Energy Research & Social Science 44 (2018) 32–40

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Pathways to electricity for all: What makes village-scale solar power successful?

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ARTICLE INFO

Keywords:
Village-scale solar power
Solar mini-grids
Economic sustainability
Affordable electricity access

ABSTRACT

This article presents new empirical research on what it takes to provide enduring access to affordable, reliable and useful electricity services for all. We analyze and synthesize the long-term experiences with three different systems for village-scale solar power supply in India, Senegal and Kenya. Since this scale of electricity provision forms part of village infrastructure, it requires particular types of knowledge, policies and support mechanisms. This research therefore investigates how village-scale solar systems can be designed, implemented, sustained and replicated in ways that make them accessible and useful for the community members. Drawing on a socio-technical and practice-oriented approach, we show that the electricity system's degree of adaptedness to its social context affects many important qualities of the system such as the relevance of the available electricity services for the people, the system's operational and economic sustainability and the potential for replication. Achieving such adaptation notably requires a flexible approach on the part of implementers, funders and local actors before, during and after implementation. We also show the need for institutionalization of decentralized electricity provision, discuss the current ambiguities in policies, regulations and funding mechanisms for village-scale solar power, and provide recommendations to policy makers and donors.

1. Introduction

An increasing number of households, businesses and public institutions find opportunities to transit from traditional off-grid solutions such as kerosene lamps, paraffin candles and diesel generators to the use of electricity from solar photovoltaic (PV) systems at different scales, including mini-grids [1]. However, solar PV technology is still only benefiting a small portion of those without conventional electricity access [2–4]. Moreover, the growth in the use of solar power has mainly been limited to small systems providing basic services, especially light and phone charging [4]. How, then, may one realize the untapped potential to utilize solar electricity for a wider range of electric services and for a much larger number of users? In Africa for instance, we have probably seen only the beginning of a process towards increased utilization of the enormous solar resources, both through grid and off-grid solar PV [5]. The research presented in this article aims to contribute to new knowledge about this constantly changing field, for the sake of the further progress towards realizing this potential. To this aim, it is crucial to analyze existing long-term experiences with solar power systems in terms of how they may be organized, operated and maintained so as to reach remote areas, become economically sustainable, and provide affordable and reliable electricity services to all in different geographical contexts. As we will show, some of these goals (e.g. affordability and economic sustainability are sometimes conflicting, inviting attention to how different goals are balanced and managed in practice.)

Focusing on the *scale* of electricity provision is also necessary because it strongly influences the ways in which these systems are financed, organized, sustained and scaled up, as well as the opportunities and responsibilities they imply for users [6–8]. There are three main scales for use of solar PV technology. The first scale is standalone solar PV systems for individual users. Social science studies of such systems have focused on business models, operational and economic aspects, affordability and socio-economic impacts [9–13]. The second is the village or community scale; as described in the following, and the third is larger scale, often grid connected use of solar PV. In the present discussion, we have chosen to study electricity supply organized at the village scale, which includes mini-grids, energy charging centers and other small-scale solar energy models of villages. Since such solar

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https://doi.org/10.1016/j.erss.2018.04.027
Received 11 September 2017; Received in revised form 11 April 2018; Accepted 13 April 2018

power supply forms part of village infrastructure, its successful implementation requires other types of knowledge, policies and support mechanisms than individual standalone systems and centralized grid electricity supply as shown by previous studies [14–19].

When choosing to study this particular type of delivery model for solar power, we do not dismiss the potential importance of other kinds of systems, but village scale systems are interesting for several reasons. Firstly, they have a potential to increase the number of people with access to electricity in each community and increase the range of electricity services available. Secondly, they free users from the responsibility to invest in equipment, operation as well as battery replacement and other large and small maintenance. Thirdly, they provide good opportunities for the use of more power-demanding equipment [5]. Not least for these reasons, international energy experts expect village scale systems to play an important role to achieve universal access [20,5]. Small, solar PV based mini-grids can serve small remote settlements that would usually not be considered for electrification through grids or large conventional mini-grids because they lack the economies of scale (potential number and size of customers) to make conventional electrification technically or economically viable and because these settlements are usually in areas with very limited economic activity. Also, in East Africa it has been observed that private solar businesses are reluctant towards establishing sales and service infrastructure in remote areas because it is difficult to become profitable [21].

We currently see the emergence of large mini-grid initiatives, several of them in Africa, with solar PV as the most important technology [22]. These initiatives make this kind of research particularly relevant, because parts of the massive funding now going into mini-grids, in Senegal for instance, do not put sufficient efforts on obtaining sustainability according to donors, project implementers and energy experts in Senegal and India observing these trends (personal communication, [23]). Some of the programs follow organizational models that have previously led to breakdowns. There is thus an urgent need to learn from the long-term experiences of various types of village-scale systems in different geographical, socio-cultural and political contexts.

In order to contribute to the knowledge needed for the success of village-scale solar power supply, we have conducted three detailed case studies, one in Senegal in West Africa, one in Kenya in East Africa, and one in India (Chhattisgarh state). These examples have been operating over several years, while also being innovative and expanding beyond the initial area for implementation. Our aim is to increase the understanding of factors that influence the achievements of such decentralized electricity supply models, considering the following criteria:

- Well-functioning system (in terms of long-term operational and economic sustainability)
- Good quality electricity access that fits with people's needs and economic situation (affordable, accessible, reliable, useful)
- The possibility to replicate the electricity supply model in large numbers

Based on previous studies (e.g. [24,7,8]), we assume that the factors that influence the achievements can be found within the following broad dimensions:

- The social and technological (socio-technical) design or configuration of the electricity system including ownership, types of services and distribution, and the way in which it is planned and implemented
- The degree of adaptedness to the social and cultural context at the local level, including socio-economic conditions, settlement patterns and the different needs of various groups
- Political factors and other national and international framework conditions

We will study the selected systems with respect to these factors. In the following, we proceed in Section 2 by accounting for the analytic framework and previous studies that have addressed components of the framework. Then we account for the methods (Section 3) and present the empirical findings, (Sections 4–6) following the structure of our analytical framework. Section 7 discusses the findings. In Section 8 we conclude and point out some key choices policy makers and donors will have to make if they aim to include sustainable, village-scale power supply in the future energy mix.

2. A framework for analyzing village-scale solar power plants

In this section we present a conceptual framework suitable for analyzing the variation of village-scale solar power supply systems. We build our framework on science, technology and innovation studies, by not merely focusing on technological dimensions or economic viability, but also by analyzing the solar power provision as socio-technical systems where the technological components cannot be separated from organizational, social, cultural and political dimensions of the systems [25–27]. We also view the village-scale supply systems as part of larger processes of system innovation, institutionalization and emerging transitions to low-carbon energy systems [28]. These processes influence the institutional and regulatory frameworks that in turn influence how village-scale systems are designed, implemented, sustained and replicated in different geographical areas.

In addition to these socio-technical system approaches, we also build on literature on energy access as well as practice theory because a given system always interacts with end users. Social practice theory provides important insights on this interrelationship due to the repetitive character of energy provision and use and the way material and socio-cultural structures such as local knowledge, ideas of progress, norms and values shape what people do with energy [29–32]. Energy practices may in turn influence the operational and economic sustainability of the electricity provision and the qualities of the electricity services [7].

Through the analytical framework we aim to get a better understanding of three dimensions of our empirical cases of village-scale solar power supply. Firstly, these systems can be characterized as specific *socio-technical configurations*. Here we address the socio-technical design and organizational model of the energy supply systems, as well as the geographical, cultural and institutional contexts these systems are embedded in at the local and national level. Secondly, we analyze the evolving *social practices of operating, maintaining and using the solar power plants* and the impacts they have on energy access. Thirdly, we reflect on the conditions for further *replicating or up-scaling* the particular models we found in our case analyses. In the following, we spell out more details of our analytical approach.

2.1. Socio-technical configurations of energy supply

Any village-scale power plant has a particular socio-technical design. By design we not only refer to the technical design parameters and components involved, but also the energy services provided and the organizational and economic features of the supply system. Such features include the system's financing model, the setting of tariffs and collection of electricity fees, the types and responsibilities of actors involved in operation and maintenance, as well as the rules for regulating subscriptions, consumption, metering, payment and compliance.

Electricity supply systems become embedded in a particular local, social and cultural context which need to be taken into account in the design phase. The type and degree of social embeddedness can either create frictions with the way the plant is operated and used, or become an important factor for the success of the electricity supply system. Population density, settlement patterns and socio-economic conditions form part of these local contexts and condition electricity use in