SolaFin2Go field trials in Sub-Saharan Africa: Off-grid village electrification and hot water supply

Adrian Pugsley, Aggelos Zacharopoulos,
Mervyn Smyth, Dominic McLarnon, Jayanta Mondol

Ulster University, Centre for Sustainable Technologies
Jordanstown, Northern Ireland BT37 0QB
+44 (0) 28 9036 6907
a.pugsley@ulster.ac.uk
www.cst.ulster.ac.uk

Abstract

More than 80% of Africa's electricity is fossil fuel generated leading to climate change effects which disproportionately affect the sub-Saharan region where 588 million people live without modern energy access. Lack of basic services such as lighting; motive power; and communications/media; compounds poverty by limiting educational opportunity; constraining ability to generate income; and leaving populations vulnerable to crime at night. Millions of low-income households burn wood, charcoal, agricultural residues or animal dung for cooking and boiling water, leading to deforestation, soil degradation and air pollution as well as physical burden and adverse health effects which disproportionately affect women. Electricity grid expansion or local mini-grid development can be cost effective in densely populated areas where industrial energy demand is present, but challenging characteristics such as low population density; low incomes; low energy demands; and difficult topography makes grid infrastructure disproportionately expensive in rural areas.

SolaFin2Go stand-alone solar-storage systems provide affordable access to both electricity and hot water for off-grid households, businesses and community facilities through improved pay-as-you-go business models enabled by an innovative FinTech platform delivered through Mobile, Cloud and Blockchain. This paper tells the story of the project from equipment design and selection through to field trial data analysis and summarises the key impacts, outcomes and scientific knowledge generated by the project. The paper explains how the ongoing field trial in Botswana will form a regional technology showcase and act as an enabling environment for developing new off-grid energy access infrastructure approaches and testing innovative prosumer energy trading service delivery models.

1 Needs analysis

Access to clean, secure, reliable and safe energy services is essential for fighting poverty and achieving economic development in developing countries (Muhumuza et al., 2018). The SolaFin2Go project aims to facilitate “entry level” energy access in Botswana where the national electrification rate is just 61% (World Bank, 2019) and most rural households rely on firewood for cooking and hot water production. Entry-level energy access is defined by the IEA (2017) as *"…having reliable and affordable access to both clean cooking facilities and to electricity… enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average”*. Typical Sub-Saharan African domestic energy consumption reported in the literature is summarized in Figure 1.

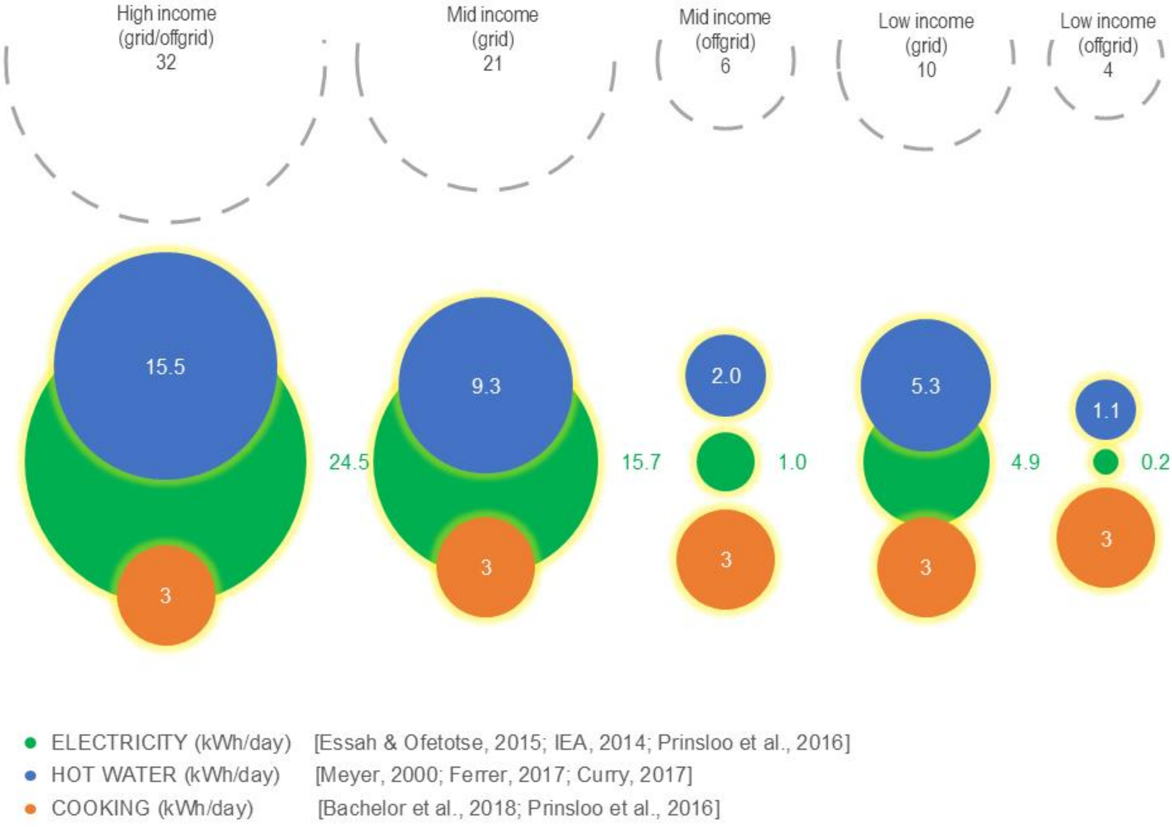


Figure 1: Typical household energy consumption in Sub-Saharan African households

Jamataka village (GPS reference -21.08, 27.14) is a socio-economically diverse medium sized rural village (~750 residents) with a local primary school, Kgotla meeting house, and a few small shops. Photographs showing the village layout, school buildings and a teachers house are shown on Figure 2. Electricity and hot water consumption in the village is limited by a combination of unavailability and unaffordability. Prior to installing SolaFin2Go prototypes, the primary school relied entirely on natural lighting, passive ventilation, and a 4kW petrol generator used occasionally to power a photocopier. Whilst the school has several computers these were rarely used owing to excessive fuel costs. Household electricity consumption in Jamataka typically relates to mobile phones (charged at local shops by solar

PV or petrol generator), torches and radios (powered by disposable batteries) and solar lanterns. Some wealthier residents have small PV systems and petrol generators and but the nearest fuel supply is more than 20km away. Outdoor wood fires are used for cooking and hot water production throughout the village, although the school kitchen and some wealthier homes use liquid petroleum gas on occasion. The village is served by a municipal mains water supply but shortages occur during dry season.

A site survey suggested that the teachers houses in Jamataka could reasonably be characterised as “low-mid income off-grid”. Whilst originally built with lighting & power circuits and hot water plumbing, the houses had no electricity supply or water boilers fitted and residents had few existing appliances. SolaFin2Go prototypes were therefore sized to provide 800Wh/day of electricity and 25L/day hot water, consistent with the upper bound of the World Bank’s “Tier 2” definition for “entry level” access (Craine et al., 2014). The project provided new low energy light bulbs (CFL and LED), a digital television and satellite receiver, and a small ventilation fan for the test house and a powerful LED security night-light for the school.

Figure 2: Proposed field trial: a) Village layout; b) Teacher’s house; c) Main school building.

2 Design concept

The concept (Figure 3) underpinning SolaFin2Go is to combine pay-as-you-go (PAYG) solar PV and battery storage with a novel heat retaining integrated collector-storage solar water to provide an affordable stand-alone energy access solution for off-grid communities. The novel

“SolaCatcher” water heater employs patented liquid-vapour thermal diode technology (Smyth, M., 2015) developed at Ulster University (Pugsley et al., 2016; Smyth et al., 2017a&b; Souliotis et al., 2017; Muhumuza et al., 2019). Owing to dramatic PV cell cost reductions and global market commoditisation in recent years, it is now more cost-effective to use standard sized (60 or 72 cell) framed PV modules for small off-grid solar power systems, rather than the traditional approach of using specialist modules sized for a specific demand and voltage. Battery technology advances have begun to see a shift from traditional lead-acid towards compact lithium-ion solutions which have long maintenance-free lifespans. However, whilst lithium-ion is used in some small solar-home-systems, lead-acid technologies remain incumbent for larger systems in sub-Saharan Africa owing to their universal availability and significantly lower initial capital costs.

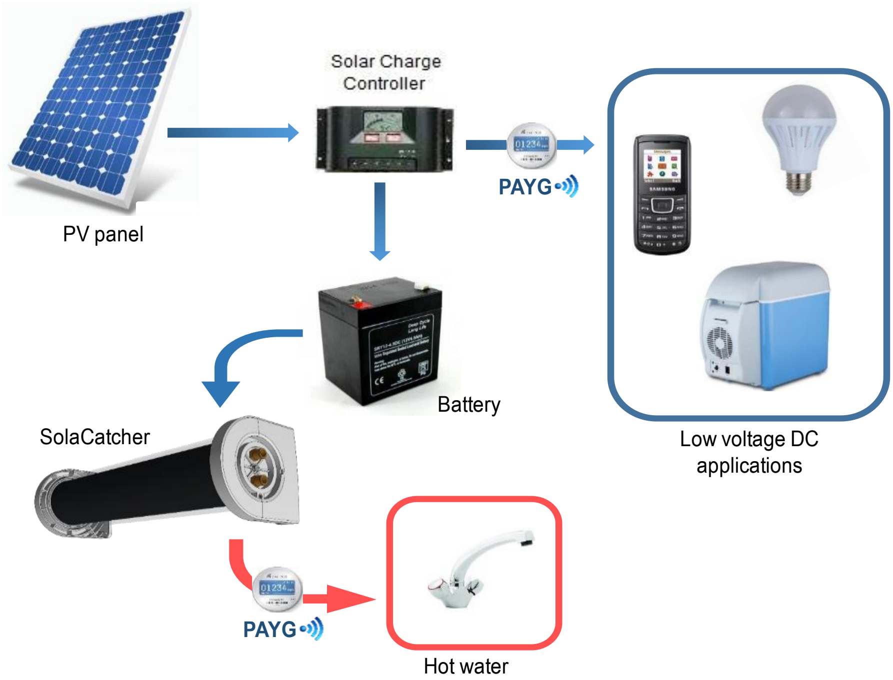
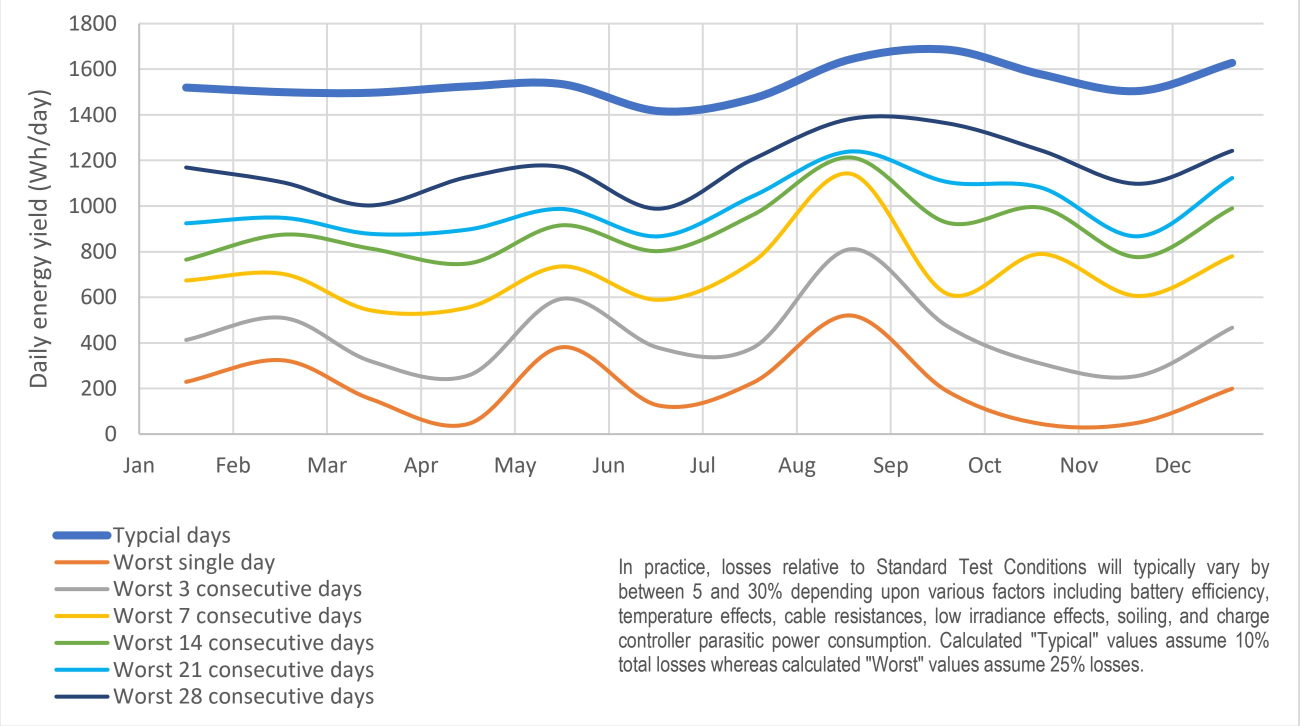


Figure 3: SolaFin2Go energy generation, storage and supply concepts

Using 22-year monthly averaged solar radiation data for nearby Francistown, Botswana (NASA, 2018) calculations were performed to estimate the daily energy yields from an equator-facing, latitude-angle tilted, 60-cell PV module, and a thermal diode solar water heater with 88 L/m^2 volume to surface area ratio. Electrical results shown on Figure 4 indicate typical sunny day yields of >1400Wh/day but only ~50Wh/day during periods of prolonged cloudy weather (often occurring during April, June, October and November) suggesting that ~1500Wh of battery storage is needed. Corresponding hot water calculations based on SolaCatcher prototype laboratory test results suggest heat collection of ~35 Wh/L/day. Assuming tank temperatures at dawn roughly equal to ambient temperature (~25°C) this would result in typical late afternoon tank temperatures ~55°C which is sufficient to supply domestic hot water at ~45°C provided that the tank volume is larger than the anticipated daily draw-off volume. Based on this analysis, a SolaFin2Go prototype design was developed with the aim of supplying 12VDC electricity and hot water through the existing wiring and plumbing at the houses. The core components of each prototype unit included:

- A photovoltaic module (60-cell polycrystalline silicon) rated 280W_p / 31V_{mp}.
- A valve regulated lead-acid AGM battery rated 205Ah / 12V.
- A solar charge controller (MPPT with 3-stage charging) rated 75V / 20A.
- A SolaCatcher solar water heater with integrated 28L storage tank.
- Battery monitor and relay enabling use surplus electricity for providing supplementary heat to the storage tank via a 100W immersion heater.
- Temperature sensors, flow meters, and LoRaWAN radio data transmitters.

One stand-alone prototype (see Figures 5b and 6) was installed at one of the teachers houses (solar collectors on north facing 20° sloped roof) and two interconnected prototypes were installed at the school office (solar collectors on opposing east and west facing 20° sloped roofs, see Figure 7). The school system was arranged with the two solar water heaters plumbed in series and the two batteries were wired in parallel. New plumbing was installed to provide a hot water service for the school kitchen and the electrical output was routed through a 2kW / 230VAC pure sinewave inverter to enable operation of the photocopier, computers and printer as well as LoRaWAN-to-GPRS communications equipment facilitating remote data monitoring.



In practice, losses relative to Standard Test Conditions will typically vary by between 5 and 30% depending upon various factors including battery efficiency, temperature effects, cable resistances, low irradiance effects, soiling, and charge controller parasitic power consumption. Calculated "Typical" values assume 10% total losses whereas calculated "Worst" values assume 25% losses.

Figure 4: Electricity yields from a 280Wp photovoltaic module (equator facing & latitude-tilted) in Francistown, Botswana

Figure 5: Comparison between proposed design (A: left) and prototype installed at teacher's house (B: right)

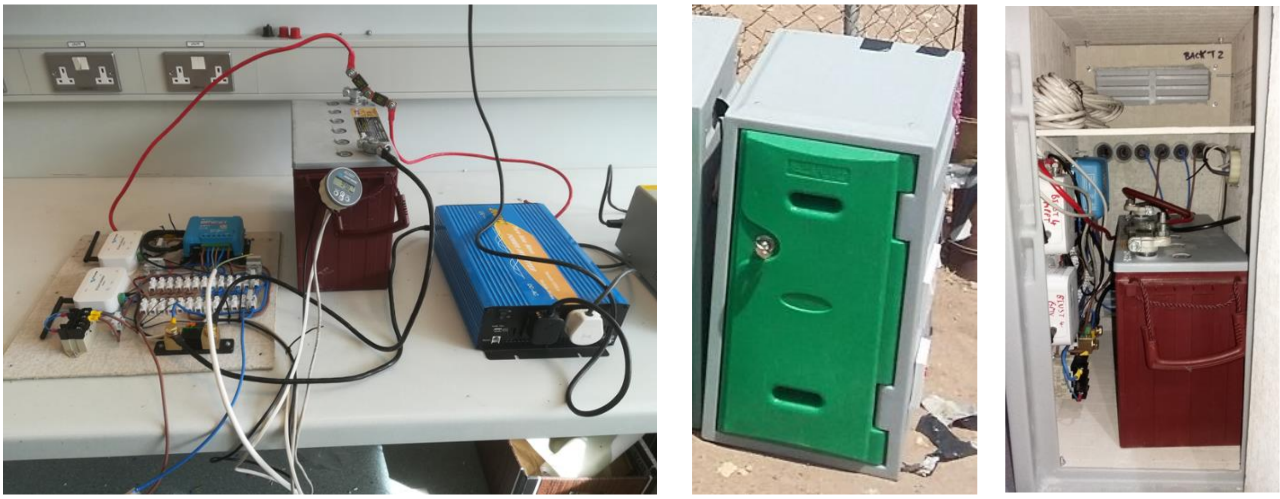


Figure 6: Battery, charger, monitor, relay, transmitters and inverter during bench tests (A: left) and installed in enclosure (B: right)

Figure 7: Rooftop installation at Jamataka primary school

3 Field trials

Field trials at the school and teachers house commenced in October 2018 and were ongoing at time of writing (March 2019). Realtime electrical data for both systems are collected every hour including PV & battery voltages, currents, and charge statuses. Realtime hot water data including tank, flow, & ambient temperatures and flow volumes are collected every 10 minutes along with solar irradiance incident on the east facing school roof. Immersion heaters are currently disabled during collection of baseline data.

Teachers house electrical data (Figure 8) illustrates how PV power (yellow, +ve) was utilised for battery charging (green dashed) and supplying user loads (blue, -ve) over a one-week period in October. User demands were highest during early morning (~40W) and evening (~60W) when loads included lights and television. Daytime demand (~10W) was largely due to mobile phones and a satellite decoder on standby. Very low overnight loads typically fell steadily from 5W at 10pm to zero by 3am, consistent with phone charging. Based on the dataset to date, average overall consumption is 350±130Wh from dawn-to-dusk and 210±90Wh from dusk-to-dawn (tolerances indicate one standard deviation). Total diurnal load has increased steadily from ~450Wh/day in October to ~650Wh/day in March with extremes ranging between 335Wh/day and 895Wh/day, consistent with the 800Wh/day design intent. Data indicates the battery is somewhat oversized (partly due to local market availability) with recorded state-of-charge (orange line on Figure 8) rarely falling <90% and having never yet fallen <78%. The PV module typically recharges the battery fully within 5 hours after dawn suggesting significant surplus power availability at midday and during afternoons. Users typically only consume ~ 34% of the potential energy yield available from the PV module. Average electrical system and battery charging/discharging round-trip efficiency (ie the ratio of energy output for consumption versus PV energy input) is ~79%, consistent with expected values for this type of system (Laboret & Villoz, 2010).

Teachers house hot water data (Figure 9) illustrates how tank temperature (red) relates to irradiance (yellow) and ambient temperature (green) over the same one-week period, where hot water consumption varied between 13 and 30L/day. The period began with a cool tank (21°C) due to a large water draw-off the preceding evening following an extended period of several predominantly cloudy days. The relatively low irradiance level on the first day (3.7 kWh/m^2) due to intermittent cloudy conditions provided a small lift in tank temperature which reaches its maximum in late afternoon (35°C) before cooling again overnight. Tank temperatures rose steadily during the following six days as a result of increasing irradiance levels which rose from 4.3 kWh/m^2 on the second day up to 7.0 kWh/m^2 on the fifth and subsequent days. On these later high irradiance days the tank temperatures exhibited reasonably steady diurnal variations from ~32°C at dawn to ~55°C during late afternoon, approximately 10-15°C above the ambient temperature. Hot water delivery temperatures were typically ~45°C during the afternoon and evening on typical sunny days, falling to ~30°C by early morning and on cloudy days. Sunny day collection efficiencies were ~43% and overnight heat loss coefficients were typically 1.3 W/m^{2}K.

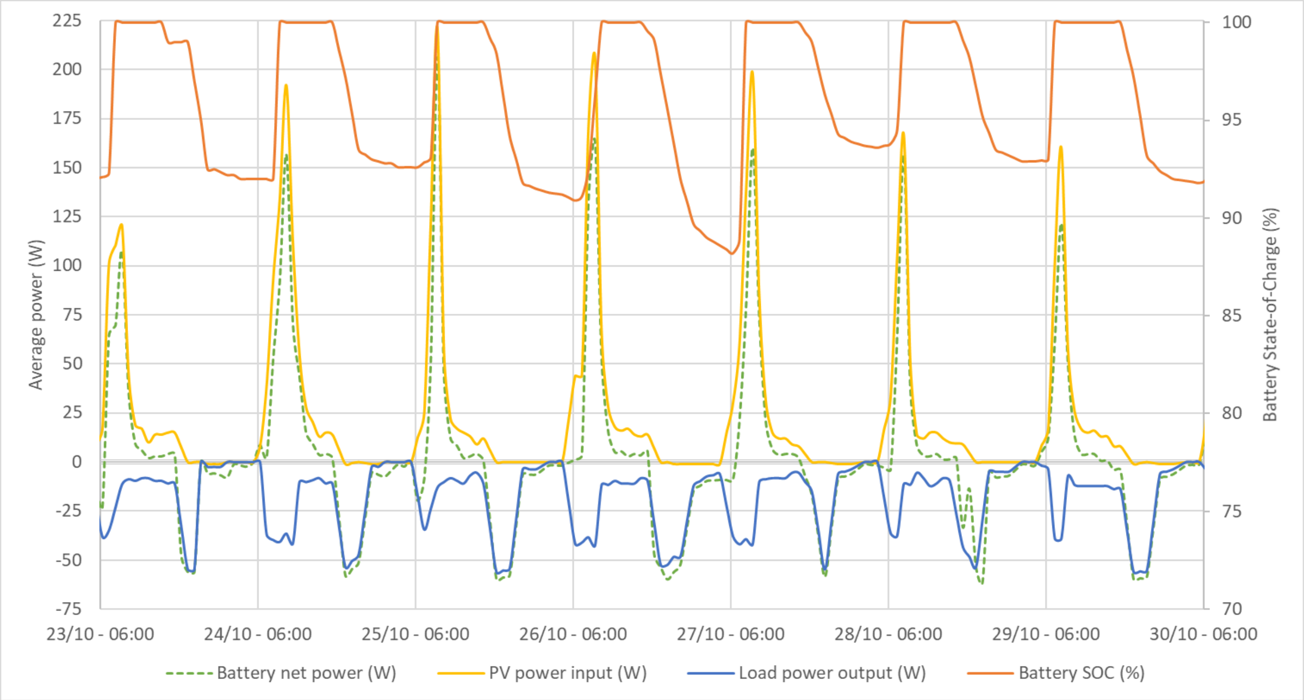


Figure 8: Teacher's House photovoltaic system data for 7 days in October 2018

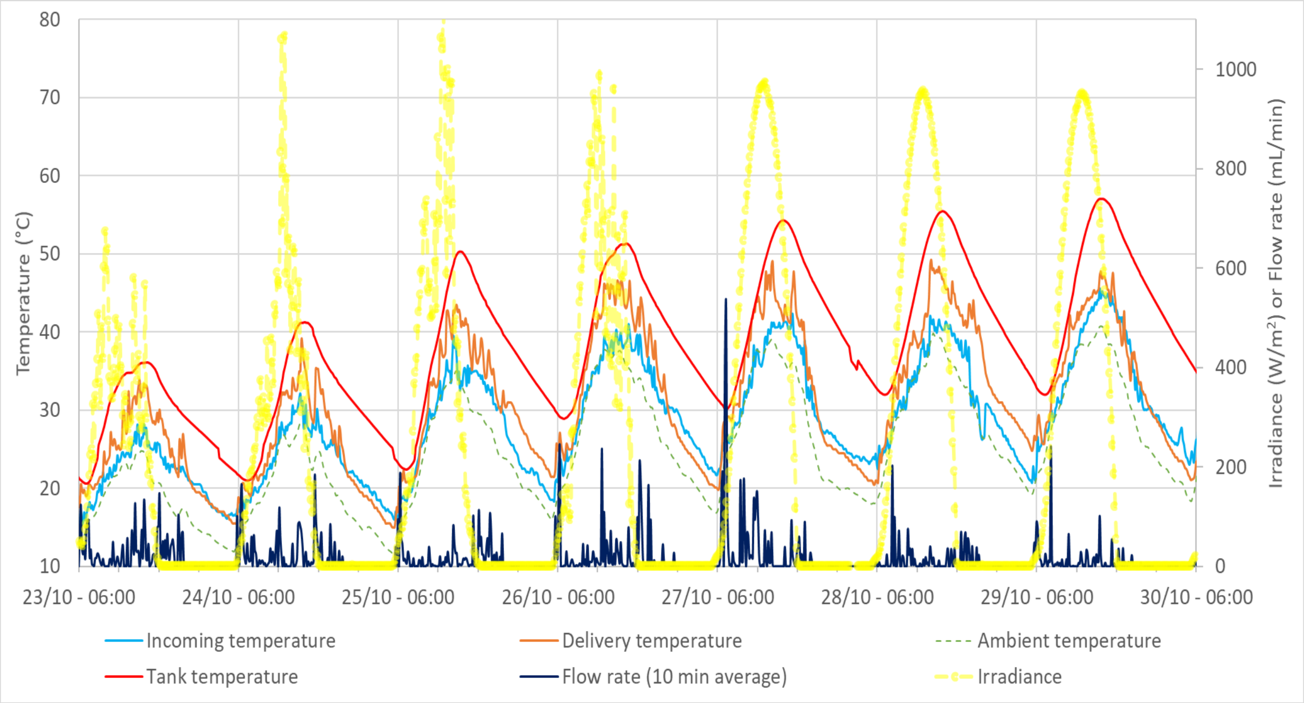


Figure 9: Teacher's House solar hot water system data for 7 days in October 2018

Cumulative consumption of 230VAC electricity by office equipment the during 98 working days between 10 October 2018 and 10 March 2019 was 48 kWh, equivalent to ~500 Wh/day on average, although usage was highly intermittent with peaks up to ~2000 Wh/day. Self-consumption for the inverter and communications equipment (GPRS internet router, LoRaWAN gateway, UPS unit) averaged 3.2A at 12V, equivalent to 900 Wh/day, bringing typical total consumption to 1400 Wh/day, marginally below design intent of 2 x 800Wh/day. The school rarely uses the available hot water, but data indicates sunny days peak tank temperatures of 69°C for the east facing unit and 74°C for the west facing unit with overnight stored water temperatures rarely falling below 35°C. Typical sunny day collection efficiencies were ~54% for west facing and ~52% for east facing. These collection efficiencies are notably higher than achieved by the equator (north) facing Teachers house unit due to early morning and late afternoon insolation being boosted by the planar reflectors located under the thermal diodes. Both Solacatchers at the school had ~1.3 W/m^{2}K overnight heat loss coefficients.

4 Future work

Solar-home-systems (SHS) are an increasingly popular solution for energy access in off-grid sub-Saharan African communities (Lighting Global, 2018). Whilst SHSs provide affordable clean electricity, users generally remain reliant on polluting fuels for thermal needs, such as hot water production, which make up a significant proportion of overall energy demand. Most SHSs utilise small non-standard PV modules which have higher unit power costs (£/W) than larger “commodity” PV modules. Limited access to finance means that users are often frustrated when their steadily increasing energy demands exceed the limited supply capacity.

The present work has tested SolaFin2Go prototypes which combine commodity PV and batteries, innovative thermal diode solar water heating technology, and IoT data monitoring aimed at enabling affordable PAYG finance and service delivery models. Field test data has confirmed the hypothesis that a single commodity PV module is inherently more powerful than needed for typical entry-level domestic systems but this reduces required battery size resulting in significant overall cost savings. Further work is required to develop the PAYG and business model aspects of the SolaFin2Go concept and to refine the hardware into a viable value engineered commercial product. Prototypes tested in the present study have capability to use the significant available surplus electricity for boosting hot water production during sunny periods – the efficacy of this design aspect will be tested during the ongoing field trial.

The SolaFin2Go team recently secured funding for a 2-year follow-on project known as “SolaNetwork” which will investigate alternative ways to utilise energy surplus through prosumer electricity trading networks and battery trading schemes. The project will also examine social and business challenges in the sub-Saharan African off-grid energy sector associated with skills capacity building, last mile distribution, sustainable service delivery, and community ownership of energy infrastructure.

5 Conclusions

The SolaFin2Go project has developed stand-alone energy access system prototypes which provide an affordable entry-level on-demand electricity (800 Wh/day) and hot water (25L/day) service for off-grid households, community buildings and small businesses. The core components of each prototype unit include a 280Wp photovoltaic module, a 205Ah lead-acid battery, a 20A solar charge controller, an innovative "Solacatcher" thermal diode solar water heater, control hardware, and LoRaWAN radio data transmitters to enable remote monitoring.

Ongoing field trials at a primary school and teachers house in Jamataka village, Botswana indicates that the prototypes perform well. Typical consumption of energy provided by the Teachers house prototype (~540Wh/day electricity and ~22L/day hot water) is consistent with the design intent (800Wh/day electricity and 25L/day hot water). Hot water delivery temperatures were typically ~45°C during the afternoon and evening on typical sunny days, falling to ~30°C by early morning and on cloudy days. Analysis suggests that the PV module produces significant surplus energy on sunny days which can be used to boost hot water supply. The system can be value engineered by significantly reducing the battery size. Electricity use at the school is dominated by self-consumption for the project's communication equipment (~900Wh/day) and intermittent use of a photocopier and computers by school staff (~500Wh/day). The school rarely use their hot water supply, despite stored water temperatures being ~70°C in the afternoon on sunny days. Solar thermal collection efficiencies are notably higher for west (54%) and east (52%) facing units than for equator (north) facing units (43%) due to early morning and late afternoon insolation being boosted by the planar reflectors located under the thermal diodes. Overnight heat loss coefficients were typically found to be ~1.3 W/m^2K.

The project has realised direct social, educational, economic, and environmental impacts in Jamataka village by: providing lighting, mobile phone charging, televised media access, and a ready supply of hot water for one of the teacher households; enabling staff and school children to use computers, printers and a photocopier; and reducing fuel costs, CO_2 emissions, and air pollution associated with petrol generators and firewood. An exciting follow-on project commencing in June 2019 will augment the ongoing field trial by testing innovative prosumer energy trading and service delivery models with the aim of developing a regional technology showcase for off-grid energy access infrastructure approaches.

6 Acknowledgements

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