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Consequences for Design of Future Solar Home Systems for Off-Grid Rural Electrification

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DOI
10.23919/DUE.2017.7931816

Publication date
2017

Published in
Proceedings of the 25th Domestic Use of Energy Conference

Citation (APA)
den Heeten, T., Narayan, N., Diehl, J.-C., Verschelling, J., Silvester, S., Popovic, J., Bauer, P., & Zeman, M. (2017). Understanding the Present and the Future Electricity Needs: Consequences for Design of Future Solar Home Systems for Off-Grid Rural Electrification. In *Proceedings of the 25th Domestic Use of Energy Conference: Towards Sustainable Energy Solutions For The Developing World* (pp. 8-15). Cape Peninsula University of Technology. https://doi.org/10.23919/DUE.2017.7931816

Understanding the Present and the Future Electricity Needs: Consequences for Design of Future Solar Home Systems for Off-Grid Rural Electrification

Thomas Den Heeten, Nishant Narayan, Jan-Carel Diehl, Jeroen Verschelling, Sacha Silvester, Jelena Popovic-Gerber, Pavol Bauer, and Miro Zeman

Abstract— Solar Home Systems (SHSs) can fulfil the basic energy needs of the globally unelectrified population. With costs as one of the biggest barriers for SHS uptake, optimizing the system size with energy needs is crucial. Where most solutions focus only on the present needs, this work also addresses the future energy needs. The methodology includes extensive mapping of the current electricity needs in rural Cambodia through data analysis on existing SHSs in the field. Additionally, a 2-month field research was carried out in Cambodia to assess the qualitative state of electricity usage and investigate the future (2021) energy needs. A data analysis was performed on 111 SHSs (100 Wp, 1200 Wh). SHS users were found to have a mean energy consumption of 310 Wh/day, with σ = 159 Wh. Most energy was consumed at night. The field research showed a clear demand for more energy and more appliances. The appliances attached to SHS in the future will be more diverse in power consumption and usage duration, resulting in a wide variety of energy consumption and high power peaks, causing fast and deep battery discharges. Three load profiles are presented. Solutions are discussed that can be applied to ensure the SHSs fit with future energy needs.

Index Terms—energy consumption, energy matching, load profile, low-income countries, solar home system, rural electrification.

1 INTRODUCTION

Almost a fifth of mankind still lacks access to electricity, with around 85% of them living in the rural areas [1]. Topography, policies, quality of the electricity-grid, and other regional factors surrounding these unelectrified villages severely limit grid-based electrification as a real, potential and immediate solution to mitigate energy poverty [2, 3]. Although there are also urban populations living without electricity, the lowest electrification rates are found in rural areas. Table 1 shows, as an example, the electrification rates for Cambodia, India & South-Africa.

With 1.3 billion people unelectrified and another 1 billion having unreliable grid access, the potential market for local renewable energy production and especially solar home systems (SHSs) is huge [4]. An SHS is also the de-facto choice of technology to provide electricity, given that most of the regions lacking electricity simultaneously enjoy some of the highest sun-hours in the world [2]. Consequently, the global market for SHSs is growing rapidly. Despite the growth, the SHS market remains a harsh market. Several barriers like infrastructure, financial constraints, consumer awareness, policies, quality assurance, skills and knowledge make the electrification of low-income rural households worldwide difficult [4-7].

Table 1. Electrification rates, rural vs urban [8]

Electrification rate	Urban	Rural	Total
Cambodia	91.3%	18.8%	31.1%
India	98.2%	69.7%	78.7%
South Africa	96.6%	66.9%	85.4%

As such, a dedicated PV-storage energy system design for communities in low-income settings can be a complex task, especially if the emphasis is on a low-cost, affordable solution that takes current and (foreseeable growing) future needs of the people into account. Both technical as well as non-technical or socio-economic factors have a huge bearing on the way the system should be designed and developed [2, 7].

One of the biggest hurdles are the financial barriers, a challenge for both companies as well as consumers. SHSs come, relative to the context, at high upfront costs. Decreasing the SHSs' upfront costs is therefore an important aspect in the challenge to provide more rural households with a SHSs. Regardless of the business models used by SHS vendors, these upfront system costs are for many poor households still a barrier, despite the decreasing price trend of the SHS components. While in 2003 a SHS of 20 Wp was economically competitive with kerosene lamps, in 2015 this was true even for a 70-80 Wp [9]. Fig. 1 illustrates the cost break-down of a typical SHS in 2009 and 2014.

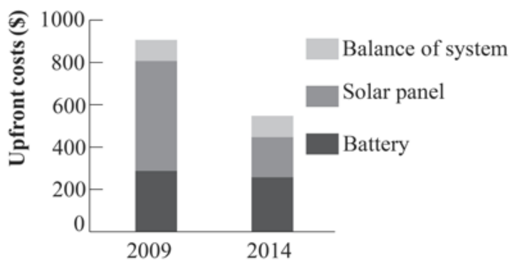

Fig. 1. SHS costs: 2009 vs 2014. Costs are based on a system suitable for powering standard appliances: a 19" TV, radio and lights [4].

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The main contribution to the lowering of the upfront costs of SHSs has been the decrease in price of the Photovoltaic (PV) modules. The price of the battery stayed more or less the same, and is by-far the most expensive part of an SHS. The costs of Balance-of-System (BOS) have not decreased much, but BOS still lasts much longer than the battery in an SHS.

Consequently, from a technical design perspective, much of the challenge in minimizing costs in an SHS hinges on the successful optimization of battery lifetime [2]. Battery can account for more than 50% of the total SHS costs while having the least lifetime among all PV system components [10]. Lowering the price of SHS should not affect the system quality (and the consequent user satisfaction). One of the main reasons for unsatisfied customers are systems that are undersized and/or overused, resulting in power failure [4]. Therefore the challenge would lie in “minimizing the costs associated with the battery while enhancing its lifetime, thereby increasing the system and power availability while reducing the system costs” [2].

In this light, it is crucial that the SHS is designed to match user-needs [4]. The load profile (energy demand and usage patterns) of the end-users has a direct impact on the required system and components sizing. However, knowledge on user load profiles (demand side) is limited or outdated. In the report “The State of the Global Off-Grid Appliances Market” Global Leap [11] states “There has been little investigation into the real or specific usage patterns of off-grid consumers, leaving manufacturers unsure of consumer preferences and quality requirements”. The same report states that there is a lack of robust ground-level consumer data on the needs of off-grid consumers.

In addition, there is not only a need for up-to-date user load profiles for the current situations but also on how these load profiles can develop in the near future. Access to modern energy services does not stop with one light. Light might be the primary need of the users, but users also aspire to watch television, power a fridge, and heat an iron [12]. If their income increases, people often upgrade to more advanced and more powerful sources of energy as well as more/bigger electric loads [12]. Nevertheless, a majority of the current SHS solutions focus on the present, limited needs. Transition to the future needs a different approach, accounting for both the increasing user needs and the exponentially evolving technologies. With changing demands, different system sizes and configurations need to be designed.

Progress in consumer electrification has sometimes been described in terms of an ‘energy ladder’ that goes from no electrification to pre-electrification to full electrification [1]. As one moves up the ladder, the quantity and quality of electricity supplied increases and a greater number of human needs can be satisfied. Likewise the Sustainable Energy for All (SE4ALL) initiative has developed a multi-tier framework for analysing access to electricity [13]. Solar Works [12] developed an ‘electricity ladder’ to describe the development of their (potential) users from no light, via a single light, towards an SHS or a grid connection (see Fig. 2).

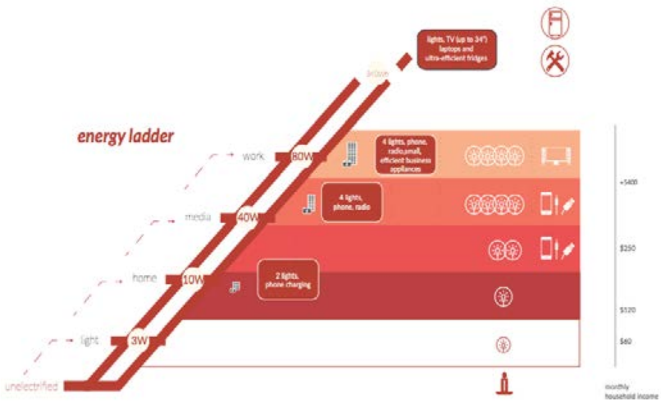

Fig. 2. Electricity ladder developed by Solar Works [12].

All models mentioned above describe the gradual increase in need and demand of energy and/or electricity by the end-user, but do not provide detailed insights in the load profile distributed over the day and over the year, which is crucial to design an optimized and efficient SHS. It is therefore important to keep (future) energy demands in mind as well. The aim of the specific research project described in this paper was to map the usage of SHSs (load profiles) both now and in the near future. The methodology developed and the gathered insights will support SHS designers in system optimization and determining the right size for current and future SHSs, in order to improve SHS performance and decrease system costs [2].

2 Method

It was decided to map the current and future usage of SHSs in one particular context, rural Cambodia, to get a detailed insight. At the first place, rural Cambodia has relative low rural electrification (see Table 1) and as such is at the beginning of the electrification process. Secondly, the researchers did have a long relationship with Dutch-Cambodian SHS producer and provider Kamworks, which could provide usage data of current systems in place as well as could facilitate field research.

2.1 Research Questions (RQs)

The research questions driving this work are formulated as:

i. What is the current energy consumption (load profile) of SHS users in rural Cambodia?

ii. What are the future energy needs (load profile) of SHS users in rural Cambodia?

iii. How do these energy needs influence the technical design of SHSs?

The year 2016 was taken as a reference for the ‘current’ situation and the year 2021 as a point of reference for the future needs. Making scenarios for longer-term futures would result in less reliable input for the project.

Two methods were used during the research phase: a quantitative data analysis and qualitative field research. Focus, with both methods, was on owners of Kamworks’ SHSs in rural Cambodia.

2.2 Load Profile

The electric energy consumption of a household can be expressed in a *load profile*. The load profile is a graphical expression of the demanded power over a specific period. The load profile is an important factor in determining a balanced, optimal system size for an SHS.

Load profile estimation is often a tricky and non-trivial exercise. While the load profiles for most electricity users in the west can be aggregated for purposes of a more accurate demand estimation, clustering for better electricity rates with reference to the utility, etc., the electricity usage in places like rural Cambodia presents a different type of challenge. Not only is the load usage not discernible, but also the total energy needs change over time. Furthermore, there is a gap between the needs, wants, and reality.

2.3 Quantitative data analysis

The first part of the research was an extensive quantitative mapping of the current load profile in rural Cambodia through analysis of data logged from existing SHSs in the field.

The following SHS performance parameters were used in analysis:

- *Power input (W).* The electricity supplied by the PV panel.
- *Power output (W).* The electricity that is consumed by the user.
- *Battery State of Charge (SOC, in %).* The percentage of charge that is left in the battery. 100% means that the battery is fully charged.

The analyzed SHSs have the following characteristics:

- 95 Wp or 100 Wp solar panel;
- 12 V, 100 Ah, lead-acid battery.

The analyzed SHSs were equipped with performance loggers and a GSMA module. The system performance logs were sent by each SHS through SMS. The logs were sent on a 20 minutes interval, starting on April 14th, 2014 until April 12th, 2016. A total of 111 SHSs were analyzed.

2.4 Qualitative field research

Additionally, a 2-month field research was carried out in Cambodia to assess the qualitative state of electricity usage. The aim of the qualitative field research was twofold: 1) To verify the results the quantitative analyzes (current load profiles) in the field, 2) to elicit from the users future demand for appliances and future usage patterns to construct future load profiles (2021).

To verify the current load profile, the participants are asked what appliances are used in combination with the SHS, and when the appliances are used. A dedicated booklet for this research was designed where participants could fill in their answers. Participants could visualize their usage pattern on a timeline of one day (see Fig. 3).

Seven households were visited during the research. Five out of these seven households were analyzed during the quantitative data analysis. The data of the performance logs of these five households can therefore be compared with the findings during the household visits.

Fig. 3. Timelines of appliance-usage in the 7 interviewed households.

To estimate future demand for appliance and investigate future usage patterns, two methods were used: 1) Expert interviews and 2) household visits.

In total, 16 stakeholders from the Cambodian SHS market were interviewed. These experts were asked to state their personal vision on the SHS market and to indicate what the current barriers are for SHSs, and what hampers the adoption of appliances in rural Cambodia. The main goal was to find out what appliances in the future are likely to be used in combination with SHSs.

The household visits did have the purpose to get insights on future energy demand from the perspective of the SHS user. During the household visits, the SHS users were interviewed, and a simulation game was played with the participants (see Fig. 4). During this simulation game, the ownership of larger SHSs was simulated. Participants were able to purchase appliances. However, SHS users were limited by time, price, and energy consumption. In this way, users had to set priorities and make deliberate choices for appliances. The simulation was used as a discussion starter. After the simulation game, SHS users were asked to predict their expected usage pattern of the chosen appliances. Participants could visualize their future usage pattern on a timeline of one day.

The investigation of future usage patterns was done with the same households that participated in the verification of current energy consumption.

Fig. 4. Simulation game on the future electricity needs.

2.5 Load profile tool

During this research, a load profile tool was developed that can support SHS designers in predicting future load profiles, also in other environments. The purpose of the load profile tool is twofold: 1) construct future load profiles and 2) understand and estimate the influence of specific appliances on the load profile. The load profile tool is parametric, since energy consumption and usage patterns can change over time [14] and appliance demand is often location specific [15].

The following parameters can be adjusted in the load profile tool:

- appliances owned by SHS user;
- power rating of appliances;
- usage patterns of appliances.

For most reliable results, the load profile tool requires input from the SHS designer as well as awareness from the users on the desired usage.

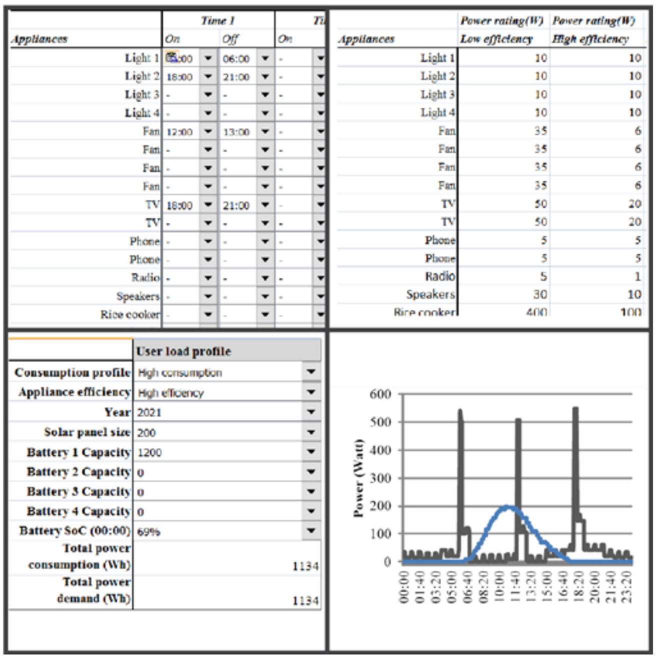

Fig. 5. Snapshots of Load profile tool.

3 RESULTS

This section presents the results of the research. In the first part, the current load profile will be analyzed (RQ 1). In the second part, the future load profile will be discussed (RQ 2).

3.1 Current load profile

Fig. 6 presents the mean load profile of 100 Wp SHS users in rural Cambodia over the measured period. The mean load profile will be explained by describing a regular day in the life of a rural Cambodian household.

Before sunrise, a small increase in energy consumption is found. This happened when food was prepared by a household member, and the lights were switched on.

Between sunrise and sunset, energy consumption is low. Cambodians spent their time outside the house, for example working in the rice field. A small peak is found around noon. This occurred during lunch, when households power , for example, a fan. Roughly one-third of the total energy consumption is consumed between 6 AM and 6 PM.

A large peak is seen at night. This peak is caused by the usage of multiple appliances at the same time. After sunset, households will turn on their lights. Furthermore, many households will watch television. Occasionally, the fan is turned on.

During the night, many households power one light. In the mean load profile, this is reflected in the relatively stable power output between 11 PM and 5 AM.

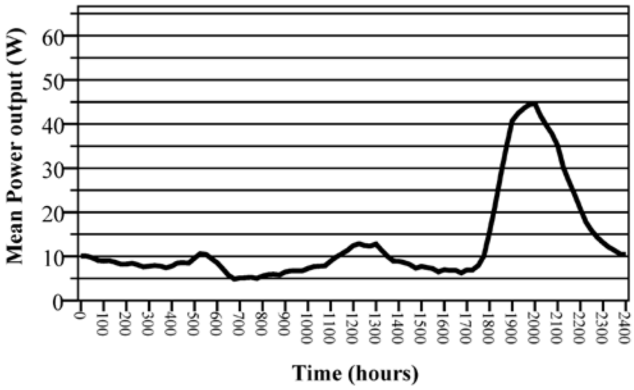

Fig. 6. Mean load profile.

Fig. 7 presents a boxplot of the power output of all SHSs in the households on one day in 2016. A boxplot of the power output is made for every hour of the day. The blue bar represents the values in between the lower quartile and the upper quartile. The horizontal black lines in the blue bars represents the median. The vertical black lines are the values between minimum and maximum values, excluding the outliers. The dots and asterisks represent values of the outliers. Outliers with a power output higher than 110 W are not included in the graph. A wide variety in energy consumption can be observed. Each household has its unique load profile shape, which can change from day to day.

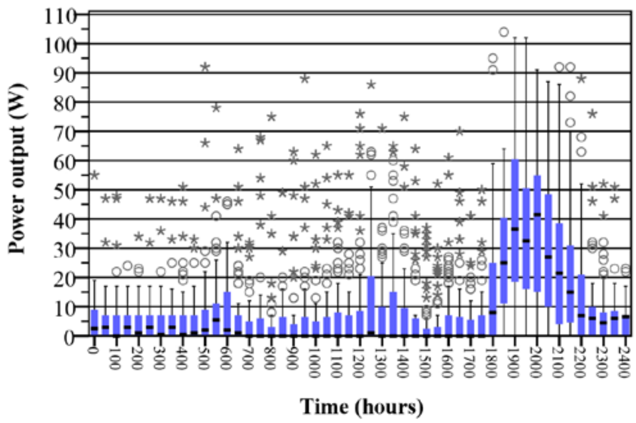

Fig. 7. Boxplot of power output of SHSs in all households on one day in 2016.

Fig. 8 presents the mean energy consumption per household. Although all the households that were part of the research owned the same type of system (100 Wp), there is a wide variety in energy consumption. The mean energy consumption for all users is 310 Wh/day, with a σ = 159 Wh.

The main reason for this variety is the presence, absence, type, and extent of usage of a television. Some households indicated not having money to buy a television. Furthermore, the power rating of the television influences the daily energy consumption. During the household visits, in some houses older, energy consuming CRT televisions were found, while in other households were in possession of newer, more efficient LCD/LED TVs.

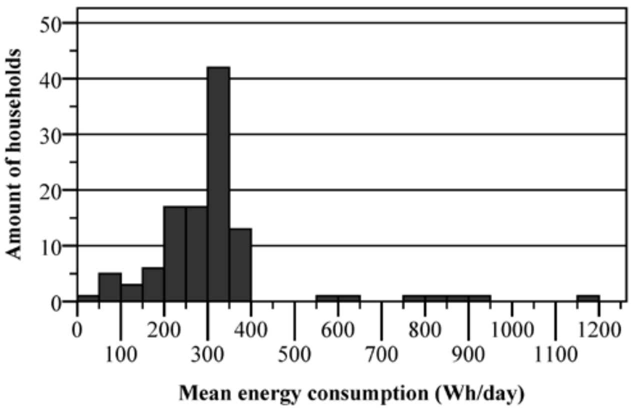

Fig. 8. Mean daily energy consumption.

From the data analysis, it seems that seasonal differences have minimal impact on energy consumption. Energy consumption per day is similar during all the months. Furthermore, no particular correlation was found between daily energy consumption and household size.

3.2 Relation of current load profile with system performance

Fig. 9 displays both the load profile as well as the power input (W) by the solar panel on a given day of one chosen household. This example illustrates the need for a battery: most energy is consumed at times when there is no solar energy generated.

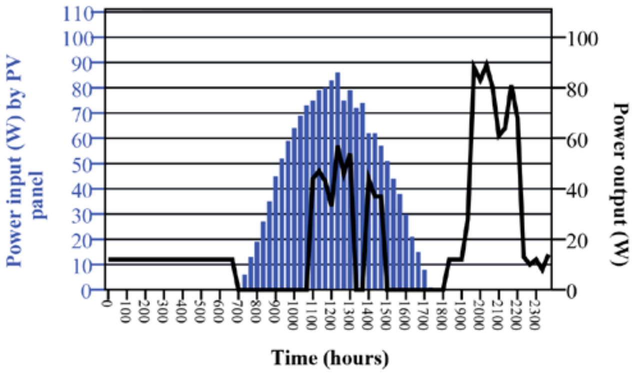

Fig. 9. Load profile and power input by solar panel on a given day of one chosen household.

Fig. 10 presents the mean SOC (%) of the battery, of all SHSs over all measured days. During the day, the battery gets charged by the 100 Wp solar panel. This starts slowly at 6 AM after sunrise. 6 AM is also the time when there is a slight peak in energy demand. This energy demand causes the drop in state of charge, to the lowest point of the day. After 9 AM, there is a clear surplus in solar energy and the battery starts charging. The battery SOC keeps rising until 6 PM, when the sun sets. After this, energy demand increases again and the battery SOC drops.

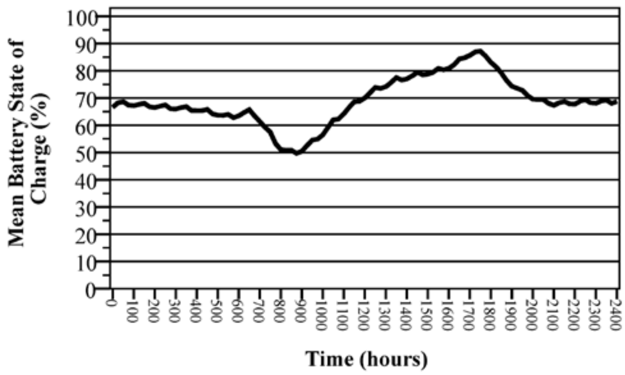

Fig. 10. Mean battery SOC of all 111 SHSs over all measured days.

3.3 Future load profiles

The field research resulted in a clear future demand for more energy. Participants in the field research indicated being satisfied with their SHS but would like to use the TV longer and add more appliances, such as a rice cooker, a water kettle, an iron and a refrigerator.

For the estimation of future load profiles, this research has put forth three types of SHS users in rural Cambodia: low, medium and high energy consumption users. For these three types of users, the load profile tool discussed in section 2.5 is used to predict load profiles.

The appliances that are owned by the types of SHS user are presented in Table 2. The selection is based on the interviews with the experts and users. The usage patterns are determined based on the constructed timelines by SHS users. For the power rating of these appliances, appliances designed for the off-grid low-income market are selected from [16] and [4].

Table 2. Appliances that are included in future load profiles.

	2016	Low 2021	Medium 2021	High 2021
Light	X	X	X	X
Phone	X	X	X	X
Fan	X	X	X	X
TV	X	X	X	X
Audio system			X	X
Water kettle			X	X
Rice cooker			X	X
Iron			X	X
Refrigerator				X

Possessing more appliances and different usage patterns results in higher daily energy consumption for the medium and high future load profiles. The total daily energy consumption is 270 Wh/day for the low load profile, 975 Wh/day for the medium load profile and 1134 Wh/day for the high load profile. On days when the iron is used, 100 Wh more energy is consumed by the household. Fig. 11 displays the daily energy consumption per household for the future load profiles.

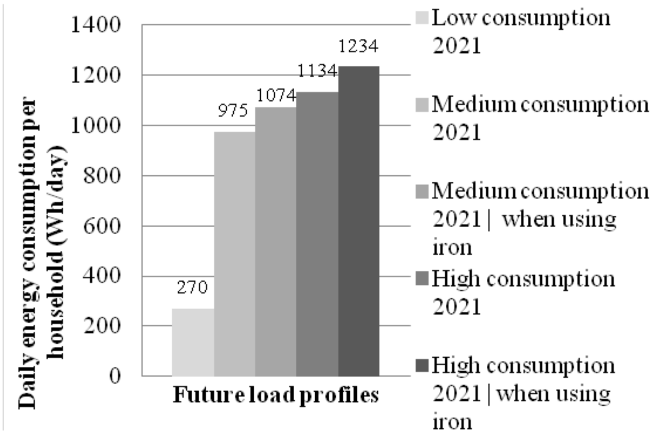

Fig. 11. Daily energy consumption per household of future load profiles (Wh per day).

Fig.12 to Fig.14 present the resulted load profiles for the low, medium and high energy consumption households, on a regular day. As participants indicated not to use the iron and audio system daily, it is decided to display the days when these appliances are not in use.

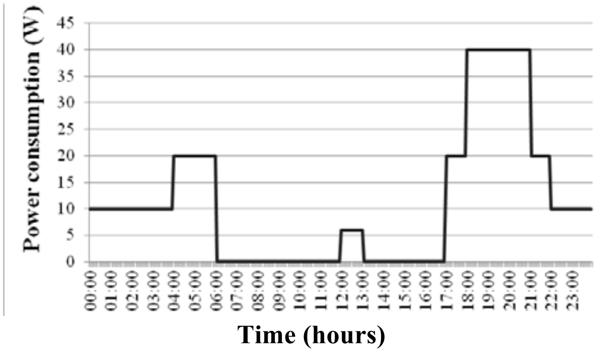

Fig. 12. Low energy consumption user load profile.

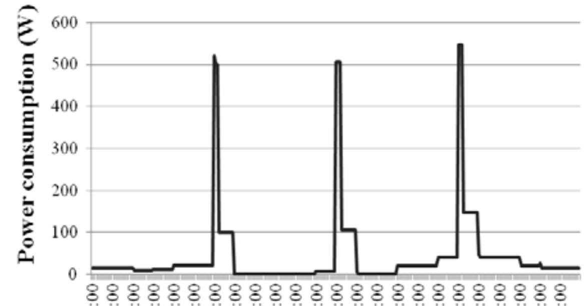

Fig. 13. Medium energy consumption user load profile.

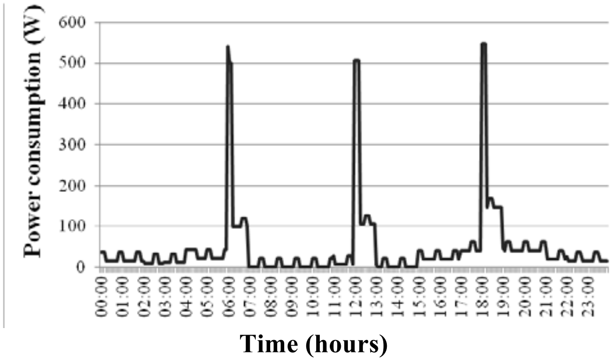

Fig. 14: High energy consumption user load profile.

The presented load profiles display a wide variety. Adding more appliances will have impact on the load profile. Some appliances will be used daily and at specific times (water kettle, rice cooker), while other appliances might only be used every now and then (audio system) or perhaps once a week (iron). Fridges will need to be continuously connected, while water kettles, irons and rice cookers will cause high peaks for a short time in the profiles.

3.4 Relation of future load profile with system performance

Fig. 15 simulates the estimated battery SOC of an SHS (200 Wp, 1200 Wh), corresponding with the future load profile of a high energy consumption user on a day with average irradiation in rural Cambodia. The high energy consumption causes deep discharges, especially in the early morning. Furthermore, the sudden high power peaks cause fast discharges.

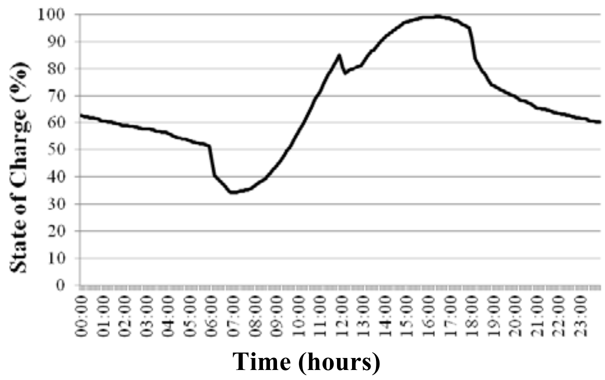

Fig. 15. Battery SOC of High energy consumption user load profile with a 200 Wp, 12V 100 Ah battery SHS, and assuming 5.5 Equivalent Sun Hours.

4 IMPLICATIONS ON THE ELECTRICAL SYSTEM DESIGN AND OUTLOOK (RQ 3)

The above presented findings on the current and future load profiles have a direct impact on the optimal electrical design and sizing of the system.

4.1 Battery size and LLP

The Loss of Load Probability (LLP) is a metric used to measure the performance of a power delivering system on the basis of its down time. It is defined as the ratio of the expected amount of time the system fails to deliver the demanded power to the total amount of time the system was designed to deliver power for. LLP is a value to measure when the user cannot be supplied by the demanded power, throughout the year. For example, an LLP of 5% indicates a 5% downtime throughout the year. Thus, from the user-perspective, a 0% LLP is desirable.

In this work, an SHS model was constructed with minutely PV irradiance (from Meteonorm tool [17]) and minutely load data as estimated from the field work with various sizes of PV and battery. Consequently, an annual simulation was run for an arbitrary calendar year, to evaluate the effect of system size on the LLP metric.

Fig. 14 shows the results of the SHS model simulation. LLP has been evaluated for 3 different possible Wp sizes for the PV, viz. 200, 300, and 400 Wp. Various battery sizes (up to 4 kWh) are considered for possible system combinations with each PV size and evaluated for their corresponding LLP values.

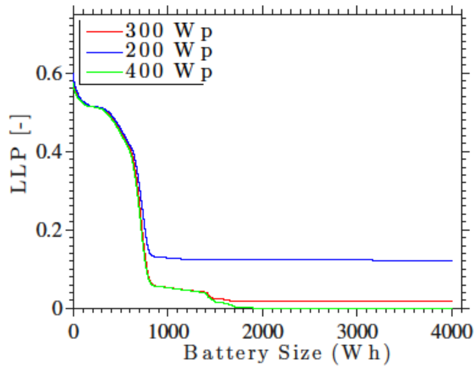

Fig. 16. LLP of a profile in 2021 with medium power consumption.

It can be seen that PV sizes of 200 Wp and 300 Wp are insufficient to reach 0 LLP regardless of the battery size (up to 4 kWh). However, a minimum battery size of 1.7 kWh with 400 Wp PV is enough to ensure a 0 LLP for the given load profile throughout the year.

Similarly, different load profiles in the future were examined and evaluated against the metric of LLP. This study helped in identifying the appropriate system size, i.e., the (Wp, kWh) needed so that the SHS meets the load demands of the future with 0 LLP.

4.2 Battery charge & discharge profile

The battery charge/discharge profile is a direct consequence of the correlation between the PV output (which in turn, is dependent on solar irradiance) and the load profile. Since there is a limit on the PV output-controllability, much of the onus of the characteristics of battery usage revolves largely around the load consumption patterns. For instance, a load profile having many peaks causes high C-rate discharges of the battery, which in turn reduces the lifetime of the battery.

The battery SOC and Depth of Discharge (DOD) also have a bearing on the system size and therefore the technical design of the system. As the higher average DODs lead to faster decay of the battery [2], a higher size may be preferable to ensure a higher average SOC and therefore a lower average DOD, therefore leading to a longer battery life. However, this also leads to larger upfront costs as the battery size increases.

4.3 Increasing consumption demand and diversity of appliances

While the current SHSs are intended to mainly power lights, mobile phones and a limited number of appliances (fan, TV), it is clear from the obtained results for future load profiles that not only will the power consumption increase several times, but also the appliances will be more diverse in power consumption and usage duration. This also follows from the energy ladder described in section 1. Furthermore, the choice of appliances may vary from one rural area to another.

High peak power appliances

The future load profiles show that the peak power consumption increases even more drastically than the average consumption due to the loads with high power peaks. This will have implications on the system design and sizing (PV Wp and battery kWh) as well as the technology choice (needs for storage with diverse energy density and cycling behaviour potentially resulting in a hybrid battery solution) to accommodate these peaks.

More efficient (DC) appliances

It should be noted that there are considerable recent developments in the field of high-efficiency DC appliances (fans, TVs, and refrigerators), which, while being more expensive, result in a reduction of the size of PV and battery due to their lower energy consumption. According to [10], this will result in a shift in the components cost distribution within the system, making the battery a smaller percentage of the total cost than it is today and the balance of system more dominant in percentage, which implies that the electronics including power electronics, communication, and control (especially with the trend of added functionalities of energy management, etc.) may become the higher cost factors and as such need to receive greater attention in the future. Additionally, the extent of the increasingly efficient DC options available in the market today, as catalogued extensively in [15], proves further the impetus that DC-based SHSs enjoy going forward.

SHS vendors/manufacturers also usually tend to oversize the system for this reason. As discussed previously, choosing efficient DC appliances does help in reducing the battery size due to lower power consumption. In other words, these efficient appliances can help in ensuring a longer-lasting battery for the same system size.

5 Discussion

The biggest barriers for the faster adoption of SHSs are lack of financial means and limited system size to meet electrical needs. The 100 Wp SHS is insufficient not only in powering more appliances, but also in powering the current range of appliances for a longer time. Stakeholders in the Cambodian SHS market indicated to work on larger SHSs, while appliances are becoming more efficient. However, this may not result in satisfying the exponentially growing future electricity needs. Financial limitations will remain an issue, but some users will be able to finance larger systems and more appliances as a result of higher income, subsidies or through loans or gifts.

From the technical standpoint, it can be said that the optimal battery size to be selected for an SHS should be based on a delicate balance between upfront costs, running costs, and the Loss of Load Probability (LLP) for the off-grid system [2]. Additionally, the choice of appliances dictates system usage due to power rating, efficiency, and usage duration of the appliances.

In general, a lower battery size for the same PV size in an SHS will lead to a potentially higher LLP. Additionally, it would also amount to higher DODs, and therefore to a faster degradation of the battery. On the other hand, a higher battery size will lead to much lower LLP as well as DODs, with the additional benefit of the battery lasting longer. However, this would come at a higher battery upfront cost.

The future SHS

An approach to answer the growing and diverse electrical needs could be a modular system, designed to be configurable for different areas and expendable as the consumption needs of a household grow in time. This would make sense both for the manufacturers as they can optimize the module for the best performance and costs due to the economies of scale and the user as they can expand the system over time and by doing so spread the financial burden over time as well.

Although it was not an explicit research goal and as such was not addressed in the field study, it can be assumed that looking broader than the consumptive use of energy in a household and enabling productive use (powering tools, lights, and appliances in small shops, etc) of energy in a household or larger level could further improve lives in target communities. This could again be enabled by a scalable, modular SHS.

This stresses the importance of future innovations in the SHS market. The authors earnestly believe that impactful breakthroughs in this field can only be achieved my multidisciplinary collaborations between researchers in the field, local (community-level) stakeholders, electrical engineers, product designers, and policy makers, among others.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Delft Global Initiative (DGI) of TU Delft for financially supporting the fieldwork as well as the larger project of which the works described in this paper are a part of. The authors also thank Bunheng Souy for his instrumental support in local user surveys in rural Cambodia and Justin Kane for helping out with setting up the simulation game for the field research. Employees of Kamworks in Cambodia are gratefully acknowledged for their support throughout the project.

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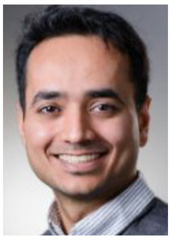

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