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Village-level solar power in Africa: Accelerating access to electricity services through a socio-technical design in Kenya

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ABSTRACT

Village-level solar power supply represents a promising potential for access to electricity services. Increased knowledge is needed for the development of solutions that work for the users and are viable in the long run. This article analyzes a solar power model developed and tested through action research in collaboration between a community in Kenya and a team of social scientists and technical experts. The analysis includes the reasons for its socio-technical design, and the actual functioning of the model. The research shows that an energy center model can cover basic electricity needs in areas with dispersed settlement patterns, where mini-grid based systems as well as conventional grid extension meet significant challenges. Such areas are representative for large geographical areas in Africa. We show that portable lanterns and low prices may enhance access to suitable services. Committed follow-up of the local actors, and a flexible socio-technical design – allowing for improvements after implementation – contribute to economic sustainability and smooth functioning. Close attention to the socio-cultural context and the challenges of users, operators and managers is required. Our research draws on theories of socio-technical change and users' innovation, and presents a five-step analytical framework for analysis of village-level power provision.

1. Introduction[1]

Globally, 1.2 billion people lack access to electricity [1]. While conventional grid extension has been the predominant mode of electrification in almost all the countries around the world, they have important shortcomings. First of all, centralized grid-based electricity systems often do not reach remote areas and tend to offer services only to the more privileged groups, whereas many poor individuals, households and enterprises remain unconnected [2–4]. Secondly, many conventional systems are based on the use of fossil fuels which have detrimental effects on the global climate and the local environment. Dependence on the import of fossil fuels with volatile prices also makes countries – and institutions and individuals – financially vulnerable. Solar power and other decentralized off-grid electricity systems at the village-level[2] may potentially provide sustainable electricity supply to a variety of users in a more democratic way [1,5]. Other energy technologies such as modern cooking stoves, as discussed by Lambe et al. [6] on renewable energy in Africa, may have positive distributional and environmental effects. However, electricity is a crucial, conditioning factor for a range of modern services such as information, communication and light, which are generally desired amongst populations who do not have access today (e.g., Tenhunen [48]; [7]; Matinga [49]). The issue of how to provide increased electricity access therefore deserves attention in research and in practice.

The solar resource is vast and available in most places where electricity access is needed. The solar photovoltaic (PV) technology can be placed in or near settlements, is technically easy to operate, scalable and can be dimensioned according to shifting demands.

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1 These results derive from the Solar Transitions project which was financed by the Norwegian Research Council (project no 190138).

2 Village-level systems usually consist of a central array of solar cells in combination with a battery bank to store electricity for night-time use, and a local distribution system such as a mini-grid to connected households or a distribution system for pre-charged lanterns.

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Not least, compared with large regional or national systems, electricity systems at the village-level have some interesting features, which motivated our research. Village-level power supply systems seem able to provide a *larger portion of the population in each rural community* with access to electricity services than conventional grid extensions or solar home systems[3] in poor, rural communities [8,9]. This point is related to affordability, physical accessibility, and flexibility of use. Another advantage of village-level systems, in contrast to solar home systems, is that the investment in equipment and responsibility for operation and maintenance do not remain the responsibility of individuals but of implementing agencies and local entities, except for repair and replacement of appliances used within the house. Moreover, the development of village-level systems potentially gives end-users more influence in deciding how electricity may best be used to benefit the village as a whole.

An important question to ask in attempts to use village-level solar power is how it can actually be initiated and organized in practice to create electricity supply that can be sustained, expanded and scaled up, and meet the users' demand. As we have accounted for in another publication on the experiences with decentralized systems in India, which also provides an extensive review of the empirical literature [10], some of the challenges on the supply side include difficulties in getting access to financing of investment costs, insufficient training and support of local operators and lack of experience with maintenance and repair as well as supply chain for spare parts. Over time, the allocation of electricity among the users as well as the payment and revenue collection has also tended to be difficult. These challenges have negatively affected the potential to achieve economic self-sustenance, which is an important goal for village-level projects. Another core challenge in research and practice has been a lack of focus on the socio-cultural and gendered contexts in which electricity is introduced (for treatments of these issues see, e.g., [7,11]). Such knowledge is required for providing solutions for electricity that is affordable and accessible to all [10,12–14].

There is a strong need for increased academic and practical knowledge on how to develop approaches to village-level solar power supply that overcome such challenges and accelerate their implementation. There is need for solutions that can be implemented widely and contribute to societal transformation toward a more equitable and green global society. Many academic studies on off-grid electricity supply concentrate on technical and economic issues, for instance by focusing on providing cost-effective technical solutions and optimization of resource use [8]. However, more attention is needed in terms of how local energy systems can be socially organized and how the social and technical elements of the systems interact and affect the long-term viability of the systems. It is also important to give attention to contextual factors at different levels of society, such as the socio-cultural, material conditions and political factors which influence 'the room for maneuvering' during implementation and when the new energy solutions are provided and taken in use.

In this article, we present experiences from a demonstration project in which a solar-based energy center was established. The objective is to raise some central issues with regard to how village-level power supply can be socially organized, sustained, expanded and scaled up in order to achieve desired qualities mentioned above. The results derive from an action-research project carried out by a team of social scientists and practitioners from Kenya, India, Austria and Norway. The first part of the research included an in-depth case study on village-level solar systems in the Sunderban Islands in West Bengal, India. Then, building on insights obtained from the Indian example and other contexts, the team conducted action research in a remote village in Kenya. An innovative model for supply which took the form of an energy center gradually developed in close cooperation with the village community. This practical project was commissioned in March 2012 and has thereafter been improved and expanded.

In Sections 2 and 3, we discuss the theoretical framework and methodology. In Section 4, we describe the results of the action research in terms of the energy center model, some of the challenges encountered, and adjustments made underway. We aim to show how emerging practices of local actors influence and develop a local electricity system as it evolves over time. Our purpose is not to provide a case study of the experiences of one single locality. Rather, we use the conducted action research to demonstrate aspects that may be important to take into account in research and practice on localized solar power supply in general. In Section 5, we conclude with a critical analysis of the social and economic qualities of the power supply model, including the degree of access to electricity services among various groups in the community, and the system's degree of financial self-sustenance, long-term viability, independence and ability to expand. Dilemmas between such qualities are discussed. We also discuss the replicability of the model in terms of how governments, NGOs and private businesses could build on these results and other emerging initiatives for replication elsewhere.

2. Theoretical framework

Our research draws on concepts of socio-technological change and transitions to sustainability. (For a similar approach focusing on micro-hydropower in Tanzania, see [15].) This cluster of theories provide a useful perspective for examining the dynamic interaction between people and technology at various levels, including the way end-users contribute to the innovation of socio-technological systems such as village-level solar power supply. After explaining some key theoretical concepts below, a framework for the case study will be presented.

2.1. Understanding socio-technical change

The socio-technical systems perspective emphasizes that technology and society develop in mutual interaction – they co-evolve, creating socio-technical change, not only technological change [16–18]. Technology and society shape each other and are deeply intertwined. A co-evolution of the technical and the social takes place both at the micro-level of the practical use of the technology and at more structural levels of society where policies, regulations, and laws are interdependent with technological infrastructures and knowledge production.

A socio-technical system has been defined as a configuration of heterogeneous technical and social elements, including technical devices or artifacts, organizational aspects, involved actors and social practices in the implementation and use as well as competences linked to the technologies [19–21]. Power relations, discourses and meanings related to the technology and ways of using the technology are also important [7,22,23].

One may think of socio-technical systems in a macro-perspective, for example in terms of the global system for production and use of fossil fuel, which has held a hegemonic position within modern energy supply for decades. For such well-established systems, the comprehensive co-evolution process has led to integration and mutual adaptation between technologies,

[3] A solar home system is a system for individual buildings that consists of a solar PV panel in combination with a battery and a charge controller, supplying direct current (DC) electricity to run small appliances like CFL/LED lamps, fans and TVs.

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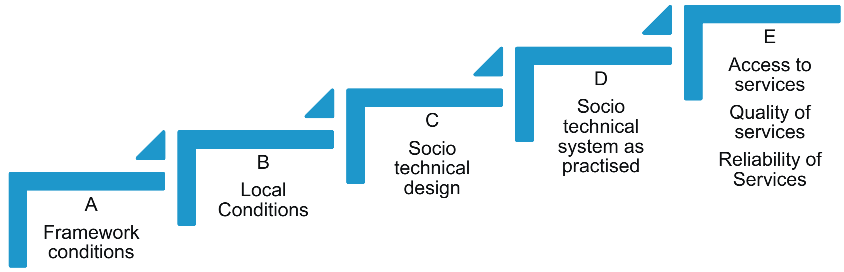

Fig. 1. The five-step analytical framework for examining and understanding village-level power supply.

actors, institutions and other elements. However, in the long-term perspective, such systems are also subject to change. Alternative socio-technical systems emerge, promoted by various actors due to the shortcomings of the dominating solutions and promising features of new technologies, and some of them might grow strong enough to play an important role in society. A new socio-technical system develops gradually by the work of individual and collective actors involved, through experimentation, trying and learning, and efforts to influence policies, education systems and regulations. The outcomes of such system innovation are open and uncertain, and learning from failure as well as from achievements is common.

Emerging socio-technical systems, such as innovative ways of organizing off-grid renewable energy technology are much less embedded in dominant socio-technical structures than conventional energy technologies. A village-level infrastructure for supply and use of electricity is at the same time a complex socio-technical system in itself. The local system consists of a range of social and technical heterogeneous elements [19–21] including the kinds of energy services it can provide, the prices to pay for these, the buildings and technical equipment required to provide them, the specific characteristics of this equipment, the knowledge needed for operators, users of the services and project owners, the economic arrangement for sustaining the system, the style of customer relations, and organizational arrangements.

The interaction and mutual shaping between technology and society can be observed in such decentralized systems at the micro level. In our previous research in the Sunderban Islands in India and other similar research on village-level power supply, such dynamics appeared over time through the characteristics of the energy model, the practices developed by the users over time and the implementers' and local operators' responses [10,24]. The case illustrated the importance of such projects in order to work on the details of the socio-technical configurations or designs to be implemented in a long-term perspective. The case also showed that an intensive learning process and unpredictable developments might be expected after implementation.

To make the system work well for the users, these elements have to be carefully developed in their details, so that they might create positive dynamics between people, technologies and the wider, local context. In operation, the system will nonetheless have its own dynamics, which may or may not be possible to change by the people involved, for example in cases where they would want to make changes to improve the way the system works [10]. In general, the actual use of a technology is not given at the outset. When a technology is employed, users often adapt and domesticate it to fit their needs, interests and general situation [25,26]. It will vary between technologies to what extent such domestication processes are possible or desirable. However, people's way of using a technical devise can always be done in unexpected ways. The concept of *user innovations* captures the observation that people's ideas about and uses of technology in real life settings often differ from the initial intentions of the technology developers [27]. A project implementer, who contributes to innovation and learning processes through practical projects, may also be seen as 'a user' of the technology where innovative compositions of socio-technical systems may be created.

These perspectives inform the analytical framework to be presented below, and they are combined with the literature from energy studies mentioned above and practical experience on the ground. These points of view combine into the framework presented here below. Importantly, as acknowledged in the literature on social acceptance (e.g., Sovacool and Ratan [51]; Wüstenhagen et al. [50]),[4] social aspects of technological change must be strongly emphasized because they are decisive for how the technology can be used and how it can become a beneficial part of people's lives and of particular places and communities. The case presented below illustrates the complexity of local socio-technical configurations and how they may work in practice and how they may change, which helps understanding how the village-level power supply may be designed, implemented, sustained and replicated.

2.2. *An analytical framework for examining village-level power supply systems*

A five-step analytical framework for examining village-level power supply systems has been developed and employed in the present research. Anchored in a socio-technical systems perspective, the framework is composed in a way so as to help accounting for and understanding the various features (heterogeneous factors) that come into play when a new system is planned, implemented and taken in use. We employ the framework in a normative way in that distributional aspects (providing broad access) are also considered.

Five dimensions are seen as particularly important in order to get an in-depth and holistic understanding of how energy systems at the village-level work, how they can be expanded and replicated, and what kind of electricity access they provide and to whom, and the underlying reasons for such characteristics of the systems, including the extent to which they provide equitable access to electricity.

The first dimension to consider is the role of the national and international framework conditions (denoted as dimension A in Fig. 2) in terms of policies, regulations, institutions, financing schemes, available technologies and maintenance infrastructure, which affect the initiation, design and implementation process of a

[4] The mentioned works on social acceptance of renewable energy technology have similarities with the framework developed in the present discussion, but whereas these contributions are mostly concerned with the phases before the new technology is accepted and its introduction and use (e.g. market acceptance), our framework keeps closer attention to the socio-technical system itself and how it evolves and continuously changes. Also, our model includes end-users' involvement in defining needs (and thus the design of the system), whereas social acceptance literature tends to measure potential users' attitudes toward existing technologies.

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new system and the way it works in practice and changes over time (see [28]). Local systems have linkages to such framework conditions, including the wider socio-technical system that they belong to, as explained above. A local system might also have linkages to or be influenced by *other* socio-technical systems, both the dominating ones (also called regimes in the socio-technical systems literature [16,29,30]) and emerging systems (also called 'niches' [31], Raven [47]). These systems create opportunities and barriers for the actual use of technology on the ground. Developments in society in general are also likely to play a role.

Secondly (dimension B), it is necessary to study the local, social, economic/material and socio-cultural context, including the geographical and demographic characteristics of the area. It is also crucial to understand the dynamics between technology and society at this level. In every case of off-grid electricity systems, also when employing 'standardized' models for supply, the characteristics of the community involved are likely to impact the way in which the local energy system is designed, implemented and taken in use. As noted above, through their appropriation and domestication of new technologies, users also affect solutions and outcomes.

Thirdly (dimension C), it is important to understand the details of the social and technical design of the planned energy system, as intended by the implementing actors, and the considerations that were made in the design process (Fig. 1).

The socio-technical design is of course crucial to how the energy system will work, but the ways the system works in practice (dimension D) always differs from what was planned and anticipated. A range of factors interact with the socio-technical system and affect the way it works. As a result of this dynamic process, it should be expected that the system deviates from plans and continues to change over time. This step in the analysis constitutes the most important part of the five-step framework, firstly, because it is often overlooked conceptually and in practice (deviations from plans are either considered as unintended consequences or as failures in fulfilling project goals). Secondly, the actual practicing of the socio-technical system is decisive to the outcomes in terms of the reliability and quality of the services provided and people's access to them (aspect E). Here we focus on what kinds of groups are able and motivated to use electricity, for what purposes, and at what times, etc. Moreover, it is the way the socio-technical system functions in practice that determines the system's long-term viability and replicability and the potential for scaling up.

We proceed by accounting for the methodology and methods used before presenting the village-level power supply model which was developed through action research in Kenya.

3. Methodology

We employ a trans-disciplinary approach in which researchers, practitioners and local actors take part in the research.[5] The team consists of 13 people in total and brings together a diversity of experiences within the fields of solar power and rural electrification, enabling the understanding of a range of aspects of the studied cases, and enhancing the development of a model for village-level power supply to be tried out and analyzed.

We use the term 'model' in a broad sense in that we focus on the process of establishing a new system (anchored in the five-step analytical framework) as well as on the resulting configuration of the village-level power supply (solar energy center) which continues to evolve. Hence, a power supply model is here considered as a dynamic entity. The reason for calling it a model is that once a local power supply is established and practiced, many of its main characteristics remain relatively stable.

3.1. Action research

Action research is a way of combining social science methods with the planning and implementation of practical activities in real life settings [32,33]. This can provide deeper insights because the researchers get to see societal issues from the 'inside-out' and 'bottom up'. Moreover, the results from research may be challenged when faced by real life issues. This methodology may also produce better practice because feedback from the research can be used to support, monitor and adjust social practices and the way they change over time. In the present study, action research activities also included to actively transfer findings from India to Kenya while adapting the model to the Kenyan context.

Action research poses certain methodological challenges in that the analysis is carried out by insiders who have ownership to the practical action in question and who might not be sufficiently critical or overlook issues which an outsider might wish to scrutinize. We address this potential danger by attempting to scrutinize the results in a critical way and by providing transparency in terms of methods and uncertainties.

3.2. Selection of locality for action research

The locality for this experimental activity was selected to enhance the model's relevance and applicability in geographical contexts with particularly harsh living conditions. Kenya was selected because the country is typical for many countries in the South in that it has a low rate of electrification, which is a situation the government seeks to solve. Kenya also has a relatively well developed sector for solar home systems and government led installation of solar PV systems at schools and health clinics, as well as various kinds of actors advocating increased use of solar PV through innovative models. This provided interested collaborating partners in Kenya who could play central roles in the development of models relevant for countries and local, socio-cultural contexts in the South where alternative and complementary solutions to conventional grid extension need to be considered.

The team selected a village which we thought would be representative of Kenya's arid and semi-arid lands which make up 88% of the country and are inhabited by approximately 25% of Kenya's population (of around 40 million people) [34]. These areas have the highest incidences of poverty and the lowest level of access to basic services in the country. The resulting model and lessons learned are therefore tailor-made for poor, remote villages in dryland areas. These are the most challenging places to reach by conventional rural electrification because of the dispersed settlement patterns and high levels of poverty. The research is therefore relevant for many parts of sub-Saharan Africa and elsewhere.

3.3. Methods and main steps in the research process

A local energy system may be composed in a variety of ways in terms of the choice of electricity services, how they can be delivered, how much they cost, what kind of technical equipment can be used, how many people are involved in the operation, and who are in charge of management, operation, saving of revenues and maintenance. The energy center model to be presented is the result of a process which aimed to develop an approach for solar based power supply that would suit the local conditions and be beneficial to many end-users. The empirical data derives from documenting *the process* of developing the model and the

[5] Disciplines represented include engineering and economics, human geography, sociology and social anthropology.

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reasons and considerations for doing so and from documenting *performance* after the implementation of the pilot project.

The action research in Kenya was initiated in 2009 and the power supply was in operation in March 2012. The research and dissemination continue up to the present (2015). The first phase of data collection included social science research on the local context in Kenya. The methods composed of two surveys,[6] several field visits and a range of interviews with a broad range of actors in formal positions as well as private people (women and men). We also arranged focus group discussions (working cooperatives, elders' group, church communities, etc.) and asked school children to write short texts about life in the village.

The data obtained in this phase were crucial for developing the model. The issues covered various aspects of people's living conditions, their expressed energy needs and discussions about what kinds of electricity services that would meet their demand. The same aspects were in focus during the iterative process of cooperation between the research team and the local community that went on through a range of meetings and conversations in parallel with this data collection. This was action research, and the second phase of the research process, which included the planning, implementation, monitoring and further improvement of the model.

The planning process was inclusive by inviting all interested people to attend public meetings at four different times during the planning process, in addition to repeated meetings with a broad group of village leaders and various committees (school, water) and livelihood groups. Between 20 and 40 persons attended each of the public meetings. Since the format of public meetings does not suit all, the social science methods mentioned above were designed in order to capture the views of those who might not attend the meetings nor speak in public, and ensure the inclusion of the views of young, old, women, and disadvantaged groups. Members of the research team thereby represented the views of such groups during team considerations on the socio-technical design.

Also informing the planning and implementation process, the team investigated the national framework conditions for off-grid electricity supply in Kenya, the characteristics of the international solar PV market and other relevant factors outside the local level. Documentation of performance constituted the third phase of data collection, where we focused on aspects such as economic and technical performance, management and organizational issues (including gender aspects), the model's degree of suitability in the local context, access and affordability for various groups and so on. This documentation is ensured by (i) keeping gender specific records of registered customers and the services they obtain (format: detailed income books, weekly summaries and monthly financial reports), (ii) regular observation and face-to-face discussions with staff and board members (repeated visits), (iii) regular phone calls with staff and (iv) various sub-studies involving data collection on specific issues, like renting of lanterns and how they are used by whom in the homes [35], and three master thesis [36–38].

As noted, the involvement of the research team (as 'insiders') in the planning, implementing, following up and improving the model is likely to affect the knowledge produced which might have advantages but also disadvantages. To meet the challenges, we bring forward our biased position and attempt to assess results in a critical way. The conclusions can be tested by other observers. We expect to have obtained additional and in-depth insight into the case than what would have been possible if we had only observed and not actively taken part in the intervention. We also believe that our enduring and committed presence which includes paying attention to (and registering) any detail that might jeopardize the viability of the local socio-technical system and its intended outcomes, enhances understanding and learning.

4. Results

The research resulted in the establishment and use of a specific model for village-level solar power supply in the form of an "energy center" in Ikisaya village in Kenya. Also, through the documentation of the process and the results in this particular case as well as experiences with decentralized systems elsewhere, we developed the conceptual framework for examining and understanding the village-level power supply systems in general, as described. When analyzing the results from Ikisaya, we follow this five-step framework. Due to space limitation, the fifth aspect will be limited to affordability and the quality of services, and we will not deal with the social impact of the new services on everyday life in the present work, but in forthcoming publications.

4.1. The role of the national and international framework conditions

An important starting point for the development of the model for village-level solar power supply was the features of the Kenyan energy sector. The use of solar PV technology in Kenya has been developing during the last three decades. A few mini-grids have been established, supplying electricity produced by micro hydropower and/or diesel generators in rural areas. However, solar PV based mini grids, which was the type of technology that our research team had observed in the Sunderbans, India, were not yet in place in Kenya. We therefore initiated the idea of a demonstration project on solar mini-grids as an opportunity to explore new ways of applying solar technology in remote Kenyan villages. Government representatives and other renewable energy actors in Kenya expressed that a demonstration project on solar mini-grids would be relevant for the energy sector in the country.

The Kenyan government's work on renewable energy is integrated in the governmental agencies[7] that work with electricity provision in general. The conventional ways of working on rural electrification are dominating these units. The example of Kenya demonstrates that it is a long-term process to change the way such units and the energy sector operates. One of the visions behind the action research presented here was to create a model that could be taken up by the government or in other ways inspire their work.

Kenya has some remote power grids that are operating in isolation from the national electricity grid, as parts of the government's work on rural electrification. They are placed in relatively large rural towns with district headquarters. There were about 15 such isolated power grids in 2009. They supply electricity for 24 h per day mostly from larger diesel generators and are operated by professional technicians hired by Kenya Power.[8] Subscription and payment are organized in the same way as for the national grid. They are expensive to operate because of the high price of diesel, which motivates a search for alternatives. As in many other countries, the electricity grid in Kenya reaches only a portion of the population (i.e., around 19%). In rural areas it is only around 7% [39] and in urban areas 50% [34]

[6] The first survey included 70 of the 384 households and the second survey included 20 households. Both surveys was based on representation of geographical area, gender, socio-economic conditions and livelihoods.

[7] The Ministry of Energy and Petroleum, Kenya Power (the power utility) and REA (Rural Electrification Authority).

[8] Two of these are operated by KenGen.

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A means for producing at least some electricity for households not connected to the electricity grid in Kenya is the use of solar home systems and solar lanterns, among those people who can afford it. These are provided through the private market. Less than 5% of the rural households in Kenya had such systems as per 2009 [40,41], although Kenya is one of the world leaders on per capita installation of solar home systems. The ways of using electricity from these small systems are for communication and connectivity between the rural and urban people (mobile phone, radio and TV) and for education related purposes; light for education has been shown to have less priority than what is often assumed, because the use of TV competes with the use of light due to the very small amounts of power available [42,43].

A trend that was observed underway in the project period was a change in the Kenyan market from a previous emphasis on solar home systems, which are often installed by qualified solar technicians, to smaller, more efficient, and cheaper solar systems that are based on 'plug and play' principles. A large number of such products for individual users have appeared in the market, as part of a broad trend in the African market. These come in many different price ranges, and with a wide variation in technical quality, lighting output and life time. According to the Lighting Africa program, the sale of such smaller solar lighting systems has increased by 200% from 2010 to the middle of 2013 with about 700,000 solar lanterns sold to off-grid communities in rural Kenya [44]. These systems have made the technology more affordable (they have LED lights which require less power and thereby smaller solar PV panels), though they need battery replacement every 2–4 year, and are far from affordable for all.

These and other trends and characteristics of the energy sector in Kenya and international trends influenced the team's considerations on how the pilot project should be designed. There were no specific policies or regulations that had significant impact on the project, but rather the general achievements in the "solar PV niche" in Kenya and other parts of the overall energy sector, which were built upon. Firstly, the team attempted to develop options that could give more flexibility in terms of how and when electricity could be used, expand the range of services compared to household systems, and enhance affordability. Secondly, the team sought to develop a model that could be interesting for different kinds of project implementers (including the government), in terms of being low cost, economically sustainable and well functioning in operation. The team met with government officials as well as other energy sector actors in Kenya before and during the project in order to discuss the team's plans and results and inquire about their work in related areas.

4.2. The role of the local context

The energy center model is the result of a process aimed at identifying an approach for energy service delivery *suited to fit the local conditions*. As described in the methodology section, the research team made considerable efforts to map and understand the socio-economical, material and cultural context ahead of electrification.

Ikisaya village is located in a dryland area, and drought constitutes a major challenge. The village is a sub-location in Malalani location[9] of Kitui District in the Eastern Province of Kenya.[10] Ikisaya consists of clusters of houses, 383 households in total. Six of the clusters (wards) have different names and each is led by a village elder. The wards have differing proportions of clans with a common ancestry family background.

The relatively few settlements are distributed across a large area; the population density is only six persons per km^2 [34]. The average household has five to six members. Farming, charcoal production and livestock keeping are the main sources of livelihood. The crops include maize, sorghum, cow peas, green grams and millet. As a result of frequent droughts, however, agriculture is hardly sufficient to sustain the livelihood needs of the local community and food aid is often required. There is a small polytechnic school in the village, a sub-chief's office, a primary school, three churches, a few shops and kiosks and a maize mill operated by a privately owned diesel generator. Within Ikisaya people commute mainly by foot, bicycle or donkey. It is not uncommon for people to walk 6–8 km to get to the village tap, the school and the market which are located in the same place. Water scarcity is a fundamental and reoccurring problem in this dry area.

Kerosene and dry cell batteries used to be the main sources of energy for lighting. Our initial survey indicated that the average household expenditure on lighting was about 3.2 Euros per month. We later learned that some families could not afford to purchase kerosene at all, but rather used the cooking fire at night as their only light source. Phone charging services were provided by businesses using small solar PV systems also before the energy center developed. The average expenditure on phone charging was reported in the survey to be about 1 Euro per month.

Life in Ikisaya is gendered, as in any social context. Both men and women denote themselves as farmers and both men and women are members of various working cooperations. Men tend to hold formal positions in village life, although there were exceptions. When the team introduced gender balance as a principle for setting up the various committees (e.g., one person of each gender from each of the six wards elected for the Electricity Board) and recruiting staff, we were first met with a certain level of skepticism. For example, in a public meeting some men uttered critical comments when the research leader invited women to speak, but this premise seemed growingly to become accepted. As a sign of this, the Board later appointed a woman who had been central in the process for the position as IT Clerk at the Energy Center. Later on she has been made responsible as the Manager of the center.

These findings from Ikisaya, and other related findings from Sunderban, India, and beyond, informed the design of the model in important ways. First of all, the distributed settlement pattern implied that the construction of a mini-grid would only be used by households and shops located close to the village market. The project had a limited fund for investments (ca. €42,000) and a mini-grid system would not be able to accommodate people living further away. Also, given the level of poverty in the area, such a system would not be financially viable, that is, capable of covering operation and maintenance costs. Secondly, with the goal to provide broad access and the observed variation in people's expenditure patterns on kerosene (the alternative light source to electricity), the project wanted to keep the costs of using the services at a minimum. Thirdly, according to the project's objectives, it was important to prioritize the kind of services that end-users considered to be most important. Due to the funding limitations and the objective of economic sustainability, some of people's most important needs, improved water supply and a medical fridge for storing medicine, could not be fulfilled through the project. However, people also provided good reasons for why other type electricity's potential uses would be particularly important, in addition to light and mobile charging. For example, a photo-copying machine in the village would be important. Having a computer in the village would provide children and adults with 'computer literacy'. The value of being able to watch television was highlighted and captured by one man in this way: "When I have seen what the President looks like, I will also feel like being part of Kenya." In

[9] Malalani comprises 1270 households.
[10] Ikisaya is located 250 km east of Nairobi and 100 km east of Kitui town.

Fig. 2. Ikisaya Energy Center.

order to accommodate for these concerns within a limited budget, an "energy center model" was developed.

4.3. The socio-technical design of the electricity supply system

A key characteristic of the electricity model developed in Ikisaya is that all services are housed in one center proximate to the community. The Ikisaya Energy Center (Fig. 2) is located close to the village market. To achieve economic sustainability and possibly enable expansion, the center is designed to be operated by local residents on financial principles.

4.4. Design of the building and the electricity services

The center is based on a 2.16 kilowatt (kW) solar PV system which provides energy for a range of services such as lantern charging and renting, charging of mobile phones, IT-services (typing, printing and photo-copying) and television and video shows. The building was constructed in the process and is designed to house the services offered.[11] The total investment cost was approximately €43,000.[12]

In contrast to grid-based systems which tend to require high connection costs,[13] the principle that customers pay a modest amount for each service was expected to enhance broad access. The system was designed to limit the amount of batteries in order to reduce costs for battery replacement, which would facilitate economic sustainability. In terms of the number of lanterns that could be charged, the system was dimensioned to be able to charge 120 lanterns per day.[14] Because the lanterns are rented out for two nights at a time, the system could effectively charge a maximum of 240 lanterns. The phone charging system could charge 120 phones per day. The Center also has kept some solar lighting solutions for sale to interested customers, giving the users options to rent or purchase by making staggered payments. Detailed information on the system's main characteristics has been published in a report intended for practitioners [45].

4.5. Institutional and operational design

The energy center is operated and managed through a community based organization (CBO), the Ikisaya Energy Group, which was formed on the initiative of the community. The energy center is registered with the local authority as a business entity and operated as such. The users of the energy center were encouraged to become members of the CBO so as to have a voice in how the energy center is operated and managed. The CBO membership elects a 12-member board with gender balance and geographical balance.[15] Six members from this board then form the executive committee responsible for overseeing the management of the energy center.

The recruitment of staff was accomplished through an open process in which five positions (manager, IT clerk, accountant/book keeper, charging attendant and evening attendant) were announced on boards in Ikisaya and neighboring villages. A committee, which included administrative leaders in two neighboring villages, selected the best candidates based on a set of predefined criteria which the researchers helped develop. Because training would be provided, formal technical education was not considered necessary except for the position of charging attendant. This lack of demand for technical background was expected to encourage female applicants in addition to male. The criteria also put emphasis on people's motivation for wanting a job at the center and their previous level of commitment in community activities. As a result of this recruitment process, four men and one woman were engaged as staff at the center, while additional women were hired later on when positions became vacant.

4.6. The way the system works in practice and its (long-term) viability/sustainability

Shortly after the opening of the center, several challenges were observed with regard to the lantern renting, summarized in Table 1 which also indicates how the staff responded.

Although some of the measures had effects, the capacity of the energy center was far from exploited (with negative effects on financial viability). However, there was demand for lantern renting in neighboring towns and villages. In response, the Ikisaya Energy Center moved some of the PV panels, charging equipment and lanterns to neighboring trading centers[16] where they currently have five agents handling these activities. These agents are existing shop-owners who could easily understand the lantern renting business. They rent out the lanterns in their area of operation, keep a portion of the revenue as commission (~30%) and pay the remaining amount to the Energy Center. Out of the total 213 lanterns that were available in the Center in May 2014, 47 lanterns were directly rented out and another 166 lanterns were rented out through the agents. Thus the lantern charging and renting service has evolved from being a purely centralized model where the lanterns and lantern charging system were all housed at the energy center to a decentralized model where lantern renting services are also provided in neighboring villages through agents. Fig. 3 illustrates the revised design of the system.

To further improve the financial performance of the center, the salary costs were cut and from March 2013, the center has been running with only three staff employed. Moreover, to increase revenue, the energy center introduced hair cutting as an additional service. The hair clippers are powered with some of the surplus energy available from the solar PV system, powering the IT system.

[11] The area of the building is slightly below 70 square feet.

[12] €11,000 for the building structure which houses the energy center and €32,000 for the solar PV equipment, furniture and appliances.

[13] In Kenya, the connection cost charged by the distribution utility was around 35,000 Ksh in 2013.

[14] The lanterns and charging system had been developed in India by The Energy and Resources Institute (TERI) in cooperation with Indian lantern manufacturers to improve lantern design and quality and facilitate efficient charging.

[15] Geographical balance helps to ensure balance also between clans.

[16] These agents are located in the trading centers of Endau, Malalani, Ndovoini, Kathua and Yiuku, which are 8–10 km away from the energy center.

Table 1
Overview of challenges identified over the first few months of operation and strategies developed to address them (based on [45]).

Challenge	Reasons	Strategy developed
Very low uptake of rental lanterns (8/120) during the first month of operation	Customers unhappy because they were only permitted to rent the lanterns for 2 days and when they returned them, they still had power. As a result of this they felt that they had paid for more than they got	Consumer education – the center arranged for a public meeting where the reason behind renting out the lanterns for only two nights was given. Also explained was that completely discharging the lantern battery would shorten its life
Delay in returning of lanterns, i.e., customers kept lanterns for an extra day resulting in lost revenue	Convenience of keeping lantern longer. Poor enforcement of fines for overdue lanterns by the charging attendant and agents. Periods of drought and famine	More stringent enforcement of fines for overdue lanterns and at the same time introducing a lower fine than initially suggested. Patient, clear and repeated explanations of the reasons for the rules and fines. Suggestions for how to find practical solutions for the customers for bringing and delivering lanterns, including school children carrying lanterns before and after school
Lantern renting service not affordable for all	Low income for large parts of the population, neither kerosene nor lanterns affordable, some households only using firewood for lighting	Considering lowering the price for lantern renting, but this was not yet possible if financial self-sustenance is to be upheld

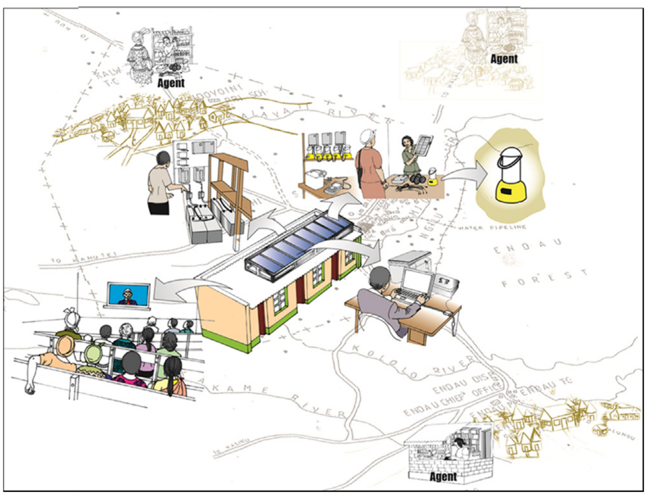

Fig. 3. The revised energy center model.

The energy center staff carries out many typing jobs, which takes a lot of their time, while adding relatively little to the revenue because of the low price per page of typing. However, the service is regarded as important for the community and the staff is reluctant to increase the price. Similarly, the copying and printing services are not running with a profit (expensive ink), but costs are kept at a minimum in order to make the services available. Up to present, the center runs with enough income to cover its operation costs and setting aside money for battery replacements. The center has done a major battery replacement in the Energy Center batteries and the lanterns.

These findings demonstrate the importance of keeping the new socio-technical system of village-level electricity generation flexible enough to adapt to problems and demands which only emerge during use. The question of financial viability lies within the system's capacity to adjust according to shifting circumstances, where demand, that is, people's need for various services and their ability to pay for these services constitute the most important variables. One may reach a point where no more adjustments are possible because people simply do not prioritize electricity's services over other major concerns. As seen, to some, the lantern renting, which is kept at a minimum level of €0.18 for two consecutive nights, is perceived as out of reach. If the battery technology of lamps were improved, keeping them 3–4 days rather than 2 would be more convenient for the customers (Fig. 4).

The present discussion does not include an in-depth treatment of the fifth aspect of the model, which is how electricity users perceive the quality of services and to what extent various groups have access to the services. However, a few points are given here. A relatively high frequency of using the renting and charging services reflects that many people find them useful and glimpses from how the staff run the center indicates that they have a concern for the situation of users. A user feedback survey by Sharma and Palit [35] in Ikisaya indicates that most of the users were using the lanterns for studying. However, multiple uses of the lanterns, such as using the lantern during household chores or while going outside the home in the dark, were also observed in most of the surveyed households.

Fig. 4. Lantern renting customer at Ikisaya Energy Center.

Among the many reasons stated for the adoption of solar lanterns, the most crucial ones were the quality of light, the savings made due to reduced kerosene usage and the absence of soot, heat, and the possibility of fires. This is important from a social

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perspective but is also central in the quest of making the services viable and long lasting. Finally, this type of endeavor calls for ethical reflections. Inviting a community to take part in a project like this raises a potential danger of putting people under pressure to support the system instead of focusing on their own needs. We cannot be certain that we have not participated in creating such problems, and we observed tensions in the village associated with the project during a short period. Observing the situation in the village over several years, the overall trend is strengthened cooperation between people with different backgrounds in terms of families, clans or status in the village, through the group of staff, the board as well as cooperation on activities external to the center. Any intended change is political and we trust that the overall effect of the arrival of the center in Ikisaya is for the better to the population at large.

5. Conclusions

Our research provides knowledge on some of the central aspects that are important for designing, implementing and following up village-level solar power supply. Several of the findings are also relevant for village-level systems based on other technologies than solar PV and for the implementation of technologies in new socio-cultural contexts in general. Moreover, our findings support and specify results of comparative analyses of renewable energy projects in developing countries. Sovacool [46] distils 10 success factors from such a comparative study, among those the importance of income generation, the building of capacity and local institutions, or the active participation of communities.

We have argued that the five dimensions of the analytical framework presented are a useful perspective for examining and understanding such systems. The framework is based on the insight that the technological design of village-level PV systems is only one dimension of a more encompassing socio-technical system which includes cultural and institutional contexts, the social organization of the operation and use of the power plant, and also changing social practices, demands and expectations which require learning processes and the eventual adaptation of the local energy system.

The research and experiences extracted through the demonstration project in Kenya show that the cultural, economic and technical 'details' of the design and implementation process are likely to be decisive for the usefulness and viability of the model, as exemplified by the procedures for the lantern renting and other operational details. Moreover, close attention is required on the socio-cultural and geographical context both during planning and after implementation of the energy supply. For example, the distributed settlement patterns in the semi-arid area selected in Kenya, which is relevant for large geographical areas in Africa, reduced the suitability of mini-grid systems which were observed in India and instead led to the development of a decentralized energy center model. Contextual sensitivity is required for selection of the most important, potential electricity-related services and for designing their configuration and prices so that the services become useful to various groups of end-users. Moreover, we find that active encouragement of women's participation is crucial to achieve a high level of local satisfaction regarding service delivery and other operation of the plant.

Another key result is that the socio-technical design should have sufficient flexibility, allowing for changes and improvements because demand and practices of use are often difficult to foresee and are shaped only during the use phase of a technology. Flexibility is also important in order to facilitate creativity and innovation by local actors. Organizations that fund or initiate such projects should be prepared for changes in the project even after implementation. Furthermore, budgets should allow project implementers to follow-up the local actors and their ideas and suggestions after implementation, providing technical, organizational and economic support for better adapting the system to local needs and circumstances and further develop innovative solutions. Such support will gradually increase the ability of the local population to become independent of outside support for operating and maintaining the energy system and to strengthen their self-confidence in developing the systems in innovative ways. Sustainable institutional structures for the follow-up of decentralized power provision must be developed in parallel with initiatives for replication.

Economic sustainability is an important quality of a village-level infrastructure system, but may be difficult to achieve in poor, remote villages. There is a difficult balance to make in terms of ensuring affordability for the users on the one hand and economic self-sustenance of the system on the other. However, so far, this project shows that smart socio-technical designs and good follow-up of the local actors can at least enhance economic sustainability. Time should be allowed from the outset for building up the business performance gradually. The research also shows that economic sustainability depends on nearly all aspects of the energy model, including the relevance and affordability of the services to the users, the overall social organization including the rules for use and payment, the operational routines, the motivation of the operators and how they communicate with the users of the services. However, there is still need for improving affordability to achieve broader access to the electricity services.

The energy center model is probably not interesting for replication through private sector investment because of the significant upfront investment required and the small margins. In its current form, the model would not attract businesses, since these could generate quicker and more substantial returns elsewhere. A capital subsidy would therefore be required if an identical model is to be replicated. Even though the word 'subsidy' has become unpopular in electricity sector reforms, it still has relevance in many cases in view of the need to electrify low-demand, inaccessible rural areas – and is even less costly than the extension of the electricity grid which is regarded as a public good. Nevertheless, components of the model could be interesting for private sector investment. Revenue and expenditure trends indicate that the lantern renting and mobile phone charging services are the highest and most consistent source of revenue; they represent 70% of all revenue generated by the energy center and about 50% of the operation and maintenance costs. An analysis of investments costs also indicates that a model that targets only the provision of lantern renting and mobile phone charging services would require less than one third of the investment costs used for Ikisaya Energy Center. Such models with provision of only recharging lanterns and mobile phones could also be taken up as a business by local entrepreneurs in Kenya and other African countries, if provision of low cost loans can be facilitated to initiate the business. Here, the entrepreneurs can invest some money as their equity and set up the station in their own homes, thereby reducing the capital expenditure, and the balance amount can be taken as debt from local financial institutions. However, in such cases a facilitating agency will be required who can build the capacity of such local entrepreneurs to manage the operation and maintenance of such systems and bundle smaller projects for reduced transaction costs and their bankability.

A key lesson regarding economic performance is that location is a primary consideration when selecting the services to be provided and best way to deliver them. In areas where household incomes are low, it may be necessary to focus on the provision of the most basic services, i.e., lighting services (lantern renting) and phone charging only. In economically active areas, the demand for TV and IT services would be higher, as would be the ability to purchase lanterns or small solar home systems.

The project has led to spin-off effects in Kenya as a possible route to provide electricity services in remote areas. It has attracted the interest of the government of Kenya, and a pilot project for the government is implemented in another part of the country, involving the same team and a government representative. The model also has replication potential in other countries where there are poor, scattered unserved communities. There are about 600 million people in sub-Saharan Africa living without any form of electricity access and a substantial portion of them reside in remote, isolated scattered, arid and forested regions where expanding central grid or setting up local mini-grid may be techno-economically infeasible. Such communities with low demand can be served using the Energy Center model discussed above. However, further research is required on how such a model can be customized to the local context and replicated and followed up in a large number of places in various geographical areas, which kinds of actors can best contribute (private sector, civil society and government), and which policy changes can facilitate various actors' engagement in such efforts. The issue of replication and up-scaling will be treated further through ongoing work by the same research team.

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