar PV), 716 kWh (battery)

In specific, we calculated the “potential” national and international revenue streams as follows. First, national revenue streams encompass diesel and electricity subsidies. The actual value of diesel subsidies (in USD/kWh) in currently operating diesel powered village grids was determined by the difference between the LCOE of diesel powered village grids at Indonesian and at world diesel prices (as given by Blum et al. 2013). The difference between the LCOE of diesel powered village grids (at Indonesian diesel prices) and the Indonesian national electricity tariff (charged by PLN and paid by already electrified rural poor households) yields current electricity subsidies. Second, to determine international revenues in form of carbon certificates (in USD/kWh, compare Table 2), we use Blum and colleagues’ (2013) result on the absolute yearly emission reduction potential (205.4 tCO₂/village/year) and multiply it with the yearly produced electricity and a carbon price of 9 – 15.5 USD/tCO₂⁸.

⁷ However, it is probably the lower end of the villagers’ WTP as in such community agreements, villagers typically set the tariffs at the lower end of what they are able to pay.

⁸ An interview with an active expert in the carbon market revealed that these prices are paid to Gold Standard certified projects – for more on Gold Standard projects and points of critique see Nussbaumer (2009) or Rogger et al. (2011).

For local, national and international revenue streams, average values along with sensitivities (indicated by ranges), and data sources please refer to Annex A.

3.2 Qualitative approach

For the barrier analysis, we conduct – as suggested by Yin (2003) for studying complex contemporary phenomena – qualitative research. Extensive field research with a desktop literature review was combined to explain investment barriers and measures for investors to address them. In such an explanation building process one often iterates between literature and field research (Yin 2003). This is also the case in our study. During the field trip of 2011 the general market situation of RVGs was studied in Indonesia and when combined with desktop research the research question was narrowed down and helped in the preparation for the second field trip of 2012. The data collected so far was then complemented by another round of literature review. The following paragraphs refer to our interview sampling approach, the content of the literature review and the analysis of the data.

When performing field trips within Indonesia different kinds of relevant actors were included as an important strategy for the sampling, to allow the capture of different perspectives on perceived barriers/risks. We conducted semi-structured interviews⁹ with six private sector actors, eight representatives from the public sector, four employees of development agencies, and three representatives of non-profit organizations. Six of the interviewees were interviewed twice within a time interval of one year. Additionally, four private sector actors were interviewed whom are operating RVGs in Lao PDR or Cambodia; their insights were used to triangulate and strengthen the analysis on measures for investors (for more details on interviewees compare Annex B). While several interviews were conducted in English those interviews with non-English speaking actors were supported by a translator or conducted by the native Indonesian speaking co-author of this study¹⁰. To further triangulate the interview results, we visited four operating mini grids (two of them in Indonesia, and one in Lao PDR and Cambodia) and collected feedback upon presenting our research at the International Conference on Sustainable Innovation at the Universitas Muhammadiyah Yogyakarta, Indonesia.

The in-depth literature review encompasses scientific articles and practical literature (reports, case studies, project information) on two topics. First, literature on investment barriers for RVGs in Indonesia was consulted. Second, literature on measures for investors to address barriers such as business model features, best practices and lessons learnt to overcome barriers to RVGs was included. This second kind of literature was not restricted to Indonesia¹¹.

⁹ As part of each interview, we compiled a background analysis of written data, such as websites and media coverage, which we used to customize interview guides.

¹⁰ On average, interviews lasted 60 minutes and were conducted face-to-face with the exception of one telephone interview. Interviews were recorded when acceptable to the interviewee; if not, the interviewer took detailed notes.

¹¹ In contrast to the barrier analysis, we included literature from different countries and on different rural electrification technologies to identify measures to address the barriers. The underlying assumption is that similar barriers can be solved by similar measures.

To analyze the collected data, the recorded interviews and interview notes were transcribed. These transcripts were then coded for barriers and the measures to address them. We grouped barriers thematically as well as along the local, national and international level in order to obtain a final list of barriers. In a last step we matched the barriers with suitable measures stemming from the field research and the reviewed literature.

4 Potential returns of RVGs in Indonesia

As discussed in the introduction, RVGs are assumed to become attractive for investors if there is a cost-revenue situation which allows for positive returns. Other authors claim that “most of the mini-grid projects suffer from non viability as cost of electricity generation from such projects is high while the return through tariff is low¹²” (Palit & Chaurey 2011, p.274). However, they only refer to the local revenue stream (the tariffs) and omit additional potential revenue sources from the national and international levels. Contrarily, this study considers potential revenue streams on all three levels: local, national and international. We structure the description of the potential revenue streams along these three geographical levels (compare Annex A).

Revenues on the local level refer to electricity sales to the villagers. While some authors independent from Indonesia argue to use villagers’ income levels (or also sometimes referred to as ability to pay) as proxy for local revenues others suggest considering the WTP (Zerriffi 2011)¹³. WTP includes other factors besides income levels, for example educational levels or kerosene consumption (Komatsu et al. 2011; UN AGECC 2010; Phuangpornpitak & Kumar 2011) and is therefore understood to be more accurate. We therefore consider WTP in our analysis. Our obtained data reveals that WTP ranges from 0.12 to 0.25 USD/kWh and turns out to be considerably higher than PLN’s electricity tariff for poor rural households connected to the grid (0.09 USD/kWh).

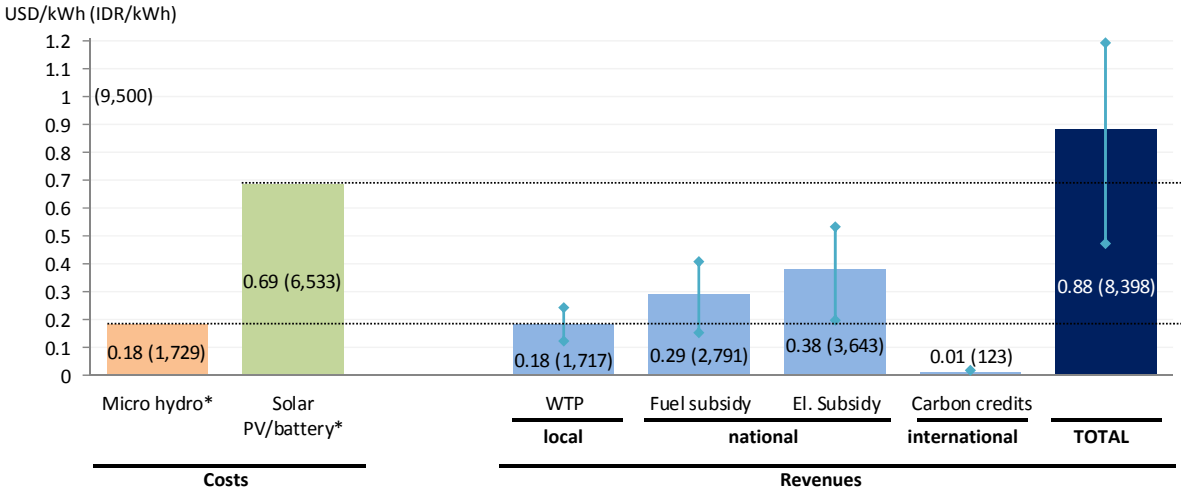
At the national level, we look at potential revenue streams from a re-distribution of national subsidies. Previous studies have shown the detrimental effect of fossil fuel subsidies (especially for renewable energies) (Blum et al. 2013; IISD 2011; Schmidt et al. 2012; Fattouh & El-Katiri 2012). Subsidy phase-out is a difficult endeavor generally (UNEP 2008) and in Indonesia (Mourougane 2010), we argue that a re-distribution of subsidies towards renewable energy projects could be less problematic (compare Section 6). The underlying assumption is that RVGs replace a diesel powered village grid, which would otherwise be built. Diesel is the standard technology for village grids in Indonesia (Senoaji 2008; Blum et al. 2013). The subsidies that the diesel village grid would receive could generate an additional revenue stream if passed on to the RVG. There are currently two kinds of subsidies in the Indonesian electricity tariff system (Braithwaite et al. 2012; Differ Group 2012; Permana et al. 2012; Gunningham 2013). First, a fuel subsidy which protects local diesel prices against world

¹² Palit and Chaurey (2011) state that the high cost is associated to capital, operation and management costs and the low returns are linked to low incomes and therefore low financial ability to pay for electricity.

¹³ Literature is not consistent regarding the question whether the WTP is lower (Martin 2009; Cook 2011) or higher (Zerriffi 2011) than the villager’s ability to pay, but concludes that a) the WTP and the ability to pay have to be balanced (Roland & Glania 2011) and b) the WTP varies greatly between countries (White et al. 2008).

price fluctuations¹⁴. And second - as PLN sells at fixed prices, also in off-grid areas – an electricity subsidy bridges the gap between the government-regulated retail electricity tariffs (0.08 – 1.04 USD/kWh) and the real cost of electricity supply across the PLN network (electricity production cost is 0.09 – 0.35 USD/kWh)¹⁵ (Blum et al. 2013; Mourougane 2010; IISD 2011; Braithwaite et al. 2012; Haeni et al. 2008; Permana et al. 2012). Re-distributing the fuel subsidies to RVGs could result on average in 0.30 USD/kWh of revenues, re-distributing the electricity subsidies on average in additional 0.39 USD/kWh.

At the international level, we consider carbon credits as a potential revenue stream. RVG projects reduce (existing and marginal) CO₂ emissions – at the height of 0.96 kgCO₂/kWh (Blum et al. 2013) – while providing the possibility of economic development for a village. Additionally, under the current political subsidy environment they are not per se profitable. For these reasons they qualify for receiving premium priced carbon credits, e.g., certified by the Gold Standard (The Gold Standard Foundation 2012). The resulting revenues range from 0.009 to 0.016 USD/kWh.



* Source: Blum et al. (2013)

Figure 4 Cost and revenue estimates for micro hydro and a solar PV/battery powered RVGs. Values are in USD/kWh and those in brackets in IDR/kWh. An exchange rate of 9,500 IDR/USD is assumed.

Figure 4 compares these potential revenues and the costs. The cost data by Blum and colleagues (2013) show that micro hydro powered RVGs¹⁶ exhibit substantially lower life-cycle generation costs than solar PV/battery powered RVGs, which is caused by higher investment costs for the solar PV modules and batteries. Our results reveal that locally sourced revenues can fully cover the RVG’s cost in the case of micro hydro, meaning that investors can realize RVGs with a relatively small need to tap into national and international revenue streams. In the case of solar PV/battery powered RVGs, the local revenue stream only covers 17%-36% of the (much

¹⁴ This fuel subsidy is reaching unsustainable levels and increasingly becoming a major strain on the GoI’s spending (Braithwaite et al. 2012; Haeni et al. 2008; Differ Group 2012; Permana et al. 2012; IISD 2013).

¹⁵ The higher prices refer to more remote areas where electricity provision is more expensive.

¹⁶ A study by the IFC (Bardouille et al. 2012) calculated the costs of micro hydro powered RVGs at around 19.5 USD/kWh supporting Blum et al. (2013).

higher) generation costs¹⁷. However, one has to keep in mind that the WTP, and therefore local revenue streams, can vary strongly with income and location (White et al. 2008). It is probable that WTP rises with the increase of productive activities based on electricity¹⁸. When looking at revenue streams on the national level, we find significant effects of potential subsidies on the return of RVG projects (compare also IISD 2011): Our results suggest that in all cases, a re-distribution of fuel and electricity subsidies (at the height presently found in the Indonesian fuel market and for electricity generated by PLN) towards RVGs have the potential to cover the majority of the production cost. For micro hydro powered RVGs, the contribution from a full re-distribution of either one of the subsidy types would by far over compensate the costs of a typical project (by 64% and 114% calculated for the average values). For solar PV/battery powered RVGs, the contribution from shifted fuel subsidies can account for 23% - 58%, and electricity subsidies for 28% - 77% of production costs. At the international level, we identify that revenues from carbon credits could yield only between 5% - 9% of the production cost of micro hydro powered RVGs and 1% - 2% of the production cost of solar PV/battery powered RVGs – which originates from low carbon prices (which might even further decline) (Point Carbon 2013). Our findings support earlier claims stating that it is “extremely difficult to make carbon financing economically viable for rural electrification projects” (Yadoo 2012).

When summing up all potential revenues, we find that this sum in both RVG types exceeds the respective costs. This indicates that RVGs can potentially yield profits of 0.07 – 0.57 USD/kWh. While micro hydro powered RVGs can often be financed with local revenues only, the solar PV/battery powered RVGs heavily depend on further revenue streams (see Section 6). Theoretically, RVGs get higher potential returns the further away they are from the national grid due to potentially higher benefits from a subsidy re-distribution. While our results highlight that a major barrier for the diffusion of solar PV/battery powered RVGs lies in a not yet favorable cost-revenue balance, it can be assumed that at least in the case of micro hydro powered RVGs the reason for the non-diffusion originates from additional risks¹⁹. Investors typically face many barriers when trying to secure the underlying cash flows which can translate into investment risks (Waissbein et al. 2013; Glemarec 2012). To understand the low diffusion rate of RVGs (and especially of micro hydro powered village grids) one therefore needs to analyze these barriers as done in the next section.

5 Investment barriers and measures for investors to address them

To address the risks specific to RVGs in Indonesia, we first identify the barriers through a barrier analysis. These barriers can stem from stakeholders on the local, national or international level, i.e. the same levels as the revenue sources. The barriers can translate into investment risks in the planning, construction and operational

¹⁷The IFC (Bardouille et al. 2012) calculates costs of 0.34 USD/kWh for a solar PV (without battery) powered RVG. However, such a configuration is capable of covering electricity demands during daytime only, and does therefore not satisfy household needs, which mainly occur in the evening (Blum et al. 2013; IIEC 2006; Saengprajak 2006).

¹⁸ However, as long as PLN tariffs remain at the rate of 0.09 USD/kWh villagers living relatively close to the national grid will not be willing to pay a tariff which is twice this price.

¹⁹ Blum's et al. (2013) LCOE calculation already assumes an elevated risk level (as typical in the energy sector in Indonesia) via the discount rate of 12.5% (UNFCCC 2010).

phase, which might discourage investors from investing (or increase financing costs and thereby the generation costs) (Glemarec et al. 2012; Waissbein et al. 2013). In a second step, we turn to the role of BOO investors²⁰ and discuss how they could become active in addressing the underlying challenges. By doing so we highlight the important role of investors in mitigating investment risks, which – as a literature review revealed – is an often neglected aspect in research on RVGs (Bhattacharyya 2011; Kaundinya et al. 2009; Bhattacharyya 2012). Table 3 provides an overview of the barriers and measures for investors for each the local, national and international level. The following sub-sections are structured along these three levels and describe barriers as well as the corresponding measures. Whenever the information is based on literature we cite the respective studies whereas information based on interviews is referred to as *interviews* (details on the specific *interview* sources are provided in Annex C).

Table 3 Barriers and measures for investors to address them (in Indonesia)

	Barriers (based on <i>interviews</i>)	Measures for investors to address the respective barrier (based on literature review and <i>interviews</i>)
Local (Section 5.1)	Lack of understanding the customers' needs	Conduct market research to understand village specifics Introduce customer service Involve the community
	Lack of decentralized operation, maintenance and administration	Implement a decentralized organizational structure Employ locals
	Unsteady electricity demand and uncertain forecasts	Do scenarios for the demand forecast of each village Increase modularity and flexibility of design of the RVG Educate customers on efficient electricity use Agree with local businesses on fixed and regular electricity purchases
	Lack of local human resources	Train and up-skill own, local staff Retain trained and skilled staff
	Lack of local financial resources	Design a locally adapted tariff and payment scheme Foster local productive use and entrepreneurship Provide customers with access to loans
National (Section 5.2)	Lack of standards and knowledge transfer on best practices	Draw from and advocate for existing best practice examples and standards Conduct pilot projects, then scale up
	Lack of information and data	Collect and share information and data
	Lack of national network of investors	Attend and conduct workshops, seminars and conferences Build strategic partnerships
	Lack of national technology supplier network	Buy from local suppliers whenever possible Buy from international suppliers where necessary
	Strongly regulated electricity market	Advocate for market liberalization
	Ineffective governmental structures	Maintain professional contacts to governmental units in order to gain trust Decentralized operation, maintenance and administration
International (Section 5.3)	Lack of national financial resources (debt and equity)	Reduce business risk Employ new financing schemes
	Lack of international financial resources (debt, equity, carbon)	Reduce business risk Employ new financing schemes Loan from impact investors Apply for carbon credits
	Negative externalities caused by international donors	Strengthen NGOs, governmental agencies and other non-private actors in their understanding of free market mechanisms

²⁰ We assume BOO investors, as the barriers can affect all phases of the project cycle.

5.1 Local level

On the local level we identified five barriers which transform into challenges for BOO investors and can be addressed by specific measures.

5.1.1 Lack of understanding the customers' needs

In order to assure the sustained success of an RVG, projects ought to be seen rather as projects improving the livelihood of villagers than as mere energy projects (Kumar et al. 2009; UNDP 2011). To this end, investors must understand their investment context, including also user practices (Johnson 2013). In our interviews, Indonesian practitioners stated that RVG projects often suffer from understanding the needs of their customers (*Interviews*), i.e., the villagers who consume and pay for the produced electricity. Doing successful business requires knowing these customers and their needs and designing products and services accordingly. BOO investors specifically face the challenges of an "electricity is for free" mindset, difficulties in collecting electricity fees, avoiding electricity theft, and sensitively handling their position as monopolists (*Interviews*). To address these challenges BOO investors could start by **conducting market research to understand village specifics** (UNEP 2005; Roland & Glania 2011; Sovacool et al. 2011b). Market research tools which are recommended for rural contexts are home stays, field trips²¹, contacts with competitors and cooperation with local organizations. In a second step, **customer service can be introduced** (De Vries et al. 2010; Bambawale et al. 2011; Gradl & Knobloch 2011; Roland & Glania 2011; Sovacool et al. 2011a; Sovacool et al. 2011b; Bardouille et al. 2012). Such service consists of proper maintenance services including product performance guarantees and warranties as well as regular visits in the villages in order to collect feedback. Further, these activities can be supported by **involving the community**²² actively (Yadoo & Cruickshank 2010; Sovacool et al. 2011b; *Interviews*) also with a sensibility for the BOO investor's own position as monopolist. Concrete activities include stakeholder meetings (Bardouille et al. 2012; Rickerson et al. 2012), in-kind support for villagers (Sovacool & Valentine 2011; Rickerson et al. 2012), co-operation with existing income-generating organizations (e.g., coffee or rice farmers) (Aron et al. 2009), and community ownership²³ and management²⁴ (Yadoo 2012; Aron et al. 2009; Glemarec 2012). Such community activities are time-consuming, yet as experts from other NGOs state, a prerequisite for customer acceptance (Alvial-Palavicino et al., 2011; *Interviews*).

²¹ However, the practitioner guide REEDToolkit (UNEP 2005) questions the quality of responses gathered during field trips.

²² While the village chiefs might be good entry points for investors, involving more villagers benefits feedbacks from users, especially as the local governments' capacity is often limited (*Interviews*). Additionally, the concept of user innovation (Von Hippel 2005) might be considered in an RVG service context.

²³ Perceived community ownership (or sometimes also referred to as cooperative approach) is more important than actual legal ownership (Yadoo 2012).

²⁴ Possible disadvantages of community-centered models can be the time intensity to establish the cooperative, as well as the risk of technical and financial failure over time and the dependence on the community members (Glemarec 2012). Yadoo and Cruickshank (2010) and Cook (2011) on the other side stress that operation and management costs are lower in cooperatives and Palit and Chaurey (2011) explains that "due to equity, commitment and transparency" cooperatives are successful. They also show that this holds in particular true if there is a productive use of electricity.

5.1.2 Lack of decentralized operation, maintenance and administration

Typically Indonesian organizations (including rural electrification organizations) tend to implement centralized structures with headquarters in Jakarta or other major cities. However, this is not the most effective structure in a decentralized, rural context as local presence matters (see 5.1.1). BOO investors are consequently challenged by long travel distances and complicated distribution channels (*Interviews*). Hence, practitioners are convinced that BOO investors would benefit from **implementing a decentralized organizational structure** (*Interviews*), referring to small, independent and flexible units (Schmidt & Dabur 2013). When implementing such structure, assuring a continuous knowledge flow between the sub-units is crucial to distribute learning by doing and using (see 5.1.1). The decentralized structure is strengthened by **employing locals**, even if skilled labor is scarce (compare 5.1.4). Concrete actions are, e.g., the training of own, local staff, sub-contracts with local business partners (e.g. franchises) or cooperation with local organizations (Rickerson et al. 2012; Yadoo & Cruickshank 2010)²⁵.

5.1.3 Unsteady electricity demand and uncertain forecasts

Our field studies revealed that due to the variety of villages across Indonesia with respect to population, prosperity, cultural and social structure, the demand for rural electricity services can vary greatly²⁶ (*Interviews*). This makes it challenging for BOO investors to estimate electricity demand and future growth in demand levels. BOO investors are therefore urged to take measures to understand the current demand and **to perform demand forecast scenarios**. This involves a basic assessment of each village in the development phase of the RVG. The system is then sized accordingly incorporating future extension of production capacities (Rickerson et al. 2012). The latter is influenced by possible population and economic growth which can be reinforced by access to electricity (Roland & Glania 2011). As it is “essential to introduce flexibility and scalability right in the planning phase” (*Interview with public sector representative*), BOO investors can increase their flexibility in meeting a growing demand by **increasing the modularity and flexibility in the design of the RVG**²⁷. This allows integrating future capacity, e.g., by adding power sources such as solar panels and integrating several RVGs into a smaller regional grid. In practice, the creation of a smart (real time metering) flexible system increases the relevance and robustness of the RVG (Dean et al. 2012; Bardouille et al. 2012; Rickerson et al. 2012; Bazilian et al. 2011). **Educating customers on efficient electricity use**, is a supportive measure which helps to shape electricity demands (Yadoo & Cruickshank 2010; Bazilian et al. 2011; Cook 2011; Glemarec 2012; Rickerson et al. 2012, *Interviews*). Finally, **arranging fix priced buy-off agreements with small local businesses**²⁸ (where possible) lowers insecurities in the electricity forecasts (Bardouille et al. 2012).

²⁵ The positive side effect of employing locals are the shared responsibilities for service and maintenance as well as independent operations and management (Gradl & Knobloch 2011; Yadoo 2012; Dasappa et al. 2011).

²⁶ The uncertainty stems – amongst others – from misuse, or overuse of electricity and unknown economic development of the village.

²⁷ Programs such as Paladin Live by Power Analytics help to plan adjustments in the system size. This particular program shows the capacity, availability and reliability of a RVG by analyzing real time data (Dean et al. 2012).

²⁸ Including base-load customers like mobile telephone companies (powering their towers) might decrease the relative load variability, however, system costs might raise strongly, especially in case of solar-powered RVGs, where the battery capacity needs to be increased to cover consumption during the night.

5.1.4 Lack of skilled local human resources

While in 2008 the average Indonesian adult illiteracy rate was at 7.8% (UNESCO 2009), this rate is much higher in rural areas where RVGs are implemented²⁹. Consequently the lack of skilled (and motivated) local human resources in rural Indonesia to build, operate and manage RVG power plants³⁰ represents a major barrier (*Interviews*) and BOO investors cope with the challenge of identifying and employing skilled local staff. In a first step they therefore **employ, train and up-skill own, local staff** (Bardouille et al. 2012; Yadoo 2012) and possibly also cooperate with local micro and small enterprises in order to enhance technology transfer and ensure long-term maintenance (Aron et al. 2009; Feibel 2010; Roland & Glania 2011; Rickerson et al. 2012; *Interviews*). Public financial resources sourced from international organizations, NGOs and the government can be invested to create a supporting "capacity building unit". Training tools, cooperation with local academic institutions (Rickerson et al. 2012) or peer-to-peer trainings (De Vries et al. 2010) have proven successful in practice. In a second step, the **trained and skilled staff has to be retained**, which can be fostered through fair salaries (*Interviews*), potentially also performance-dependent salaries (Roland & Glania 2011) or additional benefits such as health insurance or housing programs.

5.1.5 Lack of local finance

Finally, in rural Indonesia the villagers lack financial resources (*Interviews*). On the one hand, villagers have low income levels; on the other hand a banking system providing loans to rural locals is absent (Monroy & Hernandez 2005) and as an interviewee from the private sector states "The villagers won't be able to get funding and realize a RVG project on their own. Typically they'd have to turn to some sort of institution" (*Interview with private sector representative*). BOO investors have the challenging task to implement a business approach that targets poor customers (also referred to as an inclusive business approach). Only if energy access is affordable, rural electrification of the poor is sustainable (UNDP 2011). In the case of RVGs such an approach can be threefold; (a) A **locally adapted tariff and payment scheme** starts with the determination of the tariff³¹. Such a tariff results from balancing commercial viability and the consumer's WTP (Roland & Glania 2011; *Interviews*) while considering levels of demand and supply (Rickerson et al. 2012). Furthermore, the payment has to be

²⁹ A report by the Indonesian Ministry of Education and Culture (2012) states the following illiteracy rates for Tenggara: 10-16%; West Sulawesi: 10%; and Papua: 36%. All three regions have rural electrification rates below 60% (compare Figure 2).

³⁰ An analysis by the IFC (Bardouille et al. 2012, p.92) found that "skills development and capacity building are not major concerns for most small power providers" of diesel powered village grids, however that RVGs "require higher levels of technical sophistication to operate smoothly". We are not aware of any government program which systematically trains villagers as village grid technicians.

³¹ Proven tariff schemes (mainly based on Roland and Glania 2011) are the "graded electricity tariff system" where tariffs are based on pre-determined capacities, "electricity-based tariffs" where electricity meters in households monitor the use of electricity and consumers pay per kWh, "pre-paid mechanisms" where customers pay in advance for a certain amount of electricity and a load limiter then regulates the access to electricity, or "demand regulating tariff schemes" where tariffs react to electricity production (Rickerson et al. 2012). Ideally also future maintenance cost is included in the tariffs (Aron et al. 2009).

organized in an efficient way for customers and the BOO investor³² (Bardouille et al. 2012; Gradl & Knobloch 2011). For tariffs as well as for actual payments, BOO investors will profit from incorporating the villagers' preferences as well as from ensuring clear definitions and high transparency (Roland & Glania 2011; *Interviews*). (b) In the long run, private investors in RVGs also benefit from **fostering local productive use and entrepreneurship** (Monroy & Hernandez 2005), because with the economic development of the village the customers' purchasing power increases and results in a higher likelihood of sustained future cash flows (Roland & Glania 2011; Bardouille et al. 2012; Aron et al. 2009). Concrete actions that foster productive use and entrepreneurship are e.g. business incubation services (Bellanca & Wilson 2012), entrepreneurial trainings (Yadoo 2012) and encouraged trade between villages. Besides capacity building, "soft aid" can be provided, such as technical and agricultural equipment at low-cost, e.g., machinery for agro-processing, seeds and live-stock (Aron et al. 2009; Gradl & Knobloch 2011; *Interviews*). Also investments in complementary infrastructures such as roads and the communication system support entrepreneurial efforts and trade (Yadoo 2012). (c) BOO investors can **provide their customers with access to loans** (Glemarec 2012; Monroy & Hernandez 2005) for production equipment powered by electricity. As besides equipment, villagers with entrepreneurial intentions³³ often require training and loans. Common ways to provide villagers with this access to finance are via cooperation with local micro-finance institutions and/or local commercial banks, e.g., the Indonesian Bank Perkreditan Rakyat or People's Development Bank (DB Climate Change Advisors 2011), or by integrating micro-finance into the BOO investors' own business model and offering tailored financial vehicles to local entrepreneurs³⁴. However, such investors currently have few RVGs in their lending portfolios as they prefer more small scale electrification options (such as solar home systems or solar lantern businesses) or grid extension due to these concepts' lower complexity and hence lower investment risks (*Interviews*).

5.2 National level

On the national level we identified seven barriers which BOO investors should address.

5.2.1 Lack of standards and knowledge on best practices

Despite the more than 900 RVG projects and pilots across Indonesia, there is still a lack of standards, certification and knowledge transfer on the best practices of management and operation (*Interviews*). In order to close this gap, BOO investors can heavily **draw from and advocate for existing best practices and standards**³⁵ (Roland & Glania, 2011; *Interviews*), while ensuring that own best practices and standards are advocated through publications, conferences and seminars. Own attempts are leveraged by cooperating with peer public and private stakeholders. The development of own best practices eventually emerges from **conducting**

³² The following factors are at discussion in this matter; the occurrence (monthly, weekly, with harvest), the kind of payment (cash, "in kind"), and the collection (trained villagers, mobile payment, prepaid payment, leasing of electricity appliances) (Yumkella et al. 2010; Roland & Glania 2011; Bardouille et al. 2012; Bellanca & Wilson, 2012; Glemarec 2012; *Interviews*)

³³ Lemaire (2011) shows the example of solar home systems that access micro credits to support the creation of a dynamic self-sustained market for rural electrification through renewable energy.

³⁴ Most beneficial for villagers would be access to loans at lower than usual interest rates (Van Mansvelt 2011).

³⁵ IEC (International Electrotechnical Commission) Technical Specification Series 62257 provides, amongst others, useful standards for village grids (Roland & Glania 2011).

robust pilot projects and scaling them up without too much deviation (Drewienkiewicz 2005; Feibel 2010; *Interviews*).

5.2.2 Lack of information and data

In Indonesia, as well as in many other non-OECD countries, there is often a lack of reliable data on natural resources (water flow in rivers, wind strengths, irradiation, and rain fall), population and infrastructure in rural areas (*Interviews*). BOO investors have to close this information gap by own means in order to be able to e.g. identify villages which could be promising business cases. Activities include the **collection and sharing of information and data**, which involves own investigations in villages, accessing and improving existing data bases (such as e.g. Aviation and Aerospace Agency Indonesia 2012; Bureau of Statistics Indonesia 2012; Energypedia 2012), and sharing and distributing data through partners such as universities and national research institutes (*Interviews*).

5.2.3 Lack of national network of investors

Despite efforts by the Indonesian Ministry of Energy to synchronize RVG projects, there is currently only little coordination ongoing between different organizations and projects (*Interviews*). This testifies to the absence of national networks. Often, this results in stand-alone projects and few spillovers of knowledge and experience. BOO investors can act as stimulants in the creation of such networks. They can **attend and conduct workshops, seminars and conferences** in order to get in touch with public and private organizations within and outside of Indonesia (*Interviews*). Furthermore, they can invest in **strategic partnerships with private and public actors** (UNEP 2005), e.g., through collaboration in market analysis, project implementation, financing or through formal long-term contracts with contractors and suppliers.

5.2.4 Lack of national technology supplier network

Even if Indonesia managed to increase general production levels, this holds only partly true for the technological components of a RVGs; locally produced micro hydro turbines do exist, but barely any solar photovoltaic panels, switch gears and control panels. This results in a limited local technology supplier network as most suppliers are from outside Indonesia (*Interviews*). The consequences are not so much higher cost – Indonesia has enacted a VAT and duty exemption for renewable energy core components (The Pew Charitable Trusts 2011) - but long delivery times for parts for repair or capacity extension. BOO investors face the trade-off of choosing from the limited selection of Indonesian suppliers (if at all available), accepting longer delivery times (and thus potentially longer outages), or having higher stocks which involves fixed capital). The recommended approach is to **buy from local suppliers if possible** (*Interviews*) and with this contribute to the extension of a national technology supplier network. This will keep the investor's fixed capital low and reduce delivery times for spare parts. **If local suppliers are absent, buy from international suppliers**, while considering stocking up with the most important spare parts (*Interviews*). This reduces dependence on international delivery times while keeping fixed capital limited.

5.2.5 Strongly regulated electricity market

The Indonesian electricity market is strongly regulated (*Interviews*, see also Section 2) resulting in fixed sales tariffs including heavy fuel and electricity subsidies (see e.g. Blum et al. 2013) and in PLN's dominance over IPPs and cooperatives in terms of power production. The latter is likely to change due to the opening of the power market since 2009. However, this partly liberalized market still limits BOO investors' freedom of action and lacks incentives for private investments. Measures as **advocating for market liberalization** can be undertaken (*Interviews*). However, such efforts are challenging and resource intensive (see Section 6 for policy recommendations).

5.2.6 Ineffective governmental structures

Practitioners observe that "there are 36 Ministries in Indonesia, several of them have rural electrification programs, yet still there is little cooperation" (*Interview with a development agency representative*). Due to the large number of national Indonesian governmental entities involved in rural electrification (going far beyond the Ministry of Energy and Resources or rural development), there are often overlapping functionalities and a lack of transparency³⁶. The role of regional governmental entities is rather marginal (compare also Figure 1). Furthermore, existing national regulations, and support schemes for rural electrification and renewable energy are not fully implemented yet. BOO investors can only indirectly address these facts by **maintaining professional contacts to regional governmental units in order to gain trust** and to leverage the units' importance (*Interviews*). Finally, this could incentivize the national government to implement a more decentralized, flexible approach. Additionally, BOO investors benefit from **decentralized operation, maintenance and administration** (compare section 5.1.2), e.g. by employing locals who are familiar with the governmental structure and by implementing an organizational structure which combines strong central offices in main cities with decentralized, flexible branches in order to cope with the governmental structure (*Interviews*).

5.2.7 Lack of national financial resources (equity and debt)

Similar to the very scarce financial resources at local level, there is also a lack of equity sponsors and Indonesian banks that provide capital at reasonable financing cost (for international equity and debt sponsors see 5.3.1) (Aron et al. 2009; *Interviews*). The most important measure that BOO investors can undertake in this regard is to **reduce business risks**. Common actions which reduce these risks are cost-effective choices of technologies³⁷ (UNEP 2005; Bardouille et al. 2012; Rickerson et al. 2012; *Interviews*), management and operation models, the bundling of projects in order to increase the market size and with this the attractiveness of investments (Roland & Glania 2011), the provision of guarantees for debt and equity investors (such as first loss risk guarantees, loan guarantees) if existent³⁸ (Bellanca & Wilson 2012; Roland & Glania 2011), and finally a sound business plan (UNEP 2005). Further, BOO investors can **employ new financing schemes** (Aron et al., 2009; Chaurey et al.

³⁶ Also more generally (i.e., independent from RVGs), Indonesia's institutional structures are hampering private sector engagement. This is for instance reflected by Indonesia's rank in the *Ease of Doing Business Ranking* - 128 out of 185 - (The World Bank 2013) and in the *Corruption Perceptions Index* (Transparency International 2013) – 118 out of 174.

³⁷ The village grid modeling software HOMER (Hybridization Optimization Model for Electric Renewables) identifies the most cost effective option for RVGs (Dean et al. 2012).

³⁸ While single RVGs might not be able to access such financial instruments due to scale and transaction cost issues, the bundling of projects might open-up such access.

2012; Glemarec 2012; Rickerson et al. 2012; *Interviews*) such as combined loan equity schemes where e.g. soft loans from private investors are combined with community equity or public-private loan schemes where loans are partially provided by private actors and partially by public actors such as a development agency or the government (such undertakings are also called Private Public Partnerships³⁹). In our interviews, a non-profit sector representative stated: “Through the establishment of collateral (i.e., register a company for the single RVG) we demonstrate to the private investor the potential of a stable return. This becomes sort of a mini IPP scheme” (*Interview with non-profit sector representative*).

5.3 International level

On the international level we identified two major barriers, which transform into challenges for BOO investors and can be addressed by specific measures.

5.3.1 Lack of international financial resources (debt, equity, carbon)

As financial resources on the local and national level are tight, BOO investors try to tap international resources. However, there is also a lack on the international level which again hits BOO investors in their struggle for funding (*Interviews*). It requires keeping up with international standards and involves higher transaction costs as well as currency challenges as equity and debt are usually provided in USD or EUR and not in the Indonesian currency IDR. The measures introduced in Section 5.2.7 (reducing business risks and employing new financing schemes) are applicable, however can be extended by two additional measures: Besides from commercial banks, BOO investors can **lend from impact investors** which accept higher risks at lower rates of return (Bellanca & Wilson 2012; *Interviews*). However, impact investors’ due diligences can be slow and more laborious as they cannot rely on standard financial assessments alone, but also collect data on e.g., social and environmental impacts (Yadoo 2012). Also their budget is limited compared to that of commercial banks. Concerning the measure of **applying for carbon credits** (Glemarec 2012); even if today there already existed a tailored carbon market product which would fit the requirements of RVGs, e.g., the Clean Development Mechanism (CDM) or its Programme of Activities (PoA), applying for carbon credits has drawbacks. They have a low financial potential as shown in Section 3 and the transaction costs for participating in carbon markets are high (Michaelowa et al. 2003; Michaelowa & Jotzo 2005; Ascui et al. 2007; Schneider et al. 2010). However if the CDM/PoA are understood as a quality insurance they potentially could lower business risks and help accessing equity and loans⁴⁰.

5.3.2 Disturbing international donor influence

It occurs that Indonesian private and public actors perceive international involvement as disruptive to national and local efforts in rural electrification, especially when it hinders the development of a private market (*Interviews*). First, one can observe that international donor organizations that consult Indonesian policy makers often follow their own agenda and miss out on coordinating their efforts with other international and national

³⁹ An even more focused variation of the Private Public Partnership is the Pro-Poor Public Private Partnership where the villagers are considered as consumers that receive benefits while at the same time being partners for business ventures.

⁴⁰ We regard it as rather speculative whether RVGs in Indonesia might profit from future additional climate finance (e.g., provided by the Green Climate Fund).

actors (*Interviews*). Furthermore, international donor organizations compete on the Indonesian job market for the most skilled and trained employees (international and Indonesian ones). In this struggle for labor, international donor organizations typically attract the best employees as they pay high salaries. In a labor market with a limited number of skilled labors, this results in a lack of skilled employees for the private and the local public sectors (*Interviews*). Reacting to such a market environment involves dialogue with international donor organizations in order to **strengthen their understanding of free market practices** and their importance for sustainable development (Bellanca & Wilson 2012).

6 Discussion: The role of government in attracting private investment

Our results in Sections 4 and 5 have shown that RVGs in Indonesia can potentially be an interesting business case for private investors if managed well. However, the findings also reveal that the investors' room for maneuvering is limited. In order to increase the diffusion rate, the investment environment and hence the risk/return profiles of RVGs need to be further improved via government action (see also Roland & Glania 2011). In Indonesia with its centralistic governmental organization (compare Section 2), such action has to mainly come from national regulatory institutions. Two topics seem to be most important: subsidy re-distribution (compare Section 4); and improving the investment environment through public action (compare Section 5).

Currently fossil fuel and other (non-renewable) energy subsidies in Indonesia are amongst the highest in non-OECD countries (Braithwaite et al. 2012; Mourougane 2010; Haeni et al. 2008). Due to the increasing pressure of these subsidies on public budgets and their negative effects in encouraging energy efficiency, the government is currently in the process of implementing subsidy reforms. However, reductions and abolition of subsidies in Indonesia is a very sensitive topic and tied politically as phasing out subsidies can have negative social effects, especially for the poor (Braithwaite et al. 2012; Mourougane 2010). For example, in 2012 “plans to raise subsidized fuel prices [...] failed to get the majority in the voting for approval from House of Representatives” (Permana et al. 2012, p.21) . The situation might be different when re-distributing subsidies from fossil fuels to renewable energy (DB Climate Change Advisors 2011). Subsidy shifts towards RVGs leverage private investments into rural electrification. It is hence the poorest communities – those without electricity – that would profit most. So the rationale of subsidies (to support the livelihood of the poor) would be upheld while removing their negative environmental side effects.

The results shown in Figure 4 (Section 4) highlight that per unit of electricity delivered especially by micro hydro projects only needs a small fraction of the subsidies, which are currently embodied in diesel based off-grid electricity generation. This is – to a lesser extent and depending on location – also often valid for solar PV/battery powered RVGs. Therefore, for RVGs to replace the standard option (diesel powered village grids), not all subsidies that would be embodied in diesel based electricity generation would have to be re-distributed fully. Hence, through subsidy re-distribution public money could be saved and in fact these savings could increase over time. Assuming increasing global fossil fuel prices, diesel subsidies would have to be increased over time in order to keep end-consumer prices in Indonesia relatively stable. At the same time, due to falling technology costs, especially in the case of solar PV/battery powered RVGs (Peters et al. 2011; ESMAP 2007; IRENA 2012), the re-distributed subsidies of future projects will have to be much lower; similar to a subsidy

phase-out over time. Subsidy reform could also help to terminate the misperception that diesel powered village grids exhibit lower costs than RVGs⁴¹ (Blum et al. 2013).

From a climate perspective, as diesel generators can be regarded as the business-as-usual solution for rural electrification in Indonesia (Haeni et al. 2008), a re-distribution of subsidies from fossil fuels to renewable off-grid technologies would substantially reduce the baseline emissions from rural electricity generation in Indonesia. In a recent article, Schmidt and colleagues (2012) argue that subsidy phase-out could be an integrated part of Nationally Appropriate Mitigation Actions⁴² (NAMAs) and should be encouraged through future climate finance schemes. Along the same line, we argue that subsidy re-distributions could potentially be credited as unilateral contribution to climate finance. Note that in order to assure efficiency of public spending, re-distributed subsidies should be paid based on the performance of a project instead of solely providing grants for equipment upfront (Ghosh et al. 2012). Furthermore, subsidies should only be one part of the revenue streams for private investors. Local payments for energy should especially be an integral part of the RVG business models. Finally, over-subsidization should be avoided (compare e.g., Hoppmann et al. 2013 for some negative impacts of over-subsidization in developed countries).

While our paper is focused on RVGs in Indonesia, the above thoughts also generally hold true for most off-grid technologies for other non-OECD countries, with low electrification rates, large decentralized renewable energy potentials and high subsidies for fossil-based electricity generation.

The second aspect where government action is required concerns improving the investment environment apart from a fuel subsidy reform. Our analysis (Section 5) shows that a whole array of barriers (translating into risks) stands in the way of private investments. While BOO investors can address many barriers via their business models (mainly those on the local level), others (mainly on the national level) go beyond their sphere of influence. Many of these barriers can translate into investment risks – scaring off investors and/or increasing financing costs. As the risk/return profile of projects must be attractive for investors and in the current situation RVG investments in Indonesia underlie high risks, only few investors with large risk appetite can be attracted (explaining the very low diffusion rate of privately financed RVGs).

Two recent UNDP studies (Glemarec et al. 2012; Waissbein et al. 2013) show that improving the investment environment by reducing the investment risks can attract new private investments and lead to lower financing costs and thereby substantially lower electricity generation costs. While these studies focus on on-grid renewable energy, we assume this is generally also the case for RVGs, as they are typically also based on a project finance structure, and therefore discuss them in light of our results⁴³. The UNDP defines two ways of de-risking renewable energy investments: financial instruments (e.g., guarantees or risk insurance) and policy instruments (e.g., technology standards or improved energy legislation). While the former mitigates the financial impact in

⁴¹ Widely spread in Indonesia as an interviewee confirmed “Rural Electrification through renewable energy has two problems: People can’t afford it and the government can’t afford to provide it” (*Interview*).

⁴² NAMAs are a key element of the in international climate negotiations and describe “sets of policies and actions tailored to the circumstances of individual countries that they agree to undertake as part of their commitment to reduce emissions.” (Höhne 2011, p.32; Michaelowa et al. 2012).

⁴³ We are aware that the risk categories partly differ between on-grid and RVG projects, e.g., due to different stakeholders involved. However, our discussion refers to the general line of thought that de-risking is essential for project-finance-based private investment.

case of a negative event affecting the project, the latter reduces or entirely removes the barriers that underlie the risks and thereby reduces the probability of a negative event occurring. Using the example of on-shore grid connected wind energy, their study shows that both financial and policy de-risking is effective and efficient.

In case of RVGs, the economic efficiency of financial instruments – if they are available at all – is more questionable; due to the small project scales of RVGs and the high transaction costs, these instruments can be expected to be very costly on a per kW basis. A solution to this might be the bundling of projects (e.g., through the CDM's PoA) so that the scale (e.g., in terms of kW) is increased and the impact of the transaction costs reduced at least to some extent. Together with the typically higher cost of financial instruments (compare Waissbein et al. 2013) this lack of micro-financial de-risking instruments and lower efficiency means that the role of policy instruments gets even more important in the case of RVGs. Other than for financial instruments, the economic efficiency of policy instruments is much less correlated with the individual project size but rather with the size of total investment that occurs on the national (in case of national policy instruments) or regional level (in case of sub-national instruments). Therefore, policy instruments to improve the investment environment should primarily act on the national/regional level, similarly as Waissbein et al. (2013) argue in the case of on-grid renewable energy. From our findings in Section 5 and reflecting upon insights from Glemarec et al. (2012) and Waissbein et al. (2013) the following four policy actions seem most effective in order to improve the investment environment for RVGs and thus reduce some predominant risks:

1. Energy market risk: Conduct a reform of the national renewable energy and electrification policies in order to align them. Part of this reform should be the effectively improved market access for private BOO investors and a re-distribution of subsidies (see above).
2. Institutional/licensing risk: Reduce overlapping functionalities and partly diverging programs of government bodies and agencies. Similarly to Waissbein et al. (2013) a “one-stop-shop” for RVGs could be created and equipped with the necessary executive competences. Such a RVG body could also be responsible for collecting and exchanging data (e.g., on renewable energy potentials, technologies or suppliers).
3. Technology risk: Introduce technology standards for RVGs so that suppliers, BOO investors and end-consumers have a good basis for their contracts and so that transaction costs are reduced (see also Roland & Glania 2011).
4. Financial risk: To improve the access to finance, the newly founded Indonesian Climate Change Trust Fund (ICCTF) could prioritize the support of RVGs. Special small scale finance vehicles for BOO investors could be designed and offered (see Section 5.1.5).

While this is just a very short list, further action could improve the investment environment and thereby leverage the diffusion of RVGs. Very important in this regard is educating investors (meaning both debt and equity sponsors), as they are often not familiar with the investment opportunities in off-grid projects. Generally, investors perceive projects in rural areas as riskier than projects in urban areas (Rickerson et al. 2012). By putting this risk perception in perspective, private investors could become more interested in RVGs (Roland & Glania 2011). The results on how to improve the investment environment for RVGs are country specific. In order to formulate policy recommendations for other countries, we regard a barrier analysis for that country as indispensable.

All the proposals discussed in this section promise to substantially increase the attractiveness of RVGs for private investors. However, we are fully aware that implementing these proposals would not be easy. The role of the political economy is pervasive when it comes to such reform projects, but discussing its role would go far beyond our research and the scope of this paper.

7 Conclusion

In this paper we ask how the risk/return profile of RVGs can be improved in order to attract private investments. First, we focus on the return aspect and identify potential local, national and international revenue streams for RVGs and compare them to costs. The analysis shows that potential local and national revenue streams are able to cover costs and therefore build the base for a profitable business case, at least in case of micro hydro powered village grids. While local revenue estimates are based on the WTP for electricity, national revenues are based on potentially re-distributed subsidies, both revenue streams are substantial. The role of international revenues in the form of climate credits turns out to be limited. Second, in order to understand the risk aspect, the paper analyzes investment barriers on a local, national and an international level and matches them with measures that BOO investors can take to remove the barriers. We find a wide range of measures for investors; however, we argue that BOO investors cannot solve the low diffusion of RVGs by themselves and that policy reforms are needed. The two most important governmental activities in this regard include the re-distribution of fossil fuel subsidies towards RVGs and public de-risking measures such as reforming the national renewable and electrification policies, reducing overlapping functionalities, introducing technology standards for RVGs, and improving access to finance.

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ANNEX

Annex A

Table A Potential revenue streams with lower and upper bound of considered values

Revenue streams	USD/kWh (IDR/kWh)	Method of determination	Sources
Local level Willingness to-pay (WTP)	Average: 0.18 (1,729) Range: 0.12 – 0.24 (1,136 – 2,285)	The range is determined through the lowest and highest available tariffs currently paid in Indonesian RVGs. These are determined through community agreements. The average is un-weighted.	Data from non-commercial RVG project field surveys Interviews
National level Fuel subsidies Electricity subsidies	Average: 0.29 (2,791) Range: 0.15 – 0.41 (1,420 – 3,866) Average: 0.38 (3,643) Range: 0.20 – 0.53 (1,865 – 5,039)	Diesel subsidies are calculated by subtracting the global fuel prices from the local fuel prices (following IEA’s opportunity cost approach). Electricity subsidies are calculated by subtracting PLN’s tariff from the LCOE of a diesel powered village grid (at Indonesian prices). The ranges are a function of location: fuel gets more expensive the more remote it is used; therefore the lower value is applicable for more central RVGs. The average represents medium distance from fuel distribution centers	IEA, 2010
International level Carbon credits	Average: 0.01 (9.5) Range: 0.009 – 0.016 (86 – 152)	The yearly emission reduction potential of a village (205.4 tCO ₂ /village/year) is divided by the yearly electricity production (365days * 558.5 kWh/village/day) which yields a relative emission reduction potential (0.001 tCO ₂ /kWh). This multiplied with the carbon price of 9 – 15.5 USD/tCO ₂ , results in potential carbon revenues in USD/kWh. The range is determined by the range of carbon prices. The average is un-weighted.	The Gold Standard - official website, 2012 Interviews

Annex B

Tabel B Overview of interviews for the risk analysis

	Interviewed persons in different organizations (Org.)		Geographical scope	Risk aspects	
	2011	2012		Barriers	Measures
Private sector (Prv)	Org.1 Person A Org.1 Person B Org.1 Person C	Org.1 Person A Org.1 Person B	Indonesia	X	X
		Org.2 Person A	Indonesia	X	X
		Org.3 Person A	Indonesia	X	X
	Org.4 Person A Org.4 Person B		Lao PDR		X
	Org.5 Person A		Cambodia		X
	Org.6 Person A		Cambodia		X
	Org.7 Person A		Global		X
Public sector (Pub)	Org.8 Person A Org.8 Person B Org.8 Person C		Indonesia	X	X
	Org.9 Person A		Indonesia	X	X
		Org.10 Person A Org.10 Person B	Indonesia	X	X
		Org.11 Person A Org.11 Person B	Indonesia	X	X
Development agencies (Dev)	Org.12 Person A Org.12 Person B Org.12 Person C	Org.12 Person A Org.12 Person B Org.12 Person C Org.12 Person D	Indonesia	X	X
Non-profit sector (Npr)	Org.13 Person A	Org.13 Person A Org.13 Person B	Indonesia	X	X
		Org.14 Person A	Indonesia	X	X

Annex C

Table C Barriers, measures and respective interview sources

	Barriers <i>Interview sources*</i>		Measures to address the respective barrier <i>Interview sources*</i> (for literature review sources see respective sections in Section 5)
Local (Section 5.1)	Lack of understanding the customers' needs	<i>Prv, Dev,</i>	Conduct market research and understand village specifics
		<i>Npr</i>	Introduce customer service
			Involve the community <i>Npr</i>
	Lack of decentralized operation, maintenance and administration	<i>Prv</i>	Implement a decentralized organizational structure
			Employ locals
	Unsteady electricity demand and uncertain forecasts	<i>Prv, Pub,</i>	Do scenarios for the demand forecast of each village
		<i>Dev</i>	Educate customers on efficient electricity use <i>Npr</i>
			Agree with local businesses on fixed and regular electricity purchases
	Lack of local human resources	<i>Prv, Dev</i>	Increase modularity and flexibility of design of the RVG
			Train and up-skill own, local staff <i>Prv, Pub</i>
Retain trained and skilled staff <i>Npr</i>			
Lack of local financial resources	<i>Prv, Pub,</i> <i>Dev, Npr</i>	Design a locally adapted tariff and payment scheme <i>Npr</i>	
		Foster local productive use and entrepreneurship <i>Npr</i>	
		Provide customers with access to loans <i>Prv</i>	
National (Section 5.2)	Lack of standards and knowledge transfer on best practices	<i>Prv, Pub,</i>	Draw from and advocate for existing best practice examples and standards <i>Npr</i>
		<i>Dev</i>	Conduct pilot projects, then scale up <i>Prv, Dev</i>
	Lack of information and data	<i>Prv</i>	Collect and share information and data <i>Dev</i>
	Lack of national network of investors	<i>Prv</i>	Attend and conduct workshops, seminars and conferences <i>Prv, Npr</i>
			Build strategic partnerships
	Lack of national technology supplier network	<i>Prv</i>	Buy from local suppliers whenever possible <i>Prv, Npr</i>
			Buy from international suppliers where necessary <i>Prv, Npr</i>
	Strongly regulated electricity market	<i>Prv</i>	Advocate for market liberalization <i>Npr</i>
	Ineffective governmental structures	<i>Prv, Pub,</i> <i>Dev, Npr</i>	Maintain professional contacts to governmental units in order to gain trust <i>Prv</i>
Organize company in a decentralized, flexible structure while employing locals <i>Prv</i>			
Lack of national financial resources (debt and equity)	<i>Prv, Npr</i>	Reduce business risk <i>Prv, Npr</i>	
		Loan from impact investors <i>Npr</i>	
		Employ new financing schemes <i>Prv, Npr</i>	
International (Section 5.3)	Lack of international financial resources (debt, equity, carbon)	<i>Prv, Npr</i>	Reduce business risk <i>Prv, Npr</i>
			Loan from impact investors <i>Npr</i>
			Employ new financing schemes <i>Prv, Npr</i>
			Apply for carbon credits
Negative externalities caused by international donors	<i>Prv, Dev</i>	Strengthen NGOs, governmental agencies and other non-private actors in their understanding of free market mechanisms	

* Abbreviations: Prv = private sector, Pub = public sector, Dev = development agencies, Npr = non-profit sector

Annex I

Paper 3

Applying the *Technological Innovation System and functions* framework to a complex technology in a Least Developed Country – implications from an extreme case

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Keywords: Sustainable transition; low-income country; institution; off-grid electrification; geographical level

Abstract

The central idea of this paper is to apply the *TIS and functions* concept to an “extreme” case that has not been previously investigated in the *TIS* community and differs strongly from cases analyzed thus far. Such an application can demonstrate the general validity of the concept in such cases and can help to identify weaknesses and potential room for improvement. Thereby, we aim to enrich the current theoretical debate in the *TIS* community in terms of the two most prominent discussions: the set and the definitions of *functions*, and the *geographical levels*. The “extreme” case consists of a thus far not investigated relatively complex technology in a least developed country (LDC): mini-grids in rural villages of Laos. Our findings provide new empirical insights into diffusion processes of a rural electrification technology in an LDC, which can be valuable for practitioners and policy makers. At the same time, our analysis points to shortcomings of the current *TIS and functions* framework, which we address by discussing the role of institutional factors beyond regulation – specifically cultural aspects – in the framework and their potential as a basis for the choice of appropriate *geographical levels*. Finally, we propose an extension of the definition of one *function* and discuss whether *functions* can be seen as dynamic capabilities on a systems level.

1 Introduction

While there are a number of frameworks useful for characterizing the innovation and diffusion of technologies (e.g., Rogers (2003) is very well suited for analyzing the diffusion of consumer products (Lundblad, 2003)), in this paper we apply the framework of *Technological Innovation System (TIS) and its functions*, which has been proven to deliver valuable insights into the development and diffusion processes of infrastructure technologies (Bergek, 2012; Truffer et al., 2012)¹. Even if often applied to innovations in the field of renewable energy and European countries, the framework is universally applicable (Hekkert et al., 2007; Bergek et al., 2008; Truffer et al., 2012). Being a relatively young field, the *TIS and functions* research community is still debating how to refine and further develop the framework in order to improve its explanatory power and its policy impact. Two topics are currently particularly discussed (Bergek, 2012; Truffer et al., 2012; IST, 2013): first, the set of *functions*, their role in the system and their individual definitions; and second, the role of *spatial aspects* and their integration into the *functions* framework via the distinction of *geographical levels*. From its inception, the *TIS and functions* framework has been strongly informed by empirical analyses. We build upon this tradition by starting off with a case which, however, significantly differs from analyzed cases². Hence, this paper follows the idea that applying the framework to a new “extreme” empirical case is useful for challenging the generalizability of the existing theoretical framework and thereby providing insights for the ongoing debate on how to improve it.

The innovation and diffusion of technologies is not independent from the socio-economic context in which they take place (Dosi, 1982; Rosenberg, 1982). The influence of socio-political, i.e., non-technical, parameters in this context is especially high for novel technologies and increases with the complexity of a technological artifact (Hughes, 1987; Tushman and Rosenkopf, 1992; Nelson and Nelson, 2002). Consequently, applying the *TIS and functions* framework to a new and rather complex technology in a country with socio-political parameters that differ strongly from the contexts in which the framework has been developed and applied thus far, promises to yield the most interesting findings: The first question in this regard is, how and to which extent is the current framework generalizable especially with regards to the *functions*, whose definitions are dominated by socio-

¹ In fact the genesis of the *TIS and functions* framework was empirically driven by infrastructure technologies, specifically renewable energy technologies.

² In his opening speech at the IST Conference 2012, Frank Geels, the Chairman of the STRN, called for papers which challenge the existing transition frameworks – among others – by applying new empirical data, within and outside the OECD context. This paper addresses this call by challenging the framework of the *functions of technological innovation systems (TIS)*. *TIS and functions* is a key framework in the field of sustainability transitions (Markard et al., 2012), for which the IST (International Sustainability Transitions) conference is the core annual meeting (www.ist13.ch). The STRN (Sustainability Transitions Research Network) is the respective research community network (www.transitionsnetwork.org).

political aspects? Second, can new findings be generated regarding *geographical levels*, if the case reveals new specifics – e.g., if a new level becomes relevant, that has not been looked at before?

We consider mini-grids in Lao People’s Democratic Republic (Lao PDR)³ to be such “extreme” case for three reasons. First, mini-grids are more complex in production, installation, and especially operation than the few technologies analysed in developing countries in previous studies (compare Section 2). Second, as a least developed country (LDC), Laos is a socio-economic context that differs strongly from countries analysed thus far. Third, the role of different *geographical levels* is persuasive: While the technological components are mostly developed and manufactured by firms outside of Laos, a mini-grid is typically installed and operated in rural villages. Hence, technological competence for operation and maintenance is needed at the *local* level. Hitherto, the *local* level has been ignored in *TIS and functions* analyses.

Our analysis reveals that institutions – specifically the non-regulatory aspects – are not well enough anchored in the *TIS and functions* framework and its definitions and therefore might have been overlooked in extant empirical studies. Additionally, our findings imply that the scope of one *function* should be extended. With regards to the *spatial aspects*, we propose to explicitly consider institutions when selecting the relevant *geographical levels*.

Besides providing theoretical insights, this paper is of practical relevance. For low-income countries, the development and diffusion of rural electrification technologies and specifically mini-grids based on renewable energy sources is commonly understood to be effective means of eradicating poverty and at the same time promoting sustainable development (UN AGECC, 2010; Cook, 2011; UNDP, 2011). Mini-grids are therefore a cornerstone technology in several international support programs as well as the United Nations’ Sustainable Energy for All Initiative (UN, 2013). However, despite the fact that renewable power technologies including renewable energy-based mini-grids in developing countries often bear lower costs than the baseline technologies (UN AGECC, 2010; Schmidt et al., 2012; Blum et al., 2013; Waissbein et al., 2013) the current diffusion rate of these technologies in developing countries is not sufficient to reach the initiatives’ goals in terms of poverty reduction and limiting average global warming to 2°C (GEA, 2012). To address this issue, this paper also aims to better explain the (lack of) diffusion of renewable energy-based mini electricity grids in Laos using the *TIS and functions* framework, thereby strengthening the empirical base of innovation studies in low-income contexts.

The remainder of the paper is structured as follows. Section 2 reviews the *TIS and functions* framework and the existent literature applied in developing countries. Section 3 briefly introduces the case, i.e., the mini-grid technology and Laos, and Section 4 describes our methodological approach.

³ Also referred to as Laos.

Based on the results in Section 5, Section 6 discusses theoretical and practical insights while Section 7 concludes.

2 A review of the *TIS and functions* framework and its application in developing countries

The *TIS* framework is frequently used to analyze systemic challenges regarding a specific technology's innovation and diffusion. The *functions* are an extension of the framework often used to identify bottlenecks and to derive policy recommendations (Bergek et al., 2008). Section 2.1 introduces the framework and a selection of issues currently debated in the *TIS* community. Section 2.2 reviews empirical research applying *TIS and its functions* to developing countries.

2.1 *TIS and functions*: The framework and debated issues

The *innovation system (IS)* literature has its roots in evolutionary economics and theories of interactive learning. It achieved prominence in innovation research in the 1990s (for an overview see e.g., Edquist 1997; Edquist et al. 2007). The *IS* literature defines the diffusion of innovation as a systemic process. Hence, the approach goes beyond analyzing a single organization and beyond a cost-competitive economic point of view (Jacobsson and Johnson, 2000). Depending on the investigated object, researchers have distinguished between national/regional, sectoral, and *technological innovation systems* (Carlsson et al. 2002; Malerba 2002). Of these various levels of analysis, the *TIS* focuses on specific technologies. Carlsson and Stankiewicz (1991, p.93) define a *TIS* as a “dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology.” *Actors, networks, institutions*, and the *technology* are also referred to as the *structural elements* of a *TIS* (Bergek et al., 2008). The central element, the *technology*, is defined by Bergek et al. (2008, p.408) as “material and immaterial objects [soft and hardware] [...] used to solve real-world technical problems,” and complemented by the concept of orgware (Hekkert et al., 2007)⁴. *Actors* encompass all entities/agents that are (passively or actively) involved in the diffusion of a technology, while *networks* refer to the intermediate forms of organization that serve to exchange information and other resources (Carlsson and Stankiewicz, 1991). *Institutions*⁵ refer to regulatory, normative and cognitive aspects that affect the *actors* and thereby the technological development (Carlsson and Stankiewicz, 1991; Markard and Truffer, 2008; Markard et al., 2012). The *TIS* helps to explain why a certain technology in a given environment

⁴ The terms soft-, hard- and orgware are defined by Dobrov (1979) as technical means, methods and procedures, knowledge and organizing activities which together account for the different facets of a technology.

⁵ Even if “in everyday language there is no clear distinction between institutions and [institutional] organizations” and as “often they are used as synonyms” Edquist and Johnson (in Edquist 1997, p.46) suggest so separate between institution and institutional organizations in research. We follow their advice and hereafter only refer to institutions, and not to institutional organizations when using the term *institutions*.

performs better in terms of development and/or diffusion than a rivalry technology or the same technology in different environments. A few years ago, a stream within the *TIS* literature introduced the concept of *functions*⁶, which aims to identify bottlenecks in the diffusion of one technology in (typically) one country and to derive policy recommendations (Bergek et al., 2005, 2008; Jacobsson and Bergek, 2006; Hekkert et al., 2007). Bergek et al. (2008, p.408) state that *functions* “directly influence the development, diffusion, and use of new technology and, thus, the performance of the innovation system.” Sometimes they are also referred to as *dynamic elements* of a *TIS*. As the *functions* are an emerging concept there is no complete agreement on the set of *functions* and their definitions (Bergek, 2012). In our analysis, we rely largely on Hekkert et al. (2007)⁷ as their definitions (see Table 1) are the outcome of a longstanding academic exchange between researchers from Sweden and Holland. Also they are formulated in a comprehensive way and validated in the course of many empirical applications.

⁶ The concept of *functions* has originally been introduced by Carlsson and Jacobsson (2004) to the *(T)IS*. Bergek et al. (2005) defined a set of seven functions which was also published in the context of developing countries (Jacobsson and Bergek, 2006). The in this research used definitions of the seven functions by Hekkert et al. (2007) originate from this research stream.

⁷ Currently, there is no agreement in the *TIS and functions* research community on whether *functions* are defined as processes or activities (Bergek, 2012). In our study, we will refer to *functions* as processes (Bergek et al., 2008).

Table 1 – Definitions of *functions* by Hekkert et al. (2007, p.586f)

Function	Definitions
F1 <i>Entrepreneurial activities</i>	“The existence of entrepreneurs in innovation systems is of prime importance. Without entrepreneurs innovation would not take place and the innovation system would not even exist. The role of the entrepreneur is to turn the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities.”
F2 <i>Knowledge development (learning)</i>	“Mechanisms of learning are at the heart of any innovation process. For instance, according to Lundvall: “the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning” [...]. Therefore, R&D and knowledge development are prerequisites within the innovation system. This <i>function</i> encompasses ‘learning by searching’ and ‘learning by doing’.”
F3 <i>Knowledge diffusion*</i>	“According to Carlsson and Stankiewicz the essential function of networks is the exchange of information. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors and market. Here policy decisions (standards, long term targets) should be consistent with the latest technological insights and, at the same time, R&D agendas are likely to be affected by changing norms and values. For example if there is a strong focus by society on renewable energy it is likely that a shift in R&D portfolios occurs towards a higher share of renewable energy projects. This way, network activity can be regarded as a precondition to ‘learning by interacting’. When user producer networks are concerned, it can also be regarded as ‘learning by using’.”**
F4 <i>Guidance of the search</i>	“The activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users fall under this system <i>function</i> . An example is the announcement of the policy goal to aim for a certain percentage of renewable energy in a future year. This grants a certain degree of legitimacy to the development of sustainable energy technologies and stimulates the mobilization of resources for this development. Expectations are also included, as occasionally expectations can converge on a specific topic and generate a momentum for change in a specific direction.”
F5 <i>Market formation</i>	“A new technology often has difficulties to compete with incumbent technologies, as is often the case for sustainable technologies. Therefore it is important to create protected spaces for new technologies. One possibility is the formation of temporary niche markets for specific applications of the technology [...].This can be done by governments but also by other agents in the innovation system. Another possibility is to create a temporary competitive advantage by favorable tax regimes or minimal consumption quotas, activities in the sphere of public policy.”
F6 <i>Resource mobilization</i>	“Resources, both financial and human, are necessary as a basic input to all the activities within the innovation system. Specifically for biomass technologies, the abundant availability of the biomass resource itself is also an underlying factor determining the success or failure of a project.”
F7 <i>Creation of legitimacy</i>	“In order to develop well, a new technology has to become part of an incumbent regime, or has to even overthrow it. Parties with vested interests will often oppose this force of ‘creative destruction’. In that case, advocacy coalitions can function as a catalyst to create legitimacy for the new technology and to counteract resistance to change.”

* The original definition by Hekkert et al. (2007) focuses exclusively on knowledge diffusion through networks. This definition falls short as knowledge is also diffused outside of networks; we therefore interpret the function slightly differently from Hekkert et al. (2007).

** For the analysis in this paper, we use a broader definition of the function and include: “The function captures the breadth and depth of the knowledge [...] and how that knowledge is diffused and combined in the system” (Jacobsson and Bergek, 2006), thereby going beyond the diffusion through networks, only.

Recently, Bergek (2012) as well as Truffer and colleagues (2012) identified some shortcomings of the framework, summarized the currently debated issues in the *TIS and functions* community and presented a research agenda. Bergek (2012) focuses on the theoretical advancement of the *functions* concept and highlights the yet to be stabilized set and definitions of the *functions*. Furthermore she points to the open question whether the *functions* have the role of activities or processes within the

system. Truffer et al. (2012) focus on the specific empirical field of energy-related *IS* to identify current shortcomings. Among other things, they highlight the need to incorporate *geographical* aspects in the *TIS* framework. While Bergek et al. (2008) mention the importance of *international* components, only the most recent publications call for a more specific integration of *geographical* – often also referred to as *spatial* – aspects in *IS* research (Coenen and Truffer, 2012; Coenen et al., 2012; Truffer and Coenen, 2012; Truffer et al., 2012). New empirical research differentiates between *international* and *national* (or *regional*) levels (Binz et al., 2012; Dewald and Truffer, 2012; Schmidt and Dabur, 2013). However, more research in novel empirical *geographical* settings is needed (Coenen et al., 2012). Also, thus far, only *international*, *national* and *regional* levels have been distinguished and analyzed – whereas the *local* level was ignored.

2.2 Application of *TIS and functions* in developing countries

Empirical research has strongly influenced the development of the *TIS and functions* framework.⁸ Such research is essential for deriving policy recommendations for specific technologies in certain environments – the ultimate aim of the framework. Since its beginnings, *TIS and functions* literature has been empirically strongly focused on renewable energy technologies, predominantly in European countries (see e.g., Johnson & Jacobsson 2001; Bergek & Jacobsson 2003). Innovation in the energy sector is still one of the strongest empirical streams in *TIS* research (Truffer et al., 2012): to date there have been about 50 publications applying *TIS and functions* empirically (Bergek, 2012; Truffer et al., 2012), of which most tackle energy *technologies* and only a few investigate other *technologies* (e.g., Fogelberg & Sandén 2008; Bélis-Bergouignan & Levy 2010; Kubezcko et al. 2006).

In terms of geography, the general *IS* literature theoretically and empirically incorporates developing country contexts. Lundvall et al. (2009) tackle the link between innovation and development, address *geographical* aspects, including *regional*, *national*, and *international* levels, and investigate *institutions* and policy making for development. Malerba and Mani (2009) describe actors, structures, and dynamics of sectoral innovation systems on the examples of various developing countries. And Jacobsson and Bergek (2006) introduce the *IS* and *functions* to development studies and argue that an *IS* in a developing country focuses on catching up rather than on “new to the world” innovations. In the *TIS and functions* research, empirical analyses outside high income countries are seldom.

⁸ However, initially the *functions* had been derived from the literature (Bergek, 2012).

Table 2 – Empirics on *TIS and functions* in a developing country context (based on the collection of literature applying *functions* by Bergek 2012)⁹

Authors (Year)	Technology	Geographical Context
(Agbemabiese et al., 2012)	Improved cook stoves	Ghana
(Binz et al., 2012)	Onsite wastewater treatment	China
(Liu and Kokko, 2012)	Neighborhood electric vehicles	China
(Schmidt and Dabur, 2013)	Large biogas	India

Currently, there are only four studies applying the *TIS and functions* to a developing country context (see Table 2). Of these articles, two contribute to the *geographical levels* debate (Binz et al., 2012; Schmidt and Dabur, 2013). Of the four identified articles, three focus on large industrializing economies (China and India); and only one article (Agbemabiese et al., 2012) focuses on an LDC, namely Ghana, however analyzing a relatively simple technology, namely cook stoves.

3 Introduction to the case: mini-grids in Laos

The mini-grid technology is well suited for our purpose in that compared to the only other technology analyzed via the *TIS and functions* framework in an LDC thus far (and compared to other off-grid technologies such as solar lanterns or SHS) its installation, operation and maintenance (O&M) are rather complex. Therefore the role of socio-political aspects can be expected to be very relevant (Hughes, 1987; Tushman and Rosenkopf, 1992). The complexity makes the technology also well suited for our aim of addressing the *geographical levels* debate: while the *technology* is mainly developed and produced on the *international* level (i.e., outside of Laos), its also complex installation and O&M take place on the *local* level – the Laotian village.

Laos is for four reasons an interesting geographical choice. First, as an LDC¹⁰ the context for technology innovation and diffusion in Laos is likely to differ strongly from the contexts thus far mainly analyzed – e.g., in terms of institutional settings and resource endowments. Second, Laos’ situation makes the consideration of *geographical levels* highly interesting: for an LDC with low technological capabilities, technology diffusion (facilitated by inputs and provision of funding, knowledge, and technologies) from the *international* level is highly important; on a *national* level a rather centralized system is in place where regions matter less; rural villages (*local* level) are disconnected geographically and also separated by their diverse ethno-linguistic backgrounds (compare Section 3.2). Third, the country strives for economic growth and understands electricity

⁹ Three additional papers using the *functions* framework in developing countries were identified (Van Alphen et al., 2008; Dantas, 2011; Gebreyesus and Sonobe, 2012), however, they apply the *functions* to several technologies or entire sectors and not to single technologies.

¹⁰ “The national poverty line in Laos is based on nutrition. A person is poor if she or he consumes less than an amount that buys 2,100 Kcal/day (plus a 30% allowance for non-food items).“ (UN 2010, p.3)

access as an appropriate means to help foster it (Lao PDR's National Assembly, 2011). In Laos, energy topics have relatively high political prominence compared to LDCs like Cambodia, where health issues are more pressing. Fourth, Laos has high renewable energy potential and is not locked into fossil fuel-based energy production¹¹. In summary, the *combination* of the selected technology and country result in an “extreme“ case in the sense, that a relative complex technology requiring a set of technological capabilities is analyzed in a country where the socio-political context differs strongly from the contexts in which complex technologies have thus far been analyzed. In the following subsections, the technology and the country are introduced in more detail.

3.1 The Technology

The mini-grid *technology* evolved in the 1980s in developing countries when energy authorities realized that a centralized electrification approach, which until then was the dominant strategy (in both industrialized and developing countries), is often not the most economic option for electrifying remote areas (Peskett, 2011). As a consequence, less costly technologies evolved, among them mini-grids.

In this paper we follow the World Bank ESMAP and define *mini-grid* as an isolated (i.e., off-grid), small (typical sizes vary between 5kW and 200kW) electricity grid which powers a rural village (ESMAP, 2007)¹². A mini-grid's purpose is to connect one or several power sources to the households of a village and other consumers (such as workshops) and balance the load with the supply. Frequently used power sources are diesel generators, micro hydropower plants¹³, wind power plants, biomass gasifiers, solar PV power plants or a combination of these (the latter is referred to as a hybrid system¹⁴). The choice of the power source depends on the availability (and cost) of natural resources. As we focus on renewable energy-based mini-grids in this study, the term mini-grids refers to renewable energy-based mini-grids from now on. The core components of a mini-grid are synchronizers, transformer(s), potentially a back-up battery to address intermittency of the sources; switchgear and the respective software to balance the load with the supply from the power plant(s), as well as the wiring (see Figure 1). In case the power source(s) produce direct current (DC)¹⁵, additional inverters are needed to feed the AC village network. The load is determined by the village's electricity demand, which depends on the number of households, their electric appliances (such as lamps, rice cookers, TVs, and radios), the demand of the social infrastructure (e.g., schools and medical centers)

¹¹ The *TIS* concept is often criticized for neglecting the influence of existing technological regimes (Smith et al., 2010). This critique is not so relevant in our case selection due to the absence of a dominant regime providing the same services.

¹² Sometimes also referred to as a *village grid* or *micro utility*.

¹³ In Laos pico hydro technology is used to electrify single households rather than whole communities (Bambawale et al., 2010).

¹⁴ Hybrid systems are claimed to be more reliable as the power production technologies can complement each other in a temporal sense (Roland and Glania, 2011).

¹⁵ Micro hydro, biomass gasifier, and wind power plants typically produce AC, while solar PV and batteries' output is DC (Roland and Glania, 2011).

and businesses (e.g., small grocery shops, coffee-processing plants and rice mills), and their respective consumption patterns (Blum et al., 2013). While mini-grids typically serve the same purpose, no single standard design exists, as each mini-grid has to be adjusted to the context in which it is implemented. For example, the final design heavily depends on factors such as amount and variability of supply and demand, and the availability and cost of materials and power sources (Inversin, 2000). Of the various off-grid electrification solutions, renewable energy-based mini-grids have the highest development potential and are thus well suited to address poverty and climate change simultaneously (Legros et al., 2009; Cook, 2011; Yadoo and Cruickshank, 2012).

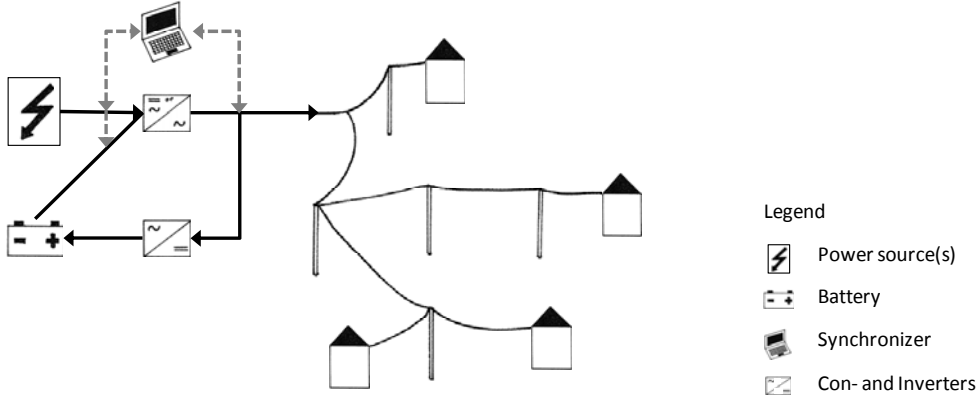


Figure 1 – Simplified sketch of a mini-grid design based on Roland and Glania (2011), Lopes et al. (2012), and Suwannakum (2007)

While mini-grid technology has progressed over the last years (especially profiting from developments in electronic power switching, renewables and battery technologies), some technological challenges remain, such as increasing the reliability of the used components and balancing demand and supply in case of extreme events such as unusual weather events (Peskett, 2011; Lopes et al., 2012). In order to resolve these issues, learning by doing and using are highly important. In addition, research into decreasing system costs is currently ongoing. An international community of researchers is addressing technical as well as economic, social, and political questions in theoretical studies (see, e.g., Phrakonkham et al. 2010; Brent & Rogers 2010; Alvial-Palavicino et al. 2011). This community meets in specialized conferences (such as the OTTI conference series 2003 and 2006; and the IOREC 2012). There researchers and practitioners share lessons from implemented projects (see, e.g., Khennas & Barnett 2000; Feibel 2010; Peskett 2011).

3.2 The Country

Lao People’s Democratic Republic is a relatively small (236,800 km²), land-locked, mountainous South East Asian country with an estimated population of about 6.5 million in 2012 (The CIA World Factbook, 2013). Its population is characterized by multiple ethnicities and religions (see Figure 2a). In 2010, about 26% of its rural population lived below the national poverty line (2010 estimates by

The CIA World Factbook 2013). The Lao PDR GDP per capita is estimated at 1,338 USD/year in 2012 (International Monetary Fund, 2013) which puts Laos in the category of an LDC (UN-OHRLLS, 2013). Formerly a closed economy, Lao PDR has become more market-oriented since adopting the “New Economic Mechanism” in 1986 and since allowing foreign investments in the 1990s (IMF, 2004; Kislenko, 2009). Laos understands the provision of electricity as a major requirement to reach its envisioned economic growth rate of at least 8% and its related development goals (Lao PDR’s National Assembly, 2011). Today, the electricity sector is dominated by the state-owned electricity utility Electricité du Laos (EDL), which operates under the Ministry of Energy and Mines (MEM) and controls the grids as well as the majority of power plants. There are three major regional grids (the Northern, central, and Southern grid) which are not yet interconnected in a national grid but are projected to be so in the future (Phonekeo 2008, *PUB*). In 2008, Laos’ own electricity production (consisting of 97.3% hydropower and about 2.7% fossil fuels) was complemented by Thai and Vietnamese electricity supplies (Phonekeo, 2008; LIRE and Helvetas Laos, 2011)¹⁶.

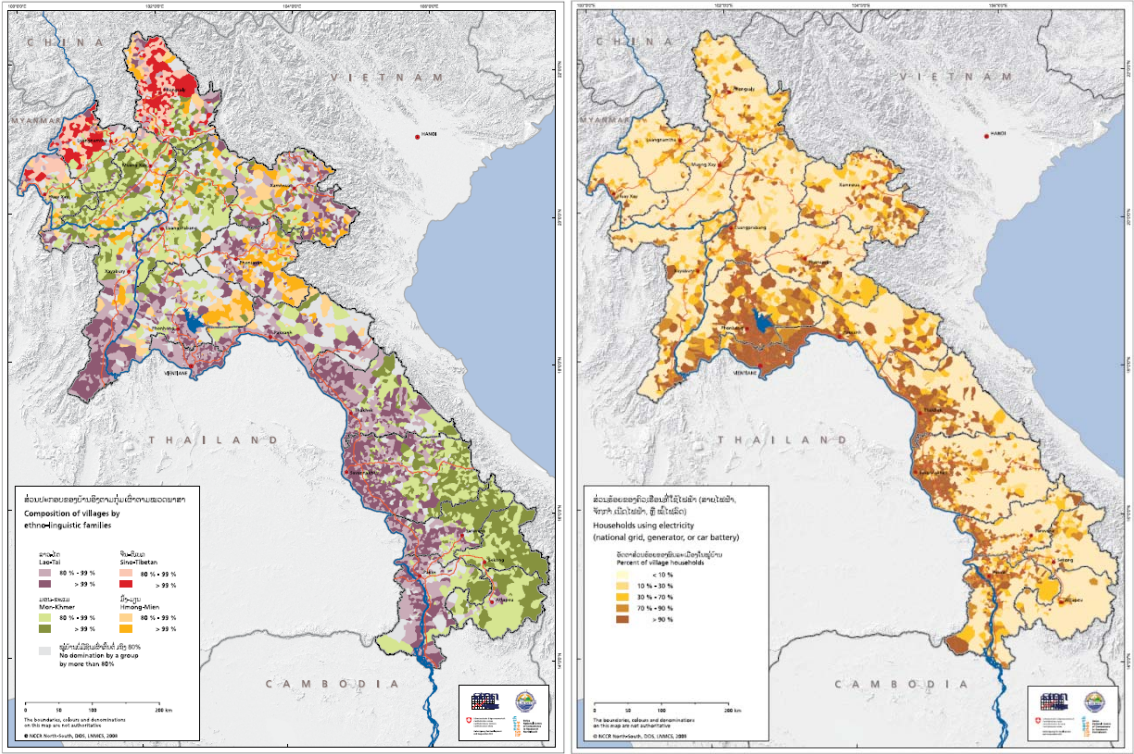


Figure 2a/b – Comparison of Laotian villages by ethno-linguistic groups (2a, left) and electrification rates (2b, right) in 2005 (Messerli et al., 2008)

In terms of rural electrification, Lao PDR managed to increase its electrification rate from 15% in 1995 to 73% in 2011 but the electrification rate varies strongly across the country’s regions (in counts of electrified households, compare also Figure 2b). The government aims to reach a 90%

¹⁶ The import surplus might in future turn to an export surplus, as investors from Thailand are currently building a large hydro dam in Laos, which exclusively provides power to the Thai grid. For more information on this controversially debated project see, e.g., The Economist (2012).

electrification rate by 2020 through grid extension, resettlement of villagers, and off-grid solutions (NIPPON KOEI and Lao Consulting Group, 2010; Lao PDR's National Assembly, 2011). Of these 90%, the government's current aim is to provide 81% of the population with grid electricity and 9% with off-grid solutions, namely in very remote and sparsely populated areas (Bambawale et al., 2010).¹⁷ However, while for these 9% several (competing) electrification plans exist, so far no electrification strategy has been enacted (ADB, 2010; Bambawale et al., 2010; NIPPON KOEI and Lao Consulting Group, 2010; Lao PDR's National Assembly, 2011; LIRE and Helvetas Laos, 2011). For the remaining 10% of the population (comprising thousands of villages) not even plans exist. Thus far, the investments in rural electrification have been managed by the Rural Electrification Division (RED) under the Ministry of Energy and Mines (MEM). Donations for rural electrification are to a large extent provided by international donors such as development agencies, international organizations (IOs, such as the World Bank and Asian Development Bank ADB), and non-governmental organizations (NGOs). They are provided in the form of programs, such as the World Bank's former Southern Provinces Rural Electrification Program (SPRE) or its current Rural Electrification Program (REP), and they focus mainly on grid extension along with SHS and few micro hydro powered mini-grids. (For an overview of all World Bank programs, see Bambawale et al. 2011, p.5). There is no official strategy to develop mini-grids, nor are there any related statistics. Through our field research and review of the literature, we identified about 68 installed renewable mini-grids in Laos¹⁸ (Helvetas Laos 2011; FONDEM 2009; ADB 2010; Phonekeo 2008; Bambawale et al. 2010, *PRV, PUB*).

In summary, mini-grids are well aligned to Lao PDR's development targets, its limited financial resources and renewable energy resources.

4 Method and Data

Following Yin (2003) we apply a qualitative single case study design. This is appropriate for explanatory and exploratory purposes in a complex, contemporary, and social context that has not been previously explored in depth (Eisenhardt, 1989; Gibbert et al., 2008). We particularly draw from the advantage that "single-case research typically exploits opportunities to explore a significant phenomenon under rare or extreme circumstances" (Eisenhardt & Graebner 2007, p. 27) as "atypical or extreme cases often reveal more information because they activate more actors and more basic

¹⁷ Grid extension is a costly solution with estimated costs of 11,000 to 15,000 USD/km, (NIPPON KOEI and Lao Consulting Group, 2010; LIRE and Helvetas Laos, 2011). Therefore, in many geographical areas it is more expensive than off-grid solutions such as SHS or mini-grids (LIRE and Helvetas Laos, 2011).

¹⁸ Different sources estimate that between 31 and 68 renewable energy-based (and 46 diesel-based) mini-grids have been installed in Laos. However, it was not possible to determine how many are still operational (Helvetas Laos 2011; FONDEM 2009; ADB 2010; Phonekeo 2008; Bambawale et al. 2010, *PRV, PUB*).

mechanisms in the situation studied” (Flyvbjerg 2006, p. 229). In the following sub-sections we describe our interview sampling (4.1), the data collection (4.2), and the analysis (4.3).

4.1 Sampling of interview partners

In our sampling of interview partners, the goal was to cover all relevant stakeholder groups in the Laotian mini-grid *TIS* in order to get a complete picture of *actors, institutions, networks*, and the *technology* as well as the processes in the *TIS*. We aimed to create a representative sample of interviewees on all three levels involved, the *local, national, and international* levels. Table 3 provides an overview of the interviewees; the stakeholder group they belong to and the *geographical level* at which they operate, as well as a stakeholder code. This code is used in the results section to indicate the source of interview findings.

Table 3 – Overview of interviewees

Stakeholder group	Code	Person	Interviewees	Geographical level
Private sector (companies)	<i>PRV</i>	1	Director of a private Laotian company	<i>national, international</i>
		2	Communications manager at a Laotian private company	<i>national</i>
		3	Village technician, Laotian, male	<i>local</i>
		4	Renewable energy consultant	<i>international</i>
		5	Impact investor	<i>international</i>
		6	Project manager at a clean energy investor	<i>international</i>
		7	Regional manager at a clean energy investor	<i>international</i>
Public sector (Government)	<i>PUB</i>	1	Head of the RED at the MEM	<i>national, international</i>
Development cooperation sector (non-governmental organizations NGOs, international organizations IOs, development agencies)	<i>DEV</i>	1	European project manager in a development agency based in Laos	<i>national, international</i>
		2	European project manager in an NGO based in Laos	<i>national, international</i>
		3	Laotian project manager in an NGO based in Laos	<i>national, international</i>
		4	Regional renewable energy expert in an IO	<i>national, international</i>
		5	Regional mini-grid expert in a development agency based in South East Asia	<i>international</i>
Villagers	<i>VIL</i>	1	Hmong, female villager 1	<i>local</i>
		2	Hmong, female villager 2	<i>local</i>
		3	Laotian, male villager & technician	<i>local</i>
		4	Laotian, female villager	<i>local</i>

4.2 Data collection

Following Yin (2003)’s analytical procedure, we follow an iterative process in collecting and analyzing data. For our analysis we drew from primary data sources, such as semi-structured interviews and on-site observations of a mini-grid which we obtained during two stays in Laos in 2010 and 2011. As another important source of information we extensively consulted existing literature

such as reports, policy documentation, websites, and other documentation (Eisenhardt & Graebner 2007). Specifically, we proceeded in seven sampling steps:

- (1) Through a web search, we obtained a first impression of the mini-grid *TIS* in Laos and its problems and identified a list of potential interview partners.
- (2) To complete the list and to refine our semi-structured interview guidelines, we followed Yin (2003)'s suggestion to conduct a pilot, and we visited Laos in 2010 for the first time for an exploratory face-to-face interview. For this pilot interview we selected a central actor in the *TIS* based on our web search who would be helpful in testing our interview guidelines and identifying additional interview partners.
- (3) After obtaining an extended list of potential interviewees, we requested interviews for mid-2011 and scheduled seven of a total of 17 interviews.
- (4) As preparation for the interviews, we scanned related documents and tailored the interview guidelines to each interviewee¹⁹.
- (5) We then conducted the arranged interviews and arranged for ten additional ones, five of which were conducted with Laotian nationals (mostly end-consumers) in their native languages (Lao or Hmong), translated by a Laotian to English. The high number of interviews which were arranged during the stay in Laos highlights the importance of on-site research, especially if interviewees are not easy accessible by email or phone or, like the villagers, have no English language skills. Each interview lasted between 30 and 120 minutes. With the consent of the interviewee, interviews were recorded; otherwise the interviewer took detailed notes.
- (6) To triangulate information provided by the different interviewees, we included observations of a visit in a mini-grid and additional written information obtained from interviewees. The visit to a mini-grid included a visit to the power plants, inspection of the civil construction, and a visit to the village and its grid network (see Figure 1). The observations were documented in videotapes and the researchers' notes. The additional written data provided by interviewees was of special value, as much of Laos-specific documents are not available online; interviewees therefore provide an important source of presentations, non-public policy documentation, and report drafts.
- (7) Finally, interviews were transcribed and saved together with the other documents (videotapes from the mini-grid visit and written secondary data) in a central, standardized electronic case study database, which facilitates the replication of the analysis.

4.3 Data analysis

To analyze the collected data, we structured the information via coding. Throughout this process, we followed an explanation-building logic which is applicable to both explanatory and exploratory

¹⁹ The interview guidelines are available upon request.

contexts (Yin, 2003). A defining characteristic of such logic is its iterative character, the consideration of rival explanations and the opportunity to examine the evidence from perspectives other than the one initially defined (Yin, 2003). For our analysis we used the software Atlas.ti. We applied a code list including all structural and dynamic elements of the *TIS*, and the three *geographical levels*. The list of codes was extended along the coding process whenever a peculiarity was not covered by the codes. In applying a reduction process (Marshall and Rossman, 1989) for additionally identified codes, we concluded that the most prominent additional code was “culture.” After coding all interview transcripts from Laos, we identified bottlenecks in the *TIS*.

5 Results

This section presents our findings on the structural (Section 5.1) and dynamic (Section 5.2) elements of the mini-grid *TIS*. In both subsections, the findings are structured along the elements as defined in the *TIS and functions* framework, and they touch upon the three *geographical levels* where relevant. Finally, we summarize the root causes of the identified bottlenecks in Section 5.3.

5.1 Structural elements

The structural elements of the *TIS* comprise the *technology*, the *actors and networks* as well as the *institutional* settings (Jacobsson and Bergek, 2011). The *technology* has been described in Section 3; the following paragraphs summarize the two remaining building blocks.

Actors and networks

In our research, we identified actors from the private sector, the non-profit sector, the public sector, and villagers. Table 4 provides an overview of relevant actors along the *geographical levels* (*international*, *national*, and *local*). We find that most different actors can be found at the *international* level, with the majority having a development-cooperation background. On the *national* level, the government and its sub-units are the central actor; however there is also a small private company, a few research institutes, and NGOs. *Locally*, villagers – acting as both electricity consumers (customers) and partly as technicians – are the only actor group. In the subsequent paragraph we show how the different actors are interrelated.

Table 4 – Actors in the Lao mini-grid TIS

Level	International	National	Local
Actors	Private companies <ul style="list-style-type: none"> – Project-based working companies – Technology suppliers International organizations (IO) <ul style="list-style-type: none"> – World Bank & International Finance Corporation (IFC) – Asian Development Bank Development agencies <ul style="list-style-type: none"> – JICA, NEDO (Japan) – NORAD (Finland) Nongovernmental organizations (NGO) <ul style="list-style-type: none"> – Helvetas (Swiss) – Fondem (French) Research Institutes <ul style="list-style-type: none"> – Swiss Federal Institute of Technology – Finland Future Research Center – Université Paris-Sud 	Private company <ul style="list-style-type: none"> – Renewable energy company Governmental units <ul style="list-style-type: none"> – Ministry of Energy and Mines (MEM) – Rural Electrification Division (RED) – Provincial Department of Energy and Mines (PDEM) Nongovernmental organizations (NGO) <ul style="list-style-type: none"> – National branch of Helvetas – PORDEA (Lao) Research institutes <ul style="list-style-type: none"> – Lao Institute for Renewable Energy (LIRE) – Local branch of the Finland Future Research Center 	Villagers (Consumers, Technicians)

Networks on *international* levels are strong but mainly exist within or between developed countries. Networks between the *international* and *national* levels are based on work visits (e.g., consulting, technical implementation of mini-grids) and local representations of international NGOs (e.g., Helvetas’ branch in Laos) in one direction and educational visits (e.g., national government representatives participating in international conferences and studying in universities abroad) in the other direction. On the *national* level, there are formal networks such as the organizational structure within the MEM (e.g., RED and the PDEM), which includes reporting, or project-based links between private companies and development-oriented organizations. At the same time, as most national actors live in the capital city Vientiane – which is rather small, thus allowing for exchange – informal networks exist (which are more difficult to identify). Turning to the *local* level, we find that while international actors seem to be well connected to national actors and the national government formally interacts with villagers through regulations, for example, international actors are barely connected to local actors. The only exchange here occurs during the limited time of the implementation of a mini-grid and is usually handicapped by language and custom issues. Within the *local* level, the villages have a strong sense of community and usually own a village council (however this depends on the ethnos of the villagers). Through relatives, single villages are connected to other villages and the towns but this is typically true only for those of the same ethnos.

Institutions

In the description of the institutions, we follow the same geographical order as above. On the *international* level, there are no binding regulatory institutions which are relevant for mini-grids in Laos; however, international normative and cognitive (i.e., cultural) institutions are relevant in that it is the developed countries’ duty to support developing countries (e.g., as documented in the

Millennium Development Goals) and as embodied in the current paradigm²⁰ that market-based solutions can best address many of today's development challenges (see e.g., the key statement of the World Bank's president Jim Yong Kim in a BBC interview (BBC, 2012)). At the *national* level, foreign support for development is welcomed in Lao (*PUB*). However, Lao PDR has a communist tradition and today remains a single party-ruled socialist republic (Pholsena, 2006; Kislenko, 2009). A certain skepticism towards market-based approaches is therefore prevalent (Kislenko 2009, *DEV*). Instead of individualism and entrepreneurship, values such as universal equality and the importance of community (collectivism)²¹ – values which are perceived to be in contrast to individuality and entrepreneurship – are promoted (Pholsena, 2006; Kislenko, 2009). In terms of languages, Lao is the official national language and English and French are used for international matters, while in the countryside 80 different local languages are spoken (Kislenko, 2009). In terms of national regulation, only a few indirect policies exist which support mini-grids (*DEV*); however, mini-grids are negatively affected by the complicated and sometimes slow and nontransparent bureaucratic process for obtaining permits (*DEV*) and high levels of corruption (Transparency International, 2013)²². On the *local* level, national regulation applies. However, normative/cognitive aspects of institutions differ from national ones and often even from village to village, due to many different ethnoses (Pholsena, 2006; Kislenko, 2009). While national educational levels are low, they are even lower in rural areas (Messerli et al., 2008). *Local* people largely lack language skills besides their native tongue, which is seldom Lao and differs with their ethnoses (Pholsena, 2006; Kislenko, 2009). In addition, the villages differ in their poverty levels, income-generating activities, and entrepreneurial spirit, (among other characteristics), which is also partly related to the ethnoses of the villagers (Kislenko 2009; Pholsena 2006; Epprecht et al. 2008, *DEV*). However, they appear to share a common paradigm, i.e., to view electricity similarly: most villagers are convinced that grid electricity is reliable and that the government (as the general “caretaker” for infrastructure) will provide them with access to (grid) electricity (*DEV*).

5.2 Functions (dynamic elements)

After having described the building blocks of the *TIS* for mini-grids in Laos, we now turn to the *functions*.

²⁰ In our study, paradigms go beyond “technological paradigms” as defined by Dosi (1982) as they also comprise the non-technical realm.

²¹ The collectivistic mindset is also supported by the dominant Buddhist (and among the Chinese and Vietnamese minorities often Tao and Confucian) traditions (Kislenko, 2009).

²² In 2012, Laos ranked 160 of 174 in Transparency International's Corruption Perceptions Index. This indicates the perception of the level of corruption in the country's public sector (Transparency International, 2013).

F1: Entrepreneurial activities

While in other developing countries such as Nepal or Sri Lanka, the relatively successful diffusion of mini-grids has mainly been driven by rural entrepreneurs (Peskest, 2011), in Laos private sector engagement in constructing and operating mini-grids is limited. On a *local* (village) level, entrepreneurial experience with mini-grids and related technologies is lacking (*DEV, PRV*). This has several largely institutional reasons. In the prevailing communist paradigm, market-based solutions, and entrepreneurial spirit are not solicited, and the state is expected to be the centralized supplier of infrastructure (Kislenko 2009; Pholsena 2006, *DEV*). More highly entrepreneurial Laotians – often ethnically stemming from China or Vietnam – tend to live in urban rather than rural areas (Pholsena, 2006; Kislenko, 2009) and therefore focus on business opportunities other than electrification. Hence, the extant pilots have been (often completely) installed and/or heavily supported by international partners (e.g., by international development agencies) (Milattanapheng et al. 2010, *DEV, PRV*). Due to an unfavorable national investment environment with high regulatory uncertainty (The World Bank, 2013)²³ and high levels of corruption (Transparency International, 2013) international private investors often refrain from investing in (rural) Laos (*PRV*). Currently, it is rather non-for-profit organizations that import the technology, cover the initial investments, build, and then transfer the mini-grids to the local communities (*DEV, PRV*). The lack of local entrepreneurs and international for-profit investors and the resulting dependence on non-profit actors is also the main reason that up-scaling has hardly occurred thus far. Finally, the regulatory environment is not only a hurdle for international investors (see above) but also hinders the few existing local business undertakings (The World Bank 2013b, *PRV*).

F2: Knowledge development (learning)

The mini-grid technology is mostly developed and improved in OECD countries such as Germany or the US, but it has also seen development in several non-OECD countries such as China, Nepal, and Indonesia, i.e., at the *international* level (*DEV, PRV, PUB*). In addition, most knowledge of economic, managerial, and social aspects of mini-grids is developed *internationally* (Brent & Rogers 2010; Yadoo & Cruickshank 2012; Ulsrud et al. 2011; Phrakonkham et al. 2010; Alvial-Palavicino et al. 2011; Blum et al. 2013; ESMAP 2008). Despite the existence of a small Laotian Research Center (LIRE), technical knowledge development is lacking on the *national* and *local* levels; even if the technology is applied locally, once installed it is mostly not further developed or adapted (*DEV*). Only very limited local knowledge development takes place with regard to managerial and social aspects, e.g., consumer needs specific to each village (*DEV, PRV*). Such local knowledge development is partly based on learning by doing as each mini-grid has to be individually designed to a village. Villagers are

²³ In the World Bank's 2013 Ease of Doing Business Report, Laos ranks 163 out of 185. In the sub-category "protecting investors," Lao is second to last (The World Bank, 2013).

barely involved in this process. The potential for learning by using the technology is typically high for mini-grids and could improve the technology (*DEV, PRV*). However, often villagers lack the basic knowledge necessary to allow for such learning. Hence, the learning feedbacks from using the technology *locally* to the development on the *international* level are limited (*DEV, PRV*).

F3: Knowledge diffusion

Knowledge is embedded in technology, written documents, and people (human resources); it travels with them within and between *geographical levels*. Additionally, networks are important for knowledge diffusion (Hekkert et al., 2007; Schmidt and Dabur, 2013). As discussed in Section 5.1, the networks are relatively strong between the *international* and *national* level, but the *local* level is not well connected to either of the other two levels. While knowledge within the *local* level is exchanged between neighbors, relatives, and friends through word of mouth (*VIL*), *internationally* developed knowledge of operations, management, and usage of mini-grids is diffused through training of local technicians and villagers (*DEV, PRV*). However, much of this knowledge is forgotten (*DEV, PRV, VIL*). The reasons are manifold, but the most significant one is the villagers' low educational levels paired with too few training units or manuals which technicians do not understand (e.g., because of illiteracy and language issues) (*DEV*). At the same time there also is a lack of transfer of knowledge from the *local* level – e.g., about customs and consumption patterns – to the *international* level (*DEV*). Such knowledge would support the technical development of mini-grids and the replication of successful operations and management approaches. The bottlenecks in the mutual exchange between the *international* and the *local* level stem in large part from (a) the villagers' low levels of education, lacking English skills, and no access to information and communication technologies (*DEV, PRV*), and (b) the international actors' lack of understanding of and adaptation to the different languages, and heterogeneous customs across Laotian villages. One might think the *national* level could provide the missing link by facilitating the translation of languages and customs. But even if first attempts in acquiring international knowledge are promising (*DEV, PRV, PUB*), there is no organizational unit that can serve as a “central brain,” absorbing and storing knowledge, and making it accessible to actors on the *national* and *local* level.

F4: Guidance of the search

As resources in Laos are scarce, resource transfer from the *international* level is a prerequisite for the smooth functioning of the mini-grid *TIS*. Therefore, the *international* level has a strong guiding role through (a) financial resources (in the form of donation, grants, and soft loans), and (b) non-financial resources (e.g., in the form of capacity building or supporting policy making). However, simultaneously there is strong competing international guidance for technologies that are alternatives to mini-grids, i.e., grid extension or SHS (ADB, 2010; Bambawale et al., 2010, 2011; NIPPON KOEI and Lao Consulting Group, 2010; LIRE and Helvetas Laos, 2011). This results in a lack of clear

guidance (*DEV*). Due to the communist political order and Laos' central structure, the government plays a major role on the *national* level and could potentially provide such clear guidance (*DEV, PRV, PUB*). However, the government acts rather opportunistically by accepting financial support for all kinds of electrification concepts from international donor organizations (e.g., the World Bank-funded Rural Electrification Master Plan strongly favors grid extension and SHS (NIPPON KOEI and Lao Consulting Group, 2010; LIRE and Helvetas Laos, 2011) or the resettlement of the rural population into towns with grid access (Cunnington 2011, *DEV*). This lack of a clear technology strategy results in a discontinuity and inconsistency in the guidance of the search (especially as many international donors only provide support once for a single locale) (NIPPON KOEI and Lao Consulting Group, 2010). On the *local* level, knowledge of electricity and its benefits diffuses to villagers by learning from acquaintances or relatives living in town (*F3, F5*). However, villagers barely become informed about the different solutions (mini-grid, grid extension, SHS), and their advantages and disadvantages (*DEV, PRV*). This often results in high expectations for any electrification approach (including mini-grids), e.g., in terms of reliability (*DEV, PRV*).

F5: Market formation

While international actors provide grants and donations for initial technology investments, and capacity building, they do not engage as financial build-own-operate (BOO) investors due to the unfavorable investment environment (The World Bank 2013b, *DEV, PRV*). This often results in pilot mini-grids with relatively low tariffs (*DEV, PRV*), which in turn affects the other villages' – electrified or not – willingness to pay cost-covering tariffs for electricity. In conclusion, international actors (unintentionally) do not support the formation of a self-sustaining market. National actors, most of all the government, would have the rationale to support the formation of a mini-grid market as economic calculations reveal it as the financially favorable electrification solution in remote areas where the cost of grid extension is disproportionately high and SHS provide only limited electricity (NIPPON KOEI and Lao Consulting Group, 2010; LIRE and Helvetas Laos, 2011). However, the government does not have a stringent strategy to foster mini-grids (compare *F4*). On the *local* level the demand for electricity depends on the size of the tariff and the villagers' knowledge of the benefits of electricity (willingness-to-pay, *F3*) (*DEV, PUB, VIL*). A study by the World Bank revealed that the rural population is willing to pay about 0.13 USD/kWh (NIPPON KOEI and Lao Consulting Group, 2010), which is more than triple EDL's current tariff of 0.04 USD/kWh²⁴ for grid-connected households (Bambawale et al., 2010; Ibrahim et al., 2010). However, the general willingness-to-pay for mini-grid electricity decreases if tariffs in mini-grid pilots are low and/or technical problems cause supply bottlenecks (*DEV, PRV, VIL*). Despite these potential revenues, which should be able to cover the cost

²⁴ Laos' residential tariffs are among the lowest in South East Asia (Bambawale et al., 2010; MEM Lao PDR, 2010).

(NIPPON KOEI and Lao Consulting Group, 2010; Blum et al., 2013), local markets do not develop, which is related to the lack of entrepreneurial spirit (see F1) and the lack of resources (see below).

F6: Resource mobilization

On the *national* and *local* levels, (trained) human and financial resources are scarce (*DEV*, *PRV*). While Laos' average level of education is low in international comparison, educational levels in rural areas are typically even lower than this average (Lao PDR's National Assembly 2011, *PRV*). This leads to a lack of Laotian engineers and technicians in rural as well as urban areas (Lao PDR's National Assembly, 2011). On the positive side, the local manual labor force is abundant (*PRV*). As for financial resources, a weak private financial sector exists on the *national* level; however, villagers typically do not have access and have to rely on informal capital markets, which are also limited in financial power (*DEV*). Furthermore, public financial resources are scarce and potential spending for electrification competes with other issues. Hence, Laos' electrification depends to a large degree on international resources (*PUB*). However, international financial and human resources are subject to high competition between different electrification approaches (mini-grid, grid extension, SHS, etc.), various organizations in Laos²⁵, and developing countries and other topics in international development support (*PRV*, *PUB*). This competition results in a lack of continuity of financial resource supply in the Lao mini-grid *TIS*.

F7: Creation of legitimacy

Mini-grids' legitimacy is based on different factors depending on the level, and it varies between the levels. The general international community acknowledges mini-grids as promising solutions to rural electrification in developing countries²⁶ due to their cost-effectiveness, their potential for productive use and their climate neutrality (Peskett, 2011). However, despite their clear limitations in terms of poverty reduction (Legros et al., 2009; Cook, 2011; Yadoo and Cruickshank, 2012), other technological solutions also enjoy a good reputation with many organizations (ADB, 2010; Bambawale et al., 2010; NIPPON KOEI and Lao Consulting Group, 2010; UNDP, 2011). *Nationally*, focusing especially on the government, mini-grids have low legitimacy (NIPPON KOEI & Lao Consulting Group 2010, *DEV*, *PUB*). This is a result of the government's tendency to follow their biggest donors' current strategy of trying to foster grid extension and SHS (compare *F4*). On the *local* level, mini-grids are legitimate as long as they offer reliable and affordable electricity (NIPPON KOEI & Lao Consulting Group 2010, *DEV*, *PRV*, *VIL*). However, as the villagers' paradigm is to trust the state to provide them with the best solution, the *national* lack of legitimacy for mini-grids has spread

²⁵ Organizations compete for skilled employees; better salaries and the organizations' reputation matter and lead to a scarcity of skilled employees in small organizations in the non-profit and private sector.

²⁶ Compare the World Bank's Rural Electrification Master Plan (NIPPON KOEI and Lao Consulting Group, 2010).

to the *local* level, resulting in a local belief that grid electricity is more reliable and affordable than electricity supplied by mini-grids²⁷ (Milattanapheng et al., 2010; NIPPON KOEI and Lao Consulting Group, 2010).

5.3 Systemic root causes for bottlenecks

Throughout our analysis, we identified a large array of bottlenecks in the diffusion of mini-grids in Laos. Other than a barrier analysis, the *TIS and functions* framework encompasses the capability to identify systemic roots of these bottlenecks and to derive systemic policy recommendations (Smits and Kuhlmann, 2004; Wieczorek and Hekkert, 2012).

One of the most important empirical observations is that the institutional settings (such as dominant paradigms, expectations or beliefs) of the mini-grid *TIS* differ strongly across the three *geographical levels*. On the *national* level, the most decisive institutions are arguably regulatory ones. While the government aims at economic growth and development, it is hesitant to implement and support policies that attract and support private investors and entrepreneurs. Furthermore, the regulatory actors display low technological capabilities and a reluctance to choose mini-grids as the appropriate technology for the electrification of the (at least) 10% non-electrified population outside of the grid range. Despite mini-grids' advantages over alternative technologies, national regulators indiscriminately support technologies of all kinds. Hence, the regulatory institutions on the *national* level remain weak. On the *international* level, the paradigm that LDCs need external support to induce economic growth and development and that such support should foster private sector involvement is consistent across actor groups. However, international actors' choice of appropriate technologies, the amount and means of resource transfer and the time horizons and scale of support differ widely. This results in technology plans and offers of support that are inconsistent and sometimes even contradictory. At the *local* level as well, some institutional settings are homogeneous and others heterogeneous: across the country, villagers believe the central state should provide the infrastructure and are rather skeptical of entrepreneurship. Additionally, the general level of education and professional training is low, often leading to unrealistic expectations vis-à-vis electrification on the part of the villagers. The heterogeneity of the institutional settings is of a cultural nature: the many ethnicities, languages, and dialects make each village *sui generis*.

These different institutional settings also reduce the flow of tangible and intangible resources – mainly knowledge – between the three *geographical levels* of the *TIS* in a situation where knowledge is relatively unbalanced between the levels. The cultural heterogeneity of villages hampers knowledge flows on the *local* level, i.e., between villages, as well as from the *international* to the *local* levels and vice versa: As information related to mini-grids comes predominantly from the *international* level and

²⁷ However, villagers have incomplete information on the reliability of the Laotian grid, which is in fact technically not more reliable than mini-grids (*DEV, PRV*).

is mostly coded in English or Laotian (not in the many languages that the different villages speak), it is not well received and is often not retained. For their part, villagers are unable to make their needs heard, which can result in a mismatch between local needs and international supply of resources. These lacking flows of knowledge consequently dampen systems building dynamics. Inconsistent notions of the appropriate electrification technology, villagers' noted attitudes towards the state's responsibility for infrastructure choice, along with the national government's lack of any technology preferences all contribute to great variability in technologies and concepts implemented from village to village. This reduces the chances of realizing network effects, which undermines the diffusion of mini-grids beyond the demonstration stage.

6 Discussion

This section first discusses the implications for the theoretical debate on how to improve the *TIS and functions* framework and then derives practical implications of our study's key results.

6.1 Implications for the ongoing *TIS and functions* debate

The main purpose of this paper was to apply the *TIS and functions* framework to an “extreme” case that differs strongly from cases analyzed thus far, thereby testing the framework under rigorous conditions. In the authors' view the framework generally functioned well in identifying the (systemic) bottlenecks for the diffusion and further improvement of mini-grids in Laos. As summarized in Section 5.3, our results revealed two main root causes for the non-diffusion of mini-grids in Laos that can enrich the theoretical debate: mismatches of institutional settings and the related impaired stock and unbalanced flow of knowledge. These two factors structure the discussion in the remainder of this section, which describes how they can inform the two discussions on the definitions of *functions* and the role of *geographical levels*.

Institutional settings

Institutions are generally considered in the *TIS and functions* analysis as a structural element. Our case however suggests that institutions should play a more central role in the framework in multiple ways. A precise definition of the concept at the outset is crucial as a more comprehensive view allows a better understanding of institutions. Although isolated attempts have been made to include such a view in the *TIS and functions*, as in Bergek et al. (2008) citing the seminal definition by North (1994) that focuses on culture, norms, laws, regulations and routines, no consensus on definitions has been reached thus far. A review of all studies that apply the *TIS and functions* empirically revealed that while the regulatory aspect is well covered, the cultural aspect of institutions has been seriously neglected²⁸: only one single empirical study makes cultural aspects explicit (Vidican et al., 2012). In

²⁸ The papers we reviewed are those listed in the collections by Bergek (2012) and Truffer et al. (2012).

our study, the importance of cultural aspects became very obvious in the case of Laos. However, also in other contexts (including developed countries) the factor culture might be relevant to explain the innovation and diffusion of a specific technology (Wirth et al., 2013) but might be less obvious and therefore be overlooked in *TIS and function* analyses. While culture is not a prominent aspect of the *TIS and functions* framework, other frameworks analyzing technological innovation and diffusion consider culture more explicitly: e.g., Rogers acknowledges cultural compatibility or incompatibility of an innovation; (Rogers 2003); in the multi-level perspective (MLP) one of the three levels, the socio-technical landscape, comprises “shared cultural beliefs, symbols and values” (Geels 2004, p. 913) To give culture an appropriate role also in the *TIS and functions* framework and avoid the danger of it being overlooked, we recommend strengthening the cultural aspects firstly in the structural element *institutions*, as the *TIS and functions* analysis is decisively influenced by the interpretation of this element. Institutional theory regards culture as part of holistically defined informal institutions (Scott, 2008), and defines it as “self-imposed codes of behaviour” which have a decisive influence on the evolution of institutions (North 1990, p.43). This definition has found its way into economic, political and cultural theory, sociology, and other transition frameworks, e.g., the MLP; we propose including this definition of institutions into the *TIS and functions* framework.

Secondly, we recommend integrating the holistic concept of institutions in the definition of the *functions*. This informs the first of the two debates in the *TIS* community that we seek to contribute to: the one on the role, the set and the definitions of *functions*. In fact the current *function* definitions bear institutional components (Hekkert et al., 2007; Bergek et al., 2008). Yet our literature review revealed that if these are empirically considered at all, they are only considered in terms of their regulatory dimension, neglecting the important cultural dimension which is prevalent in different *functions*. Our case of the Laotian mini-grid *TIS* shows that many *functions* can be strongly affected by the factor culture: e.g., *entrepreneurial activities (Function 1)* on the *local* level are weak to a large extent because villagers are skeptical of entrepreneurship. In Laos this skepticism has strong cultural roots linked to the villagers’ communist heritage and collectivist religious beliefs (compare Section 5.1).

Shifting the discussion to the second debate, the one on the role of *geographical levels*, we note that in accordance with recent empirical research (Binz et al., 2012; Dewald and Truffer, 2012; Schmidt and Dabur, 2013), our analysis differentiated three *geographical levels*²⁹ with regard to the identification of bottlenecks in the *TIS*. In our case the *geographically* split analysis proved highly useful and especially insightful where bottlenecks occur at *geographical* interfaces. As argued in Section 5.3, it is

²⁹ While other authors considered *international* levels (often as technology sourcing) and *national* levels (as levels where relevant regulations are set in place) as well as *regional* ones (see e.g. Binz et al. 2012; Dewald & Truffer 2012; Schmidt & Dabur 2013), we chose the *local* level for case-specific reasons, i.e., in order to include that level where the technology is implemented and used. Although this proved a valid choice in the case at hand, in general, the choice of levels of analysis that provide the most added value must be assessed on a case-by-case basis.

mainly institutional mismatches (including cultural aspects) on and between these levels that cause these bottlenecks. Hence, the selection of suitable *geographical levels* should consider institutional factors, including cultural aspects, and not only be guided by the location of the technology source and usage, as thus far done in extant literature (Binz et al., 2012; Schmidt and Dabur, 2013)³⁰. At this point, our case empirically supports earlier claims by Coenen et al. (2012); reviewing the work of economic geographers, they find that they “have drawn extensively on institutional analysis to successfully explain geographically uneven technology development, diffusion and innovation” (Coenen et al. 2012, p.973). Consequently, in the case of a federal governmental system and/or strong cultural differences between regions of a country (as in India, for example) a *regional* level might have to be pulled in.

Knowledge stocks and flows

As for institutional mismatches, our analysis shows that the unbalanced stocks together with the hampered flows of knowledge are an important bottleneck for the successful diffusion of mini-grids in Laos. We find that on the *national* and the *local* level, knowledge is often poorly absorbed or if absorbed at all, frequently quickly lost. Also this finding can inform the first *TIS and functions* debate (on the role, the set and the definitions of the *functions*). Knowledge loss may be less relevant (and obvious) in industrialized country contexts (therefore again potentially being overlooked) but can be assumed to be an issue in many developing countries³¹. In addition, knowledge that is transferred and retained *locally* is only seldom transformed and exploited. In a similar vein, earlier research on *IS* in developing countries noted that adaptation and acquisition of knowledge, skills and technologies is central (Van Alphen et al., 2008) and that the diffusion of applied knowledge follows the building up of specialized human capital (resource mobilization) (Jacobsson and Bergek, 2006). The *function knowledge diffusion* with its current definition therefore falls short and should be extended to include the retention and adaptation aspects, in order to be more universal and allow the consideration of knowledge issues (predominantly) found in developing countries. This finding is well in line with earlier research in development economics (Bell et al., 1984; Katz, 1984; Bell and Albu, 1999) which highlights the role of technological capabilities and knowledge absorption in the case of technology transfer. In this regard, also organizational science literature provides a helpful concept: *absorptive capacity*, which is defined as a firm’s “ability [...] to recognize the value of new, external information, assimilate it, and apply it to commercial ends” (Cohen & Levinthal 1990, p.128). While the concept of absorptive capacity was originally developed to describe knowledge management

³⁰ Our study shows that *geographical/territorial* levels, such as counties or villages, do not necessarily have to be congruent with institutional, e.g., cultural, ones (compare heterogeneity concerning ethno-linguistic groups in rural Laos Figure 2a).

³¹ Loss of knowledge can however be a serious issue in developed countries; e.g., if an actor or a person leaves an innovation system tacit knowledge might be lost (compare findings from the management literature, e.g., Jasimuddin et al. 2005; Hall & Andriani 2003)

processes within firms, it has also influenced the national innovation systems literature (Dahlman and Nelson, 1995; Edquist, 1997; Goodwin and Johnston, 1999; Narula, 2003; Castellacci and Natera, 2012). From its inception, the *TIS and functions* framework borrowed heavily from (evolutionary) economics and related innovation system literature as well as from organizational science (Carlsson and Stankiewicz, 1991). We therefore regard using the concept of absorptive capacity³² as defined in organizational literature as valid and suggest extending the *function knowledge diffusion* to *knowledge absorption* and thereby enriching earlier definitions (e.g., those of Hekkert et al. 2007; Bergek et al. 2008). To this end, we propose defining *knowledge absorption* as all processes that influence information flows in networks, including the *acquisition*, *assimilation* (storage and distribution), *transformation* and *exploitation* of knowledge (also in terms of learning by doing, using and interacting), to borrow from the corporate absorptive capacity literature (Todorova and Durisin, 2007).

The concept of absorptive capacity is part of the dynamic capability field in the management literature. Dynamic capabilities are defined on the firm level as the abilities to “integrate, build, and reconfigure internal and external competencies to address rapidly changing environments” and thereby become a source of competitive advantage (Teece et al. 1999, p.516). The so-called Carnegie school, which was highly influential in the development of the concept of dynamic capabilities (Gavetti et al., 2007), defines firms as complex “systems of coordinated action” (March & Simon 1993, p.2). The similarity of this definition to the definition of *TIS* as “dynamic network of agents interacting” (Carlsson & Stankiewicz 1991, p.93) raises the question of whether the *functions*’ role can be understood as *dynamic capabilities at the system level*.³³

6.2 Implications for practitioners

Instead of deriving recommendations for each bottleneck, in this section we focus on the systemic root causes summarized in Section 5.3 and offer suggestions for how mini-grids can be scaled up from demonstration projects through systemic political means.

The first root cause was the observation that a well-informed technology selection based on a technology needs assessment (see e.g., UNDP 2010) by the Laotian government could help filter the international support offered and thereby increase the likelihood of systems building and economies of scale and consequently the effectiveness and efficiency of international support.

However, selecting one or a limited number of preferred technologies is not sufficient. To address the situation of unbalanced knowledge and facilitate knowledge and resource flows, actors at the *national*

³² Recently a *TIS* study used the concept of absorptive capacity, enriching innovation systems with management literature. However, it kept the level of absorptive capacity strictly to the firm (Pohl and Yarime, 2012).

³³ First attempts in a similar direction, for example by defining system resources (Markard and Worch, 2009), have been made and suggest that this may indeed be possible.

level need to take a “translating” role between the different villages as well as between the *international* and the *local* level.

In summary, an alignment of the institutional settings is a prerequisite for bringing the diffusion of mini-grids beyond the demonstration stage. To this end, Laos needs a consistent technology strategy for electrifying that portion of the population which cannot be electrified via grid-extension cost-effectively. First, a technology needs assessment which equitably balances the pros and cons of different electrification technologies and results in the selection of preferred technologies would be one cornerstone of such a strategy. Second, to ensure the large-scale diffusion of the selected technologies, it also seems crucial to overcome the paradigm shaped by the communist heritage and to allow policies that attract and support entrepreneurs and the necessary private investment. Another important cornerstone would be the establishment of an institutional body that collects mini-grid-related knowledge from the *international* and the *local* level, stores, translates, and passes it on to the *local* and *international* levels, and mediates between actors from different cultural backgrounds. Such a “central brain” should be familiar with the different paradigms, languages, and codifications for knowledge and customs, and it should have access to actors on all *geographical levels*. A recent UNDP study on grid-connected wind energy in developing countries suggests a “one-stop-shop”, which serves as focal point, knowledge facilitator and mediator for all actors relevant for the development and diffusion of the technology (Waissbein et al., 2013). Such “one-stop-shop” could similarly work for mini-grids but (at least in the case of Laos) needs to be equipped with personnel from different cultural backgrounds in order to address the cultural heterogeneity of the country.

Based on such a technology strategy, Laos could request long-term, appropriately scaled, technology-specific, foreign support and/or evaluate and filter offered support.

While these practical implications are case-specific, we suppose that similar problems stemming from mismatches between institutional settings across the *geographical levels* can be found in many other developing countries where the diffusion of mini-grids (and other desired technologies) is very slow. Lately, also development cooperation practitioners are increasingly becoming aware that in the past rural electrification projects and support programs have often been framed too narrow, ignoring “deeper barriers related to technologies; infrastructures (e.g., local manufacturing, installation, and maintenance capabilities); markets; government policies and regulation; user practices; social norm; and cultural meaning” (Johnson 2013, p.1). Hence, a proper understanding of the situation in other countries and meaningful policy recommendations require case-specific analyses, which may utilize the *TIS and functions* framework.

7 Conclusion

This paper had two goals: first, to enhance the ongoing debate on how to advance the *TIS and functions* framework; and second, to provide new empirical insights into the reasons for the low diffusion rate of the mini-grid technology in Laos. To these ends we applied a qualitative single case study design and conducted desk research as well as two field trips (including interviews and visits to mini-grids) between 2010 and 2011.

The analysis' findings point to a mismatch between the institutional settings on the *international*, *national*, and the *local* (i.e., village) levels, which seems to be reflected in the cultural differences identified. Our paper provides implications for the current debates in the *TIS* community. With regard to the debate on the role, set and definitions of *functions*, we firstly suggest strengthening cultural aspects in the definition of the structural element *institutions*. Secondly, we recommend reconsidering institutional aspects, including cultural ones, in the definitions of the *functions*. For one specific *function* – *knowledge diffusion* – we propose an extension of the definition (making use of organizational theory) towards *knowledge absorption* to include all processes that influence information flows in networks, including the acquisition, assimilation (storage and distribution), transformation and exploitation of knowledge (also incorporating learning by doing, using and interacting). Based on this we discuss whether generally the *functions* could be seen as *dynamic capabilities on a system level* rather than processes or activities as currently debated.

As for the debate on making *geographical levels* explicit in the *TIS and functions* framework, we suggest considering all relevant institutions, cultural ones included, in the choice of appropriate *geographical levels*, instead of solely relying on the source and usage of technology.

In terms of implications for policy makers, we propose a national technology-specific electrification strategy which aligns the institutional settings and thereby removes the key barriers to the diffusion of mini-grids in Laos. Our findings specifically demonstrate the importance of two cornerstones of such a strategy: first, a selection of preferred technologies based on a “technology needs assessment”; and second, the establishment of a national body to collect, store, translate and pass on knowledge related to the selected technology as well as to mediate and translate between actors from different cultural backgrounds.

Despite these insights, our study reveals several limitations of which we highlight two. First, our study is limited to one single case: mini-grids in Laos. Additional studies analyzing other technologies in the context of “extreme” countries (such as least developed countries) could improve and extend the findings and help increasing the generalizability of our findings. Second, the paper's policy recommendations remain on a rather abstract level, as we experienced, applying the *TIS and functions* framework is valuable in identifying bottlenecks and their systemic root causes but does not easily yield concrete policy recommendations. In order to tap the full potential of the framework and derive

more specific and meaningful policy recommendations, other literature, from the field of development economics for example, may need to be integrated. E.g., more details on how to establish the suggested institutional body serving as “central brain” could be provided by consulting studies analyzing such features.

To conclude, challenging an existing theoretical framework by applying them to novel (and potentially “extreme”) cases proved fruitful in the authors’ view. Therefore we recommend doing further analyses applying transitions frameworks to such cases.

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Annex I

Paper 4

Unlocking the full potential of *Technological Innovation System and its functions* framework – a viewpoint

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Abstract

Many *technological innovation system (TIS)* studies including those that use a functions approach focus a) on issues of sustainability, like renewable energy technologies, and b) formulate policy recommendations to foster sustainable transition (for an overview see Truffer et al. 2012). However, these policy recommendations often remain relatively unspecific and policy makers are not advised well on how to tackle the complex and often systemic challenges associated with sustainable transitions. Our paper contributes to the ongoing debate about how to improve the translation of *TIS* research findings for the political sphere. To this end, we try to build bridges to established strands of research outside the ‘traditional core’ of transition studies by showing ways of enriching *TIS functions* approach findings with strands of knowledge from related disciplines. Specifically, we aim at increasing the policy relevance of *TIS and its functions* approach by discussing the potential complementary role of economic theories.

1 Introduction

Technological change is one cornerstone addressing today's environmental challenges. Among other issues, a significant and prompt renunciation from the current path of CO₂ emissions is urgently needed to curtail climate change (Pizer & Popp 2008). In order to direct technological change in its particular speed and direction, policy interventions are often needed to overcome certain barriers, which might hinder a rapid diffusion of the respective technology (Jaffe et al. 2002). Hence, the evaluation of different paths of technology innovation is a necessity question for today's policy makers. The *technological innovation system (TIS) and functions* framework respond to this by providing a tool to determine the various factors influencing technological innovation and diffusion.

The beauty of the analytical framework provided by the *TIS and functions* approach is its applicability to each singular technology (Carlsson & Stankiewicz 1991). This in turn results in high policy relevance when it comes to the question of how policy could incentivize the diffusion of the specific technology. In addition, the framework reduces the complexity of the considered case while at the same time providing a systemic view of it. The strength of the analytical framework is its *scanner function* by which it identifies systemic weaknesses (Smits & Kuhlmann 2004) – also referred to as bottlenecks (Markard & Truffer 2008; Johnson 2001; Jacobsson & Bergek 2011) in the *TIS*. The bottlenecks serve as starting point for policy recommendations to enhance the innovation and diffusion of a technology and thereby providing a sustainable transition (Bergek et al. 2008). However, based on a review of the existing literature in this field we found that although the *functions* approach is well suited to identify bottlenecks and pinpoint to systemic problems in a *TIS*; so far conclusions on policy recommendations are rather generic and too broad, if existing at all (see also Jacobsson & Karltorp 2012; Bélis-Bergouignan & Levy 2010). From the authors' experience working with political institutions, policy makers prefer relatively concrete and substantiated recommendations in order to find them meaningful and integrate them into existing policy.

Our paper contributes to the ongoing debate about how to improve the relevance and applicability of *TIS and functions* in research findings for the political forum. With this viewpoint we argue that by building bridges to established strands of research outside the innovation systems literature is a well suited means to better harness the potential of *TIS and functions* in terms of providing policy recommendations. This is closing a circle as the emergence of the *TIS* (Carlsson & Stankiewicz 1991) and its *functions* framework (Carlsson & Jacobsson 2004; Bergek et al. 2005; Jacobsson & Bergek 2006; Bergek et al. 2008; Hekkert et al. 2007) has been interdisciplinary in its outset (Johnson 2001; Fagerberg et al. 2006). In specific, we see room for making policy recommendations that are more specific and relevant by linking the functions approach, in particular the identified bottlenecks,

respectively to the existing theories from related fields: We argue that economics, organizational, and/or political science are particularly well suited in this regard. Especially economic theories, which is a classical domain to formulate policy recommendations concerned with the diffusion of innovation and technologies. Organizational studies and political sciences are important to consider as they encompass central actors of the innovation system who play a very crucial role in prompting technological change. While all three disciplines promise to be relevant, the examples used in this paper mainly stem from economic theories which best reflects the authors' expertise.

Our paper is structured as follows. Section 2 summarizes the *TIS and functions* framework and its roots; section 3 introduces our *TIS and functions* fitness program. We then apply the suggested program to two selected bottlenecks in section 4. Section 5 concludes with suggestions for further development of the fitness program.

2 A short review of *TIS and functions*

The roots of *TIS and functions*

The *TIS and functions* framework belongs – together with the national, regional, and sectoral innovation system – to the literature stream of systems of innovations which broadly speaking aims at explaining technological change. Innovation systems generally assume that technical change happens through the interplay of different actors strongly influenced by their institutional environment (Carlsson & Stankiewicz 1991). The approach was developed by drawing from “different theories of innovation such as interactive learning theories and evolutionary theories” – however does not consider itself as a theory but rather a framework (Edquist 1997, p.5). The practical purpose of innovation systems is to derive policies that foster technological change (Edquist 1997).

While National Innovation System (NIS), Regional Innovation System (RIS), and Sectoral Innovation System (SIS) have a sectoral level of analysis, the TIS describes a system of innovation which focuses on one specific technology – including its development, its production and its usage. It is defined by Carlsson and Stankiewicz as a “dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology“ (Carlsson & Stankiewicz 1991, p.93). In order to make the *TIS* performance “measurable” and to derive policy recommendations on how to support a desired technology, the concept of *functions* was developed. While a *TIS* analysis describes the static elements of the system, the *functions* describe its dynamics. Thus a “deeper understanding of socio-technical dynamics provides policy makers (and other actors) with a more solid base for policy interventions”

(Geels et al. 2008). While initially introduced by Johnson (2001), Bergek et al. (2005) firstly defined a set of seven functions, and Hekkert et al. (2007) published a set of definitions often used in empirical research (see Annex 1). Bergek and colleagues (2008) provided a guideline to conduct *TIS and functions* analysis, a scheme for analysis. It describes the procedure step by step and targets at identifying key policy issues (Bergek et al. 2008). Similar to the systems of innovation, the *functions* approach has interdisciplinary roots (Johnson 2001; Jacobsson & Bergek 2004; Carlsson & Stankiewicz 1991; Malerba 2002) . The set of functions is “based on a multidisciplinary base of literature (including evolutionary economics, political science, institutional economics, sociology of technology and population ecology) and by including dynamics the TIS approach came to include a broader flora of sub-processes than if it had been limited to one discipline” (Jacobsson & Bergek 2011, p. 46).

Today, the two sets of *functions* by Bergek and Hekkert are the ones predominantly used in empirical analyses (Bergek 2012; Truffer et al. 2012),. They slightly differ in the number and definition of *functions*¹. However, *TIS and functions* research mostly applies similar investigative questions regarding the success of a specific new technology and monitor this technology with the rigor of the proposed structure of analysis (Bergek et al. 2008; Suurs & Hekkert 2009; Praetorius et al. 2010; Hekkert & Ossebaard 2010). In the examples we provide for this viewpoint we refer to the set of *functions* provided by Hekkert et al. (2007) (Annex 1), while acknowledging the scheme of analysis provided by Bergek et al. (2008).

Advantages and shortcomings of *TIS and functions*

The framework has some clear advantages; first its uniqueness is its systemic approach that allows for integrating the different actors, networks and institutions (Carlsson & Stankiewicz 1991). Second, its interdisciplinary roots make the concept accessible to researchers from different fields (Jacobsson & Bergek 2011). Third, the combination of empirical phenomena and pragmatic theoretical choices make different *TIS* analyses comparable without *ceteris paribus* cases (Bergek et al. 2005; Johnson 2001; Jacobsson & Bergek 2004; Rickne & Jacobsson 1999). Fourth, *TIS and functions* is a handy tool to scan the innovation and diffusion process of a technology and identify bottlenecks that hinder the progression (Johnson 2001; Smits & Kuhlmann 2004; Bergek et al. 2008; Jacobsson & Bergek 2011). Fifth, its intention is to make research insights more beneficial for policy making and with this it seeks to solve real-world challenges (Hekkert et al. 2007; Bergek et al. 2008). Finally, related to all of the aforementioned points, with the capability to describe bottlenecks in their systemic nature, *TIS and*

¹ Often empirical researchers build a set of functions combined of the two or slightly modified to their own best knowledge.

functions are therefore able to identify systemic policy issues, which is the decisive advantage of the framework (Wieczorek & Hekkert 2012; Smits & Kuhlmann 2004).

While the advantages are diverse, there are also shortcomings. Besides the youth of the framework and the accompanying “teething troubles” (for a list of currently debated issues see e.g., Jacobsson & Bergek 2011; Bergek 2012; Truffer et al. 2012) – a main shortcoming is the unspecific policy recommendations that are derived from these empirical studies. This viewpoint addresses exactly this limitation by proposing an approach that builds upon the *TIS and functions* framework and hence supports the framework to harness its full potential.

3 Enriching TIS & functions

Empirical research not only identifies relevant policy issues, but goes one step beyond and develops policy recommendations. A short survey of recent empirical papers applying the *functions* approach, listed in two recent reviews (Bergek 2012; Truffer et al. 2012), shows that most empirical *TIS and functions* studies focus on: (a) issues of sustainability; out of 50 papers 45 are (renewable) energy-related and (b) formulate policy recommendations to foster sustainable transitions. However, out of 50 scientific, empirical articles on *TIS and functions* as listed by Bergek (2012), 45 derive very broad or no policy recommendations based on the identified bottlenecks and much less (approximately five) formulate these in a specific, direct applicable way. Therefore, many analyses remain underexploited for informing policy in a meaningful way.

We recommend to add an additional step to the *TIS and functions*’ scheme of analysis proposed by Bergek et al. (2008) where “by analyzing weaknesses in the functional pattern of the TIS (i.e. “what is actually going on”), we can identify the key blocking mechanisms that, in turn, lead us to a specification of the relevant policy issues.” (Bergek et al. 2008, p.423).

We put forth that theories that have served well in providing meaningful policy recommendations regarding very specific questions in the past could also serve *TIS and functions* scholars to solidify their policy implications. Such complementing theories encompass economic, organizational and political science theories. If one understands the *TIS and functions* framework as an indicator in order to identify bottlenecks in a system, then we propose to extend this indicator further by consulting

literature that has analyzed specific bottlenecks in order to derive tailored policy recommendations to tackle these bottlenecks². With this goal, we suggest the following procedure:

1. Conduct a *TIS and functions* analysis as proposed in step 1-6 in Bergek et al. (2008): this yields a set of bottlenecks and general policy issues (each associated to specific *functions*). The six steps are the following:

Step 1: the starting point for the analysis: defining the TIS in focus

Step 2: identifying the structural components of the TIS

Step 3: mapping the functional pattern of the TIS

Step 4: assessing the functionality of the TIS and setting process goals

Step 5: identify inducement and blocking mechanisms

Step 6: specify key policy issues

2. For each identified bottleneck (and the related policy issue), choose the literature from, e.g. political, economic or organizational science which is well suited to addresses the specific bottleneck and to develop policy recommendations.
3. Apply the theory to the bottleneck and with this help (re-)formulate a specific policy recommendation. Depending on the newness of the so gained insights it might even be fruitful to include a second iterative step and interview the most important TIS players (again) to answer questions which have newly arisen.

Identifying the complementary (economic, organizational or political) theory which fits a bottleneck best is challenging – especially for young and even highly specialized researchers. However, we are convinced it can be fruitful in order to come up with feasible policy recommendations increasing the relevance of the *TIS and functions* framework for policy-making.

As indicated above, we are utmost convinced that the most valuable theories can be found in economic, organizational and policy science. Besides political science, economic theories are the classical domain to formulate policy recommendations concerning diffusion of innovation and technologies. In addition, economic theory is one of the very few disciplines that demonstrate the ambition to provide foresighted policy recommendations daring to anticipate future conditions. However, the precise implementation guidelines for the various actors involved are not generally provided by economic theory. Organizational studies can help us to understand the inner logic of those

² Researchers need to gain detailed insights into the domain of the respective bottleneck; they for example need to understand the financial market, or the education and training system.

actors in the innovation system that play a crucial role in inducing technological change (Utterback 1971; Hekkert et al. 2007; Bergek et al. 2008). Political sciences are naturally an important source for *TIS and functions* as political power or strength is prevalent in some of the functions and, if nothing else, policy recommendations are to be drawn from this analysis (Bergek et al. 2008; Jacobsson & Bergek 2011). It is a great opportunity for the TIS and functions framework to capitalize on these disciplines' findings and integrate the best and most suitable insights into their policy recommendations. This suggestion does not come out of left field, as it basically activates the very basics of the *TIS and functions* framework (Jacobsson & Perez Vico 2010).

4 Two exemplary cases

To illustrate the potential of combining TIS with other literature in order to provide more specific policy recommendations, we show ideally how additional literature could strengthen the policy recommendations within two existing papers regarding the function *market formation* (F5). The choice for this specific *function* is motivated by the natural fit of *market formation* with economic theories. Specifically, we chose empirical papers on renewable energy technologies in two different contexts, one from an industrialized country and one from a developing country. Renewable energy technology was chosen as it reflects the TIS' empirical strength along with the authors' field of expertise. The distinctive country contexts reflect that different bottlenecks and the various theories that may have to be applied in diverse geographical contexts (Binz et al. 2012).

4.1 Negro et al. (2008): Biomass gasification in the Netherlands

In the paper, "The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system" Negro et al. (2008) apply the *TIS and functions* to identify "what really happened within the system." (p. 74f.).

With regard to the *function market formation* (F5) they identify a "lack of market formation by the Dutch government" (p. 66) in the first years of biomass gasification in the Netherlands. However, during that timeframe there was an attempt to implement biomass gasification through an initiative, which "can be regarded as the creation of a niche market for gasification technology (F5)" (p. 67).

The policy recommendations based on the sum of the identified bottlenecks are given on a rather abstract level, emphasizing "a structural misalignment [...] between the institutional framework within which the technology could have been developed, on the one hand, and the technical requirements on the other. Here, the government should have intervened by creating the right conditions for emerging technologies like biomass gasification, for instance by stimulating the System Functions [...] The

main blocking factor – throughout the entire period – is the absence of the national government with respect to a clear and consistent policy towards biomass gasification” (p. 74).³

Based on the identified bottlenecks which hinder the rise of an appropriate market for biogas, how could the paper profit by drawing from economic theory? We see a number of subsequent questions that economic literature could enlighten along with additional questions that policy makers would typically ask, based on our expert experience. For example, the authors proposed to create a protective environment for gasification technologies through policy/state intervention as “the innovation system did not function well enough to protect emerging technologies in the market environment” (p. 74). In line with this idea, it is often agreed upon, within the economic discipline, that welfare can be enhanced by a policy targeted towards an innovative technology, in this case biomass gasification (Boadway & Bruce 1984). But *how* could and should this be done?

A key question following the authors’ recommendations is the concrete choice of mechanism and its design implicating different consequences, e.g. with regard to welfare. What are potential efficiency losses due to rent seeking behavior, e.g. among project developers (Tullock 1967; Krueger 1974)? What policy (design) would indeed lead to a technology or sub-technology lock-in or lock-out (Unruh 2000; del Río & Unruh 2007; Hoppmann et al. 2013) and what are the alternatives to that chosen technology? What are potentially suitable political instruments, what are the characteristics and design option of those (Jaffe et al. 2002) and what are the different effects to be expected from their implementation (see e.g. the case of wind in (Butler & Neuhoff 2008)? To not only shed light on these questions from a theoretical point of view, a comparison with a similar case that has been evaluated ex post along these lines seems promising (e.g. PV in Germany) – as proposed by Negro et al. Such a procedure would also capitalize on one of the advantages of the *TIS and functions* approach, namely the possibility to compare cases indirectly by applying the standards of the functions approach.

4.2 Schmidt & Dabur (2013): Large-scale biogas in India

For the case of developing countries, we analyzed a paper written by Schmidt & Dabur (2013): “Explaining the diffusion of biogas in India: a new functional approach considering national borders and technology transfer”. An array of bottlenecks were identified by the two authors for the *function market formation*. We focus on two bottlenecks, namely the “lack of market openness” and a “high level of bureaucracy”. Both might cause a “lack of participation by private sector” combined with “favour (such as subsidies) to conventional energy and non-consideration of externalities” which negatively affects “the relative competitiveness of biomethanation technology”. With regard to the

³ More concrete policy recommendations are postponed by the authors as they understand their study as a starting point for a comparison of differently successful cases.

national *TIS* the authors recommend to “reduce bureaucratic hurdles; [and] gradually phase-out fuel and fertilizer subsidies”.

These policy recommendations directly address the bottlenecks and already mention the first important concepts in this realm. What remains unaddressed are the questions that follow from these recommendations and that would typically be asked by policy makers, e.g., how bureaucratic hurdles could be reduced? The developing economic literature and reports by practitioners from developing cooperation, such as the World Bank, proposes models to address this issue: “Removing obstacles to innovation means fighting anticompetitive and monopolistic practices, suppressing bureaucratic hurdles, and adapting the regulatory framework to support the search for and diffusion of novelty. It is a task that by nature should mobilize many areas of government—taxes, customs, procurement, and standards, for example—and requires vigilant action. This task is particularly necessary, but difficult, in developing country contexts” (IEA et al. 2010, p.13). Building on such sources, Schmidt & Dabur could have provided more concrete insights on where to start overcoming these barriers would be most efficient and more effective. Similar questions arise with regard to the policy recommendations tackling the lack of market openness, namely the removal of subsidies for fertilizers. Would it be best to gradually phase-out these subsidies, to cut them off immediately or to redistribute them (Birol et al. 1995; Stiglitz 1997). In case of the latter, what could be expected in terms of rent seeking (Sturzenegger & Tommasi 1994)? Even more far-reaching questions – that certainly would not be in the focus in a first step – would be: What effects could be expected in regard to the traditional fertilizer industry if biogas by-products replace their products? In the case of a gradual phase-out or cut-off, how would prices for agricultural products and energy prices be affected and how would an input price change in these two areas affect economic inequality and the poor (Ray 1998)? Resource reallocation, e.g. subsidy redistribution, mostly comes at a price, and what are the costs of such an expenditure-switching policy (Ray 1998)? Without answers to some of these questions, the policy impact on their analysis is likely to be very limited, giving away the opportunity for real impact in the political arena.

Having illustrated how our approach could be fruitful for two specific cases, in the following we provide a number of theories from economic and organizational sciences that potentially fit the *functions*⁴. This list is not exhaustive, but useful to get a first impression. Often theories can differ between the industrialized and developing country context therefore we listed them accordingly.

⁴ Some of them informed the genesis of the functions in the first place.

Table 1 – Selection of other economic and organizational theories along functions of a TIS (functions as in Hekkert et al. 2007; Bergek et al. 2008)

Function	General theories	Theories specifically referring to developing countries
F1 Entrepreneurial activities	<ul style="list-style-type: none"> • The entrepreneur as source of creative responses and new combinations of economic value creation leading to economic change: (Schumpeter 1912; Schumpeter 1942) • Locus of entrepreneurship: (Rumelt 2005) • Entrepreneurship as a field of research: (Shane & Venkataraman 2000) • Geography of enterprise: (Krumme 1969) • The dichotomy of individual and opportunity as key paradigm for entrepreneurship research: (Eckhardt & Shane 2003) • Entrepreneurship research: (Acs & Audretsch 2010) 	<ul style="list-style-type: none"> • Cultural differences in entrepreneurship: (Morris et al. 1994) • Economic development and cross-border investments: (Dunning 1958; de Mello 1999)
F2 Knowledge development	<ul style="list-style-type: none"> • Knowledge as competitive advantage: (Argote & Ingram 2000) • Strategic alliances and knowledge transfer: (Mowery et al. 1996) 	<ul style="list-style-type: none"> • Technology transfer: (Davies 1977)
F3 Knowledge diffusion	<ul style="list-style-type: none"> • Global production networks: (Ernst & Kim 2002) • Knowledge based international growth: (Autio et al. 2000) • Absorptive capacity: (Zhara & George 2002; Cohen & Levinthal 1990; Todorova & Durisin 2007) 	<ul style="list-style-type: none"> • International technology diffusion: (Keller et al. 2000; Keller 2001) • Industrial clusters in developing countries: (Bell & Albu 1999)
F4 Guidance of search	<ul style="list-style-type: none"> • Search cost/transaction cost: (Coase 1960; Williamson 1979; Simon 1991) • Critique of TC theory in firm context: (Ghoshal & Moran 1996) • Theory of the firm: (Rumelt 1997) 	
F5 Market formation	<ul style="list-style-type: none"> • Favorability of Markets: (Smith 1776) • Markets as mechanisms to make use of disperse and incomplete knowledge in society: (Hayek 1945) • Sociological view of market creation: (Fligstein 1996; White 1981) • Networks for market development: (Coviello & Munro 1995) • Role of politics and customers in green market creation: (Wüstenhagen & Billharz 2006) • Diffusion: (Rogers 2003) 	<ul style="list-style-type: none"> • Trade, FDI and technology transfer: (Saggi 2002)
F6 Resource mobilization	<ul style="list-style-type: none"> • Sociology's Resource mobilization perspective: (McCarthy & Zald 1977) • Opportunity perception: (Sorensen & Sorenson 2003) 	<ul style="list-style-type: none"> • Economics of development: (Gillis et al. 1992)

F7 Legitimacy	<ul style="list-style-type: none"> • Organizational legitimacy: (Suchman 1995; Dowling & Pfeffer 1975) • Social acceptance of RET: (Wüstenhagen et al. 2007) • Window of opportunity: (Perez & Soete 1988; Tyre & Orlikowski 1994)
F8 Development of positive externalities	<ul style="list-style-type: none"> • External effects/external economies: (Marshall 1890) • Dominant design and firm survival: (Suarez & Utterback 1995) • Competition and network externalities: (Porter 1998; Katz & Shapiro 1985)

The theories chosen for each function are only first traces into fields that could answer the most typical questions in that field. The literature listed encompasses seminal papers in their area of expertise. They are selected to be a starting point for venues into the theories and consequently literature which would improve policy recommendations as a consequence of the bottlenecks identified in the respective function.

5 Conclusion

In this viewpoint we propose to enrich empirical analyses which are based on the *TIS and functions* framework with related theory, hence literature in order to improve the policy relevance of these analyses. In specific, we suggest to continue using the framework as a “scanner” to identify bottlenecks which hinder the innovation and diffusion of a technology. However, instead of directly deriving policy recommendations from these identified bottlenecks – as mostly being done in empirical *TIS and functions* analyses today – we propose to draw from further literature that specifically addresses each identified bottleneck and combine the findings from the *TIS and functions* analysis with these insights. This can either directly result in more specific policy recommendations or lead to questions, which – in a second iterative step – could then be addressed via interviews with actors in the TIS. In order to illustrate our arguments, we choose two exemplary publications applying the *TIS and functions* empirically and discuss how the papers’ policy recommendations regarding one specific function could become more specific by combining the authors’ findings with additional literature. Finally we offer a non-exhaustive table of literature ordered by the frameworks’ functions, which serves as stimulus for the question: which literature could help *TIS* scholars in making recommendations for policymakers more specific?

We are convinced of the frameworks’ large potential in terms of informing policy makers and providing them with proposals on how to support a specific technology. Policy advice is an important

target of the *TIS and functions* framework - and empirically, most papers tackle highly relevant real world problems. However, the policy relevance of the framework remains mostly untapped – a fact that has already been recognized within the *TIS* community: “Due to different disciplinary backgrounds only a limited number of insights from the field of innovation studies are applied to this new and rapid growing field of sustainable socio-technical change” (Hekkert & Negro 2009, p. 584). In order to unlock the high potential of the framework and turn the *TIS*’ multidisciplinary into an advantage, it is necessary to make the policy recommendations more specific and enrich them with findings from other disciplines (Bélis-Bergouignan & Levy 2010).

One might ask why should *TIS and functions* scholar not leave the specific policy recommendations to scholars from the other disciplines (who focus on each bottleneck)? The answer lies in the frameworks’ advantage: other than most approaches the *TIS and functions* framework bears the potential to identify systemic bottlenecks. In many cases, only systemic policy instruments can remove such systemic bottlenecks (Smits & Kuhlmann 2004; Truffer et al. 2012; Jacobsson & Bergek 2006). Therefore, it is important, that *TIS and functions* scholars provide recommendations for systemic policy intervention, which are meaningful to policy makers.

Besides increasing the level of specification, in order to escalate the policy relevance of *TIS and functions* analyses, researchers ideally make clear why policy should support the specific technology analyzed. Our literature review revealed that most papers fall short of explaining the reasons that speak for policy intervention in the first place. Specifically, if papers propose technology-specific support, the question has to be considered whether technology-specific policies are justifiable and what the (dis-)advantages of such specific instruments compared to technology-neutral instruments are (Azar & Sandén 2011). In summary, when using the functions framework to provide policy recommendations, researchers need to make an argument addressing the technology-specific normativity.

To conclude, we are hopeful, that the *TIS and functions* research will be able to increase its policy impact, when being able to provide more specific policy recommendations. At the same time, we are aware that this is not an easy task that comes at low cost. We regard this paper rather as a stepping stone in the entire discussion of how to progress transitions research.

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ANNEX 1

Definitions of *functions* by Hekkert et al. (2007, p.586f)

Function	Definitions
F1 <i>Entrepreneurial activities</i>	“The existence of entrepreneurs in innovation systems is of prime importance. Without entrepreneurs innovation would not take place and the innovation system would not even exist. The role of the entrepreneur is to turn the potential of new knowledge development, networks and markets into concrete action to generate and take advantage of business opportunities.”
F2 <i>Knowledge development (learning)</i>	“Mechanisms of learning are at the heart of any innovation process. For instance, according to Lundvall: “the most fundamental resource in the modern economy is knowledge and, accordingly, the most important process is learning” [...]. Therefore, R&D and knowledge development are prerequisites within the innovation system. This function encompasses ‘learning by searching’ and ‘learning by doing’.”
F3 <i>Knowledge diffusion through networks</i>	“According to Carlsson and Stankiewicz the essential function of networks is the exchange of information. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors and market. Here policy decisions (standards, long term targets) should be consistent with the latest technological insights and, at the same time, R&D agendas are likely to be affected by changing norms and values. For example if there is a strong focus by society on renewable energy it is likely that a shift in R&D portfolios occurs towards a higher share of renewable energy projects. This way, network activity can be regarded as a precondition to ‘learning by interacting’. When user producer networks are concerned, it can also be regarded as ‘learning by using’.”
F4 <i>Guidance of the search</i>	“The activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users fall under this system function. An example is the announcement of the policy goal to aim for a certain percentage of renewable energy in a future year. This grants a certain degree of legitimacy to the development of sustainable energy technologies and stimulates the mobilization of resources for this development. Expectations are also included, as occasionally expectations can converge on a specific topic and generate a momentum for change in a specific direction.”
F5 <i>Market formation</i>	“A new technology often has difficulties to compete with incumbent technologies, as is often the case for sustainable technologies. Therefore it is important to create protected spaces for new technologies. One possibility is the formation of temporary niche markets for specific applications of the technology [...]. This can be done by governments but also by other agents in the innovation system. Another possibility is to create a temporary competitive advantage by favorable tax regimes or minimal consumption quotas, activities in the sphere of public policy.”
F6 <i>Resource mobilization</i>	“Resources, both financial and human, are necessary as a basic input to all the activities within the innovation system. Specifically for biomass technologies, the abundant availability of the biomass resource itself is also an underlying factor determining the success or failure of a project.”
F7 <i>Creation of legitimacy</i>	“In order to develop well, a new technology has to become part of an incumbent regime, or has to even overthrow it. Parties with vested interests will often oppose this force of ‘creative destruction’. In that case, advocacy coalitions can function as a catalyst to create legitimacy for the new technology and to counteract resistance to change.”