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The Solar Transitions research on solar mini-grids in India: Learning from local cases of innovative socio-technical systems

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1 Introduction: Learning from experience

Solar cell technology (solar PV) is flexible and well suited for decentralized systems in all sizes, and has the potential to contribute to critical changes in society for poverty reduction, clean energy supply, and adaptation to climatic challenges. Increased knowledge on how such technology can best be implemented, used and adapted to local contexts is required to make it possible for a large number of people in sun-rich, remote areas in developing countries to take advantage of it.

Off-grid solar power systems in rural areas can be designed and organized in different ways, with different implications for how they work for the communities, how they can be financed, implemented, managed, operated, and kept running. Whether such systems are successful in providing electricity to the rural community, i.e. whether they can live up and be adapted to the expectations and needs of its users, whether they achieve an optimal delivery of services to the users and whether they can be operated, maintained and expanded in an efficient and sustainable manner, depends at least as much on the social and economic organization of such systems as on their technical configuration. In this paper we discuss factors that influence the opportunities to create power supply systems with so-called "solar mini-grids"[1] in ways that work in practice and are viable in the long run. The analysis is approached from a social science perspective in cooperation with technical experts, based on the understanding that the successful introduction and use of technology is dependent on keeping close attention to both the social and the technical side in a coherent manner, thus to understand the "socio-technical" systems that solar power supply systems constitute. According to such an approach, implementation and use of technological solutions in society is an open learning process which goes far beyond technical learning. Moreover, we pay attention to the surrounding "social fabric" in which the technology, when taken in use, is embedded, that is, the social practices, competences, meanings and values, institutional settings and other elements found in a given setting. This "social embeddedness" of technologies, including the degree to which households, communities and other users perceive a technology to be useful, have been found important for the technology's long term viability (Russel and Williams 2002:48). The way a technology becomes socially embedded is created through a dynamic process of social learning and mutual adaptations of both technology and the social elements with which it interacts. Further elaboration on the analytical framework will be provided when presenting the results from our research findings.

The most common ways of using solar energy for electricity supply in remote areas are solar home systems and solar lanterns, and other small, stand-alone PV-systems for homes and buildings without grid-connection. Even though such very small systems are not uncommon any more, there are still various economic, practical, institutional, market-related, political and technical challenges that have to be dealt with for such technologies to be widely disseminated and provide the desired advantages. The literature on solar home systems and other stand-alone systems deals with issues related to financing, repair and maintenance, capacity building, marketing, subsidy arrangements, socio-economic impacts on people and communities, accessibility, affordability and benefits for people, typical barriers and opportunities for the disseminations of the systems, and strategies for implementation (Palit and Hazarika 2002, Palit 2003, Chaurey 2004, Ulsrud 2004, Chaurey and Kandpal 2006, Jacobson 2006, Standal 2008, Corsair and Ley 2008, Miller 2009, Kumar et al. 2009, Urmee et al. 2009, Chaurey and Kandpal 2010).

However, in addition to such solar systems for individual buildings, off-grid photovoltaic systems can be used to simultaneously supply a larger number of users through solar mini-grids. Importantly, there are very different challenges and opportunities involved in the solar mini-grid model compared to the single user-system. The insights on the use and

[1]A solar mini or micro-grid is an electricity distribution network operating typically below 11 kV, providing electricity to a localized community and deriving electricity from a solar PV power plant with its own storage (batteries) facilities. Some energy experts distinguish between solar mini-grids and solar micro grids, depending on the size of the installation. However, for this research it has not been seen as relevant to do this separation, and the term solar mini-grid is therefore used.

organization of solar home systems are therefore only to a limited extent relevant for the understanding of similar aspects of the alternative model of solar mini-grid systems for village scale solar power supply. This is so because of the different societal scales and the different ways in which the technologies are implemented and operated, the different features of the electricity services delivered and, because of these differences, the distinct needs for social organization of the systems in local communities and institutional frameworks.

In our paper, we present and analyze experiences with strategies for implementation and social organization of solar mini-grids by building on insights from a socio-technical systems point of view. We investigate questions that need to be asked when somebody finds solar mini-grids to be an interesting option for electricity supply in an area outside the national electricity grid. For example, how should the implementation process be organized, a suitable social organization for operation and maintenance be set-up and the challenges that may occur underway be handled? How may one create a viable system, that is, one that makes the solar power supply functioning in the long run? And not least, how may the power supply system facilitate a diversity of uses of electricity for the benefit of the community?

First, we will briefly review the empirical literature on this particular model for solar power supply and point to research approaches that have been used to provide those findings. Second, we elaborate on the analytical framework to be applied in our analysis before presenting some of the findings from the Solar Transitions project's recent research on solar mini-grids in the Sunderban Islands in India. In particular we focus on the links between choices made during implementation and the effects on the operation of the plants; on the relationship between actors and institutions at various levels in the system, and on the role of operators, local customers and technological factors in jointly contributing to the way in which the system works. In our research we have attempted to get access to the valuable experiences of the people who have been involved in or affected by these kinds of options for power supply in different ways.

With such analyses we aim at increasing the understanding of the processes that embed technologies in the social fabric and provide a basis for social learning on these issues between different places, projects and solar power plants and for the transfer of such experiences between different countries. Even though useful models of social organization and technical configuration cannot simply be reproduced in different places, they can fruitfully be adapted to different local situations such as settlement patterns, user needs and habits, social and cultural traditions, e.g. in organizing common goods, and also regulatory and political conditions, subsidy schemes, etc.

2 Previous studies on electricity supply from solar mini-grids

This brief literature review points to some of the work that has been done on solar mini-grids and various approaches that have been applied in such efforts. This is done in order to contextualize our own work empirically as well as analytically. Our own analytical framework will be elaborated on in the next section of the paper.

In village-scale solar mini-grid systems (typically of 10-100 kW total installed capacity) electricity is converted to AC power (alternating current) [2] which is distributed to the users, i.e. customers, through a local electricity grid, normally during a limited number of hours[3]. Solar mini-grids, depending on the size, can supply electricity for domestic power, commercial activities (e.g. shops, video centers, computer aided communication kiosks, and small grinders) and community requirements such as drinking water supply, street lighting and vaccine refrigeration (Chaurey and Kandpal 2010). Schools and other institutions and offices are also potential customers. One or a few operators with relevant training operate and maintain the power supply system outside the view of the customers.

Many of the contributions on solar mini-grids provide analyses of the physical-technical performance of such systems. For example, Moharil and Kulkarni (2009) treat the relationship between seasonal fluctuation in solar radiation and the variation in power generation. Other studies compare the technical and economic characteristics of solar mini-grids with individual solar home systems. In the solar mini-grid model centralized and professionalized maintenance frees the individual user from such responsibilities except for repair and replacement of appliances used within the house/premise (Chaurey and Kandpal 2010). The access to AC power implies that AC appliances which are easily available can be used instead of DC (direct current) appliances normally required for solar home systems. Also, the variety in electricity's uses is potentially higher for mini-grids compared to solar home systems, dependent on regulations. On the power plant side, solar mini-grid systems may also facilitate the set-up of commercial organizations with incentives to keep the system in good working order. Finally, topographic and demographic factors need to be taken into account when considering the cost efficiency (life cost perspective) of each kind of system. A high number of densely located households and a flat terrain are factors that positively influence the cost-effectiveness of solar mini-grids compared to solar home systems (Chaurey and Kandpal 2010).

[2] Alternating current (AC) is the quality of electric power supplied through centralized, conventional electricity grids. Inverters are used to convert the direct current (DC) from the solar panels into AC power in solar mini-grids.

[3] Usually this is 220V 50Hz three-phase or single phase AC electricity distributed through low tension distribution networks.

The long term functioning and viability of technological systems has received attention in relation to solar mini-grids efforts in Senegal (Alzola et al. 2009, Camblong et al. 2009). Various problems with the operation of solar mini-grids included lack of involvement of local authorities and local populations, lack of adequate maintenance procedures or no maintenance and spare parts available, lack of local expertise, and lack of monitoring procedures. High costs and lack of financing mechanisms, mismatch between the needs and payment capacity of the users, dependence of the expertise of European and Japanese technology providers, and lack of development of local companies and know-how were also important[4]. This is in line with findings in India by Kumar et al. (2009) who point out that a large number of off-grid electrification projects, including power plants, fail because focus is generally on technical installation without paying sufficient attention to the long-term sustainability. The same kind of maintenance challenges have been found for solar home systems.[5]

The issue of long term economic sustainability of solar mini-grids was investigated by Shrank (2008), who did a case study in one of the villages with a solar mini-grid in the Sunderbans. He argued that the community management system did not create incentives for maximizing profit at each power plant, thus creating problems for the coverage of costs of the power supply. Conversely, Kirubi (2009) showed how supply of electricity in a rural town in Kenya increased people's capacity to generate an income, and thus pay the tariffs needed in order to cover the costs of operation and maintenance at the power plant. Alzola et al. (2009) regard the high cost of the initial investment as the main barrier for the extensive use of solar PV systems, and point out that direct contributions from the users, combined with financial tools such as subsidies and loans must be enough to economically support the project in the long term.

[4] Alzola et al. (2009) claim that the only way to assure the sustainability of the services is to combine deep knowledge of the local agents with technical expertise, management capacity and financial resources. Simplicity in terms of reliability of the technical installations, easy maintenance procedures, economic efficiency and local implication and appropriation of technologies is emphasized. Furthermore, they suggest that rural agents must be well integrated in all steps of the project, from initial financing operations to start-up and operation and maintenance procedures. They also point out that the electrification process itself stimulates the increase in consumption and makes more people interested to become connected, so that modularity is a must (Alzola et al. 2009).

[5] For example, an assessment of the solar based village electrification schemes implemented in North Eastern Region of India indicated a lack of availability of adequate maintenance facilities (Palit and Hazarika 2002). Palit (2003) observed, based on interactions with the implementing agencies, that though maintenance of the smaller systems were being undertaken regularly at the initial stage, the monitoring efforts were subsequently reduced or low priority is accorded to maintenance because of lack of funds, lack of technical persons, non-availability of spare parts and remoteness of the project sites. In a study of solar home system programs in Bangladesh and Fiji, it was highlighted that the ownership model; innovative financing and smart subsidies; proper policies and government collaboration as well as an appropriate institutional model for regular maintenance and monitoring were key factors to enhance a program success (Urmee et. al 2009).

Other social science research on solar mini-grids has concentrated on measuring the socio-economic impacts of such energy supply. For example, Chakrabarti and Chakrabarti (2002) carried out a survey in the Sunderban Islands in which community members said that electricity from solar mini-grids had brought them advantages, and that they would be willing to pay a higher tariff. Similarly, Chaurey and Mohanty (2007) found that provision of reliable electricity to the remote communities of the Sunderbans made a significant impact on the socio-economic development of the region, particularly for the women. According to the World Bank (2008), the impact of decentralized systems is limited compared with the potential socio-economic effect of rural grid electrification due to restrictions in supply and in the range of services offered. Socio-economic indicators, such as income, time use, education, health, etc., are central in any study of the impact of technology interventions. The present study considers end-users also to be playing an active role in the forming and development of the technological system of which they form part. Therefore, knowledge about their perspectives and experiences are thought to bring valuable input into how the selection, implementation and operation of such systems may be managed and maintained in a socially and economically sustainable manner. (Winther, in progress; and Winther, forthcoming).

This presentation of many of the literature contributions on solar mini-grids has shown that there is a good variation in the approaches applied. Many of the studies carried out so far predominantly focus either on economic and technical performance, or the reasons for and consequences of a lack of long term sustainability in operation and maintenance or the impact of such projects on electricity access and rural livelihoods. Without doubt these are important and highly relevant issues. In addition however, in-depth social science analyses on the implementation, design and use of solar mini-grids could increase the understanding of how these factors link to each other and also other potential aspects to take into account. An integrated perspective on society and technology, energy and development, and social transformations can shed light on the crucial social learning processes involved at all levels in emerging socio-technical systems such as solar power supply, and can facilitate these. Of particular significance is the dynamic interplay between social and technical factors as well as the relations between people and institutions involved at various levels in the systems. These aspects are at the centre of the Solar Transitions case study[6] from which empirical insights and analysis we provide selected parts below.

3 New insights from the Solar Transitions project

The recent findings of the Solar Transitions case study on the implementation and use of the solar mini-grid electricity supply systems in the Sunderban Islands are based on a broad approach by a diverse group of researchers and practitioners from different social science and technical disciplines representing various continents (Asia, Europe, and Africa). The case

[6] The research project is financed by the Research Council of Norway

study complements the technical, economic and socio-economic impact analyses with a deep understanding of the actual social practices developed in local power systems, personal insights and experiences of involved actors and social embedding of the technology in local contexts, to increase the understanding of the range of factors that influence the working of the local power supply system. We find it fruitful to view a local renewable energy system (e.g. a solar mini-grid system) as an example of a more general phenomenon in society, namely the emergence and development of new, socio-technical systems, and certain aspects of such processes of socio-technical change are used as the analytical framework applied in this case study.

3.1 Solar power supply as a socio-technical system in the making

This research project considers technological change as a social learning process, recognizing that a whole range of societal factors (in interaction with technological factors) influence the opportunities for people and communities to achieve technological and social changes. A central part of the social learning relates to how to implement and use the technologies at the local level, and to the general integration and embedding of the emerging technologies in society. Experimentation and related social learning processes are needed in order to be able to design the implementation measures in a way that is adapted to the local social, cultural and political context. The case study also contributes to such learning processes by analyzing the decentralized solar power supply systems as part of an emerging and not-yet-established socio-technical system, which is still not fully integrated in society. The case study carried out in Sagar and Moushuni Islands in the Sunderbans is based on insights from diverse theoretical approaches on society-technology interactions, empirical literature and practical insights on renewable energy experiences (Kemp 1994, Hoogma et al. 2002, Rohracher 2003, Ulsrud 2004, Winther 2008a and 2008b, Rohracher 2008).

A socio-technical system, for example a local system for solar power supply, can be defined as a configuration of heterogeneous technological and social elements, such as technical devices, organizational aspects, involved actors and social practices in the implementation and use, as well as competences linked to the technologies (e.g. Hughes 1983, Bijker and Law 1994). The socio-technical system for solar power supply in the Sunderbans consists of solar panels placed in fields in the middle of the villages, power plant buildings, battery banks, power conditioning units (battery chargers, inverters, etc.), electricity poles and lines, operators, owners, contractors for operation and maintenance, local committees, routines for and knowledge about operation, rules for use and payment of electricity from the power plant, appliances in the houses, spare parts, distilled water for the batteries, local institutions involved in the collection of revenue, etc. Within mature, well established socio-technical systems the different elements are often well developed and strong. In younger, immature and pioneering socio-technical systems and experiments, many of the elements in the system are weak and create problems for the pioneering activities initiated by engaged actors who want to promote the system (Hoogma et al. 2002).

Some of the elements in the solar power supply systems in the Sunderbans are part of a larger, emerging socio-technical system for renewable solar power supply (e.g., solar cell technology and factories) at the national and international levels, although the dominating part of India's power supply continues to be based on fossil fuels. Other elements are created and developed at the state level and in the local contexts, through pioneering implementation of solar power supply and the selection of organizational principles, composition of different technical elements, training strategies for operators, etc. The solar power supply systems in the Sunderbans represent interesting examples of socio-technical experiments and learning and articulation processes where a small network of actors are learning under local circumstances, creating their own formal and informal rules, and perhaps building on insights from other experiments (Raven 2005:46, 48). Such small experiments constitute important pioneering activities in order to create new socio-technical systems that sometime may achieve a significant role in society. Generally, the introduction of new technologies implies a series of experiments in order to go through the necessary learning process, as pointed out in literature on so-called "strategic niche management" (Hoogma et al. 2002, Raven 2005:45). The framework is suitable to understand and explain some of the interactions that are going on within such local experiments in which actors interact, learn about, and jointly shape the new technology, even though the approach to local experiments within strategic niche management focuses mainly on how experiments and technological niches develop into "market niches" (Raven 2005: 45). In our case study we take up the ideas of strategic niche management and explore the social learning processes in the Sunderban case in a free and open way structured by the logics and characteristics of the activities and outcomes on the ground. The empirical material – i.e. the experiences with the implementation and use of solar mini-grid systems is thus presented in a way that makes the findings as relevant as possible for practical use[7]. In the following we will examine how the interactions between technologies and actors (such as governmental departments, users, firms and local institutions) in the Sunderban experiments created a long-term, dynamic learning process and the way this resulted in a particular, local socio-technical system (cf. Raven 2005:37-43).

[7] The Solar Transitions project at large seeks to obtain a comprehensive understanding by combining four different aspects in the research, in addition to involving a diverse group of researchers and experts. The four aspects are the following: 1) The experiences with the implementation measures, 2) The experiences with the practical operation of the solar power supply system, 3) The socio-economic aspects of the solar power supply, and 4) The role of the national framework conditions. The findings brought in this paper are some of the findings from two of the main areas that were covered in the research, number 1 and 2. However, the research was done in a holistic way so that the insights in 3 and 4 also helped to get a deeper understanding of 1 and 2.

3.2 The solar mini-grid examples selected for the research project

The selected case for the research project was the solar mini-grid systems in the Sunderban Islands in West Bengal in India, because this case had been pointed out as interesting, innovative and ground-breaking by solar energy experts in New Delhi during earlier interaction. The state agency, WBREDA,[8] has 15 years of accumulated experience of developing ways of doing this kind of local power supply. As the research started, we also experienced that the WBREDA staff were interested and willing to share their experiences and insights during the research process, considering it as important to spread the lessons they had learned so that other projects elsewhere could benefit from the trying and learning that WBREDA had done.

By doing qualitative, in-depth research interviews with different people who were involved in, affected by or could otherwise observe the implementation and use of solar power supply, the project aimed to understand the various dynamics and interactions in a local electricity supply system consisting of people, technology and institutions and their respective positions, types of knowledge, visions, aspirations and other characteristics. The research methods thus consisted of qualitative interviews with implementing actors, solar power plant operators, customer committees ("Beneficiary Committees") other customers and non-customers (including households, shop owners and other business people), local leaders, students, policy makers at the national level, NGOs, research institutes and solar energy experts and companies in West Bengal and New Delhi in addition to observation of practices and conditions in the power plants and among the customers. Furthermore, an elaborated survey covering 200 households (of which half had an electricity connection and the other half had not) was conducted in the villages Bagdanga and Baliara in Moushuni Island and Kaylapara and Khashmahal in Sagar Island in order to secure quantitative data from the cases. Interestingly, during the field work the different team members with their different backgrounds of engineering, physics, practical project implementation, renewable energy expertise, consultancy, social anthropology, sociology as well as human geography sometimes noticed different aspects, and on the micro level (common interviews, sharing of field notes) various members sometimes interpreted findings slightly differently. This inter-disciplinary or perhaps trans-disciplinary approach gave a rich picture of the relevant factors. The attention of the participants was also sharpened because our group was going to implement a project in Kenya later, based on the experiences of the involved actors in the Sunderban examples. The team members were therefore especially motivated not to miss any details of the relevant factors. In one single paper only some of the most important insights from the research can be presented. First, an overview is given of the strategy that was used by WBREDA to make the solar power supply systems a reality, and thereafter some selected findings on the practical experiences with the solar power supply will be analyzed.

[8] West Bengal Renewable Energy Development Agency

3.3 Implementation and institutional set-up of the solar mini-grids

A total number of 17 solar mini-grid and solar hybrid mini-grid projects have been implemented by WBREDA between 1996 and 2010 in the Indian part of the Sunderban Islands, with aggregate capacity of more than 890 kWp. 12 of these power plants are located in villages in the two Islands where our case study was conducted, Moushuni and Sagar, and are presented in the table below.

	Name Island	Year installed	Capacity PV (kWp)	Capacity wind/biogas (kWp)	No of customers[9] Oct 2009	Visited in Feb 2010
1	Kamalpur, Sagar	1996	26	6 (wind)	71 (59/12)	No
2	Mrityunjoynagar, Sagar	1998	26	0	113 (48/65)	Yes
3	Gayenbazar, Sagar	1999	25	10 (wind)	108 (94/14)	No
4	Khasmahal, Sagar	1999	25	6 (wind)	129 (108/21)	Yes
5	Mahendranagar, Sagar	1999	25	0	118 (95/23)	No
6	Natendrapur, Sagar	2000	28.5	inc. wind	89 (63/16)	Yes
7	Dakshin Haradhanpur, Sagar	2000	25	0	NA	No
8	Uttar Haradhanpur, Sagar	2000	28.5	0	138 (109/29)	No
9	Mandirtala, Sagar	2000	28.5	0	91 (68/23)	No
10	Kaylapara, Sagar	2005	110	0	187 (157/30)	Yes
11	Bagdanga, Moushuni	2001	55	30 (wind, bio)	300 (uncertain)	Yes
12	Baliara, Moushuni	2003	110	0	250 (uncertain)	Yes
	SUM		**512,5**	**52**	**1544**	

Table 1. WBREDA's solar PV and hybrid power plants with mini-grids in Sagar and Moushuni Islands

According to the research interviews with people who had been involved for a long time with solar mini-grids (WBREDA-staff, operators, members in local committees, and households) in six of the "solar villages" visited by the research team[10] in Moushuni and Sagar Islands, the typical implementation process that was used by WBREDA looked

[9] Data from October 2009 obtained from WBREDA's record of payments. The figures in brackets show the number of customers who are on the 3 point and 5 point tariffs, respectively.

[10] Bagdanga and Baliara in Moushuni Island and Kaylapara, Khashmahal, Natendrapur and Mrityunjoynagar in Sagar Island

approximately like this, with some variations between the projects: The state agency WBREDA secured funding for the projects through the Ministry of New and Renewable Energy in India and the West Bengal state government and a few other sources. WBREDA, in many cases, identified the villages to be targeted on the islands. Alternatively, village representatives came to WBREDA and asked for a solar mini-grid system because they had seen it in another village. WBREDA held meetings with local leaders, teachers and other central persons (mostly men) in each of the villages to discuss the matter, and to tell them what would have to be the contribution from the village in order to make it possible for WBREDA to install a power plant and supply electricity to their village.

The location for the power plants was negotiated among local actors and with WBREDA, local authorities allocated government land, information meetings were held for local people, and surveys were in some cases conducted to check the interest and potential demand. Tenders were announced for the technical equipment and installation, and also for the contracting for annual maintenance and daily operation. Some challenges were met related to these different steps in the strategy especially during the implementation of the very first solar mini-grid in 1996 in Kamalpur village, which was a completely new type of experiment for WBREDA. However, the challenges were addressed underway, and in subsequent power plants, several problems were already solved by WBREDA together with the suppliers of equipment and other experts. The details on these initial challenges and efforts to solve them are beyond the scope of this paper.

During the installation phase local persons were sometimes selected and trained so that they would be able to take on responsibility for operation, daily maintenance and distribution line maintenance. In other cases trained personnel was taken from other places where the suppliers or other contractors were engaged. Supplier companies or local companies were given contracts to oversee the operation and maintenance of the power plants and be the employer for the operators. Local Beneficiary Committees (customers committees) were created in each village, for awareness raising about the benefits of connecting to the power plants and for motivating people for payment of connection fees and tariffs, as well as for looking after the amount of electricity drawn by each customer.

For different reasons, including ideas for equitable distribution of the electricity in the villages and later also cost aspects and some technical difficulties, WBREDA chose not to install meters or circuit breakers in the customers' buildings. They wanted to create an arrangement for consumption of electricity that could distribute the limited amount of electricity from such an isolated power plant to as many customers as possible, and decided to use a flat tariff. They assumed that this kind of tariff could work, since the number of supply hours was fixed and since the number of light points was also fixed. The flat tariff was set at two different levels, covering 3 and 5 electricity points respectively. The first level allowed for load requirement of the customers' appliances of 70 W – f. ex. three CFL lamps and the other level allowing for appliances of 120 W, f. ex. three CFL lamps, a table fan and a black and white TV. At each of these levels, which the customers chose among, everybody paid the same and had the same chance to use up to a certain amount of electricity. The Beneficiary Committees were responsible for controlling the agreed level and type of electricity consumption and identify over-use, which could be punished with disconnection from the power plant, usually after a warning. The customers could also be disconnected if they had not paid for some time, f. ex. a couple of months. In return, consumers would receive 5-6 hours of supply every evening starting from 1800 hrs, gradually going down to fewer hours during the life time of the power plant battery bank of 3-5 years[11], and going up again to the highest number of hours when a new battery bank would be put in place.

Figure 1 shows an outline of the institutional set up for the operation, maintenance and customer management (connections, billing and tariff collection) of the mini-grids in Sagar Island. The set-up slightly deviates from what WBREDA had planned for in the beginning (see explanation below). This illustrates that the outcomes of WBREDA's efforts in the Sunderbans were also highly dependent on the involvement and roles that different other actors took in the power supply systems.

FIGURE 1

Figure 1: Outline of the practiced, institutional organisation for the operation and customer management of the solar mini-grid system in each village in Sagar Island in the Sunderban Islands

The implementing agency, WBREDA, is the central actor in this institutional model. They are the responsible agency, they are contacted by the other actors when major problems occur, and the replacement of batteries and other major improvements depend on them. The dotted lines around the boxes of the contractor company and the co-operative indicate that these actors have come to play weaker roles than what was hoped for by WBREDA, as we account for in the next section. The role of the co-operative became to collect the electricity tariffs in the villages at Sagar Island and take care of consumers' grievance redressal instead of also playing a stronger role in the management and operation of the solar mini-grids. The arrow between the power plant operator and the WBREDA box indicates that the operators make phone calls to WBREDA to talk about problems or discuss decisions that they need to make during the operation of the power plant instead of calling their direct employer, the contractor company. The same kind of communication is sometimes done between Beneficiary Committee members and WBREDA in relation to the need for improvements in

[11] The life time of the battery banks vary with different types of batteries and with different uses and levels of maintenance

the power supply systems. Moreover, WBREDA stays in touch with contractors in order to address challenges in maintenance and operation. Since this figure only shows the institutional set-up for one single power plant, it is worth noting that WBREDA has many such local constellations to relate to, given that 17 mini-grid systems have been put in place in the Sunderban Islands[12]. This constitutes a time consuming and slightly chaotic situation for WBREDA, given that they stay in direct contact with many of the involved actors. This is also why they are attempting to further develop the institutional models or business models so that the need for monitoring, guidance and assistance from WBREDA's side can be reduced. The arrow from the customers' box to the operator means that the operators feel a pressure from the customers to stretch the limits of the solar power supply in terms of number of hours of supply, risking to use the battery banks wrongly. Operators reported that they receive complaints from the customers when there are shortened hours of supply from the power plant.

We have here shown that WBREDA developed strategies for implementation and institutional set-up, which with time gradually got adjusted through the practices of the involved actors and the interaction between technology and people including challenges that emerged underway. Such dynamics in the development of the social organization of the technology are likely to occur naturally in any similar activity, with the same potential for social learning and improvements.

3.4 Practical experiences accumulated during 15 years

In order to understand what kinds of factors, including different kinds of barriers at different societal levels that have influenced the ways in which the solar power supply systems in the Sunderban Islands have worked in practice, the access to the practical, long-term experiences of the involved actors is crucial. These experiences are a valuable asset for all who would like to understand these kinds of power supply systems better. The interplay between the social dimensions and the technical elements in the power supply systems can then be revealed, as well as the interaction between different kinds of actors (i.e. individuals, organizations, companies, etc.) that may influence the actual working of the system. Important linkages can be seen between the steps and elements in the implementation strategy described above, including the resulting institutional arrangement on the one hand and the subsequent actual working of the solar power supply system on the other. In this section, we first discuss the challenge of growing demand and use of electricity, before having a closer look at the role and situation of the local operators of the solar mini-grids. Thereafter we will discuss the dilemmas related to tariff setting before giving attention to the institutional and technical challenges related to a weak technical

[12] The rural energy co-operative society is the same for all power plants in Sagar Island. On Moushuni Island, the local Panchayat (the local political entity) plays the same role as the cooperative society does in Sagar Island.

element in these socio-technical systems, the battery bank. The outcomes of WBREDA's work were not only influenced by WBREDA's chosen strategy, but obviously also by the other kinds of actors involved, and the roles they came to play in practice.

3.4.1 The challenge of growing demand and over-use of electricity

The institutional set up with emphasis on local involvement and control of customers as described above appears to have given the intended results in many ways. For example, the rate of collected revenues has been high, as reported in earlier studies (Chakrabarti and Chakrabarti 2002). In a given village it was reported to be 100 percent (Shrank 2008). A World Bank publication highlighted the success of the Sunderban case in the following way: "Theft is almost nonexistent and defaults very few, thanks to enormous peer pressure and self-monitoring by the user group" (Gulati and Rao 2007: 129). Furthermore, the reliability of the electricity supply also appears to have been good, and the electricity seems to have been affordable, something that will be further touched upon below. An important challenge that started to be felt by WBREDA and other involved actors after some time of operation of the solar mini-grids was that the use of electricity gradually became too high compared to the limited capacity of the installed power plants.

The temptation to use more electricity than agreed

Since electricity consumption was to be administered without metering it, as explained above, it was relatively easy for customers to start drawing a little bit extra of electricity in their shops and homes. People gradually started to look for more electricity than what was calculated in the flat rate model, and other uses of electricity emerged, such as mobile charging and charging of devices or batteries for people who could not get a connection. Sometimes people also made a so-called by-pass, stretching a line over to one's neighbor who didn't have a connection. By the time of the field work the established practices of over-use seemed to have become socially accepted and silently accepted by Beneficiary Committees and operators, and the over-use had become high, as indicated by the strength of the light-bulbs used in the market areas. And even though previous penalties were reported in our interviews, it must also have been a practically difficult task for the local committees to visit and look after hundreds of co-villagers and discover and report irregularities, given the time consuming task it would be to regularly check all the customers. The flat rate, non-metered arrangement in this way started to give challenges in terms of overloading the power plants and thus damaging the batteries quicker than what would be the normal rate of degradation of the batteries. In addition to the increased demand and use of electricity from those who were connected to the solar mini-grids, there was also a potential demand from those who never got a connection although they were within reach of the power plant because they didn't take a connection in the beginning before the capacity of the power plant was saturated. Later the plant could not take more customers, and waiting lists appeared with people who had now become able to afford a connection and/or had started to become interested. This great interest from the community demonstrates the popularity of the solar power supply that had been installed and the gradual learning on its usefulness, and not only the limitations of the system.

In conclusion, demand generally outsized the capacity of the plants. At the time of fieldwork in February 2010, demand seemed to have become difficult to meet with the existing solar mini-grids and people in the villages also appeared highly motivated to become connected to the national grid with 24 hours electricity supply, which was also on the way to Sagar, the largest of the Islands[13]. Changed expectations had then been created, both by the experiences within the local system and because of the external developments. An important wish from many villagers was to be able to use a little bit of electricity also at other times of the day than in the evening when electricity was delivered from the solar mini-grids.

As mentioned earlier, solar PV is a flexible technology in terms of being modular. However, from the perspective of a village with a solar power plant, there is a given initial capacity, so that the flexibility is not experienced. There is a certain amount of electricity available (which varies with the weather conditions and seasons), and there is a two-fold challenge in either not allowing demand growth or doing the extra investment in increased capacity. It can also be noted that the same problem of rapidly growing demand and limited capacity can be observed at a much larger scale at the national level both in India and in many other countries, so it is not a phenomenon that is restricted to solar power plants. Even though a transmission line offers a significantly higher capacity, in many countries it is nevertheless difficult to provide the electricity to meet the demand.

Combinations of solar systems

A solution that has become common among relatively well-off households without access to the solar power plants in the Sunderban Islands is to install solar home systems, and a few households combined both solutions to increase the access to electricity. WBREDA has also extended their work on providing subsidies for the purchase of solar home systems in selected villages through the solar PV demonstration programme and Remote Village Electrification Programme of the Ministry of New and Renewable Energy in India, which started working in its present form from 2008 with the aim to provide basic lighting systems to *all* households of an un-electrified village. It might be done with small power plants, such as solar mini-grids, solar home systems or other solutions. In general, combining the mini-grids with charging services and solar systems for individual buildings may be fruitful in order to reach a large proportion of households, institutions and businesses in an area. Such combinations, in addition to providing flexibility capacity-wise, also make it possible to reach

[13] In February 2010 there were plans to include Sagar Island in West Bengal's main grid, though all the 13 "solar villages" there were not likely to be reached in the beginning. Moushuni Island was not included in the plans.

households located more than 2 kilometers[14] from a solar mini-grid or a similar power supply system. The strategy of WBREDA has thus changed due to the national policy changes, but the revised strategy also meets the needs for complementary solutions for the solar mini-grids that they have experienced at the local level. This revised strategy is in itself an experiment which can give interesting experiences by providing new learning processes and adjustments.

Some experiments have been done by WBREDA also at the solar power plants to address the phenomenon of growing demand, although they have mostly chosen not to expand the already installed solar power plants, since the focus has been on trying to reach more and more villages in the Sunderbans that have been waiting for light and other electricity services. However, WBREDA has routinely built the power plants much larger in the later projects than during the first years from 1996 onwards. Up to year 2000 they implemented solar PV mini-grids in the capacity range of 25 kWp – 26 kWp. Thereafter, observing a strong growth in interest and demand in the villages that had already got the solar power supply, they started to build the power plants with larger capacity, up to 110 kWp. In some places they installed additional generation units such as small wind-generators and biomass gasifiers to optimize the plant operation and meet the additional demand with minimal incremental costs. The combination with gasifiers was also chosen because it had the potential to provide better demand side management as the day-time loads consisting of commercial, community and domestic could potentially be serviced through the gasifier and the night time load of mainly community and domestic lighting could be serviced through solar PV. The 55 kWp Bagdanga power plant in Moushuni Island for example, was connected with a wind turbine and biomass gasifier (total capacity of 30 kW). The wind turbine has been used during the monsoon season when there is a higher wind resource[15].The biomass gasifier is meant to be run during the winter and the dry seasons, but had not been in use for a while at the time of field work in Bagdanga. It was unclear whether this was due to lack of dry biomass. WBREDA has not chosen to build in a mechanism for gradual expansion of the plants when the demand grows, which could be considered in such projects. This has not been seen as relevant enough for their projects due to the changes in national framework conditions and subsequent changes in the WBREDA strategy, as well as the ongoing changes in the electricity supply in the Sunderban Islands. Their solar mini-grid projects had by these reasons been put on hold for the previous couple of years, so that even upgrading and reorganization had not been prioritized. However, the latest information from WBREDA is that the upgrading of the power plants is now undertaken, and that new battery banks have been installed in 11 of the existing solar mini-grids (except Kamalpur village). An important

[14] The exact distance depends on the load. With small loads such as lighting and small appliances 2 km is realistic. With larger loads following from the use of motive power and other uses that increase the load, the distance will be shorter.

[15] The turbine had been damaged by an exceptionally strong cyclone (Aila) when the research team visited the island.

priority for WBREDA during this upgrading process is to provide new batteries and upgrading of inverters and charge controllers where needed. However, extra solar PV modules will also be added in some of the power plants to extend their capacity, and there will be some modification in distribution lines, and other adjustments. In order to address the issues of securing regular payment and limit the over-consumption of electricity, one solution that is currently being tried out by WBREDA is to involve a third party in the form of energy service providers (ESP) or franchisees for electricity distribution[16]. The responsibility of the ESP can be for example to procure electricity in bulk from the power plant, distribute to the consumers and collect revenue from the consumers. This is seen as a way of creating economic incentives for efficient collection of tariffs and controlling over-use of electricity.

Among the messages communicated from WBREDA's side were that small scale decentralized solar PV systems have their clear merits in an early phase of providing electricity to people in remote villages. Though a solar mini-grid has many of the features of central grid power supply such as substation, overhead LT lines, service connections, tariff structure, etc., they are constrained by limitations in supply duration and quantity of supply. With the gradual build up of aspiration, when people start demanding more electricity and of a quantity that enhances other uses (including motive power) than what the systems can provide within a reasonable investment cost, changes are needed in the supply. This is also in line with the mentioned findings from Senegal (Alzola et al. 2009).

Integration of the solar mini-grids in the national grid?

In a larger perspective the increasing demand can be seen as a positive effect not least because of the "pre-electrification", which may be seen as an advantage of solar PV that has become clear during the emergence of real life solar PV experiments. The "pre-electrification" phase constituted by the solar mini-grids has conditioned the market so that now it is quite clear that there is a demand for 24 hour supply which makes it economically reasonable to extend the national grid to the area even though it is remote. The grid connection (which we do not know if it is defensible from a cost point of view) at least is reasonably assured of the sales. Also, if and when the grid reaches the solar mini-grid-locations, the solar power plants can be connected to feed electricity into the conventional electricity grid with some technical modification in the inverters. When WBREDA set up the solar mini-grids in the Sunderban Islands, they used state-of-art inverters/converters of that time, which may be ineffective now for integration. However, with time, new technologies have evolved and integration of independent local grids is now possible to make the grid smarter. WBREDA, though it is yet to attempt the smart grid concept, may introduce smart grid concepts in Sunderbans by inter-connecting various independent mini-grids, which can be connected with the extending central grid to take or feed power, thereby bringing in further stability in the system. Without such an initiative, grid connection at the distribution

[16] Here an ESP/franchisee may be an individual or group of people to distribute electricity to an identified set of consumers within the command area of the power plant.

level may be a challenge due to various technical reasons which have to be addressed accordingly.

There seems to be a recent change in the thinking in WBREDA about the emerging electricity grid and the role of solar PV in Sagar Island, since it seems now like it may not be expected that the grid will reach to the "solar villages" within the next few years. The gridlines are expected to reach the island itself during 2012, but not yet the remote villages where the solar mini-grids are located. It may also be mentioned here that WBREDA has recently commissioned six wind-solar PV hybrid systems for providing electricity to five schools in the same island for operation of computers, laboratory equipment and some essential light and fan load. This indicates that even though the national electricity grid is expected to Sagar Island shortly, solar PV systems are still seen as relevant and necessary for supply of electricity in villages and institutions. As and when the grid is extended, the community may shift to this mode of supply. However, where the grid supplies is unreliable as in many part of India, and if the villages have the PV systems intact (feeding into the grid when possible), they can have the solar PV also as a supply option when the grid is disconnected. The opportunities have to be seen not only from the point of view of rural electrification but in the larger context of a sustainable development of a country and simultaneously enhancing the energy security.

3.4.2 Operators as core actors for the functioning of solar power plants

The operators of the solar power plants play a vital role in ensuring the plants' long-term functioning. These are the individuals (in the Sunderbans they are all male) who can be found within the power plant buildings, doing the daily work that is necessary in order to operate, attend to and maintain the solar power supply. The work of these persons is crucial for maintaining the function of the whole system. In addition to good technical solutions in the power plants, these people's dedication, skills and ability to make good decisions in the daily operation and maintenance is completely necessary for the performance of the whole power supply system and thus the benefits that the community members may obtain. According to WBREDA staff, all critical decisions during the operation must be taken by the operators, and a wrong decision on the part of the operator may damage the battery banks. The dependence of the operator may vary with the kinds of charge regulator and batteries used in the solar power plants. In the Sunderban systems, the charging of the battery banks from the solar panels was controlled by the charging regulator, while the discharging in the systems was strongly influenced by the persons who were managing the process and the load pressure from the customers' side. A bigger load gives more rapid discharging, and since there was little regulation and control of the load use in the villages we visited, people drew as much electricity as they could from the points that they had. Strict load management is important for the state of the battery, and this gradually became difficult in the Sunderban solar mini-grids as explained above.

The contractors as employers for the operators

With the aim of keeping the solar power plants running without a continuous need for WBREDA to follow up on operational matters, they have tried to use contractors as intermediate actors who would employ and follow up the operators and take care of technical problems. However, a problem has been that some of the contractors have had little dedication for the task. Contractors are also present for relatively short periods, because of limited contract periods, often only one year, or even down to 6 months, and because it happens in a few cases that they break the contract due to other interests, for example wanting to withdraw their business in West-Bengal and concentrate on other states. Thus, it is not surprising that some operators had experienced to have three different contractors during the last 10 years while working at the same power plant. WBREDA has started to develop contracts that can cover a long period of time, up to 10 years, and can cover both the operation and comprehensive maintenance of the plants. Several operators in the Sunderbans complained about what they felt was a lack of support from their employer, which is usually the contractor selected by WBREDA for operation of the plant. Another factor for reduced motivation for the local operators was that they generally considered their salary (down to 2000 INR per month) to be far too low, which was the responsibility of the contractors. WBREDA was in the process of addressing this problem by putting pressure on contractors to abide with regulations for workers rights, including minimum wage.

A motivational factor for the operators suggested by WBREDA for their ongoing and coming reorganization of the solar mini-grid systems was to facilitate business activities and entrepreneurship for them in relation to their work in the power plants and the access they have to electricity in their workplace (cf. Shrank 2008). The team observed signs of business activities in the solar power plants in the Sunderban Islands. If managed in a transparent way, this could increase the motivation for running the plants and ensuring money collection in a financially sustainable way.

3.4.3 Division of responsibility between involved actors

The division of responsibilities between WBREDA, the contractors and the operators gives certain challenges for WBREDA, and WBREDA's interaction with these actors is dynamic and in need of regular adjustments as new issues keep coming up. Figure 1 earlier in this chapter illustrated some challenges in this interaction. The smooth operation of the solar mini-grid systems, where several juridical bodies are involved, has required elaborated contracts with clearly defined responsibilities and regular dialogue between the parties. For example, when a set of batteries provided by a supplier broke down already after three years, a discussion centered on whether the responsibility for failure was with the contractor (including the operator) or with the battery supplier. Was the battery operated in a wrong way or were the PCU-units not working well, like the battery suppliers have tended to claim, or was it a bad product delivered from the battery supplier in the first place? Operators reputed for being particularly good argued that the recent battery problems were related to the low quality of the batteries more than to wrong use and poor maintenance, since they had kept batteries alive and in a good shape for very many years before. However, the reasons for more rapid degradation of batteries than earlier were probably also linked to other factors than the skills of the operators and the quality of the battery product delivered, such as the over-use of power from the customers, leading to a more rapid rate of discharging of the battery than the battery specifications stated. An important question is how much responsibility for various problems should be taken locally by the operator and otherwise at the village level, what should be the role of a contractor in such a system, and what kind of support and follow up should be provided from a higher level, such as from the state agency, WBREDA. A general point that can be drawn from WBREDA's experiences in the Sunderbans is that well-functioning decentralized systems require that the local level receives substantial support in some form.

3.4.4 The dilemmas of the tariff setting

An important element in the design of off-grid electricity systems relates to the setting of tariffs (the connection rate and price of the units of electricity consumed). The tariff for the solar mini-grid customers in the Sunderban area was decided based on mutual consultation between WBREDA and the Beneficiary Committees). The tariff is not regulated by state regulators as under the current electricity regulation in India, where stand-alone and off-grid systems are entirely free of licensing obligations and regulatory oversight and leave the retail tariffs purely to market forces (Dubash 2007). The Sunderban material shows that the investment costs in a mini-grid connection or a solar home system alike constitute a barrier to obtaining connection for the poorer families. However, in the long run, people's expenses on electricity in the villages investigated (connecton fee included, and depending on the number of lights) is cheaper than the landed cost of kerosene, the alternative fuel source for light. In the Sunderbans, tariffs (connection rate and price of units consumed) have been kept relatively stable over the years, indicating the influence of local committees, but at the same time keeping the tariffs down at a level that constitutes a challenge for the financial situation of the projects, even though WBREDA usually would aim to decide the tariff in such a way that it can meet the operational and maintenance expenses of the power plant. They also usually keep the tariff a little bit lower than the rate charged by private diesel generators, if operating in the village and market. Setting the tariffs will always be a balance between the economic sustainability and the affordability, and even a tariff that is insufficient to cover the operation and maintenance costs may exclude some households from becoming connected. A part of this dilemma, vital to obtain local ownership and control, is the potential conflict of interest between local groups and those in charge of the power plants when setting/adjusting tariffs.

Some of the factors that must be taken into account when trying to find the balance between the affordability and economic sustainability are such as available government funding, technical capacity, customer base, income distribution in the project area, availability of anchor customers, acceptability of measures to put a ceiling on consumption, equity issues etc. This balancing of affordability and financial viability is among the issues that need attention beyond the local level.

3.4.5 A weak link

The technically weakest part in the systems – the batteries – have given many extra challenges for the whole operation and sustenance of the solar mini-grids in the Sunderbans, including the difficulties it gives the operators and the need it creates for development of a quite advanced technical understanding in the operators. With the tendency to get battery problems, the hours of supply to the customers after a while became significantly shorter than when the batteries were new. And the other way around, with the practice among the customers to draw more electricity than was meant by the system designers, they increased the pressure on the batteries and contributed to the same problem. Today's available battery technology is better, while it is a question of costs how good batteries can be chosen. In addition, new and better charging regulators are likely to help.

According to the project engineer at WBREDA, a way to reduce the recurrent battery problems, which also involves the problem of definition of responsibilities at various levels, would be to let the contractor who is responsible for the charging controller cover responsibility for batteries from supply to operation, and in case of too early failure, also replacement. This solution would thus make one single juridical body in charge of operating the batteries in a technically sound way. This problem and suggested solution illustrates the close interconnections that exist between technical and non-technical/social 'components' in such a socio-technical system, and thus the importance of focusing on these connections to obtain viable solutions.

4 Conclusion

In this article we have presented research on some of the long term experiences with solar power mini-grids in the Sunderban Islands in India. By adapting a socio-technical approach to the emerging electricity systems in question, a range of technical and non-technical factors at various levels were found relevant for explaining some of the outcomes of this process. Due to unforeseen developments, the constant requirement for adjustments (illustrated in the modifications of the institutional set-up) and the dynamic interaction between actors and technologies on various levels, this process can be considered as having been a mutual learning process which is still going on. We have highlighted five challenges which may yield general relevance in systems of this sort. Firstly, there is the dilemma of growing demand and the system's capacity and mechanism to meet this demand, secondly, operators play a fundamental role and need constant support, thirdly, the division of responsibilities may be unclear in an evolving system like this, fourthly, there is a dilemma between affordability and economic sustainability in tariff setting, and fifthly, batteries constitute a weak link in the system, not only technically but also organizationally.

In the Sunderbans, the state agency, WBREDA, has enthusiastically done great efforts to be able to create functioning solar power supply in remote villages, starting with blank sheets and developing innovative solutions, thus providing a very interesting socio-technical experiment to learn from. Local actors have taken part in the work, eager to get light and other electricity services, not least in shops and market places, and a growing number of villages have got their mini-grid system, reaching a number of 17 in total in the Sunderban Islands. The people at the local level have gradually responded in some unforeseen ways, for example by using other and more power consuming electric appliances than what had been planned for, which again negatively influenced the technical performance of the power supply. This also demonstrates the dynamic interaction between social and technical aspects, a point that was further illustrated when we saw that battery problems increased the need for advanced skills for the operators and created other challenges for the social organization of the whole system.

The Sunderban PV plants was a new kind of experiment for the implementing agency, thus it was obviously impossible to know how the local people would use the system and adapt to it and influence it. However, due to the general dynamics and open character of social life, there will always be a potential for unforeseen consequences in initiatives of this sort. Although the growing over-use of electricity and growing aspirations of the people for supply of more electricity have been challenging to WBREDA staff who have tried to meet the expectations of the local communities, people's clearly articulated demand for more electricity shows that WBREDA has managed to supply power to many customers in a way that has convinced these people about the usefulness of electricity. Similar dynamics in which people's access to basic electricity services turns to increased demand must also be expected to occur in other contexts.

Solar mini-grid systems can be designed and organized in a range of ways, and the socio-cultural contexts where they are implemented may be very different from the Sunderbans. However, many of the insights from the Sunderban cases, and the approach for exploring them, are likely to yield relevance also in other geographical contexts. We argue that the Sunderban experiences can inform the continuous process of developing new and better ways of facilitating, implementing, financing, organizing and operating future use of the solar PV technology in a diversity of geographical contexts in ways that give as many advantages for the population as possible. New activities can fruitfully take advantage of the previous learning processes that have been going on. For example, the Government of India, through the Jawaharlal Nehru National Solar Mission (JNNSM) launched in 2010, has set a target of setting up 200 MW of off-grid solar power by 2013 and 2000 MW by 2022. Given these ambitious targets, it is important that the rich knowledge from the WBREDA solar mini-grids and other solar PV projects elsewhere are extensively shared. When starting similar activities in other geographical contexts, be it in India or any other country, it will again be a pioneering activity in many ways, since unforeseen developments are likely to emerge also here, and since the local contexts and the national framework conditions may be different – requiring adaptations in the model and further social and technological innovations. However, new efforts can build on previous experiences, which is the way socio-technical systems evolve in general. Our contribution has been to try to make the experiences from the Sunderban case accessible and subject to reflection and potential action elsewhere.

The social science perspectives that have been applied in this analysis in combination with the technical experts' insights have helped to understand the rich and multifaceted nature of the investigated case. The analysis has also demonstrated that when studying the emergence of new, socio-technical systems and how they can be implemented and organized in ways that embed them in local contexts, it is important to see the systems through the eyes of the involved people with their diverse roles at different societal levels and in different parts of the systems.

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