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The role for low carbon electrification technologies in poverty reduction and climate change strategies: A focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya

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ABSTRACT

As a potential poverty reduction and climate change strategy, this paper considers the advantages and disadvantages of using renewable energy technologies for rural electrification in developing countries. Although each case must be considered independently, given a reliable fuel source, renewable energy mini-grids powered by biomass gasifiers or micro-hydro plants appear to be the favoured option due to their lower levelised costs, provision of AC power, potential to provide a 24 h service and ability to host larger capacity systems that can power a wide range of electricity uses. Sustainability indicators are applied to three case studies in order to explore the extent to which sustainable welfare benefits can be created by renewable energy mini-grids. Policy work should focus on raising awareness about renewable energy mini-grids, improving institutional, technical and regulatory frameworks and developing innovative financing mechanisms to encourage private sector investments. Establishing joint technology and community engagement training centres should also be encouraged.

1. Introduction

An estimated 1.3 billion people, approximately a fifth of the world's population, lack access to electricity at home and the vast majority of these people live in rural areas of Sub-Saharan Africa and South Asia (IEA, 2011a). Access to electricity is vital for achieving the Millennium Development Goals (MDGs) aimed at alleviating poverty (GNESD, 2007; AGECC, 2010) and rural electrification presents a significant challenge in many developing countries (Yadoo and Cruickshank, 2010a; Zomers, 2003; Reiche et al., 2000). At the same time, climate change is a pressing global concern that is predicted to most severely affect the developing world where communities are least resilient (Zerriffi and Wilson, 2010).

These two global challenges – development and climate change – are intrinsically linked. The development of industrialised nations has been the major contributor to increased greenhouse gas (GHG) emissions (and therefore climate change) whilst simultaneously improving a country's ability to cope with the increased pressures induced by a changing climate (Klein et al., 2005). On the other hand, the poorest countries, which have emitted the least greenhouse gases, will be impacted the most severely by climate change and will be the least able to withstand weather-related shocks (Zerriffi and Wilson, 2010). Nevertheless, if those countries were to follow the same development paths as today's industrialised countries, global GHG emissions would rise even more sharply.

In order to reverse the current trajectory, there is a need to pursue poverty reduction strategies that mitigate against increased GHG emissions and improve people's ability to adapt to the new realities induced by climatic change without limiting their opportunities for human and economic development. Although identifying and implementing such synergistic strategies can be difficult, particularly in the energy sector (Swart and Raes, 2007),[1] progress on both agendas will be paramount to overall success. As identified by the Director of the UN Millennium Campaign, climate change and the MDGs share several common traits, most notably their urgency, interdependence (both are global challenges), derivation from a market failure, focus on justice (and not charity) and their need for a coherent strategy (for example, not diverting aid committed to combating poverty in order to fund mitigation activities) (Shetty, 2007). Their interplay could also provide positive reinforcement, "Climate change [...] can become a real opportunity to achieve the MDGs for the world's poor and disadvantaged" (Shetty, 2007).

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[1] The IEA estimates that achieving basic universal access to electricity by 2030 (defined as 100 kWh/person/year) would increase global GHG emissions by 1.3% (IEA, 2009). However, this increase could be reduced through energy efficiency measures and the use of cleaner sources of energy such as renewable energy (AGECC, 2010).

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Using renewable energy sources to increase access to electricity would appear to be an example of the above-mentioned synergistic strategies, contributing to poverty reduction, climate change mitigation and improved resilience (having access to electricity can improve people's adaptive capacity to weather-related shocks). There are various ways that this can be achieved: more renewable energy sources can be integrated into the generation mix of the national grid network and the grid can be extended to rural areas; alternatively, an off-grid renewable energy resource and technology can be installed at the local level. Examples of renewable energy off-grid technologies include solar photovoltaic (PV) systems, micro-wind turbines, biomass gasifiers and pico-, micro- or mini-hydro power plants. The systems could either be linked to an individual household, or connected to a local distribution network. An off-grid power generation system that is reliant on one (or several different) renewable energy source(s) and distributes power through a local grid network is often known as a renewable energy mini-grid.

To determine the extent to which renewable energy technologies reduce GHG emissions compared to fossil fuels (such as diesel generators or grid-connected coal-fired stations) it is important to conduct a life-cycle analysis (LCA) of the expected emissions from each technology, that is, consider not only the emissions produced during the electricity generation stage (direct emissions), but also those that occurred upstream (during fuel exploration, mining and fuel transportation) and those that will occur downstream (during decommissioning, waste management and disposal). For grid-connected generation sources, fossil fuel technologies can have upstream GHG emissions of "up to 25% of the direct emissions from the power plant" while the vast majority of GHG emissions from renewable energy technologies (up to 90% of cumulative emissions) occur upstream, "typically for the production and construction of the technology and/or its supporting infrastructure" (Weisser, 2007).[2] Estimations tend to vary depending on the assumptions made: following an extensive review of the literature, Weisser (2007) calculated the following approximate ranges of LCA GHG emissions: hydro 1–34 gCO_2eq/kWh; onshore wind 8–30 gCO_2eq/kWh; offshore wind 9–19 gCO_2eq/kWh, solar PV 43–73 gCO_2eq/kWh, biomass 35–99 gCO_2eq/kWh, coal 950–1250 gCO_2eq/kWh, oil 500–1200 gCO_2eq/kWh and gas 440–780 gCO_2eq/kWh (Weisser, 2007). A more recent study calculated the average life-cycle GHG emissions to be broadly similar: 90 gCO_2eq/kWh for solar PV, 25 gCO_2eq/kWh for wind, 41 gCO_2eq/kWh for hydro, 170 gCO_2eq/kWh for geothermal, 1004 gCO_2eq/kWh for coal and 543 gCO_2eq/kWh for gas (Evans et al., 2009) (Table 1).

LCAs of GHG emissions tend not to be as prevalent for smaller, off-grid technologies suitable for the electrification of rural communities in developing countries.[3] However, a comparison of the life-cycle GHG emissions of an off-grid wind system (a 400 W wind turbine with battery bank storage capacity of 46.4 kWh) with a single-home diesel generator found that the wind system "offered a 93% reduction of GHG emissions when compared to the diesel system" (both systems were designed to be able to deliver 162.5 kWh of AC power every month – the estimated power requirement of a small off-grid home – over a twenty year period) (Fleck and Huot, 2009). Another study compared an off-grid solar PV diesel hybrid system with a diesel generator and found that a PV diesel hybrid system (which lowered diesel consumption by 33%) had a "weighted average life cycle GHG emissions factor [...] 25.9% lower than for a diesel power system, even using very conservative assumptions" (IEA, 2011b).

Table 1
Life-cycle GHG emissions for various electrification technologies.

	Range of LCA GHG emissions (Weisser, 2007) gCO_2eq/kWh	Average LCA GHG emissions (Evans et al., 2009) gCO_2eq/kWh
Hydro	1–34	41
Wind	8–30 (onshore), 9–19 (offshore)	25
Solar PV	43–73	90
Biomass	35–99	N/A
Geothermal	N/A	170
Coal	950–1250	1004
Oil	500–1200	N/A
Gas	440–780	543

This paper will consider the advantages and disadvantages of using different renewable energy technologies to extend electricity access in developing countries. Given the growing consensus of developing countries, policy-makers and the donor community that poorer countries should not have to pay the price of fixing the climate 'problem' either directly (by paying the incremental cost of low carbon technologies) or indirectly (by not developing at a speed they would have otherwise achieved through higher carbon technologies), "there is an emerging consensus... that least-cost energy options should be pursued, although still with due diligence to benefit from options for cleaner development" (Nygaard, 2009, p. 4), it is vital to establish whether or not low carbon technologies are truly the best option for a developing country's ongoing human and economic development. A discussion based on existing literature will be followed by case studies of renewable energy mini-grids in Nepal, Peru and Kenya. These explore the extent to which sustainable welfare benefits can be created from off-grid low carbon technologies. Current barriers to implementation and the resultant policy implications will also be considered. It is thought that this paper will be of value to those policy-makers, donors, project planners and implementers working in the fields of rural electrification and climate change mitigation or adaptation.

2. Renewable energy solutions for rural electrification

2.1. Grid-based renewable energy

Improving electricity access by extending the national grid network can have economic, technical and social advantages when the population to be served live in urban, peri-urban or rural areas that are close to the end of the existing grid (Gouvello, 2002). The lifetime costs of extending the distribution network in these areas can be lower than installing independent electricity generators or off-grid renewable energy solutions (Gouvello, 2002). Grid-based electrification can also simplify maintenance and administrative duties (such as billing and tariff collection) in urban and peri-urban areas where centralised authorities have assumed these responsibilities. The relative cost of increasing renewable energy generation within the grid network will depend on the specific natural resources available in different countries and their reliability of supply. In fact, many developing countries already rely heavily on renewable energy resources to power their grid network. In Rwanda, for example, renewable energy constitutes 53% of total electricity generation (MININFRA, 2011).

[2] The exception is biomass systems where "the majority of emissions can arise during the fuel-cycle depending on the choice of biomass fuel" (Weisser, 2007).

[3] However, based on the experience of PV, life cycle GHG emissions tend to be lower for off-grid, rather than grid-connected, variations of the technology: a SHS emitted the lowest amount of the GHG emissions per kWh of PV output, an off-grid hybrid PV-diesel system emitted an intermediate amount of GHG emissions and a grid-connected PV system emitted the most GHG during its life cycle per kWh of PV output (IEA, 2011b).

While this may work well in countries with ample supply and a diversity of fuel sources, other countries have experienced power cuts and rationing. Power generated by hydro sources in Kenya dropped by 18.4% in 2008/09 owing to drought and their government chose to meet the shortfall using pre-installed and emergency thermal generation, almost doubling consumer charges to reflect this additional expense (KenGen, 2009; KPLC, 2009).

However, for significant proportions of developing country populations who live in more remote rural areas, obtaining electricity through access to grid power is not economically feasible given the large distances, difficult terrain and low projected levels of consumption involved (Gouvello, 2002). Additionally, due to the greater operational costs involved in distributing electricity in rural areas, the service may be poor or even non-existent in countries where the grid has been extended to serve rural populations, as in the case of rural India where there are power cuts of "14–16 h a day, on almost all days of the year" (Krishnaswamy, 2010). This may be due to poor transmission infrastructure, generation capacity shortages or mismanagement of the central grid that result in frequent black-outs or 'brown-outs' (large voltage drops that can damage appliances), particularly for rural customers at the ends of the network. The unreliability and shortage of grid power in many areas can severely hamper economic development. The economic cost of power outages has been estimated as 4% of GDP in Tanzania, 5.5% in Uganda and 6.5% in Malawi (Foster and Briceño-Garmendia, 2010). Extending these weak grids would only aggravate the situation and "existing grids would need to be backed up [that is, strengthened] before new connections could be made" (ARE, year unknown). Therefore, depending on the service quality of the existing grid network, the distances and topography involved, extending the national grid to rural areas is not always the most effective or cost efficient way to alleviate poverty in developing countries.

2.2. Off-grid renewable energy

For many countries with remote rural populations, off-grid electrification solutions (powered by a low carbon energy source or diesel) represent the optimal means of extending electricity provision in terms of the required investment, efficiency and quality of service. Compared to diesel generators, off-grid renewable energy solutions have been criticised for being more costly, less reliable and more limited with regard the range of energy services on offer. These criticisms are voiced particularly strongly when referring to solar PV technologies (Wamakonya, 2007; Nygaard, 2009; Jacobson, 2007; Ellegård et al., 2004). Solar home systems (SHS) have been criticised for being "donor driven, expensive, fragile and not fulfilling the needs of productive use" (Nygaard, 2009). Jacobson (2007), researching the Kenyan solar PV market, argues that the rural middle class receive the majority of the benefits from solar electrification, that PV hardly contributes to economically productive or educational activities and that its principal use is for TV, radio, mobile telephones and other such "connective" applications rather than income generation, sustainable development or poverty reduction. Moreover, economic, technical and organisational challenges associated with donor supported PV projects have caused a number of projects to fail within a few years (Jacobson, 2007).

However, while it is true that many off-grid renewable energy technologies may be more expensive and dependent on favourable weather conditions than a liquid fuel source such as diesel, these criticisms do not project the full story. Firstly, as shown in Fig. 1, on a levelised cost basis (that is, when capital and operating costs are totalled over the plant's economic lifetime using a 10% discount rate), several renewable energy technologies (such as biogas digesters, biomass gasifiers and micro-hydro plants) are already cheaper than diesel generators, particularly in light of their "high capacity factors and availability of size ranges matched to mini-grid loads" (ESMAP, 2007). For example, based on the levelised costs shown in Fig. 1, a 100 kW diesel generator would have to reach a load factor of over 80% in order to compete on a cost basis with a similarly sized micro-hydro mini-grid. In practice this is very difficult to achieve unless the generator is significantly under-sized (and therefore unable to meet peak demand) or if it is correctly sized but restricted to only running during the hours of peak consumption (for example, between 6 and 8 p.m.). As testified by the lead author during field visits in Peru, diesel-powered systems in rural communities are often limited to a few hours of operation per day due to financial constraints and this can have a corresponding limitation on the extent of welfare benefits produced as a result of electrification.

Secondly, the volatile, yet gradually rising, price of oil-based fuels (Owen et al., 2010) and the corresponding increased vulnerability of the poor have not been factored into these cost

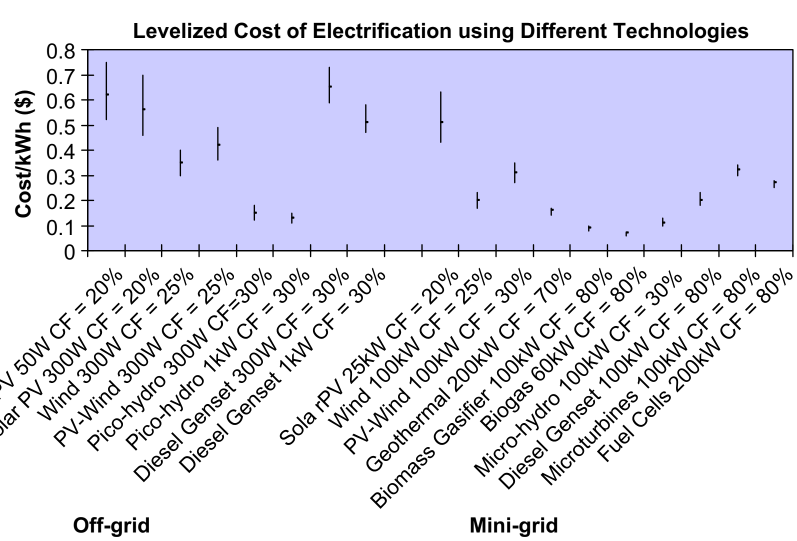

Fig. 1. Levelised cost of electrification using different technologies. *Note*: Calculations were performed for the context of India. Capital and operating costs have been totalled over the technologies' economic lifetimes using a 10% discount rate. A number of assumptions have been made related to the technologies' capital and operating costs (for more information see ESMAP, 2007). Sensitivity ranges are shown on the graph (average values are marked by a dot). CF = Capacity factor.
Source: ESMAP, 2007.

estimations, nor has the continuing fall of the price of solar PV technologies following growing markets in the North and a shift of production to China (Nygaard, 2009). Thus, the levelised cost difference between diesel and renewable off-grid power sources is likely to decrease further. The International Energy Agency predicts an oil price of USD 200 per barrel by 2030 (IEA, 2008). While it is impossible to accurately forecast price expectations in the commodity market, the gradual rise in oil prices since 2002 is thought to be part of an ongoing upward trend caused by the increasing gap between supply and demand (Soros, 2008). Several independent institutions believe that conventional oil production may soon go in decline, requiring the more cost-intensive development of unconventional resources (Owen et al., 2010). Supply and demand is "likely to diverge between 2010 and 2015, unless demand falls in parallel with supply constrained induced recession" and current reserves "will only have the capacity to service just over half of BAU [business as usual] demand by 2023": "The age of cheap liquid fuels is over" (Owen et al., 2010). Therefore, by generating energy from indigenous power sources, renewable energy power technologies can protect against fluctuations in international fuel prices, improving energy security and local resilience.

Thirdly, contrary to the criticisms levied against individual household systems such as SHS, pico-hydro or micro-wind turbines, some of the larger renewable energy off-grid systems – such as those used to generate power for an entire community as part of a local mini-grid generation and distribution system – can offer 24 h service and the ability to be used to power a range of electrical applications, comparable to those available to customers serviced by the grid. This is an important point, as substantial poverty reduction can only be achieved if a wide range of productive and non-productive (welfare-enhancing) uses of electricity are established.[4] Whereas independent household electrification systems such as SHS, pico-hydro or household wind turbines are predominantly used for lighting and small domestic appliances (for example to charge a mobile phone, power a radio or a black and white television), the lower per unit cost of some mini-grid technologies allows them to offer greater capacity.[5] By distributing AC rather than DC electricity, mini-grids can also improve system efficiency as AC appliances tend to be higher quality, more efficient and reliable than their DC equivalents designed for SHS and small wind turbines (Chaurey and Kandpal, 2010).

However, off-grid renewable energy systems, including mini-grids, also have their disadvantages. Although the interconnection of a diverse range of renewable energy technologies is thought to improve security of supply in an environmentally benign way – similar to the Smart Grid concept discussed for the European Union (EC, 2011) – isolated systems that only rely on one renewable energy source face a greater threat of supply vulnerability. Therefore, care must be taken to ensure that a diversified fuel mix is integrated into the off-grid renewable energy system (where different renewable resources are available) or that an energy storage system (for example, rechargeable batteries or biofuels) is available in times of need, albeit that this additional equipment will increase the system's capital costs. If the possibility exists to interconnect different renewable energy systems to create a larger distribution network, this may overcome some of the security of supply issues and allow a developing country to leapfrog towards a more advanced electricity system that will be more reliable, environmentally benign and responsive to local needs (Lovins and Lovins, 1982; O'Brien and Hope, 2010). Grid-connected mini-grids can also "improve power quality by supporting voltage and reducing voltage dips" at the end of village distribution systems (seen as brown-outs) and lower the cost of peak-time energy supply (Bayod-Rujula, 2009). However, the interconnection of several disparate generation systems (of varying sizes and production reliability), presents several design and technical challenges (most notably standardising the method of communication between the disparate components and deciding upon how best to control the resulting grid network) that are currently being addressed by researchers and engineers (Rhodes, 2010).

Secondly, where the maintenance and administration authority is centralised, the existence of many off-grid renewable energy systems in rural areas can create costly logistical difficulties when it comes to carrying out repairs, issuing bills and collecting tariff payments. However, to a large extent, this is also true for grid-connected rural areas, particularly communities located at the ends of the network (Gouvello, 2002). As found from interviews undertaken for the lead author's doctoral research, regional distribution concessionary companies in Peru find it necessary to decentralise the maintenance, billing and tariff collection of their grid network in rural areas, using subcontractors and a series of Authorised Centres for Payment Collection (often based in village shops) in order to lower operational costs (pers. comm., Valencia, 2009; pers. comm., Mamani, 2009). Decentralising operational activities in this way is one of the few means to make rural electricity distribution financially feasible for the concession (Mamani, 2009). However, the provided service is not always exemplary: subcontractors can work on very slim margins, are often stretched for personnel and resources, and therefore may not be able to swiftly attend to the required repairs (pers. comm., Mamani, 2009).

Some organisations attempt to lower operational costs in rural areas through the installation of pre-pay meters. Adinelsa, a centralised government authority in Peru that co-manages a number of off-grid systems with local municipalities, has found that using pre-pay meters lowers operational costs by about 66% as it is otherwise very expensive to administer tariff collections (and disconnect households who do not comply) from a central hub (pers. comm., Zuñiga, 2009). It was estimated to take approximately five years to recuperate the initial investment through these operational cost savings (Zuñiga, 2009). Other organisations choose to decentralise system management, establishing community-based organisations, cooperatives or micro-enterprises at the community level that will assume responsibility for ongoing operations and administration. The Rural Energy Development Programme in Nepal and Practical Action in Peru are two such examples of organisations that provide the necessary training and support infrastructure for communities seeking to self-manage their off-grid electrification systems (REDP, 2007; Sánchez, 2007).

In Nepal, as in rural United States, Costa Rica and Bangladesh, decentralised cooperative-managed distribution of the grid

[4] The impact of such a wide range of potential applications also translates into the improved resilience of local communities to external shocks such as extreme weather conditions caused by climate change. Alternative income streams can be started so that households do not only rely on farming that may be adversely affected by changing weather patterns (Oxfam, 2010). Farming techniques themselves are also made more efficient, while electricity can pump additional water required for irrigation should traditional sources grow scarce.

[5] Typical productive applications of mini-grids include: grain mills, rice dehuskers, water pumping, cow milking, rope-ways (these reduce transportation costs in hilly communities), carpentry, soldering, welding, metal works, mechanic workshops, bakeries, tailoring, battery charging, refrigeration (for example, milk chilling in dairy communities, storing meat and supplying cold drinks to residents and passing travellers), entertainment centres, internet kiosks and computer training workshops. Other potential applications that do not immediately generate income include learning tools for schools (for example, DVDs, computers, photocopiers, music players), refrigeration and sterilisation equipment for health centres, street lighting (this increases night-time security and is particularly important for women), rice cookers, blenders, colour televisions, music systems and ambience cooling devices.

network in rural areas is also encouraged (Yadoo and Cruickshank, 2010a). This was found to reduce system losses from around 25% to around 15% on average, mainly achieved through theft reduction (caused by illegal tapping of the grid network) (Pandey, 2005). Theft in the community of Mugling (Nepal) reportedly dropped from 35% to 15% following a shift to local cooperative management (pers. comm., Dixit, 2009; pers. comm., K.C., 2009). Similarly, "unpaid bills from as long as five years were settled once the community took over management" (Pandey, 2005). These reductions in non-technical losses are related to the greater ease with which the community can identify misdemeanours due to their proximity, as well as their ability to rectify them (often through the use of peer pressure based upon the premise that theft or non-payment would be detrimental to the entire community). The local cooperative's costs for meter reading and system maintenance are also lower than those of the previous centralised management as the linesmen live locally and can "respond immediately to service disruptions", improving the service quality received (Pandey, 2005).

Experience has shown that operational and commercial viability is strengthened if the community is made an important stakeholder in the renewable energy system (Harper, 2000). This could either be achieved through localised management (as discussed above) or by establishing systems through which users can supply (and be paid for) the fuel stock (such as agricultural waste and wood sourced in a sustainable manner) for biomass-based mini-grid technologies. A biomass gasifier in rural Uganda delivers power beneath current average costs for off-grid technologies and contributes "at least four times as much to the local economy" through the provision of fuel stock from households (Buchholz and da Silva, 2010). Unlike other energy technologies (such as biogas digesters, improved cook stoves and solar cookers) (Ni and Nyns, 1996; Ruiz-Mercado et al., 2011), social norms are rarely reported to provide an obstacle between one electrification technology (renewable or non-renewable) over another. However, actively involving the community from a project's early stages is likely to raise users' level of interest, buy-in and appreciation of the electrification system (Sánchez, 2007). Therefore, while the administration and maintenance of off-grid systems can pose a challenge in many countries, deploying local, community-based management systems also presents a number of opportunities, provided that there is sufficient interest on the part of the community and the training is sufficiently comprehensive to ensure that safe and effective operation, maintenance and administrative procedures are followed.

In summary, whether or not low carbon off-grid technologies are the best electrification option in rural areas (in terms of promoting local and national level human and economic development) will very much depend on the individual cases under question. If a community is close enough to an existing grid network that provides reliable power to both its urban and rural customers, grid extension may be preferable. Alternatively, if grid extension is not feasible, the decision falls between a diesel generator and a low carbon off-grid option. There is a wide array of different renewable energy off-grid technologies and each carries their own set of advantages and disadvantages (Table 2). Based on the existing literature, given a reliable fuel source, the installation of renewable energy mini-grids powered by biomass gasifiers or micro-hydro plants appears to be the favoured option due to their lower levelised costs, provision of AC power, potential to provide a 24 h service (depending on fuel availability) and ability to host larger capacity systems that can power a range of productive and non-productive (welfare enhancing) uses of electricity.

The following section will examine three case studies, all existing examples of renewable energy mini-grids, to assess the extent to which such projects can generate sustainable welfare benefits and thereby contribute to the human and economic development of the rural poor.

2.3. *Case studies from the field*

Three case studies of renewable energy mini-grids were conducted as part of the lead author's doctoral research. The studies were performed to assess the extent to which the electrification systems had produced sustainable welfare benefits for the rural poor. Sustainability was defined in its more holistic sense of technical, economic, social, environmental and institutional (or organisational) sustainability, as proposed by Ilskog (2008). The electrification projects all relied on the same technology (micro- or mini-hydro mini-grids), served approximately the same number of customers (around 210 households) and were commissioned in approximately the same timeframe (5–10 years prior to fieldwork). However, although all projects were independently managed and operated from within the community, the type of management model employed (cooperative or micro-enterprise) was deliberately chosen to vary. Projects that involved a more holistic approach from the implementing agent (reflected in the promotion of non-energy related activities as part of the overall project) were also contrasted with more narrowly focused electricity projects. Finally, while none of the projects required external financial assistance to meet their running costs, the third community contributed substantially more towards the capital costs (Table 3).

3. Methods

Fieldwork was conducted in the three case study sites between May 2009 and October 2010. Methods included transect walks, semi-structured interviews with users and managers, observations and photographic evidence. Villagers' perspectives were triangulated against the results of semi-structured interviews held with the implementing agencies, enabling different levels of analysis to be embedded in each case study (Yin, 2003). A series of 43 Sustainability Indicators were developed, based on the indicators used by Ilskog (2008) and adapted to reflect the lead author's prior experiences in the field. These are shown in Table 4.

The indicators were not used to rank different case studies, but an absolute value of 1 point was awarded each time the indicator was met within a case (0.5 points were awarded if the indicator was only partially met and 0 points were given where the indicator was not met). Ilskog and Kjellström (2008) found that using ranking methods to generate a common scale has a tendency to reduce large absolute differences or exaggerate smaller discrepancies between cases. The results were mapped onto spider web diagrams to pictorially depict the extent to which sustainable development was achieved by the project. Furthermore, learning from the experience of Ilskog and Kjellström (2008) where it was found to obscure interesting discrepancies between dimensions (by balancing out disparate values), the indicator values of different dimensions were not aggregated.

Ideally, sustainability indicators are designed in consultation with the various project stakeholders such as the users, government, local electricity service providers, project workers, financing bodies and so forth. However, the selection of a range of cases in different countries presented logistical and sequencing difficulties that prevented prior coordinated indicator selection during this research. Therefore, the indicators were chosen to be as broad as possible to reflect the wide-ranging concerns of different stakeholders as inferred from secondary literature on this and related subjects, including Ilskog (2008), Kooijman-van

Table 2
Key advantages and disadvantages of different electrification options.

Advantages	Disadvantages
Grid-based renewable energy	
In urban, peri-urban or rural areas that are close to the existing network, grid extension can be cheaper and more socially equitable than off-grid solutions	Grid extension is not an economically viable option for many rural areas given the large distances, difficult terrain and low projected levels of consumption
In urban and peri-urban areas the presence of a grid network can simplify maintenance and administrative procedures	The operational costs of electricity distribution (maintenance, billing and tariff collection) in remote rural areas can be higher for centralised management authorities than for local management groups
	Grid service may be poor or even non-existent in rural areas due to the high cost of distribution, mismanagement or poor transmission infrastructure. This can severely hamper economic development
Off-grid diesel generators	
Predictable source of year-round power; power production can be adjusted according to local demand patterns	High operating costs significantly increase its lifetime levelised cost, making it more expensive on a levelised basis than some off-grid renewable technologies
Lower capital costs than many renewable energy off-grid technologies	Due to high operating costs, electricity provision often needs to be limited to a few hours per evening in order to increase the load factor and decrease the unit cost of production. This can severely limit the number of productive uses and welfare benefits generated by the system
Can provide AC power that allows a wide range of appliances to function	The price of oil-based fuels is expected to rise as the gap between supply and demand increases over time. The price volatility of oil-based products can also increase vulnerability for the poor who are dependent on their services
Solar PV	
The price of PV is falling following growing markets in the North and a shift of production to China	One of the more expensive options for off-grid electrification
Operational costs are not dependent on volatile international oil markets, unlike diesel	Due to its high capital costs, lower sized units are often used as they are cheaper. This limits the amount of electricity produced and the range of uses that can be made from the system
In many countries, substantial solar markets already exist. Customers can buy certain PV technologies in shops or local dealerships	Due to its high capital costs, the rural middle classes tend to benefit more from the technology
Solar home systems are available in a variety sizes so that customers can purchase that which best suits their requirements and budget. Additional systems can be added in a modular fashion when finances become available	Prior to the introduction of quality control cheques, PV markets in some countries (for example, Kenya) were flooded by substandard products and this has made some potential customers wary of PV
Possibility to interconnect with other renewable energy based systems in the future	No power can be produced in the evenings (an alternative fuel source or storage system must be combined if a 24 h service is desired). Much less power may be produced during the rainy season in countries affected by seasonal weather variations
	Batteries are often used in connection with PV technologies and require replacing every 2–5 years (depending on usage). Users need to be encouraged to save money over time in order to afford them, however a culture of saving may be difficult to instil in some communities
Wind	
Operational costs are not dependent on volatile international oil markets, unlike diesel	One of the more expensive renewable energy off-grid options
Small-scale wind turbines can be manufactured locally from easily sourced scrap materials, as in the Hugh Piggott model. This should ease the ability to maintain the system, as most of the component parts are locally sourced	Seasonal variations in supply and potential volatility in production output. If a reliable service is required, wind turbines need to be combined with other fuel sources or an energy storage system (or both)
Possibility to interconnect with other renewable energy based systems in the future	The quality of locally produced wind turbines are likely to be of inferior quality than standardised mass-produced ones. Their cost savings are also likely to be small or non-existent
Biomass-based systems	
Lower cost renewable energy technology (can be cheaper than diesel gensets on a levelised cost basis)	The availability of some fuels may fluctuate depending on their harvest cycle. If a reasonably priced steady fuel source is not available, there may be reason to combine the system with an alternative fuel source or storage system (at additional cost)
Users can generate additional income through contribution of fuel stock	Care must be taken to ensure that the cultivation of fuel stock does not take place on land that would have otherwise been used to grow vital food crops
Operational costs are not dependent on volatile international oil markets, unlike diesel	
Depending on availability of fuel stock, 24 h service is possible	
Larger systems that distribute AC electricity can be more efficient and offer the ability to be used to power a range of electrical applications, comparable to those available to customers serviced by the grid	
Possibility to interconnect with other renewable energy based systems in the future	
Hydro systems	
Lower cost renewable energy technology (often cheaper than diesel generators on a levelised cost basis)	Seasonal variation—depending on resource availability, production may significantly drop during the dry season. This may mean that an alternative fuel source or an energy storage system should be combined (at additional cost)
Operational costs are not dependent on volatile international oil markets, unlike diesel	Applicability is limited as it requires the presence of hills (inclined slopes) and a steady water flow
24 h service possible without the need for batteries or other renewable energy sources	
Larger systems that distribute AC electricity can be more efficient and offer the ability to be used to power a range of electrical applications, comparable to those available to customers serviced by the grid	
Possibility to interconnect with other renewable energy based systems in the future	

Table 3
Key similarities and differences between cases.

	Pokhari Chauri (Nepal)	Tamborapa Pueblo (Peru)	Thiba (Kenya)
Technology	Micro-hydro	Micro-hydro	Mini-hydro
Size	22 kW	40 kW	135 kW
Year commissioned	2000	2000	2005
No. customers	239 Households	218 Households	180 Households
Ownership	Community	Municipality	Community
Management	Cooperative	Micro-enterprise	Cooperative
Technical Operations	Local employees	Local employees	Local employees
% Of capital costs paid by users	Labour and 7.5% (bank loan repaid over 2 years)	Labour only	Labour and 50% approx
% Of operating costs paid by users	100%	100%	100%
Productive uses	Some	Lots	None
Non-energy related activities promoted	Yes	No	No

Table 4
Sustainability indicators used in the research.

Sustainable development				
Dimension				
Technical development	Economic development	Social/ethical development	Environmental development	Organisational/ institutional development
Key variables				
Operation and maintenance	Financial	Improved service availability	Global impact	Capacity strengthening
Technical client-relation	Productive uses	Credit facilities	Local impact	Client-relation
	Employment generation	Equal distribution		Stakeholder participation
Indicators				
1. Service is reliable, disruptions are minimal 2. Service meets demand capacity requirements 3. System is efficient and technical losses are minimised 4. System is compatible with future grid service 5. Support infrastructure (expertise, supply parts) is readily available 6. System is well maintained 7. Advance notice about planned service disruptions is given to users 8. Service is safe to use and operate	1. Service is affordable for users 2. System breaks even (O&M costs are met) 3. System is profitable, excl. capital costs 4. System is profitable, incl. capital costs 5. A share of the profits is re-invested in the electricity service 6. Electricity is used by local industries 7. Electricity is used by a broad range of micro-enterprises 8. Electricity is used to improve agricultural activities (irrigation, food processing, refrigeration of goods) 9. Local employment opportunities have increased due to electricity 10. Profits from micro-enterprises or livelihoods have increased due to electricity	1. Electricity is used in schools 2. Education has improved due to electricity 3. Electricity is used in health centre 4. Healthcare has improved due to electricity 5. Electricity is used in community centre 6. Existence of street lights 7. Telecommunications have improved due to electricity 8. Women's burdens have reduced due to electricity 9. Micro-credit (or alternative) possibilities are available for electricity services connection and tariff payment where necessary 10. All households who want it have access to electricity service	1. Electricity is generated from a low carbon source 2. Electricity has replaced other "dirty" energy sources for lighting (e.g. kerosene) 3. "Dirty" energy sources for cooking (e.g. firewood) have been replaced or improved 4. Electricity has displaced actual or potential "dirty" energy sources for powering equipment (e.g. diesel) 5. No adverse local environmental impacts have occurred 6. Adverse local environmental impacts occurred but have been fully rectified 7. Community awareness of environmental issues and environmental surroundings have improved	1. Electricity service management organisation is efficient and effective 2. Local capacity for organisation and management has improved due to electricity 3. High sense of responsibility for system by managers 4. High degree of stakeholder participation in the system if desired 5. Greater empowerment for women through involvement in the electricity system 6. Low level of non-technical losses or payment defaults 7. Users are satisfied with the electricity service 8. Transparent financial accounts are kept 9. There is an effective channel through which complaints about the service can be made

Notes: 1. These indicators were designed by the lead author but were influenced by Ilskog (2008) and Fenner et al. (2006).
2. Economic development: indicators 2–4 can be obtained cumulatively.
3. Environmental development: where indicator 5 is obtained, Indicator 6 should be omitted and total points should be normalised out of 6. Indicator 6 carries a maximum of 0.5 points (that is, 5.5/7 is the maximum score for this dimension if indicator 6 is obtained).

Dijk and Clancy (2009), Obeng and Evers (2009), ITC (2002), as well as from the researcher's prior experiences in the field.

Nevertheless, while an effort was made to make the process as objective and transparent as possible, the lead author's choice of indicators was ultimately subjective, as was her assessment of the case studies with the corresponding allocation of points. Similarly, although each indicator receives an equal weighting (Environmental Indicator 6 is the exception), certain issues were given greater emphasis through the assignation of multiple indicators (for example, Social Indicators 1 and 2 both relate to improvements to education). Therefore, while the use of indicators can provide a useful framework against which to assess different case studies, their application does incorporate a certain degree of subjectivity.

3.1. Pokhari Chauri

Pokhari Chauri is a rural settlement of 239 households in Kavre district, central Nepal. The area had had no access to electricity and households relied on candles and kerosene lamps for their basic lighting needs. However, in July 2000 a 22 kW run-of-river hydro plant was installed by the United Nations Development Programme (UNDP)-led Rural Energy Development Programme (REDP). Households were fitted with a 100 W mini-circuit breaker and those with larger machinery (for example carpentry tools or mills) had meters installed. Electricity is supplied every day between 4 a.m. and 4 p.m. and again from 6 p.m. until 11 p.m.. Approximately 2% of the households are provided electricity for free due to their lower economic status.

The community has greatly benefited from the arrival of affordable electricity. School children now study for an average of 1–2 h more per day and teachers believe them to be better informed from increased radio and television access at home. At school, electricity is mainly used for cassette players and listening exercises in language classes, however it is sometimes used for lighting if the day is particularly overcast or rainy. Electric light aids the local health worker when conducting examinations and during night-time births. Both the school and health post now receive their electricity free of charge, thereby saving precious funds. Household savings from the displaced cost of kerosene and batteries vary between approximately 0.7–12 USD/month depending on their family size, disposable income and number of children in education.

Traditional agro-processing techniques have also improved following the installation of 3 rice mills, 1 flour mill and an oil grinder, all purchased by the community. The use of such machinery particularly benefits the local women as it used to be their job to grind the produce and it would pain their hands. Whereas previously grinding used to be done at home, the communal space created to house the community-owned mills provides an additional point of social interaction for the women and girls. Moreover, approximately 25% of interviewed households reported that the time and the effort saved by these mills allows them to process extra crops and sell them in the markets, giving their family an additional seasonal income of approximately 135–270 USD/month. New private businesses have also emerged, for example a milk chilling unit and 3 carpentry workshops.

The community has formed a cooperative to manage the electricity system and the income that it generates. All members meet on a yearly basis, when an elected executive committee informs them of the cooperative's finances and plans for the following year. Two community members have been trained as system operators and one as manager, thereby improving local skill sets and providing additional employment. User electricity tariffs are used to maintain the system and to provide members with micro-loans; these are normally repayable within 6 months and are often used to establish small cottage industries or build toilet assisted biogas plants. Interviewed households expressed satisfaction with the service provided, attesting that repairs, when necessary, were carried out quickly and to a high standard.

To keep members informed and involved in a wide range of community development activities throughout the year, 22 community organisations were formed – 11 male and 11 female (gender segregation was found to boost female participation) – by the REDP (all community members belong to one of these groups). A representative from each of these 22 groups attends the executive committee's monthly meetings, reports back and participates in one or two of the five subcommittees, organised according to different thematic interests (loans, education, legal, community mobilisation and advisory). The REDP also facilitates other trainings (for example in incense and soap-making, off-season vegetables, poultry farming, bee keeping, forest nursery and the environment, the building of pit latrines, permanent toilets and garbage pits) so that interested members can diversify their income streams and contribute to the development of the community. Community members are now more aware and pro-active about environmental issues and the local surroundings are better kept as a result.

3.2. Tamborapa Pueblo

In the year 2000, a 40 kW micro-hydro mini-grid was installed in Tamborapa Pueblo, Peru (then a community of 160 households) by the Peruvian branch of Practical Action (*Soluciones Prácticas*) as part of the Inter American Bank's Fund for the Promotion of Micro-Hydro Power Stations. Electricity is now used for a wide range of productive and non-productive uses. Street lighting improves the security of the area and makes women feel more comfortable when visiting their neighbours at night. The lighting of a local sports field creates an additional source of evening recreation for the local youth. There have been improvements to the health service due to access to electricity and the following electrical equipment is now in use: two refrigerators, a radio transmitter, a freezer, a steriliser, a suction machine, three computers, lamps, a centrifuge (for laboratory work), a Doppler machine (powered by rechargeable batteries) and a stereo (used when giving prenatal classes).

Teachers believe that the quality of education has improved and homework is of a higher standard due to electric lighting in homes. Children have access to six computers (and there is an additional machine for administrative purposes), a photocopier, five microscopes, two televisions with DVD, two printers and a stereo (used for dances). Pupils are now benefiting from the use of educational videos and CD-Roms such as Encarta (classes take it in turns to use the computer room). Moreover, since August 2007, an external businessman has established a computing school in Tamborapa Pueblo that offers three-month courses on basic computing skills. There are a total of 120 people enrolled on the courses and the centre contains eight computers and two teachers. A secondary school teacher remarked that access to these new teaching aids has stimulated pupils' interest to continue their studies—around 20% of pupils now enter into tertiary education, whereas previously only around 2% would go.

Communications and entertainment have also improved. As well as the domestic use of electricity to power televisions, radios and mobile telephones, the village now has the services of a local radio station whose transmitter is powered by the electricity produced by the micro-hydro plant. The radio station functions as a private micro-enterprise, employing five people and charging listeners to post advertisements or personal messages. Although its principal utility is to provide entertainment, it also acts as a source of information and on occasion it is used to post important announcements (such as notifications of the suspension of the electrical service). Other uses of the electricity include mills and coffee processing machines, lighting, videos and music during church services, and the domestic use of irons and food blenders.

Remarkably, since its arrival in 2000, 55 businesses have been established in Tamborapa Pueblo and over 42% of their owners consider the availability of electricity to be important, if not essential, to their enterprise. The enterprises include a computer school, 26 shops (two with public telephones, one that sells DVDs, one that provides photocopying services and one pharmacy), 12 restaurants (one with a public telephone), nine carpentry workshops, three mechanic's workshops, one electronics workshop, one radio station, three bakeries, two battery charging service providers, two fuel dispensers, two hostels and four kiosks that are only run at weekends.

Initially, as official owners and guarantors, the municipality had wanted to manage the micro-hydro plant. However the villagers resisted, believing that they would reallocate the funds collected from the tariff payments into other projects and not set aside enough with which to maintain the system in times of need. Thus, with the help of Practical Action, a local micro-enterprise system was established to maintain and manage the system and an operator–administrator team was trained accordingly. The cost of managing and maintaining the system is met by the income generated through tariff collection. As the development of productive uses was deemed important by both the managers and the implementing agency, a block tariff system was introduced with the intention of favouring those who aspired to use electricity for income-generating activities (the unit cost of electricity decreases in stages as consumption increases). Although the project has not been problem-free (one of the administrators allegedly misused the system's maintenance funds), a formal accountability mechanism (an auditing committee composed of users and municipality staff that evaluates the micro-enterprise's performance every two years to decide whether or not to renew its contract) identified this problem, replaced the administrator and ensured that the project would deliver a better service in future.

3.3. Thiba

The community of Thiba initiated their own hydro project. The national distributor had started extending the grid nearby as early as 2002, however, no transformers were being installed within 600 m of Thiba therefore it would have cost each household over 1500 USD to be connected. This was prohibitively high as it represented the average annual salary for local tea farmers. The community chairman had a vision to generate power for the community via their local hydro resources but did not have the technical expertise to be able to execute the project. Therefore, he approached GPower, a local non-governmental organisation working in electrification, for technical assistance.

There are a total of 800 members in the Thiba project and all were expected to contribute approximately 150 USD, unskilled labour and two poles for the distribution system (from local Eucalyptus trees). In return they would receive shares in the project and would be paid dividends once the system started generating a profit. 500 members are fully paid and some members paid more than the required 150 USD (for example, up to 500 USD), thereby entitling them to more shares. GPower installed the generation system (a 135 kW modified Kaplan turbine) and trained four local men to look after the operation and maintenance of the system. These men had to pass the Certificate in Electrical Engineering exams in Nairobi. However, in 2005 the Chairman broke off the relationship with GPower after the NGO had only installed part of the distribution system and connected ten households to the network.

Currently, the mini-grid distributes electricity to 180 households within a 1.6 km radius of the generation equipment and operates from 6 a.m. to 8 p.m. every day. 170 of these households are members and ten are member clients (member clients have to pay approximately 200 USD over four months to be connected however they had not wanted to contribute at the beginning of the project and therefore are not entitled to shares). All users pay a flat tariff of approximately 3 USD/month (used to pay for the technicians' salaries and repair work) and their connections are not metered. In comparison, the national distributor charges rural households approximately 7 USD/month for their metered usage. There is surplus energy on the system (peak demand is around 100 kW) therefore, for the time being, households can even use electric cookers or irons. No step-up or step-down transformers were installed in the distribution system therefore the majority of households (particularly those further away from the point of generation) experience regular voltage drops (brown-outs) that damage their appliances. Electricity is not provided to institutions such as schools or health centres.

There have been problems with the turbine since inception as its shaft becomes bent and bearings are worn down on a regular basis (once or twice a month) causing blackouts. There is a lack of funds to do rigorous repairs or purchase higher quality components. The constant need to replace the bearings and seals and reshape the shaft is consuming all the revenue accumulated from the tariffs. Connected households experience three to four days of blackouts a month as each problem generally takes one or two days for the technicians to fix (including the time required to buy the replacement parts). The regularity of the blackouts frustrates customers. The system can only just financially sustain itself at present but there are no surplus funds to pay for more thorough repairs or improvements. This self-reinforcing relationship between the lack of funds and ongoing technical problems is a major hindrance to the sustainability of the project.

The Thiba project is managed by a 17 member committee. Elections are held every three years but people have so far kept all those who were originally elected in their positions. Once elected onto the committee, the committee members decide amongst themselves who will be the Chairman, Vice Chairman, Treasurer and Secretary. In reality, these positions often go to those who financially contributed the most towards the building of the project. There is a general meeting every three or four months to outline how the committee has been spending the tariff payments. Although the committee claims to be making an effort to be as transparent and accountable to its members as possible, it is unclear how well the project is being managed, particularly as GPower believes that internal corruption caused the disintegration of their partnership.

Table 5
Results following application of the sustainability indicators.

	Pokhari Chauri (Nepal)	Tamborapa Pueblo (Peru)	Thiba (Kenya)
Technical dimension (max. 8)	7.5	7	2.5
Economic dimension (max. 10)	8	8	2.5
Social dimension (max. 10)	7.5	8	1
Environmental dimension (max. 6)	5.5	4	3
Institutional dimension (max. 9)	6.5	6.5	4

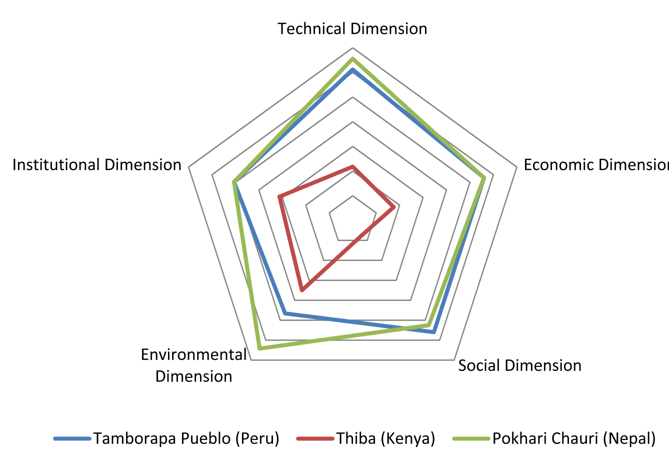

Fig. 2. Spatial representation of the sustainability indicator scores.

3.4. Results of the sustainability assessment

The scores of the different case studies after applying the sustainability indicators are presented in Table 5 and Fig. 2.

4. Discussion

The results show that micro- or mini-hydro mini-grids can produce sustainable welfare benefits provided all dimensions of sustainability are considered in the planning and implementation stages. Whereas the systems in Pokhari Chauri and Tamborapa Pueblo both scored relatively highly, Thiba's low scores were largely the product of insufficient financing that prevented the technicians from investing in higher cost components and conducting better quality repairs. This prevented the electricity service from having a greater development impact (which particularly limited the range of socio-economic benefits) and detracted from the system's overall sustainability. Nevertheless, its technicians displayed great resourcefulness to keep the system in operation. The community in Thiba had also shown great leadership and initiative to bring about the hydro plant's construction in the first place.

While their scores were broadly similar, the REDP's holistic approach (including the creation of separate male and female community organisations, the introduction of toilet assisted biogas and awareness-raising on environmental issues) gave Pokhari Chauri marginally higher scores than Tamborapa Pueblo. The most efficient and effective management system was the micro-enterprise in Tamborapa Pueblo; this was the only case to keep detailed financial accounts. Thiba's management was the least transparent and potentially the most vulnerable to manipulation and corruption. The separation of management and ownership has arguably improved the effectiveness of the management system in Tamborapa Pueblo as a formal system of checks and balances were in place.

In order to enhance the ability to make analytical generalisations from the results, these three main case studies were further complemented by eight satellite case studies (3 in Nepal, 2 in Peru and 3 in Kenya) and 67 semi-structured interviews with rural electrification practitioners. Research findings revealed three key foundations for the creation of sustainable welfare benefits: community mobilisation, productive uses and a supportive enabling environment (including access to financing, technical support and supply parts, and establishing favourable institutional, technical and regulatory frameworks).

A community mobilisation process (possibly facilitated by an implementing agency) is required for three purposes: to establish a transparent, efficient and effective management organisation responsible for the system's upkeep, to provide training to ensure that the system can be locally maintained and to promote holistic development. Contrary to an initial hypothesis, provided a minimum contribution (cash or "sweat equity") had been made (PAC, 2009), user financial contributions were not found to be as influential as the community mobilisation process with regard to generating local buy-in and commitment for a project. Productive uses of electricity both improved living standards and also enhanced the system's financial sustainability, making them essential for the creation of sustainable welfare benefits. However, improvements to other areas such as access to markets, roads, transportation and communications were also required in order to generate wider benefits for the local economy. Interestingly, while most findings appeared to transcend national boundaries and cultural contexts, the feasibility of different management options did not. Whereas micro-enterprise managed systems were advocated by experts and villagers in both Kenya and Peru, communities in Nepal were generally reluctant to relinquish control of a local project to an independent business, opting instead for communally managed options such as cooperatives.

4.1. Existing barriers and policy implications

All electrification contexts are unique owing to the medley of varying physical, socio-economic, technical, environmental and institutional factors at stake and practitioners should always perform rigorous assessments of the different electrification options available in each case (Cherni et al., 2007). However, in situations where their implementation is appropriate given the respective costs, technical efficiencies and service quality levels of the available electrification options, renewable energy mini-grids provide the policy maker and rural development practitioner with a means of combating poverty, mitigating against increased GHG emissions and improving adaptive capacity to climatic change.

Policy intervention is required in situations where technology options are not competing on a level playing field. In many cases, this is true for renewable energy mini-grids which have to compete against more established electrification methods such as grid extensions or diesel mini-grids. Awareness about renewable energy mini-grid options (both their additional benefits and challenges) can be far lower than for grid extensions or diesel alternatives, particularly in national or regional government circles which are often responsible for energy planning and development (pers. comm., Escobar, 2009). This is also true for many commercial banks and other lending institutions that perceive investment in mini-grids as 'riskier' and demand high rates of return when loans are provided (Kariuki and Rai, 2010). Therefore, an initial policy action could be to raise awareness amongst governments and financing institutions about the role that renewable energy mini-grids could play within poverty reduction and climate change strategies, clearly laying out the various advantages and disadvantages with other electrification systems.

Secondly, it is important to ensure that the relevant institutional, technical and regulatory frameworks provide a level playing field for all electrification systems. The IEA has estimated that USD 312 billion of consumption subsidies were provided for fossil fuels in 2009, almost six times the level of support given to renewable energy in the same year (IEA, 2010). In some countries, the ability to generate or distribute power independently from the national utility or regional concession is restricted either formally or informally (pers. comm., Odada, 2010). While some are passing laws to open up this space to communities and local developers, for example the Community Electricity Distribution Bylaw passed in Nepal in 2003 or the concession for local generation and distribution up to 3 MW within Kenya's Energy Act of 2006, other countries could be encouraged to follow suit. It is also important to ensure that these and other progressive reforms such as quality control standards and import tax waivers for certain renewable energy technologies are not undermined by contradictory behaviour within different government departments or bureaucratic agencies (pers. comm., Ngeno, 2010).

Improving financing mechanisms for prospective mini-grid developers (individuals or communities) is another important area which could benefit from targeted policy intervention. The World Bank and other lending institutions have started to engage with output-based subsidies, partial loan guarantees and low-interest longer-term loans to promote renewable energy systems with higher capital but lower levelized costs, although it is too early to evaluate the long-term success of many of these schemes (GPOBA, 2010; pers. comm., Sogan, 2010). There have also been instances where a bank has accepted the mini-grid's physical infrastructure as collateral for the loan being offered. For example, a commercial bank participating in the *Private Sector Participation in Micro-Hydro Development Project* in Rwanda directly purchased the micro-hydro turbine and leased it back to the developer (Pigaht and van der Plas, 2009). This project found that commerciality could be substantially enhanced if mini-grids were linked to the grid network and received additional income from feed-in tariffs; in fact, this possibility was the major driver for entrepreneurial investment (Pigaht and van der Plas, 2009). In India, tri-part financing arrangements between banks, equipment suppliers and the communities where the mini-grids will be installed have proved viable once a guarantor (such as a non-governmental organisation) can be identified to vouch for the community (pers. comm., Krishnaswamy, 2011).

Various financing mechanisms have been established to create additional revenue streams for low carbon projects in developing countries (Zerriffi and Wilson, 2010). These include the Clean Development Mechanism (CDM), the Global Environment Facility (GEF) and a number of voluntary initiatives that lie outside the official United Nations Framework Convention on Climate Change (UNFCCC) process. Most recently, a Green Climate Fund has been agreed in Cancun (UNFCCC, 2010). However, the efficacy of these mechanisms has come under scrutiny particularly (but not only) because the vast majority of funds have been channelled into larger-scale projects in relatively more affluent developing countries: 72% of CDM projects took place in China in 2009, compared to 7% in Africa (World Bank, 2010).[6] Moreover, an analysis of GEF projects has highlighted pervasive inconsistencies that detract from its ability to fulfil its mandate: over half the projects in their sample of 66 projects did not cover the incremental costs incurred from using low carbon technologies, implying that "money was being diverted from meeting development goals in order to meet global environmental goals" (Zerriffi and Wilson, 2010). Policy makers should continue to reform and sharpen these mechanisms so that they are more effective at using low carbon technologies to alleviate poverty in the least developed countries.

Improving local technical capacity regarding mini-grid installation, management and maintenance is another key area that should be addressed for renewable energy mini-grid development to gather pace and for an ongoing high quality of service provision to be provided (Corbyn et al., 2010; UNDP and AEPC, 2010). Training centres for renewable energy mini-grid technologies – similar perhaps to the International Solar School set up by the Solar Energy Foundation in Ethiopia or the CEDECAP training centre run by Practical Action in Cajamarca, Peru – need to be established in various countries to ensure the availability of local human capacity for the required technical, administrative and social skill sets. Students could not only be trained in the installation, operation and maintenance of mini-grids but also in the community engagement techniques that will be vital during the community mobilisation process (Yadoo and Cruickshank, 2010b).

5. Conclusion

The advantages, disadvantages and key barriers regarding the use of low carbon electrification technologies, and renewable energy mini-grids in particular, have been discussed following a review of the literature and case study examples. Given a reliable fuel source, renewable energy mini-grids powered by biomass gasifiers or micro-hydro plants appear to be the favoured option due to their lower levelised costs, provision of AC power, potential to provide a 24 h service and ability to host larger capacity systems that can power a wide range of electricity uses. However, in order to generate sustainable welfare benefits and contribute to the human and economic development of the rural poor, all dimensions of sustainability (technical, economic, social, environmental and institutional) must be considered in the project planning and implementation stages. A robust community mobilisation process, the development of productive uses and an enabling environment were found to be particularly important for project sustainability and welfare improvements. Policy work should focus on raising awareness about renewable energy mini-grids, improving institutional, technical and regulatory frameworks and developing innovative financing mechanisms to encourage private sector investments. Establishing joint technology and community engagement training centres should also be encouraged.

[6] The CDM is inefficient and involves high transaction costs due to its complex approval processes and governance structures. This naturally biases investors against smaller projects where the impact of such costs would be higher. Secondly, it has failed to provide a clear signal for a carbon price and the ensuing uncertainty has put off potential investors and failed to make some renewable energy projects feasible. Thirdly, the CDM has failed to channel revenues to the poorest countries or the poorest areas within those countries (World Bank, 2010). Investors prefer to seek out large-scale high impact projects in favourable investment environments that include political stability and good governance (Benecke, 2008). Fourthly, its emphasis on additionality makes it particularly hard to fund renewable energy projects in countries which have a high proportion of renewables on their existing electricity network. For more information see del Rio (2007).

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