

Simple Measurement of the Electricity Demand in Developing Countries

Method and Exemplary Measurement Results for Designing Off-Grid Systems based on the Example of Nepal

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Abstract — For rural and remote electrification in developing countries, the proven concept of off-grid power plants is the way to go as grid extension is often difficult due to several reasons. Especially for properly designing small-scale stand-alone energy systems, load profiles are essential and required data. However, in today's research, load is often modelled by simulation-generated profiles or simply empirically estimated instead of being validated through measurements.

As the current literature is lacking such data, the present study's objective is to present a method on how to measure the electricity demand of consumers through recording load time series using simple, cost-efficient and highly portable equipment. In this way, simulation-based data can be tweaked and validated. The used hardware only consists of two handheld digital multimeters, one AC current clamp adapter and a terminal device that allows to log and save the measured data.

This method was tested in Manang Valley, a rural region in the Himalayas of Nepal. 24-hour load measurements of two households, two schools and three basic hotels were performed. During application afield, the method proved to be suitable. The measurement results show patterns that allow drawing generalised conclusions on the electricity demand in Nepal's rural and remote areas. Additionally, those conclusions may be transferable to other developing countries.

Keywords — *load measurement; load profiles; electricity demand; off-grid systems; rural electrification; developing countries; Nepal*

I. INTRODUCTION

While access to electricity appears axiomatic to the majority of the world's population, still 1.1 billion people are considered not electrified [1]. Especially in Sub-Saharan Africa and developing Asia, people are limited to more ordinary energy sources like firewood or fossil fuels [2]. Both options come with

massive both local and global problems like deforestation and greenhouse gas emission.

In Nepal, the electrification rate was estimated to account for nearly 80% in 2016 [1], [3]. However, the nation's rural regions suffer from lower rates [3] including the often poor [4] and remote Himalayan regions in the north. Due to complex terrain and sparse population, the extension of the national grid to those areas is not cost-effective. Especially in developing countries these are the reasons for a large number of remote areas still not being electrified [5], [6].

Despite the majority of the, mostly hydropower-generated, electricity in Nepal being produced in the Himalayas, the region suffers from power shortage as the electricity is transmitted to the national grid, primarily existing in the flatter south [7].

Although being proven and implemented for decades [8], stand-alone and off-grid hydropower solutions need to be promoted more than ever to push electrification rates forward. With such systems, the mountain population can directly and independently benefit from their own local and surplus hydropower resources of 179 TWh/a of technical potential nationwide [9].

For the proper design of off-grid systems, detailed information about the electricity consumption patterns of the individual consumers are needed. Load profiles being the power demand time series over a certain period thereby represent the most valuable data. From these, essential quantities for the design process can be read, including maximum load and total consumed energy per unit time, relevant for the rated capacity of a system as well as for the dimensioning of a potential energy storage, respectively.

The review paper by Mandelli et al. [10] on off-grid energy systems in developing countries gives no indications on available measured load profiles in today's literature. Therefore, it can be assumed that stand-alone systems are often

designed solely based on survey data or rough empirical estimations processed by simulation tools. The validity of those methods and consequently of the design process as a whole can be drastically improved by proving the available data at already electrified regions through consumption measurements.

However, as the cost-efficiency of off-grid systems is a crucial factor, the expenditures for such validation measurements should be kept as low as possible while achieving an acceptable data quality. More and more, the low-tech approach is followed to design stand-alone systems for developing countries with fragile economies that are eminently cost-efficient yet robust. But why not transfer the low-tech and low-cost proceeding to a measurement technique?

Consequently, the aim of this study was to develop and test a method that allows to collect electricity consumption data and which is low-cost, simple and convenient at the same time. This method has the potential to play an important role in a more holistic low-cost and low-tech approach of supplying remote areas in developing countries with electricity generated by off-grid systems.

II. METHOD

A. Foundations and Requirements

The most essential datum for designing off-grid systems is the load time series. The longer the time series, the more accurate the system can be designed. In general, consumption patterns can be estimated to fluctuate not only daily but also weekly (weekdays vs. weekend) and seasonally. Therefore, load should be measured for several days to minimise the effects of potential one-time events regarding consumption and, thus, to better allow for generalised conclusions. Weekdays as well as weekends should be logged. However, a certain trade-off needs to be achieved between effort and quantity of the data to be collected.

To fulfil the low-tech approach and the application in developing countries' remote areas as well as a certain standard of data quality, the method should meet the following criteria:

- *Simplicity* (common equipment should be used)
- *Cost-efficiency*
- *Self-sufficient power supply* (for potential power cuts)
- *Ability to log and save data*
- *Long term measurement suitability* (without the necessity of human observation)
- *Sufficient data quality*

However, data quality does not need to be high-class, as in the design process some capacity buffer will be taken into account anyways.

B. Method Description

To generate the load time series $P(t)$, load is not measured directly as this would require expensive equipment. Instead, supply voltage $V(t)$ and consumer's current $I(t)$ are measured and logged individually. A recording interval of 10 s, 30 s or 60 s may be suitable. After collecting these data separately, they are multiplied in a post-processing step. In this way, the load time series is created by using Equation (1).

$$P(t) = V(t) \cdot I(t) \quad (1)$$

When recording load time series of a consumer supplied by a power source with approximately constant voltage $V(t) = V$, solely measuring the consumer's current $I(t)$ seems sufficient. However, in developing countries, supplied voltage often is by far not constant. Fig. 1 shows the voltage time series of Sabje hydropower station measured in Braga, Manang in Nepal on 20/10/2016. The drop in voltage in the evening, when load is high, is apparent in particular.

Supply voltage is measured using a digital multimeter (DMM) with an USB-interface. It can be simply connected in parallel to the voltage source to be measured. Consumer's current is measured using a AC current clamp adapter connected to a second DMM. The current clamp needs to be applied at the main line of the single-phased main box of the consumer to be measured. Thereby, only one conductor (phase or neutral) is to be covered by the current clamp.

Both multimeters are connected to the same terminal device, e.g. a laptop. Fig. 2 provides an overview of the scheme of equipment used in this method. See Fig. 3 for an example of a low-cost AC current clamp adapter and a DMM.

It is advised to use AC-only current clamp adapters instead of combined AC/DC ones. AC-only devices utilise the transformer principle instead of the Hall effect and therefore allow for a significantly lower power consumption and consequently longer battery life.

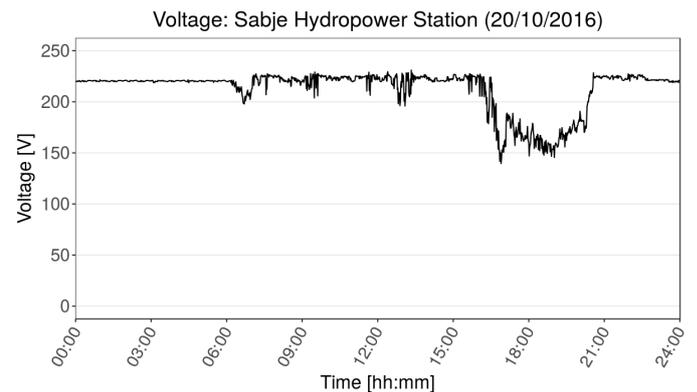


Fig. 1. Voltage at a power connection supplied by Sabje hydropower station measured on 20/10/2016

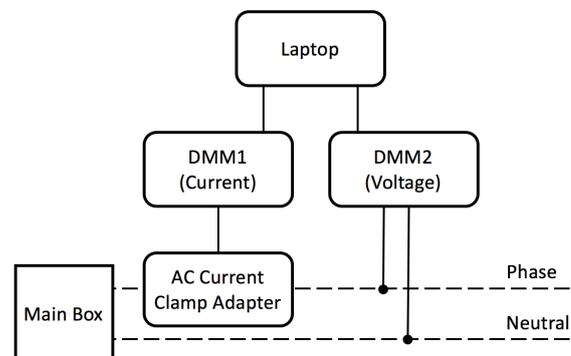


Fig. 2. Scheme of the equipment used



Fig. 3. AC current clamp adapter (left) and DMM (right). Source: [11]

Most of the multimeters capable of USB data recording come with a free software to log and save the measured data. Following, data can be exported, for example, as an Excel spreadsheet. However, note that most of the software only run on Windows operating systems.

C. Cost of the Equipment

Cost-efficiency was declared one of the major requirements of the method. In Table 1 the total costs of the setup are listed. The terminal device was chosen not to be listed here, as it is often easily available to the user. Moreover, any extra cables (to increase the possible distance between terminal device, DMM and current clamp) are not listed, either.

D. Field Experience and Limitations of the Method

Only ohmic loads can be measured with this method in an accurate way. However, in terms of data quality, this was proven sufficient in field tests. Furthermore, using the above-mentioned set of equipment, only single phased main boxes are suitable for load measurements. At least in Nepal, most of the consumers connected to stand-alone grids show a single-phased connection.

When tested, the battery life of the equipment was minimum two weeks.

It is recommended to run some pre-tests before applying this method, as the software of some DMM models can tend to be unreliable and may therefore not be suitable for measurements exceeding 24 hours. Additionally, it should be clarified in pre-tests how two DMMs can be used at one terminal device. Some DMMs already have plug-and-play USB interfaces and come with a software that allows to use two DMMs at one terminal device.

Current clamps have shown to be very handy and safe in the field when recording load profiles. They allow to measure the current time series without opening the electrical circuit of the consumer. This is both safe for the user and convenient for the consumer to be measured. Consequently, the chance of a test subject agreeing to take part in the study is likely to be higher as the power connection remains untouched while conducting the measurements.

TABLE I. COST OF THE MEASUREMENT SETUP

Item	Exemplary Model	Total Cost (Quantity)
DMM	UNI-T UT61B	120\$ (2)
Current Clamp Adapter	Voltcraft VC-510	40\$ (1)

To verify the measurements of the current clamp adapter / DMM unit, an additional current clamp with display can be carried. In this way, the right wire of the main box can be chosen more easily.

Eventually, the accuracy and calibration of the measurement setup should be tested in the laboratory before going afield.

III. TEST DESIGN

Fieldwork was conducted from 14/10/2016 to 26/10/2016 in Manang Valley, located in Manang District in the Annapurna Region of Nepal. The method was tested at the following test subjects:

- two domestic households
- three small and basic hotels (so-called lodges)
- two schools

As the available time for fieldwork was limited, only a 24-hour period per test subject was chosen for measurements. Therefore, this study is mainly a proof-of-concept of the proposed measurement method. However, it was assumed that even this very short period of data recording might deliver valuable results. The measurements were conducted from midnight to midnight to gain data of one entire day. Data was logged every 60 seconds, as this was assumed appropriate for the study's use case. Consequently, load was measured at 1440 measurement points evenly distributed over a 24-hour period at each test subject.

Complementary to the measurements, a combined survey was conducted to collect additional information about the test subjects' general electricity and energy consumption pattern. This approach is advised to follow because it allows for the recorded load profiles to be put into perspective. However, in this study the survey results are only included rudimentarily where completing the measurement results.

IV. RESULTS

In this paper, only the results of the two domestic household test subjects are included, as the authors consider them as most valuable. Furthermore, residential energy demand dominates with a share of 84.05% of the nation's total primary energy consumption [12].

In general, the households are equipped with very basic electrical devices compared to western ways of life. Therefore, also the power consumption ranks on a comparably low level. Both households are supplied by the island grid of Sabje hydropower station. With a net head of 35 m and a discharge rate of 380 l/s, its capacity is around 80 kW. Together with a second 100 kW hydropower system, the plant supplies the whole Manang Valley with electricity and is often overloaded during peak times in the morning and evening.

A. Household 1 (H1)

The measurements at H1 were conducted on 21/10/2016. Family members include the two parents and their adult son. They reside in a traditional natural material house in the village of Braga at an altitude of 3470 m. They own five types of electrical devices: A rice cooker, a television with satellite receiver, mobile phones and light bulbs.

The measured mean load was 26.4 W, resulting in a total power consumption of 633.5 Wh/d. The peak load was 65.8 W. Comparing the measured power consumption to the main box meter display (0.63 kWh/d), an accordance of 99% is calculated. The load profile is shown in Fig. 4, the load duration curve in Fig. 5. Other than electricity, approximately 4000 kg of firewood and 15 kg of LPG are consumed in the household per year.

B. Household 2 (H2)

Measurements at H2 were performed on 22/10/2016. The household consists of the two parents and their adult son living in a traditional house in Braga, comparable to H1. They have six different types of electrical devices: A rice cooker, a blender, a water boiling jug, a radio, mobile phones and light bulbs.

The mean load was 42.0 W, yielding in 1010 Wh/d of total power consumption. The peak load was 1740 W. An accordance of 89% is observed when comparing the measured value with the main box meter readings (1.13 kWh/d). Fig. 6 and Fig. 7 provide the load profile and load duration curve, respectively. In addition, the household consumes around 4000 kg of firewood and 15 kg of LPG per year.

V. DISCUSSION

A. Household 1 (H1)

In general, the electricity consumption of H1 can be classified as rather low with only around 0.63 kWh/d. This value matches quite well the reported long-time average power consumption of roughly 0.67 kWh/d. No medium or high-power devices were in use on the day of measurement.

The peak load remained below 100 W as only the television (low-power LED computer screen) with its receiver, compact fluorescent light (CFL) bulbs, and mobile phones were in use. No highly consumptive heat generating appliances like heating or cooking devices were run.

This is the reason why peak load remained below 100 W. The load profile (see Fig. 4) shows three peak load sections (07:15 – 08:30, 09:15 – 13:45 & 17:45 – 21:00) resulting from television use. The continuous night time load around 13 W can be traced to patio safety lighting. The load duration curve can be classified considerably balanced (see Fig. 5).

B. Household 2 (H2)

Electricity consumption of H2 (1010 Wh/d) is rather low and comparable to H1. However, one major difference of the load profiles of the two households are the peak load values. Due to the use of an electrical blender (350 W capacity) and a water boiling jug (1.65 kW), several medium and high-power peaks occurred with a maximum peak load of 1740 W (see Fig. 6). The measured value exceeds the reported long-term average consumption of 0.67 – 0.83 kWh/d slightly.

Three peaks exceed the ordinate axis as the scale was adjusted in order to highlight the pattern in the low-power region. The first peak (371 W; 07:20) represents blender use for preparing traditional butter tea in the morning. The second (1694 W; 09:00) and third peak (1165 W; 16:45) result from utilising the water boiling jug for preparing black tea.

The distribution of load values varies strongly due to the strong contrast of peak load and residual low load level (see Fig. 7).

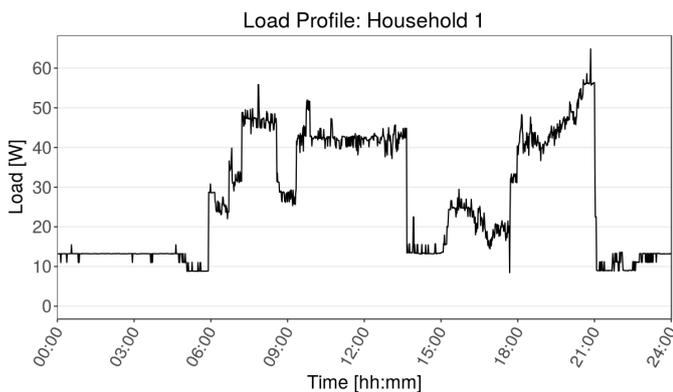


Fig. 4. Load Profile: Household 1

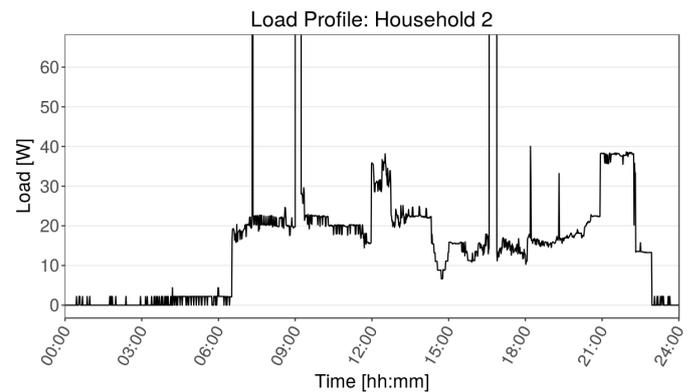


Fig. 6. Load Profile: Household 2

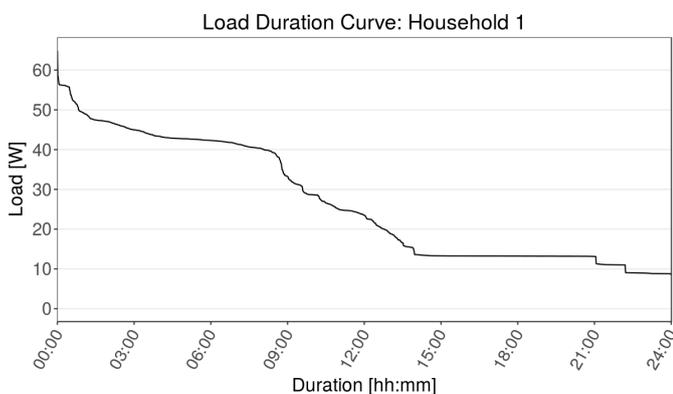


Fig. 5. Load Duration Curve: Household 1

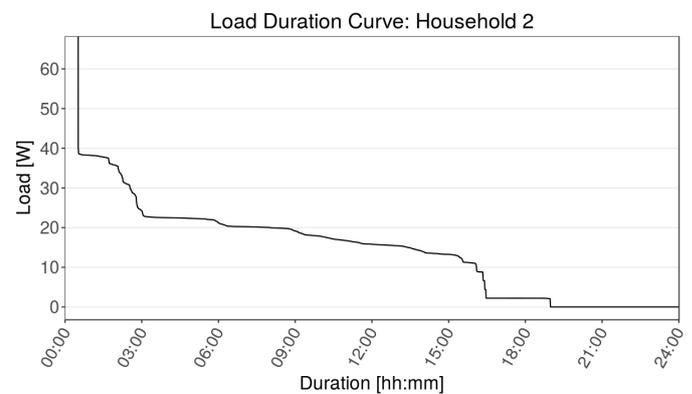


Fig. 7. Load Duration Curve: Household 2

C. Conclusions

Consumed electricity per day ranks roughly in the same magnitude at both households (633.5 and 1010 Wh/d). However, peak load values differ significantly (65.8 W and 1740 W). This is due to H1 only utilising electricity for lighting, communication (mobile phones) and information/entertainment (television) during measurements. H2 uses electricity also for cooking appliances such as a blender and a water boiling jug. Those devices are medium- and high-power, respectively, and therefore result in significantly higher peak load values. Thus, it is important to record both consumed electricity per unit time and maximum load values. Only reading the main box meter is not adequate.

Apart from the three slender peaks, power consumption did not exceed 40 W at H2. This is why the measured consumed electricity per day is comparably low at both residential test subjects.

In general, it can be concluded that for lighting, communication and information/entertainment appliances, power consumption does not exceed a certain level. If an average sized household is supplied with an electricity connection of e.g. 150 W capacity, all such devices can be easily powered. However, when electricity is also used for cooking or heating, a higher capacity per household has to be granted, e.g. 1 – 1.5 kW.

D. Practical Implications

Depending on the load profile, off-grid systems have to be designed tailored to their specific application. In the case of small-scale and stand-alone hydropower systems without energy storage for Nepal, a well-balanced load duration curve without any major peaks is desirable, as then the utilisation factor of the system is high and therefore the specific electricity generation costs are low.

Analysing both duration curves, it is noticeable that when not using electricity for cooking appliances, load is considerably balanced. Thus, when estimating 150 W per household for lighting, communication and information/entertainment purposes, a 450 W pico hydropower system without energy storage is capable of supplying three households.

Adding a battery storage to the system, also short-term high-power peaks for cooking appliances, as they were observed at H2, can be covered. Thereby, the residual electricity during the night resulting from low baseload could be used to charge the battery storage. As H2 only showed very slender high-power peaks, three households sharing one battery storage / inverter unit for cooking appliances could reduce the specific system costs.

VI. CONCLUSION & OUTLOOK

In this study, it has been proven that the applied method for collecting load data delivers decent results considering its cost-efficiency and ease of application afield. It is simple, effortless and safe to handle and the data quality is highly adequate for

application-oriented purpose. Through recording load time series, the method covers maximum load values and consumed electricity per unit time, both being essential data for the design of off-grid systems. Combining the load time series gained in the presented way with questionnaire data and simulation tools, e.g. Monte Carlo simulations, the load profiles can be adapted to changing circumstances, such as additional devices and seasonal consumption fluctuations. Therefore, it is advised to include load measurements into the design process of off-grid systems whenever possible to enhance its flexibility and lastly its validity.

Most of the equipment is considerably practical and cost-effective. However, when using a laptop as terminal device, the total costs, weight and probability of theft of the equipment during the measurements rises strongly. Recent tests have shown, that it is also feasible to use tablet devices or single-board computers, e.g. a Raspberry Pi or Arduino Nano, as terminal device. In this way, the total setup becomes even more affordable and lightweight. Using this configuration, it is easily possible to take several complete measurement setups afield to measure at various test subjects at the same time. This makes the presented method an even more powerful, yet practical and simple tool to contribute to improving the design process of off-grid energy systems.

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