Sustainable Development of Renewable Energy Mini-grids for Energy Access: A Framework for Policy Design

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ACRONYMS

ANEEL – Brazilian Electricity Regulatory Agency

CREDA – Chhattisgarh Renewable Energy Development Agency

DANIDA – Denmark's Development Cooperation

DSM – Demand-Side Management

ESAP - Energy Sector Assistance Program

ESD – Energy Services Delivery

EWURA – Energy and Water Utilities Regulatory Authority of Tanzania

MNRE – Ministry of New and Renewable Energy

M&V – Monitoring and Verification

NGO – Non-governmental Organizations

NORAD – Norwegian Agency for Development Cooperation

O&M – Operations and Maintenance

RE – Renewable Energy

REAP – Renewable Electricity Action Plan

REDP - Rural Energy Development Program

REE – Rural Electricity Enterprises

REF – Rural Electrification Fund

RERED – Renewable Energy for Rural Economic Development

RGGVY –Rajiv Gandhi Village Electrification Program

RVE – Remote Village Electrification programme

SPP – Small Power Producer

SPD – Small Power Distributor

TANESCO – Tanzania Electric Supply Company

TEDAP - Tanzania Energy Development and Access Project

UNDP – United Nations Development Programme

VESP – Village Energy Security Programme

1 INTRODUCTION

1.1 ACCESS TO ELECTRICITY

Over 1.25 billion people in the world, do not have access to electricity (Figure 1) [1]. The lack of access to electricity is most acute in countries in developing Asia and sub-Saharan Africa. Further, the majority of this unelectrified population lives in rural areas. According to the International Energy Agency, the average electrification rate (in terms of population) across the developing countries is 76%, with approximately 92% in urban areas and only around 64% in rural areas.

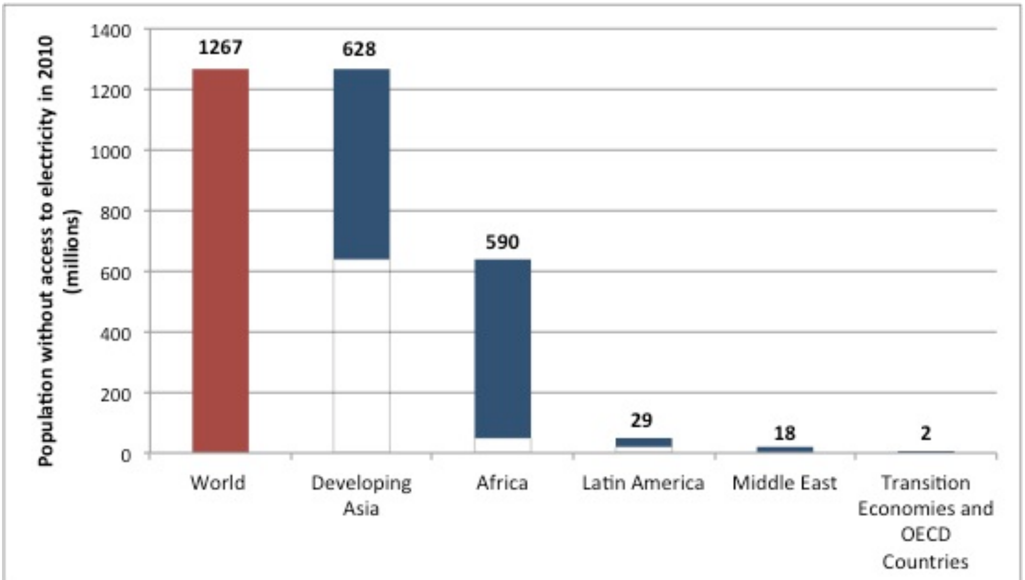

Figure 1: Population without access to electricity in 2010 (IEA 2012).

The benefits of electricity access are well recognized e.g. longer study hours for children, a reduction in domestic work burden on women by providing access to appliances, increased economic productivity, entertainment and access to enhanced healthcare, government and other services. Consequently, the governments of many countries have made the provision of electricity access their top priority.

The definitions of electricity access vary widely by country and region, including metrics such as the number of lights provided to a household, specific amount of energy available, or the number of households and institutions that are provided an electric connection in a community. In this report, we refrain from narrowly defining electricity access and refer to it as a spectrum ranging from access to affordable and reliable lighting to power availability for commercial and motive loads.

The predominant approach that most governments take to increase electricity access has been central grid extension. Several studies, however, point to the high costs of central grid extension to rural populations that can be sparse and remote [2], [3]. Low population density and a relatively poor consumer base with low electricity consumption act as disincentives for traditional utilities to provide electricity in rural areas. Even after connecting to the grid, rural consumers may not be ensured the same level of reliable access to electricity their urban counterparts enjoy, especially in countries where utilities are struggling with insufficient generation capacity, excessive losses and high cost of transmission and distribution infrastructure maintenance per customer served in remote areas [2]–[5]. Hence, although central grid extension has been successful in providing reliable access to electricity in some countries like China, Thailand and parts of Latin America, it has been a challenge to implement in other parts of the developing world [6]. As an alternative, several countries are pursuing distributed generation through mini-grids, solar home lighting systems and off-grid lighting products as an interim or a long-term solution to provide electricity access.

1.2 Mini-grids for Electricity Access

Mini-grids can be an important alternative to or enhance the effectiveness of central grid extension to increase access to reliable electricity services in developing economies. Mini-grids are defined as one or more local generation units supplying electricity to domestic, commercial, or institutional consumers over a local distribution grid. They can operate in a standalone mode and can also interconnect with the central grid when available.

Although mini-grids can use diesel generators, renewable energy-based mini-grids (henceforth referred to as RE mini-grids) use electricity generation technologies that utilize locally available renewable energy sources like solar, wind, biomass, and run-of-river hydro, thus avoiding local and global pollution. These generation technologies include solar photovoltaic and wind turbines with battery storage, biomass gasifiers and biogas digesters with internal combustion engines, micro and mini-hydro turbines, and hybrid systems (a combination of more than one generation technology). Due to their low or often zero fuel costs (except potentially in the case of biomass-based systems), RE mini-grids can be more cost effective than those utilizing diesel generators or kerosene based lighting. The latter have little capital expenditure, but have relatively high fuel costs, volatile prices, and logistic limitations.

RE mini-grids have distinct advantages over central grid extension and other decentralized energy options in providing access to reliable and affordable electricity.

1. Compared to central grid extension, RE mini-grids can be less expensive due to lower capital cost of infrastructure (depending on distance) and lower cost of operation by avoiding transmission and distribution losses [3].
2. In countries with power shortages, electricity supply through the central grid, especially in rural areas, may not be reliable. In such regions, RE mini-grids that can be designed and operated effectively, can be more reliable than the central grid in providing electricity access and can ensure local energy security.
3. Mini-grid developers have the potential to access capital beyond the traditional power sector, and may be able to provide quicker access to electricity than central grid extension that may be prone to bureaucratic hurdles and slow implementation.
4. Unlike other decentralized energy options like solar home lighting systems and off-grid lighting products, mini-grids (depending on their size) can provide electricity to not only residential loads like lighting and phone charging, but also to commercial loads like mills and oil presses.

5. RE mini-grid developers have strong incentives to pursue demand-side management, to keep capital cost of generation equipment low.
6. Development and operation of mini-grids can create local jobs.

However, there are also several challenges to successfully deploying RE mini-grids and especially to ensuring their long-term sustainability. These challenges include but are not limited to high up-front capital costs, low capacity factors, often higher residential tariffs compared to central grid consumers, insufficient financing support and investment, technology failures, lack of effective institutional arrangements to ensure reliable and efficient operation and maintenance over time, lack of mechanisms to address grievances, and uncertainty in the face of possible future central grid extension. Well-designed policies and appropriate institutional arrangements along with effective financing mechanisms can address many of these challenges and enable the successful and sustainable deployment of renewable energy-based mini-grids.

1.3 Importance of Policy Framework

While several governments have made the provision of electricity access their priority, their policies have tended to focus on electrification through central grid extension, and its implementation through traditional utilities. Decentralized mini-grids, in spite of their advantages, have received much less importance. Mini-grid deployment has often been left to private developers and non-governmental organizations with government support limited to the provision of capital subsidy. When governments have been in charge of developing mini-grids, they have often tended to focus on installation and often haven't provided adequate continued support for the systems.

In the past couple of decades, there has been a push to develop RE mini-grids in many countries including Brazil, Cambodia, China, India, Nepal, Sri Lanka and Tanzania. While there have been some successful mini-grid programs, there have also been some failures. Inadequate institutional support in combination with technical, economic and social issues have resulted in many unsustainable or defunct mini-grid systems. If mini-grids are to play a significant role in providing access to reliable and affordable electricity, a robust policy framework is essential.

While there are several studies recommending best practices for rural off-grid electrification, we aim to contribute by devising a framework that can successfully account for and include those policy practices to make sure they interact coherently among themselves and with the existing regulations. We focus on the technical, economical, financial, and social sustainability of mini-grids, in addition to assessing scalability and equity issues, in order to understand the key components that should constitute a robust mini-grid policy. We recognize that each policy component may have different ways to be designed and implemented. To illustrate the options that policy-makers may have to effect the sustainable deployment and operation of RE mini-grids, we provide examples from actual policies and programs from the aforementioned countries. The policy framework that we present would be useful to policymakers to formulate an integrated and holistic policy for RE mini-grids to be a significant option in the provision of reliable and affordable access to electricity.

2 FRAMEWORK

Government policy plays a significant role in the development of a sector, from setting rules and standards to providing incentives and enforcing penalties. A robust mini-grid policy can significantly impact the development of the mini-grid sector. Based on our own experience as well as relevant literature, there are different components of a mini-grid policy, all of which are important for its success. However, it is not uncommon that policy makers focus on a subset of these components, leaving their policies somewhat incomplete and therefore impeding the deployment, operation, and long-term sustainability of mini-grid projects. In this report, we build a framework upon which successful and sustainable mini-grid policy can be designed.

2.1 ELEMENTS OF SUSTAINABILITY

First, we identified a set of elements that define sustainability where experience indicates that their integration in mini-grid development will help to ensure that mini-grids play a critical successful role in the long-term provision of electricity access (Figure 2). Using these elements of sustainability, we assess the different components of a mini-grid policy through different lenses to inform the concerns of all stakeholders, including mini-grid consumers (community), project developers, government, utilities and financiers.

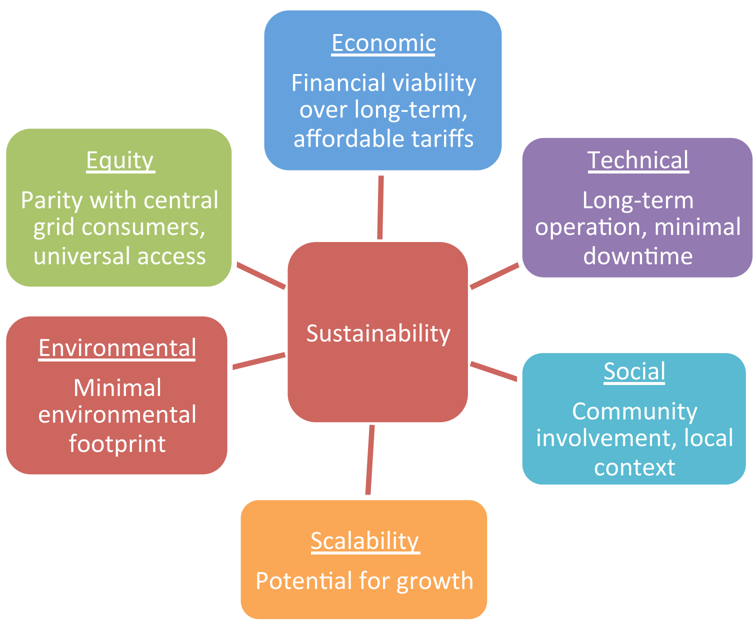

Figure 2: Elements of sustainability for assessing renewable energy-based mini-grid policies

Economic sustainability includes affordable tariffs for consumers while ensuring financial viability of the project over the long term with adequate revenue to cover operational expenses, liabilities, and profit. **Technical** sustainability ensures the reliable operation of the mini-grid system over its expected lifetime with minimal downtime. We define **social** sustainability to include the level of community involvement and how well the policy ensures that the mini-grid system caters to the local context. **Scalability** is incorporated to include a dynamic component in the evaluation, and to assess the ability of the policy to affect growth of the mini-grid sector. An **environmental** perspective is applied to assure future generations are not made worse off by present electrification efforts and resources are not depleted. Finally, we include an **equity** lens to assess the distributional aspects of a policy and how well the policy performs to ensure universal access to electricity.

2.2 Policy Components

A comprehensive policy designed to guide the development of mini-grid systems as a significant option for providing electricity access would address three broad categories – 1) institutional structure and governance, 2) technical standards and surveys, and 3) financial incentives, financing and tariffs. We present these categories and the policy components in each of these categories that in our view are essential for a robust policy to foster mini-grid development (Figure 3). In this report, we use the elements of sustainability discussed above to analyze these different policy components using examples from different countries.

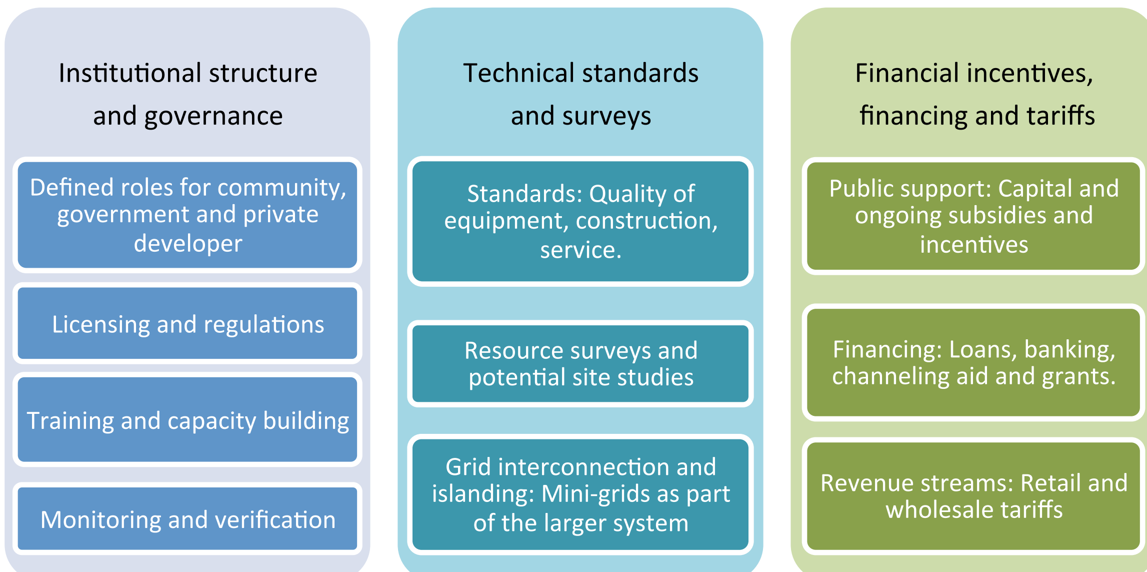

Figure 3: Categories of renewable energy-based mini-grids policy framework

It is essential for the long-term sustainability of a mini-grid system to define clear **roles** and responsibilities for all entities including the community, government, and private developer in a policy, in terms of ownership, development, and operation and maintenance. The role of **community** in all stages of mini-grid development and operation is critical for taking local context into account and ensuring that community members' needs are met. **Licensing and regulations** can ensure quality of service and could achieve pro-poor policy goals by ensuring affordable tariffs. **Training and capacity building** of all stakeholders including the local community, government and utility officials, project developers and operators are important for long-term sustainability and scalability of mini-grids. **Monitoring and verification** can ensure quality of service and equitable access to electricity, as well as facilitate mid-course corrections to overall programs.

In the technical category, **standards** for quality of design, equipment, construction, and service can facilitate long-term reliable operation of mini-grids. **Resource surveys** can help in identifying sites and reduce additional costs to developers. **Grid-interconnection** and islanded operation standards and policy mechanisms could reduce the uncertainty amongst mini-grid project developers and investors regarding their fate in the event of central grid extension.

In the financial category, government and international donor **subsidies** and **incentives** can prove critical in reducing the upfront costs of RE mini-grids and ensure operation over their expected lifetime. **Financing and investment** include loans and equity investment, essential for financial viability and scalability of mini-grids. Finally, it is important to analyze the **revenue streams** of the mini-grids that include consumer and wholesale tariffs beyond external financial support.

In the following sections, we briefly describe the policies and programs of seven countries, and then analyze the different components of their policies and programs through the lenses of the various elements of sustainability.

3 COUNTRY POLICIES AND PROGRAMS

In this report, we highlight examples from seven countries – Sri Lanka, Nepal, China, India, Tanzania Cambodia, and Brazil. This section provides only a brief background on the policies and programs implemented in each of the countries. The analysis of these policies and programs is provided in section 4.

3.1 SRI LANKA

Efforts for off-grid electrification in Sri Lanka can be traced back to the 1940s with the deployment of over 500 micro-hydro facilities to provide energy services for tea plantations, but it wasn't until the early 1990s when these systems were applied to village level electrification efforts by private actors and NGOs [10]. The Energy Services Delivery program, ESD, launched in 1997 by the Government of Sri Lanka and the World Bank provided output-based grants and financing for micro-hydro mini-grids and solar home based systems and injected over US$45 million to serve 22,000 households [11]. Its successor, the Renewable Energy for Rural Economic Development project, RERED, launched in 2002, disbursed over US$120 million to continue building capacity and support private sector investment, achieving by 2008 the electrification of more than 6,000 households supplied by over 100 micro-hydro mini-grids. Most notably, the ESD/RERED program enabled communities to build, own, maintain, and operate their systems by boosting the cooperative business model, providing training, and consultancy technical assistance, and channeling funds through existing commercial banks [12].

The Sri Lanka experience is relevant due to the decisive role that decentralized private and non-governmental organization efforts had in pushing deployment of mini-grids. It also highlights the need for a government to adjust existing policies to harmonize off-grid and on-grid schemes, reduce overlap, and increase their efficiency [12]. Finally, the focus on human resource development proved instrumental to spur a self-sustainable thriving private market for renewable energy sourced energy services in the region [11]. At the same time, it is important to note the large amount of support provided by external donor organizations to develop the sector.

3.2 NEPAL

Although micro-hydro development has a long history in Nepal since the 1960s, the two main recent programs relevant to mini-grid development are the Rural Energy Development Program (REDP) and the Energy Sector Assistance Program (ESAP). REDP, an initiative of the Government of Nepal and UNDP, played a crucial role in the development of Nepal's distributed generation program from 1996 to 2011. Under REDP, 317 village micro-hydro installations with a cumulative capacity of 5814 kW were installed and approximately 58,000 households were electrified [13]. REDP focused on building institutional and technical capacity by community organization and training. ESAP was established in 1999 with support from the Danish and Norwegian development agencies, DANIDA and NORAD, and the Government of Nepal to establish local support structures for micro-hydro projects, assistance in formulating national policies, and developing quality assurance standards and guidelines. Further, the rural energy fund, supported by the Government of Nepal, DANIDA, NORAD, and other development partners was set up to channel funds and provide subsidy for mini-grid electrification and solar energy projects [12]. In its Rural Energy Policy, 2006, the Government of Nepal recognized the difficulties in the national grid expansion for rural electrification due to Nepal's topography, its dispersed settlement pattern, and its limited financial resources, and further recognized the need for local institutions, rural energy user groups, non-government organizations, cooperatives, and the private sector to help develop and expand rural energy sources, which include mini-grids [14]. Nepal's restructured rural and renewable energy program, operating since 2012, is being supported by Danish, Dutch, Norwegian and Swedish agencies, The World Bank, Asian Development Bank and UNDP.

Nepal provides a case study of a mini-grid electrification program that was catalyzed by external donor agencies in partnership with the government of Nepal.

3.3 China

China has achieved the remarkable feat of providing electricity access to more than 99% of its population. According to the World Energy Outlook, about 4 million people did not have access to electricity in 2009 [1]. Distributed generation in China has predominantly been through the development of small hydropower plants (less than 25 MW). As of 2001-02, there were 42,000 small hydropower plants with a total capacity of about 28 GW [20]. China pursued the development of small hydropower plants beginning in the 1950s, where the plants first operated in standalone mode and were then connected to the national grid as it expanded into the rural areas [21]. In 2001, the Chinese central government initiated the Township Electrification Program (Song Dian Dao Xiang) with a target of electrifying 1000 townships (approximately 1 million people). In 3 years, 377 villages were electrified using small hydropower (264 MW) and 688 villages with PV and PV-wind hybrid mini-grids (20 MWp), making it one of the biggest decentralized generation programs implemented [22].

China's historical efforts in mini and small hydro mini-grids, their eventual integration with the central grid extension, and its recent large effort through the Township Electrification Program, especially through largely government initiatives, makes it a valuable case study.

3.4 India

With more than 290 million people without access to electricity in 2010, India has the largest unelectrified population in the world [1]. India has been pursuing several different programs and policies for the development of RE mini-grids. The Ministry of New and Renewable Energy (MNRE) has been providing capital subsidies for off-grid RE mini-grids such as biomass gasifiers, micro-hydro, and solar PV for more than a decade. In 2005, the MNRE developed the Village Energy Security Program (VESP) to support remote village communities to utilize biomass resources and offered capital subsidies to set up mainly biomass gasifier-based mini-grids [15]. The MNRE also supports mini-grids under the Remote Village Electrification (RVE) program, which was initially set up to support solar home lighting systems and lanterns in remote villages, but now also supports mini-grid development in villages not covered under India's central grid extension efforts. The mini-grids set up under these programs are mainly operated by village electricity committees formed by the local community. In the state of Chhattisgarh, the state nodal agency of MNRE has been operating more than 500 solar PV mini-grids under the RVE program, mainly due to additional subsidies from the state government and a robust operations and maintenance program run by the agency [16]. The Jawaharlal Nehru National Solar Mission announced in 2010 that, in addition to an ambitious 20,000 MW target for grid-connected solar photovoltaic systems, it aims to install 2000 MW of off-grid solar photovoltaic systems, especially for providing electricity access. Under the mission, the Central Government of India offers capital subsidies for solar plants[17]. Further, the Ministry of Power initiated the Decentralized Distributed Generation scheme under the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) grid extension program to support isolated mini-grids [18]. Finally, given the huge unmet demand for electricity, private developers have begun deploying RE mini-grids over the last few years, offering services that vary from just lighting to motive loads [19].

India provides an interesting case study with multiple programs and agencies pursuing often overlapping, rural electrification and decentralized generation initiatives.

3.5 TANZANIA

In 2009, over 85% of the population in Tanzania had no access to electricity [7]. Until the launch of the National Energy Policy in 2003, the state-owned utility, TANESCO led efforts for rural electrification. These efforts were mainly through central grid extension and some diesel-based isolated systems [8]. The National Energy Policy of 2003 paved the way for the incorporation of independent power producers into the electricity sector, with a special focus on renewable energy based generation and distribution. The Rural Energy Act of 2005 mandated the creation of a Rural Energy Agency with a special focus on renewable energy based grid-connected and off-grid projects and general energy access expansion. The agency launched the TEDAP, Tanzania Energy Development and Access Project, their flagship program to channel funds from several sources into subsidies, special collateral financing, preferential interest rates, and technical assistance to project developers. By 2010, 22 projects (42 MW of grid-connected and 17 MW of isolated projects that used small hydro and biomass power technologies) were in various stages of development, and 60 more projects were being planned [9]. Once developed, these projects would account for more than 5% of the total installed generation capacity in Tanzania.

Tanzania's small power producer push is relatively small and new in terms of number of projects, but it is growing. Their policies and structuring of institutional arrangement to allow small power producers, both grid-connected and off-grid, to be considered as viable options for electrification, can prove critical in addressing the large challenge of electrifying 85% of its population.

3.6 Cambodia

Cambodia has a low electrification rate of 30%, with 10 million people without access to electricity [1]. In 2003, Cambodia launched the Renewable Electricity Action Plan (REAP), which was focused on providing electricity to 70% of Cambodian households by 2030 based on renewable energy. The plan aimed to incorporate Rural Electricity Enterprises (REE) – who already had 600 diesel based mini-grids and over 1000 battery charging stations in operation - in a market-oriented bottom-up approach that also involved NGOs, aid agencies, and the government [23]. It recognized the inability of the central grid to reach remote areas in the country for at least two to three decades and the benefits of using renewable energy compared to fossil fuels and grid extensions. The Rural Energy Fund was formed in 2005 as a multi-ministry organization to oversee both the actual funding expenditure as well as spearheading rural electrification efforts [24].

Cambodia does not have a large number of RE mini-grid projects. But its policy of institutionalization of existing actors, in this case, diesel-based mini-grid operators who aim to play a franchisee role for the state owned utility, makes Cambodia an interesting example.

3.7 Brazil

Brazil's flagship program for rural electrification, "Luz para Todos" (*Power for All*) was created in 2003 to achieve constitutionally granted universal electricity access in the country for over 12 million people. This universalization is transferred as an obligation to concessionaires – which can be private or public enterprises - who are then liable to achieve electrification goals in a specified timeframe. Although the program focused mainly on grid extension, by 2009 Brazil's electricity regulatory agency, ANEEL, recognized that more than 250,000 households, a majority of them in the Amazon region, would be economically or technically unfeasible to be connected through grid extension. The Ministry of Mines and Energy issued a *Special Project Manual,* which included an 85% capital subsidy for mini-grids, especially with a focus on renewable energy, allowance for the use of prepaid metering, and the inclusion of rural cooperatives as implementation agents beside the concessionaires [25]. Brazil's program of RE mini-grids in the remote Amazon region is in its infancy with only 15 small hydro plants and one solar PV plant operating by 2010 [25].

Brazil's example reflects the challenges of using existing institutions responsible for central grid extension to develop a role in mini-grid development for which capacities may not be fully developed.

4 Policy Analysis

The three broad aspects of a comprehensive RE mini-grid policy are: 1) institutional structure and governance, 2) technical standards and surveys, and 3) financial incentives, financing and tariffs. In this section, we discuss these aspects of RE mini-grid policy design, by providing anecdotal examples from seven countries, and analyzing them using the six elements of sustainability described in section 2.

4.1 Institutional Structure and Governance

In this sub-section, we describe the roles that different entities, especially government agencies have played in different countries, discuss the need and extent of licensing and regulations, highlight the importance of training and capacity development of all entities, and emphasize the role of monitoring and verification to ensure reliable service through RE mini-grids.

4.1.1 Roles in Mini-Grids

What roles should be played and who should play them?

The roles and activities different stakeholders undertake for mini-grid development depends on the domestic cultural context, legal framework, economic viability, and institutional arrangement in a particular jurisdiction or country. These roles and activities include owning, building, operating, maintaining and paying for a mini-grid system. Furthermore, the most common stakeholders involved are the government, private enterprises, financing institutions, NGOs, consumers, and the community. Appropriate institutional arrangements that enable effective deployment and subsequently, operation, management, and maintenance of RE mini-grids is critical for scaling up the development of mini-grids as a significant option for providing electricity services.

In some cases, the government (or state-owned utility) is explicitly involved in building and operating the mini-girds, while in others they play a facilitator and regulator role, letting private developers and the community be in charge of the systems. Further, although the government can play these roles, there is a set of larger responsibilities that the state necessarily undertakes through specific institutions that include defining national and jurisdiction-level energy policy and electrification goals, setting rural electrification strategies and providing financial incentives for mini-grid development and operation.

Community involvement has been identified as a key component of successful mini-grids [26], though it might take many different forms. Community participation at least in high-level decision-making before and during system operation is key to the success of a mini-grid system. However, in some cases communities have been endowed with functional roles that include commercial and technical operation of the system, tariff determination, penalties definition, and monitoring and verification activities.

Important lessons are emerging of how to facilitate community involvement in the design and operation of mini-grids, and for strategies to balance the potentially competing goals of energy service and economic viability through efforts that cater to high-value customers. Differing strategies exist to meet, or marry, these goals. Metrics for community-wide satisfaction and financial viability will both be valuable in assessing the success or failure of specific mini-grid projects to meet these goals.

The private sector has assumed relevant roles in all the activities and it is remarkable how private enterprises surface when the right economic, legal, regulatory, and social conditions are met. Ranging from banking, financing, and micro-lending companies to specialized project developers to solitary village level entrepreneurs, their capacity to tailor solutions and innovate in business models has allowed them to thrive in many regions.

In **Tanzania**, the Rural Energy Agency was created to explicitly "promote and facilitate improved access to modern energy services in rural areas" [27]. The agency channels funds to the utility, TANESCO, for grid extension and, through the Rural Energy Fund, to eligible entrepreneurs. EWURA, the independent regulator, oversees licensing, tariff determination, and standard compliance [9]. Additionally, the institutionalization of private Small Power Producers, SPPs, has led to them implementing and operating mini-grid projects, while also allowing them to play a specific independent power producer or small power distributor (SPD) role when the central grid is extended to the mini-grid.

In **Cambodia**, the government created the Rural Electrification Fund in 2005 with the purpose of spearheading rural electrification efforts and meeting the 70% household level goal by 2030. The REF is a public institution endowed with a board, administrative personnel, and autonomy to draft strategic and policy guidelines on rural electrification and perform monitoring and verification activities. They manage World Bank funding for capital subsidies and feasibility and marketing studies, as well as external donor and direct governmental funding [24]. Furthermore, the approach has been to leave siting, construction, and operation to Rural Electricity Enterprises (REEs). The objective was to formalize the existing private mini-grids, mostly diesel based, that have propagated through the rural areas [24]. Under the new framework, these institutions can choose to play the SPD role (buying from the utility - Electricity du Cambodge), deploying complete mini-grid solutions, or retail solar home systems to rural households.

In **China**, the Township Electrification Program was paid for and overseen by the central government (National Development and Reform Commission). Private and semi-private firms were contracted to build the small hydropower and PV mini-grids. While the central government paid for the capital expenses, contractors were obligated to provide operations and maintenance services for three years. However, the ownership of the systems seemed to be an open question, especially after the initial contracts ended, which may jeopardize the sustainability of the systems over time [20], [22]. At the same time, the importance placed by the Chinese government on rural electrification may have resulted in another institutional framework to be put in place for the management of the mini-grid systems.

In **India**, there have been mixed approaches to mini-grid project development and different entities have assumed different roles in each of these approaches. The Ministry of New and Renewable Energy (MNRE) has dictated policy and structured programs at the central or federal level and its state-level implementation agencies have been responsible for RE mini-grid deployment, primarily through the provision of capital subsidies. The Village Energy Security Program of 2006 focused on the MNRE's state-level implementation agencies to deploy RE mini-grids in villages that were classified as economically unfeasible for a central grid extension. In most of the projects under this program, while private developers installed the mini-grid systems, the technical and commercial operation was put in the hands of Village Energy Committees composed of community members. In many states, this institutional arrangement led to some ineffective results due to lack of incentives for the committees and their capacity to get involved at the level they were required [15], [26]. Policy design needs to recognize that not all communities wish to be engaged to the same degree, and especially acknowledge the heterogeneity and varying levels of cohesiveness within a community. In other states of India, like Chhattisgarh and West Bengal, Village Energy Committees were successfully incorporated in high-level decisions alone, which proved an effective method for community involvement. In these states, the MNRE implementation agency for the state outsourced the installation and maintenance to private developers, and trained operators from the local community to handle day-to-day operation of the mini-grid [26]. Although the Village Energy Security Program was discontinued, the MNRE continues to provide capital subsidies under its Remote Village Electrification Program. The MNRE also provides capital subsidies to project developers under its Jawaharlal Nehru National Solar Mission to build off-grid solar PV plants. In 2009, the Ministry of Power, which is primarily responsible for India's largest central grid extension program – the Rajiv Gandhi Grameen Vidyutikaran Yojana – announced its Decentralized Distributed Generation (DDG) program, under which the ministry intends to provide capital subsidy to set up mini-grids in areas where central grid extension is not deemed feasible [18]. All these programs have primarily relied on private developers or non-governmental organizations to set up mini-grids, while the government agencies' role has been to provide capital subsidies and some form of monitoring. At the same time, India's Electricity Act of 2003 left the door open for private investors to build, operate, and maintain mini-grids as a private business without requiring a license, in areas that are designated as rural areas. Many private developers have begun to set up mini-grid systems and run the entire operation themselves, relying on local human resources for staffing purposes [28].

In **Brazil**, a large and complex institutional framework exists for the electricity sector, to which off-grid efforts have been coupled. The view of electricity as a key component of a broader development policy led to the creation of the National Commission for Universalization, a multi-ministry agency in charge of establishing guidelines for electricity use. The electricity regulator, ANEEL, and the main government-run electricity company, Eletrobras, are the institutional support for electrification efforts in the field and manage project approvals and subsidy disbursals. There is no specialized agency for rural electrification [25]. In Brazil, the implementation of rural electrification efforts fell to distribution concessionaires according to their operational area. Concessionaires, both private and public, are mandated to achieve universal electrification. When specific off-grid electrification guidelines were issued by ANEEL in 2009, rural cooperatives were allowed to play a more active role in off-grid electrification through renewable energy based mini-grids. However, only certain concessionaires – the ones that don't have an exclusivity contract for their concession area – can allow third parties to get involved in off-grid electrification purposes.

In **Nepal**, the Alternative Energy Promotion Center set up in 1996 is responsible for implementing the Rural Energy Policy. The District and Village Development Committees play important roles in implementing rural energy systems. Private sector organizations provide technical services that include surveys, installation, operation, repair, and maintenance. Most micro-hydro installations are operated and managed by communities [29]. The Nepal Micro Hydropower Development Association represents the private sector in policymaking, undertakes capacity development through training and workshops, and increases mass awareness through various activities. Nepal's micro-hydro mini-grid development program has been actively supported by donor agencies including UNDP, DANIDA, NORAD and others.

The **Sri Lanka** government's Ceylon Electricity Board is the national electricity utility that is currently in charge of public rural electrification efforts and has also been endowed with the role of disbursing capital subsidies for private initiatives. The Energy Policy of 2006 formally recognized off-grid systems, aiming to develop capacities on the Provincial Councils to play a decisive role in decentralized efforts and extending existing grid extension subsidies to off-grid projects as well. In Sri Lanka the private sector and NGOs have spearheaded the development of mini-grids by empowering communities to form cooperatives to deploy the systems. The community played a relevant role by establishing Electricity Consumer Societies, an intervention that has been hailed as one of the best in rural electrification [10].

4.1.2 Licensing and Regulations

What licenses and regulations should be required of the mini-grid sector?

Licensing requirements for project developers can take many forms, depending on their duration, specificity, approval process, and other conditions. One of the key aspects of licensing lies in the accountability level that the licensee has with respect to the legal electricity framework; alternatively, licensing requirements can be overly prescriptive and deter or slow mini-grid deployment. A balance is needed between ensuring reasonable service at reasonable cost for consumers, and facilitating investment and reducing transactional costs for developers.

Regulations help in ensuring fair tariffs, enforce standards to maintain quality of service, and provide a forum to address grievances, for both consumers and developers. Regulatory approvals can also include environmental impact assessments to ensure environmental sustainability of the projects. Regulations can allow RE mini-grids to qualify for meeting renewable energy targets for traditional utilities and can facilitate their participation in the renewable energy certificate market for additional revenues. Regulated tariffs can ensure affordability for mini-grid consumers as well as parity with central grid tariffs. Due to the wide range in costs of mini-grid systems, regulating consumer tariffs has usually been accompanied by some form of subsidy (either from the government or the local electricity utility) to ensure financial viability of a mini-grid project. It is essential to ensure that the incentives or subsidies that complement regulated tariffs are adequate, disbursed in a timely manner, and have minimal bureaucratic hurdles from the perspective of project developers and financiers. Inappropriately designed regulations and inefficient subsidy disbursal mechanisms could jeopardize the financial viability of private developers and drive them out of the market.

The role and degree of licensing and regulations has been mixed in different countries. In some countries, regulators decide mini-grid tariffs based on the tariffs for similar central grid consumer categories; e.g. the **Brazilian** electricity regulator, ANEEL, sets the tariffs for both grid-connected and off-grid consumers, served by concessionaires. The connections and tariffs for low income consumers are subsidized to meet the Brazilian government's goal of providing universal access to electricity [25]. However, mini-grids, especially diesel-based mini-grids in the Amazon region that are not operated by concessionaires, are not regulated.

Other countries let the project developers or community or both decide their own tariffs without approval from the government or regulatory institutions. Private RE mini-grid developers are free to set their own tariffs in **India**, since setting up a rural mini-grid system does not require a license under India's Electricity Act [26], [28]. In the government-developed projects in **India** under the Village Energy Security Program and in **China** under the Township Electrification program, village committees decide the tariffs [15], [30]. The Electricity Act of **Sri Lanka** does not allow any party other than the Ceylon Electricity Board to generate and sell electricity to consumers, unless their permission is obtained. However, the community owned and managed micro-hydro mini-grid systems, instead of selling electricity to consumers, provide membership to consumers who pay a fee, in order to circumvent the Electricity Board's requirement [12].

Some countries follow a mixed approach in deciding tariffs that takes community approval into account but still requires regulatory approval. In **Tanzania**, licensing is required for distributed generators above 1 MW, while below that they are exempted on distribution, transmission, and generation segments. Further, very small power producers (less than 100 kW) are only required to send registration documentation to the regulator, and do not need any action from it. Retail tariffs determined by the project developer need community approval before the regulator approves the project [31].

In **Cambodia,** a "consolidated" license is provided by the regulator (Electricity Authority of Cambodia) for isolated systems, which gives the right to generate, distribute, and retail electricity in a specific area [32]. Licensing also provides an opportunity for both renewable and fossil fuel based mini-grids to play a small distributor role in the event of central grid extension by the distribution utility, Electricite du Cambodge [23].

4.1.3 Training and Capacity Development

What capacity needs to be developed amongst different stakeholders to facilitate development of the sector?

Specific capacities needed to build, manage, finance or regulate decentralized projects are usually absent in a system that has predominantly relied on central grid extension and operation as the main approach for providing electricity access. For the successful development of the mini-grid sector in a country, human resource training and capacity development are essential for all stakeholders: project developers, governmental officials, regulators, local distribution utility officials, financing service providers, and the community [32]. Government policy and programs can facilitate and finance training and capacity development of different actors. Such activities have also been taken up by international organizations as illustrated by examples below.

In **Sri Lanka**, the World Bank sponsored a capacity building program in the 1990s to train micro-hydro developers. Today, many of these are actively engaged in project development, resulting in a competitive market for communities, peer-to-peer learning and auditing, which has led to 95% of micro-hydro potential being tapped in the country [10].

Similarly, the REDP program in **Nepal** emphasized community mobilization, human resources development, institutional development, natural resources management and sustainable rural energy development. Under REDP, rural energy service centers were set up to provide easy access to trained technicians and reduce the downtime in electricity services [34]. The Alternative Energy Promotion Center organizes training programs for micro-hydro managers, operators, and service center technicians and orientation training for government and non-governmental organizations.

In **China**, local capacity building for designing, operating, and maintaining the systems was defined as an integral part of the Township Electrification Program [33].

4.1.4 Monitoring and Verification

What forms of monitoring and verification should be required of mini-grid systems?

Since off-grid system deployment is essentially a decentralized business, monitoring and verification (M&V) at four different levels are critical to make sure that technical standards are met and that specific processes are carried out as they should. At the same time, the remoteness and isolation of many villages makes M&V expensive and difficult, so the use of local resources gains relevance. Experience show that monitoring and verification should be enforced in the following aspects:

1. M&V in building and construction is essential to verify that appropriate construction codes and standards are being followed. Ongoing technical monitoring includes performance of the generation unit and switchgear, maintenance, electricity generation, and fuel consumption. M&V of key parameters through an efficient monitoring system can be critical for projects that rely on performance-based subsidies as well as those that receive credits through a renewable energy certificate mechanism or a carbon abatement program like the Clean Development Mechanism.
2. Commercial and financial monitoring relates to adequate tariff charges when they are regulated and proper capital subsidy disbursal so that the sanctioned project is actually built as intended, and so that ongoing grid operation that includes maintenance, meter reading, billing, revenue collection, and penalties, is adequately carried out.
3. Consumer grievance redressal is a specific monitoring and verification mechanism that allows the customer an expedited mechanism to file complaints and receive adequate post-sale service. Consumers also need to be monitored to make sure they respect their contracts regarding consumption levels, payments and penalties.
4. Appliance standards are relevant since highly efficient appliances can significantly reduce grid overload and help achieve demand-side management objectives.

As discussed earlier, these activities can be carried out by different stakeholders depending on the policy design and institutional context.

In **India**, the Village Energy Security Program experienced many gaps in M&V. While MNRE provided capital subsidies for mini-grid deployment, there was inadequate ongoing support for operation and many of the projects went defunct [15]. However, the Chhattisgarh Renewable Energy Development Agency has developed a robust M&V mechanism to monitor the development and operation of its more than 500 solar PV mini-grids through private developers and service providers [34]. Under its National Solar Mission, India is considering online disbursal of subsidies for solar projects based on monitoring and verification using information communications technology [35].

In **China**, a study that included a survey of PV and wind village power systems in Xinjiang province found over 90% of failures were caused due to malfunctioning of system components. Further the study observed that the rural electrification program lacked a comprehensive quality management, especially commissioning checks and supervision [22].

In **Brazil** special focus has been placed on M&V efforts, and both the regulator ANEEL and the grid operator Eletrobras have the role of overseeing different aspects of operation of the Luz Para Todos program. The Ministry of Mines and Energy sanctions high-level projects that are later prioritized by State and Regional Committees according to a number of metrics. These, which include electrification level, human development index, potential productive end uses, and the existence of healthcare centers, schools, and minorities' settlements, among others, are used for evaluation of the project success. Subsidy disbursal has its own monitoring mechanism by directly verifying connections made on the field [25].

In **Nepal** and **Sri Lanka,** the community has played a critical role in keeping the commercial processes, especially the revenue collection, working smoothly. In these cases, some members of the community are paid to conduct specific functions [36], which encourages performance and effective M&V.

4.2 Technical

The technical aspects of a mini-grid policy design includes the provision of resource surveys and grid extension plans that can facilitate planning for project developers, appropriate standards that ensure safety and reliability without being cumbersome, and facilitating grid interconnection and islanded operation of mini-grids (that are relatively large in size) to reduce uncertainty in the event of central grid extension.

4.2.1 Surveys

What is the role of resource surveys and other information in scaling up RE mini-grids?

The provision of detailed surveys of resources at potential site locations and their ready availability to agencies and entrepreneurs can significantly reduce the transaction costs of deploying RE mini-grids. Other detailed information such as grid extension plans and community or potential consumers' details can prove important for scalability and rapid deployment of mini-grids.

Experience shows that decentralized approaches like those of **Tanzania**, **Cambodia**, and **India** usually rely on developers using informal means for obtaining resource location and availability information. Knowledge of the context at the village level is usually necessary to have certainty of biomass availability due to competing uses and seasonal variation. Hydropower resources, while initially identified by local community members, need to be properly assessed. Solar resource can usually be determined through solar resource maps and may not be too site specific.

Further, information such as grid extension plans are essential to coordinate with mini-grid development, so as to avoid overlap. In **India**, overlap between the central grid extension program, RGGVY, and existing mini-grids has led to early abandonment of many mini-grid projects [26].

4.2.2 Standards

What standards are essential for mini-grid systems?

Standards, if appropriately designed, can be effective and beneficial for all stakeholders. They can ensure long-term technical and environmental sustainability of the system. However, poorly formulated standards can be cumbersome and restrict innovation, especially when they specify design parameters rather than performance. Standards should be purposefully designed for rural contexts, since pre-existing regulations for urban settings or larger systems may not be appropriate for the requirements of RE mini-grids.

From the consumers' perspective, technical standards reduce safety risks associated with low-quality equipment and construction. Technical standards include those for generation equipment, distribution grid, and electricity service standards. Standardized contracts can provide certainty regarding tariffs, supply hours, mechanisms to address consumer grievances, and general service and post-sales duties and obligations both from the developer and the consumer. From a developer's perspective, standards can provide assurance that their equipment and construction is validated to operate in a specific area. For future interconnection purposes – when the central grid arrives – interconnection standards may increase the chance of existing assets to continue operation given the right regulations. Governments can require developers to demonstrate compliance with standards before subsidy disbursal as an incentive to ensure proper system design and installation.

While renewable energy-based mini-grids are usually considered environmentally benign, especially when they are small in size, certain appropriate standards and norms can ensure local environmental sustainability. Examples include requirement of appropriate plantations for biomass fuel supply to prevent deforestation, enforcement of recycling of solar PV panels and batteries at their end-of-life, and building standards for small hydro plants to ensure minimal impact on river flora and fauna.

In the case of **Cambodia,** interconnection standards have not yet been put in place, and the privately run mini-grids are not required to meet any standards. This is regardless of the fact that a license is required and therefore licensees are bound to regulator's rules, which puts a focus on monitoring and verification efforts for these grids. Similarly, in **India**, since mini-grids do not need a license under the Electricity Act of 2003 and are not regulated, developers are unaccountable in terms of technical standards. However, some state agencies like the Chhattisgarh Renewable Energy Development Agency have developed their own technical standards and enforce compliance by developers and service providers [34]. In **Nepal**, the Alternate Energy Promotion Center is responsible to ensure quality standards are met by private developers. Similarly, in **China**, the private contractors responsible for solar PV mini-grid deployment under the Township Electrification program have to adhere to quality standards set by the government.

4.2.3 Grid Integration

What happens when the central grid arrives?

A key question for the long-term operation of standalone mini-grids is what happens when the central grid is extended to that location. Depending on the policy and technical feasibility, mini-grids can be connected to the central grid where the local renewable generator feeds electricity into the central grid. Further, the mini-grid could also have the capability to isolate or 'island' itself and continue to serve its customers in the event that the central grid fails, thus ensuring reliable supply of electricity (Figure 4) [37], [38]. Mini-grids could support better 'tail-end' voltages at the end of distribution lines. However, mini-grids may not be grid compatible in terms of equipment, supply and compliance with utility standards, and there may not be a policy or financial incentives for mini-grid owners to interconnect and interact with the central grid [39], [40]. Further, significant voltage and frequency fluctuations due to poor quality of central grid supply, especially in some rural areas, may pose technical challenges to reliable integration of mini-grids with the central grid [41]. In these cases, the mini-grid may stop being operated and its equipment moved to another site, or it may keep operating in parallel, especially in areas where the central grid supply is unreliable.

From a policy perspective, integrated planning of the development of mini-grids along with central grid extension will reduce policy uncertainty for mini-grid developers, avoid redundant infrastructure, and ensure reliable electricity supply to consumers over the long term. Appropriate financial incentives and standards for interconnection are essential to ensure the safety and security of both the central and mini-grids.

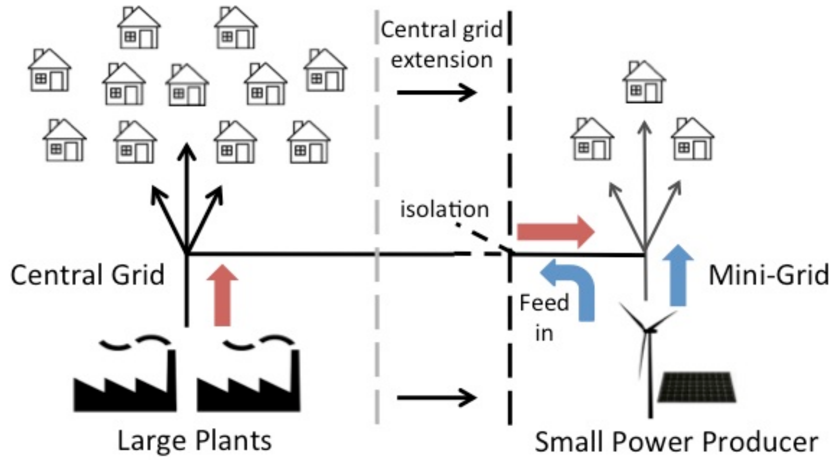

Figure 4: Grid interconnection and islanding of mini-grids

There are several examples where previously standalone mini-grids were or are being planned to be integrated with the central grid as it extends. **China's** small hydropower plants were first built and operated in standalone mode. As the central grid was extended, these hydropower plants were eventually integrated and fed into the larger grid [21]. In **Nepal**, the micro-hydro mini-grids are being interconnected and synchronized with each other to increase robustness of the grids. In **India**, the Decentralized Distributed Generation policy recommends that the mini-grid plants be "grid-ready" so as to be capable of exporting or importing power from the central grid, although the operational details are yet to be worked out [18]. In **Tanzania**, the policy includes specific conditions for both off and on-grid injection by small power producers as well as appropriate guidelines with technical standards and protocols for grid interconnection [42].

4.3 Financial Incentives, Financing and Tariffs

A developer may be able to draw upon three broad categories of funding to support a mini-grid project over its lifespan: financial incentives and subsidies from government, financing in terms of debt and equity from banks and investors, and consumer tariffs from ratepayers in the community. The balance among these resources dictates the scalability, equitability and long-term viability of mini-grid development. Figure 5 shows the three financial flows that the project developer (private, community or government) has to rely on to successfully ensure the long-term financial viability of the project. Financial incentives and subsidies, both upfront and ongoing, reduce the requirement for financing, and can result in affordable tariffs for consumers. Appropriate financing can reduce the subsidy burden on government and utilities, while allowing developers and operators to recoup their investment. Appropriate tariffs and tariff structures can ensure equitability and affordability for consumers while providing adequate returns to investors.

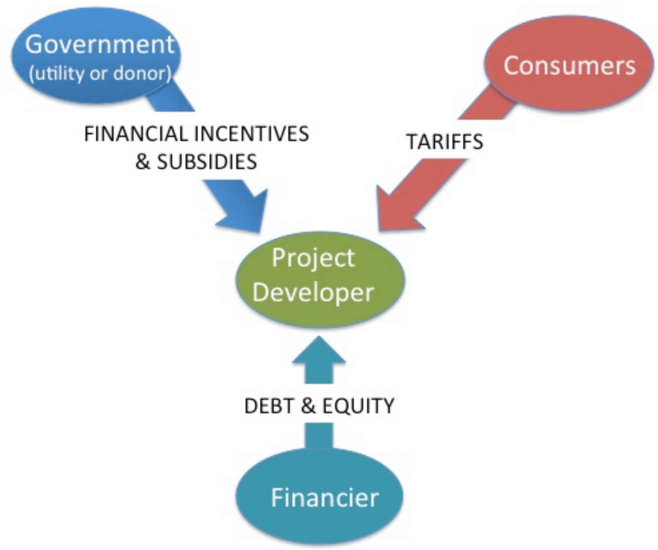

Figure 5: Financial flows for a mini-grid system

4.3.1 Financial Incentives and Subsidies

What role can financial incentives and subsidies play in the economics of mini-grid systems?

Financial assistance provided by governments, utilities, and international aid agencies and donors can prove critical, especially when committed over the long term beyond the pilot project stage. Financial assistance covers different funding streams that cater to stakeholders, usually project developers and consumers, in order to allow a combination of scalability, equity, and economic sustainability.

There are several different forms of subsidies and support that various governments have adopted. Capital subsidies are the most common form of support that reduces the upfront capital costs of a RE mini-grid. These capital subsidies may be linked to ongoing performance and disbursed in specific time intervals to ensure service delivery by project developers.

Under the Township Electrification Program, the **Chinese** central and local governments paid for all the capital expenses and some of the O&M expenses of mini-grids [22]. In **India**, the Ministry of New and Renewable Energy, under the remote village electrification program, offers capital subsidies for solar PV, micro-hydro and biomass gasifier mini-grid systems that are up to 90% of their respective benchmark prices. The provision of these subsidies is tied to a 5 year annual maintenance contract with the developer [43]. In **Cambodia**, the renewable energy fund provides capital subsidies to Rural Electricity Enterprises for the installation of mini hydro projects (US$400/kW) and biomass projects (US$300/kW) and US$45 for each household connection [44].

In **Nepal**, financial assistance is being provided for approximately half the cost of the micro-hydro installations, the predominant type of mini-grids in Nepal. This financial assistance is in the form of capital subsidy, provided through the Rural Energy Fund, set up by the Government of Nepal to combine and channel subsidies from the government and international aid agencies like DANIDA (Denmark) and

NORAD (Norway). The other half comes from district or village development committee equity investment (10%), financial community contributions in the form of cash and loans (20%), and in kind community contributions in the form of labor and locally available construction materials (20%) [29].

In **Sri Lanka**, the ESD/RERED programs funded projects through medium and long-term loans using existing institutional capacity. Additionally, they channeled a US$400 per kW subsidy for micro-hydro systems and enabled a micro-lending scheme to provide funding for service drop connections [12]. In **Brazil**, the 2009 *Special Project Manual* allowed an 85% capital subsidy, disbursed in three tiers according to project monitored progress [45].

Similarly, ongoing incentives based on energy generation (feed-in tariffs) or a fixed subsidy per connection can help cover maintenance and operational expenses and eventually profit gaps.

The Forum of Regulators in **India** is considering a model where the tariffs of mini-grids will be regulated and made equitable with central grid counterparts while the project developer will be provided an ongoing viability gap subsidy to ensure a profit margin [46]. Meanwhile, the state government of Chhattisgarh augments the capital subsidies offered by the central government of India by providing ongoing subsidy and support per household connection for solar mini-grids, as well as support for operations and maintenance through service providers [34]. In **Tanzania**, in addition to the capital subsidy of US$ 500 per connection, the requirement of power purchase agreements for small power producers allowed the government to channel ongoing generation-based subsidies to developers selling at “wholesale” level, either when injecting into the grid or when supplying an isolated system [9], [31].

Subsidy support can also be provided directly to consumers. This financial support includes subsidizing connection charges, in-home wiring, and the purchase of specific appliances. In **Cambodia**, consumers receive US$37 per connection as part of the last mile connection initiative.

Other incentives include lower tax rates and accelerated depreciation for project developers and reducing the cost of mini-grid equipment through reduction in import duties or incentives for manufacturing. Incentives for financiers such as interest and collateral subsidy will be covered in the next section. In **China**, small hydropower producers benefit from both a lower value-added tax and income taxes that are either lowered or forfeited altogether[20]. Most of the funding comes from government sources, international donors, and district and county contributions, while the local communities, considering their low income levels, are expected to pay only a small remaining portion, if any [22].

While the amount and form of subsidies is important, it is their combination and efficient disbursal that can make mini-grids financially viable over the long term and make electricity access affordable to consumers. Subsidy disbursals linked to prescriptive standards, and those involve high transaction costs due to inefficient government agencies, can stifle innovation, compromise financial viability and restrict the scale-up of mini-grids.

4.3.2 Financing and Investment

What role can policy play in financing and investment of mini-grid systems?

Financing and investment is critical for the development and scalability of RE mini-grids. Financing is usually offered by government or domestic or international banks, while private investors can provide equity. The uncertainty of mini-grid operation over the long term is often a detriment to availability of investment, and the associated risk can result in high interest loans. Government policy that provides a long-term signal to the sector can reduce the risk perception of investors and non-government banks. Government-owned banks can also provide low interest loans to developers. Interest subsidy from the government can also reduce the rates for loans. Finally, collateral subsidy, usually in the form of a fund, can guarantee a financing institution payment in case of default from the borrowing entrepreneur, thus shifting the risk from the financier to the government institution.

In **China**, the state-owned banks provide low interest (or zero-interest) loans to small hydropower plant developers. Plants are supposed to recover costs through consumer tariffs. However, in cases when the plants are not profitable, the state-owned banks have been known to not enforce payments due to the central government's emphasis on rural electrification [20].

In **Sri Lanka**, the RERED project depended on commercial banks to provide capital for micro-hydro mini-grid systems. The electricity consumer societies (ECS) for a village community had to apply for a commercial loan from a 'Participating Credit Institution' (a commercial bank that was approved by the RERED project) to cover about 80% of the cost after the US$400 per kilowatt capital subsidy. Similarly, in **Nepal**, the loans for village micro-hydro projects were administered through the Agriculture Development Bank of Nepal, to provide financing in addition to the 50-75% capital subsidies provided through the rural energy fund [12].

In recent years, private investors like Acumen Fund and Bamboo Finance are increasingly seeking to invest in entrepreneurs and private mini-grid developers as part of their larger portfolios. While RE mini-grids have the potential to be profitable purely based on consumers' willingness to pay and savings relative to kerosene and diesel use, long term policy and incentives to support mini-grids can ensure achieving both rapid growth in mini-grid deployment through investment and affordable electricity services.

4.3.3 Tariffs and Revenue Streams

What are the different tariff models and how are they affected by regulations and subsidies?

There are several tariff designs that have been used in mini-grid operations [47]. The simplest one is the fixed charge based either on connection or on number of lights and appliances. Fixed connection charges are often accompanied by load limiters to limit the number of appliances, i.e., load per connection. However, simple load limiters restrict consumer demand at all times, even during non-peak hours. Smart load limiters can be capable of restricting consumer demand only during peak load times by sensing the voltage or frequency to determine the stress on the mini-grid system [11]. In the absence of a load management strategy, mini-grid systems with fixed connection charges can eventually fail as consumers add appliances and demand exceeds supply.

Energy-based tariffs, on the other hand, require consumers to pay for the actual energy they use by metering their consumption. Such tariff schemes may also encourage conservation. Time-of-use meters, although more expensive, could further incentivize conservation during peak hours. However, energy meters and the associated costs of metering, billing, and maintenance can form a significant portion of the overall cost of providing electricity access, especially to rural consumers who are often dispersed and have low consumption levels. Pre-paid meters that require consumers to purchase units of electricity from the supplier in advance can avoid the task of meter reading, billing, and collection [47]. However, such tariff schemes may also need load limitations to prevent peak demand exceeding supply.

Further the tariff scheme, whether power or energy-based, depends on the type of technology used. Solar photovoltaic systems and other systems using battery storage are limited in energy supply, while micro-hydro or biomass gasifier-based systems are limited in the level of peak load that they can meet.

In places where mini-grid tariffs are unregulated, the project developer and the consumer community are free to decide the structure of the tariff design, including penalties for non-payment. However, the results can be quite varied, from tariffs being insufficient to cover generation costs to developers charging relatively high tariffs.

In **China**, the consumer tariffs for the mini-grid plants built under the Township Electrification Program were set by the village government or committee, and seemed to vary widely, which also affected the cost recovery of the projects [20]. Tariff subsidy was only offered to mini-grid systems that were installed after 2006. For systems that did not receive the subsidy, the tariff collection often did not cover the operator salaries and system O&M costs [22].

In **India**, standalone rural electricity generation and distribution does not require a license [28]. Consequently, project developers or communities can decide their own tariffs to ensure financial sustainability of projects. RE mini-grid consumers may have higher willingness to pay and in most cases spend less on better services offered by mini-grids relative to kerosene-based lighting and diesel generation. However, consumers, especially in the residential sector may end up paying more for electricity compared to their counterparts who are connected to the central grid, since the latter are often cross-subsidized by industrial and commercial consumers [26].

In some countries, consumer tariffs, even for mini-grids, are regulated. Regulation of tariffs often needs to be in combination with on-going subsidy support from the government or utilities to ensure the financial viability of the RE mini-grids and to ensure adequate returns to investors and project developers. In **Brazil**, tariffs are set by the regulator, ANEEL, for both grid-connected and off-grid consumers, served by concessionaires. The connection charges and tariffs for low-income consumers are subsidized by the Brazilian government to meet its goal of providing universal access to electricity. However, subsidies are presently only offered through concessionaires and there does not seem to be a mechanism to channel subsidies to private mini-grid developers or NGOs. Mini-grid development in Brazil is in its infancy and it remains to be seen how effective the subsidy mechanism works for deployment and scale-up of mini-grids [25]. As mentioned earlier, the Forum of Regulators in **India** is considering a model where the tariffs of mini-grids will be regulated and made equitable with central grid counterparts while the project developer will be provided a viability gap subsidy to ensure a profit margin [46]. Even in **China**, there is a move towards uniform pricing for electricity services in urban and rural areas through a cross-subsidy regime where the costs of decentralized renewable energy systems would be shared by the entire power grid [22]. While regulating tariffs can help achieve the objectives of pro-poor policies, an ineffective subsidy disbursal mechanism can increase transaction costs for project developers and jeopardize their financial viability.

In some cases, a combination of community decision and government or regulator approval for tariff structure is enforced. The **Cambodian** electricity framework requires a license for operating a mini-grid, and therefore makes the operators subject to tariff regulation. However, the rules establish case by case tariff setting with the objective of allowing adequate cost recovery from more expensive rural mini-grids [23]. In **Tanzania**, law mandates that retail tariffs should be determined by the developer and firstly presented to the local community for their opinion. The Tanzanian regulatory authority EWURA provides its approval after the community agrees to a tariff [42].

Drawback of using the same metering systems as grid-connected consumers is that electricity is sold in actual units rather than "electricity services." In other words, the incentives for developers to pursue demand side management such as using efficient LED lights (instead of CFLs or incandescent lights) and sell the "electricity service of lighting," can diminish since the per-unit charge to the consumer would be higher due to more expensive LED lights, even though the use of LED lights reduces the system size requirement and the overall cost of the lighting service. Regulators need to address such nuances of mini-grid operation if regulating tariffs.

5 CONCLUSION

Renewable energy-based mini-grids can be an important alternative to, or enhance the effectiveness of, central grid extension as a way to increase access to reliable electricity services. While there are a number of challenges to implementing RE mini-grids, many of these can be addressed by well-conceived policy measures. In this study, we provide a framework for mini-grid policy design underpinned by specific implementation examples from seven different countries – China, India, Brazil, Nepal, Sri Lanka, Cambodia, and Tanzania. These nations have chosen specific models for the institutional, technical and financial components in their mini-grid policies with varying results. Through our study, we highlight the critical policy components, and their interplay, that are required for sustainable deployment and operation of RE mini-grids.

Our policy framework hinges on the definition of six elements of sustainability which should be explicitly considered in policy design from the perspective of all stakeholders: a) technical sustainability to ensure long-term reliable operation of mini-grids, b) economic sustainability that ensures affordable as well as a financially viable mini-grids, c) socially coherent deployment with value-adding community involvement, d) equitable access to electricity services, e) minimal environmental footprint, and f) potential for scaling up the deployment of mini-grids. We use these elements of sustainability to provide recommendations for designing the institutional, technical, and economic components of mini-grid policies.

Policies need to be designed according to clearly defined roles for all stakeholders. Appropriate licensing and regulations can ensure compliance and affordability for consumers but should keep transaction costs low for developers and not compromise project viability. Training and capacity development of all stakeholders - including the community, project developers, government officials, regulators, utility personnel and financiers - are essential to develop a strong mini-grid sector. Robust and appropriate monitoring and verification mechanisms should ensure quality of service without being cumbersome to stakeholders. Suitably designed standards can guarantee quality and reliability of service. Availability of resource surveys and central grid extension plans can assist project developers in planning optimal deployments. A clear vision regarding the role of mini-grids reached by central grid extensions – including the question of whether mini-grids can interconnect with the central grid or if they must be dismantled when the grid arrives - will reduce uncertainty and avoid stranded assets. Policies need to strike a balance between governmental financial incentives and subsidies, as well as the developer's debt-to-equity ratio and the consumers' tariff rates. Finding this balance is essential to the affordability, viability, and scalability of mini-grids.

We emphasize the importance of concurrently considering all components of a mini-grid policy, designing each component through the lenses of different stakeholders, and fostering mini-grids as an integral part of a country's electricity access efforts. Policymakers have multiple options, and it is the combination of these in the institutional and financial capacity of the government context that will decide the success of the program. There are no silver bullet solutions, but a thorough understanding of the existing technical and institutional capacities, as well as the stakeholders' interests and socio-cultural context will enable the design of an effective policy instrument.

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