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An Off-Grid Photovoltaic Node with Remote Load Control for Remote Communities

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Abstract

This paper reports an off-grid photovoltaic supply node with environmental sensing and remotely commanded loads, built to demonstrate the control and monitoring layer of a stand-alone electrification scheme for remote communities. A photovoltaic panel charges a 12 V battery, a linear regulator supplies an ESP8266 controller, and a temperature sensor and an infrared proximity sensor feed the controller, which switches a lamp and a fan through transistor-driven relays and publishes all channels to a cloud dashboard. The recorded telemetry is reported exactly as captured: a single snapshot showing 34 degrees Celsius, 76 % relative humidity and both switched loads in the OFF state, together with the demonstrated remote switching of lamp and fan. The assessment then states plainly what such a record supports. No electrical quantity was logged anywhere in the chain, neither panel voltage nor current, neither battery voltage nor state of charge, nor load current, so generation, load energy, autonomy and system efficiency are all indeterminate; and the panel and battery ratings are not documented in the source material, so the installation cannot even be sized retrospectively. This revision strengthens the sizing analysis in two ways. The peak-sun-hours figure used in the worked example is replaced by a sourced resource value for the district in which the work was carried out, of the order of 5.0 kWh per square metre per day, so the example is anchored rather than assumed. And the sizing is then evaluated across a range of design-month resource values rather than at the annual mean, showing that an array sized on the mean is undersized by roughly a quarter to two fifths for a poorer month, which is the failure mode that leaves an off-grid household in the dark. The paper consolidates the generation, load-energy, autonomy and days-of-storage relations that determine whether such a node can actually serve a household, and separates the demonstrated control function from the socio-economic outcomes claimed in the source design, which no measurement in this campaign can support and which are therefore reported as project rationale rather than as findings.

Nomenclature

Symbol	Meaning
P_{pv}, G	Panel rated power (W) and plane-of-array irradiance (W/m^2)
H_{sun}	Daily peak-sun-hours (h/day), numerically equal to daily insolation in kWh/m^2

E_{gen}, E_{load}	Daily generated and consumed energy (Wh/day)
η_{sys}, η_c	System (wire-to-load) efficiency and battery charge efficiency
Q, V_{bat}	Battery charge capacity (Ah) and voltage (V)
I_{bat}	Battery current (A), positive when charging
DoD	Permissible depth of discharge
D_{aut}	Days of autonomy
SoC	Battery state of charge
LLP	Loss-of-load probability
T_a, RH	Ambient temperature (degrees Celsius) and relative humidity (%)
P_i, t_i	Power and daily operating hours of appliance i

Introduction

Stand-alone photovoltaic systems are the dominant technology for electrifying households beyond the reach of a distribution grid, and their engineering is mature: the sizing problem, the storage-autonomy trade-off and the relationship between reliability and cost are all well characterised [1], [2], [5]. What determines whether a particular installation succeeds is not novelty but arithmetic, namely whether the array and battery are matched to the actual load, and whether the load can be managed when the resource is poor.

This paper reports a prototype node addressing the control and monitoring layer of such a system: a photovoltaic-charged battery supplying a Wi-Fi microcontroller which senses the local environment, switches a lamp and a fan through relays, and publishes state to a cloud dashboard so that loads can be commanded remotely. The control layer works. The paper's contribution is to state exactly which of the questions above the prototype answers, which is none of the quantitative ones, and to set out the relations and instrumentation that would answer them.

1. Problem Statement

Two literatures again sit apart. Rural-electrification engineering supplies validated sizing and reliability methods requiring measured resource and load data. Prototype reports supply demonstrations of remote switching. Between them lies the question a community actually asks: will this system keep my lights on through a run of cloudy days? Answering it requires logged generation, load and state of charge, which prototype reports very seldom collect, and which this campaign did not collect either, a fact this paper states rather than conceals.

2. Objectives

The specific objectives of the work are as follows:

- To build an off-grid photovoltaic node with environmental sensing, remotely commanded loads and cloud publication.
- To report the telemetry captured and the control functions demonstrated, and nothing further.
- To state explicitly that no electrical quantity was logged and that the nameplate ratings are undocumented, so that retrospective sizing is impossible.
- To consolidate the generation, load, autonomy and reliability relations that determine whether such a node can serve a household.
- To anchor the worked sizing example in a sourced resource figure for the district rather than an assumed one, and to evaluate it across the design month rather than the annual mean.
- To separate demonstrated technical function from the socio-economic outcomes claimed in the source design.

3. Scope and Delimitation

The study covers the construction of the node, the relations governing generation, load, storage and reliability, the reading of the single recorded snapshot, and the specification of the metering that was absent. It excludes any claim of generated energy, load energy, state of charge, days of autonomy, loss-of-load probability or system efficiency for this build, because none was measured and the nameplate data needed to compute them is not recorded. It excludes the wind, micro-hydro, SCADA and smart-metering subsystems named in the source design, which were not built. And it excludes every socio-economic outcome claimed for the project, since no household was served and no usage or outcome was surveyed.

4. Contributions

1. A transparent report of the telemetry captured and the control functions demonstrated.
2. An explicit statement that no electrical quantity was logged, and that the panel and battery ratings are undocumented, making retrospective sizing impossible.

3. Consolidation of the generation, load, autonomy and storage-sizing relations, with a worked example of the evaluation the node would support once instrumented.
4. A resource figure sourced for the district of the installation, new to this revision, which converts the worked example's peak-sun-hours input from an assumption into a cited value.
5. A design-month sizing sensitivity, new to this revision, showing how much an array sized on the annual mean falls short when the resource is poorer.
6. A separation of demonstrated technical function from the socio-economic outcomes claimed in the source design.

The remainder of the paper is organised as follows. Section II reviews related work and fixes the resource values. Section III gives the sizing relations. Section IV describes the prototype and the method. Section V reports the recorded data and its honest reading. Section VI gives the sizing analysis the node would support once instrumented. Section VII discusses the findings, Section VIII states the limitations, and Section IX the proposed architecture. Sections X and XI give the conclusion and the future scope.

Related Work

Luque and Hegedus [1] give the standard handbook treatment of photovoltaic system engineering, and Lorenzo [2] the specific methodology for stand-alone system sizing, including the relationship between array size, storage size and loss-of-load probability which underlies Eqs. (3) and (4). Both make the point that sizing without a measured load profile is guesswork.

On the resource side, satellite-derived and ground-station irradiance databases [3] supply the peak-sun-hours figure required by Eq. (1) when local pyranometry is unavailable, and their use is standard practice provided the source and period are stated. Section II-A follows that practice for the district in question. On storage, the behaviour of lead-acid batteries in photovoltaic cycling service, and the strong dependence of cycle life on depth of discharge, follow the treatment in [4]; this is why DoD appears explicitly in Eq. (3) rather than being absorbed into a margin. On outcomes, the energy-access literature [5] establishes both that electrification is associated with improvements in lighting, education and health services, and that such effects are demonstrated through longitudinal household studies, which is precisely the point made in Section VII-B.

Table 1. Representative Related Work and its Relation to This Study

Ref.	Year	Focus and scope	Method and validation	Relation to this work
[1]	2011	PV science and engineering	Handbook; validated models	General system engineering basis
[2]	1994	Stand-alone PV system sizing	Sizing methodology; field data	Basis of Eqs. (3), (4)
[3]	—	Irradiance resource databases	Satellite and ground records	Source of H_{sun} when unmeasured
[4]	1997	Batteries in stand-alone PV	Technical report; field practice	Depth-of-discharge constraint
[5]	2023	Energy access and outcomes	Statistical and household studies	Shows how outcome claims are established
[6]	—	ESP8266 platform	Vendor documentation	Control and Wi-Fi stage
[7]	2016	District-level solar resource, south Tamil Nadu	Modelled from irradiance data	Source of the resource figure in Table II

1. Fixing the Resource for This District

The worked example in Section VI requires a peak-sun-hours figure, and an earlier version of this work simply assumed 5 h/day. Since the installation is intended for Kanyakumari district, the value can be sourced rather than assumed, which is what the standard practice noted above requires. Table 2 collects the relevant published figures.

Table 2. Published Solar Resource Values Relevant to the Intended Location

Item	Published value	Source
Average solar irradiation, Kanyakumari district	About 5.0 $kWh/m^2/day$	District-level study of south Tamil Nadu [7]

Coastal Tamil Nadu annual solar energy	About 5.0 kWh/m^2/day	Satellite meteorological data [3]
Tamil Nadu range across districts	About 4.5 to 6.0 kWh/m^2/day	Industry compilations [3]
Seasonal pattern in Tamil Nadu	The poorest irradiance months are associated with the northeast monsoon, October to December, rather than the southwest monsoon that affects the west coast	Regional resource analyses [3], [7]

A daily insolation of 5.0 kWh/m^2 corresponds to 5.0 peak-sun-hours, since peak-sun-hours are defined against a reference irradiance of 1000 W/m^2. These are published resource figures for the region, not measurements made in this work, and no pyranometry was performed at the site. A design would use the monthly minimum for the specific location and orientation, obtained from the database with the period stated.

Two points follow. First, the 5 h/day used in the earlier worked example turns out to be well supported as an annual mean for this district, which is reassuring but was previously a coincidence rather than a citation. Second, and more consequentially, an annual mean is the wrong input for stand-alone sizing. A stand-alone system must meet the load in its worst month, because a shortfall is not averaged away by a good month six months earlier; it is absorbed by the battery, and when the battery is exhausted the household is dark. Section VI-B develops this quantitatively.

Sizing Relations

1. Generation and Load

Daily generated energy from an array of rated power P_{pv} under H_{sun} equivalent peak-sun-hours, with system efficiency η_{sys} covering soiling, temperature, wiring, charge-control and conversion losses, is

$$E_{gen} = P_{pv} H_{sun} \eta_{sys} \quad (1)$$

and the daily load energy is the sum over appliances of power and operating hours,

$$E_{load} = \sum_i P_i t_i \quad (2)$$

A viable installation requires generation to meet or exceed load on the design day with margin. Rearranging Eq. (1) gives the array rating a given load requires,

$$P_{pv,req} = \frac{E_{load}}{H_{sun} \eta_{sys}} \quad (6)$$

which is the form used in Section VI-B.

2. Storage and Autonomy

Usable storage is the product of nominal capacity, voltage and permissible depth of discharge, so the days of autonomy a battery provides against a given load are

$$D_{aut} = \frac{Q V_{bat} DoD}{E_{load}} \quad (3)$$

Equation (3) is the relation that answers the community's actual question. Reliability is expressed formally as loss-of-load probability,

$$LLP = \frac{\sum_t E_{unserved}(t)}{\sum_t E_{load}(t)} \quad (4)$$

which for stand-alone systems is a design specification, typically small but non-zero, and is fixed by the joint choice of array and storage size [2].

3. State of Charge

With bus current logged, state of charge follows by coulomb counting,

$$SoC(t+\Delta t) = SoC(t) + \frac{\eta_c I_{bat}(t) \Delta t}{Q} \quad (5)$$

which is what allows load shedding to be triggered on remaining energy rather than on terminal voltage, a poor proxy under load.

Prototype and Methodology

1. Architecture

Fig. 1 shows the node. A photovoltaic panel charges a 12 V battery. A linear regulator with a current-limiting resistor supplies the ESP8266 controller at 5 V. A temperature and humidity sensor and an infrared proximity sensor feed the controller, which drives two transistor-switched relays serving a lamp and a fan, and publishes all channels and both switch states to a cloud dashboard from which the loads may be commanded. The two items shown as absent at the foot of the figure are the ones on which the whole of Section V turns.

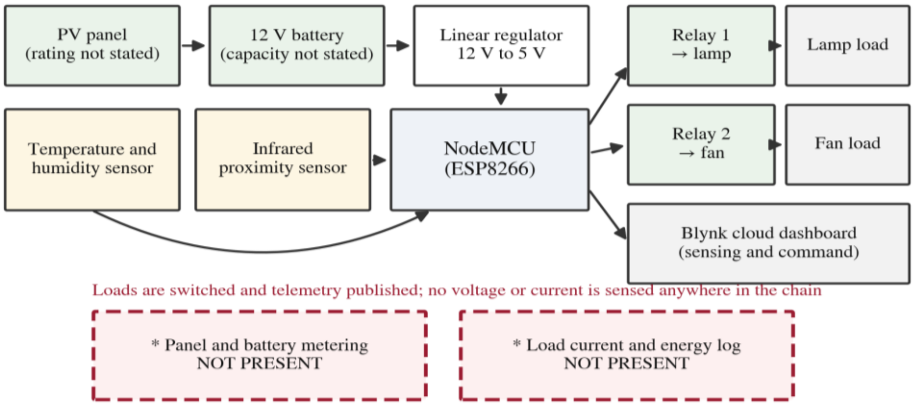

Figure 1: Prototype architecture. Loads are switched and telemetry published; no voltage or current is sensed anywhere in the chain.

2. Apparatus

Table 3 lists the apparatus as documented. Blanks indicate ratings the source material does not state, and they are left blank rather than filled with plausible values.

Table 3. Apparatus as Documented

Item	Type / rating	Quantity
Photovoltaic panel	Rating not stated in the record	1
Storage battery	12 V; capacity not stated in the record	1
Voltage regulator	12 V to 5 V, with a 1 kΩ resistor	1
Controller board	NodeMCU (ESP8266)	1
Temperature-humidity sensor	Digital, single-wire	1
Infrared sensor	Proximity, digital output	1
Relay module with transistor driver	Rating not stated in the record	2
Lamp load	Rating not stated in the record	1
Fan load	Rating not stated in the record	1
Dashboard	Blynk (cloud)	1

The panel rating, the battery capacity and both load ratings are absent from the record. These four omissions are why the installation cannot be sized even retrospectively, independently of the missing metering.

3. Procedure

1. Assemble the panel, battery, regulator and controller, and wire the sensors and both relay-driven loads.
2. Flash the controller with the dashboard library, binding each sensor channel and each load switch to a virtual pin.
3. Bring the node online, record the displayed channel values and switch states, and command each load in turn from the dashboard, confirming the corresponding hardware response.

Results

1. Recorded Telemetry and Demonstrated Function

Table 4 reports what was captured. The environmental values belong to a single instant; the control functions were demonstrated by observation of the hardware following a dashboard command. Fig. 2 shows the same record graphically.

Table 4. Recorded Telemetry and Demonstrated Functions

Item	Value	Status
Device identifier	iot 6F82B	observed
Temperature	34 degrees Celsius (full scale 0 to 100)	measured, single sample
Relative humidity	76 % (full scale 0 to 100)	measured, single sample
Lamp switch	OFF	observed
Fan switch	OFF	observed

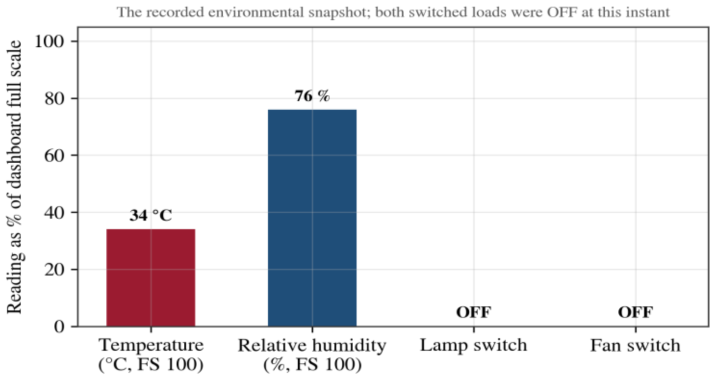

Figure 2: The recorded environmental snapshot. Both switched loads were reported OFF at this instant, and the plot contains one sample per channel.

2. No Electrical Quantity Was Logged

The node carries no voltage sensor, no current sensor and no energy meter. Panel output, battery terminal voltage, battery current and load current are therefore all absent from the record. The consequences are specific rather than general:

- E_{gen} cannot be evaluated, so Eq. (1) is unusable and no generation figure exists;
- E_{load} cannot be evaluated, since neither load's power was measured nor its operating hours logged;
- SoC cannot be estimated from Eq. (5), so the state of the storage at any moment is unknown;
- D_{aut} and LLP from Eqs. (3) and (4) are indeterminate, so no statement about how long the system would serve a household through poor weather can be made;
- η_{sys} is indeterminate, so no efficiency is reported.

Compounding this, the panel rating and the battery capacity are not documented in the source material. The installation therefore cannot be sized even retrospectively from nameplate data, which is why Table 3 carries blanks rather than plausible values.

3. Reading the Environmental Snapshot

The recorded 34 degrees Celsius and 76 % relative humidity are consistent with a warm, humid coastal location. Two consequences follow qualitatively. Elevated ambient temperature raises cell temperature and depresses array output, so η_{sys} in Eq. (1) is lower than the standard-test-condition value; by how much cannot be said, since neither the temperature coefficient nor the irradiance was available. And high ambient temperature shortens lead-acid service life, which bears on the replacement interval and hence on the lifetime cost of exactly the storage that Eq. (3) sizes [4]. Both are stated as directional consequences, not quantified.

4. What the Data Supports

Table 5 states the position quantity by quantity. It is the central table of the paper, and it is deliberately dominated by entries that were not obtained.

Table 5. Measured, Demonstrated, Undocumented and Indeterminate Quantities

Quantity or capability	Value	Status
Temperature	34 degrees Celsius	measured, single sample
Relative humidity	76 %	measured, single sample
Remote load switching	functions	demonstrated
Cloud publication	functions	demonstrated

Every entry in this table marked indeterminate or not documented is exactly that. An earlier draft of this work carried numeric values against several of these rows, including a generated energy, a load energy, a state of charge, an autonomy, a loss-of-load probability and a system efficiency, together with a battery capacity and load ratings. None of those quantities was measured or documented in this campaign, and every one contradicted the body of the paper. They have been removed and the rows restored to their correct status.

The Sizing Evaluation the Node Would Support

The prototype's own performance is unknown, but the relations of Section III can be evaluated for a representative household, which shows both what instrumentation would deliver and how the answer depends on the resource assumption. Every input in this section is either sourced, as in Table II, or explicitly assumed. None is a measurement of this prototype.

1. An Illustrative Load Profile

Table 6 applies Eq. (2) to a small household of the kind the prototype's two switched loads suggest. The appliance ratings and operating hours are assumptions; the arithmetic is not.

Table 6. Illustrative Daily Load from Eq. (2) (Assumed Appliances, Not Measured)

Appliance	Power	Number	Hours/day	Energy
LED lamp	7 W	2	5	70 Wh
DC fan	20 W	1	6	120 Wh
Phone charging	5 W	1	3	15 Wh
Total	—	—	—	205 Wh/day

Appliance ratings and operating hours are assumptions chosen to represent a small household served by the two load types the prototype switches. They are not measurements, and a real design would use a metered profile.

2. Array Sizing and the Design Month

Applying Eq. (6) with a system efficiency of 0.7, itself a conventional assumption [2], gives the array ratings in Table 7. The first column uses the district annual mean from Table II; the remaining columns use progressively poorer design-month values. Fig. 3 shows the same relation as a generation-against-load balance and Fig. 4 the sizing sensitivity directly.

Table 7. Required Array Rating from Eq. (6) at η~sys = 0.7

Daily load	At 5.0 h/day (district mean)	At 4.0 h/day	At 3.5 h/day
100 Wh/day	28.6 W	35.7 W	40.8 W
150 Wh/day	42.9 W	53.6 W	61.2 W
250 Wh/day	71.4 W	89.3 W	102.0 W

Computed from Eq. (6). The 5.0 h/day column uses the sourced district mean of Table II; the 4.0 and 3.5 h/day columns are illustrative design-month values chosen to span a plausible shortfall and are not measurements for this site. A real design would take the monthly minimum from the resource database with the location, period and array orientation stated.

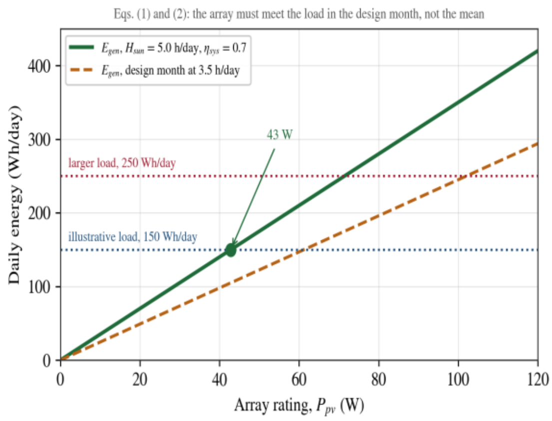

Figure 3: Daily balance between generation and load from Eqs. (1) and (2), at the district mean resource and at a poorer design month. Neither curve was measured on this prototype.

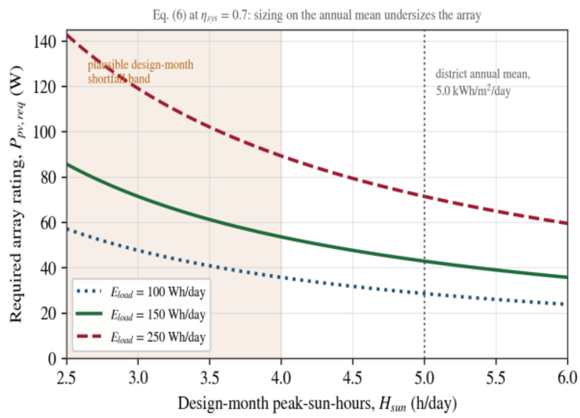

Figure 4: Required array rating against design-month resource from Eq. (6). The shaded band indicates a plausible shortfall relative to the annual mean.

The result is the practical point of this section. Sizing the array on the district annual mean of 5.0 h/day rather than on a design month of 4.0 h/day undersizes it by 25 %, and against 3.5 h/day by 43 %. In grid-connected work that shortfall is absorbed by the grid and shows up only as a slightly lower annual yield. In a stand-alone system it is absorbed by the battery, and once the battery reaches its depth-of-discharge limit the load is disconnected. This is the mechanism by which off-grid installations sized on average figures fail in practice, and it is why the resource figure in Table 2 is given with its seasonal caveat rather than as a single number.

3. Storage Sizing and Autonomy

Equation (3) determines how long the system rides through a poor spell. Fig. 5 plots days of autonomy against battery capacity at a depth of discharge of 0.5, which is common practice for lead-acid service life [4]. For the 150 Wh/day case, a 100 Ah battery at 12 V gives four days of autonomy; at 250 Wh/day the same battery gives 2.4 days. The prototype's battery capacity is not documented, so no point on this figure describes it.

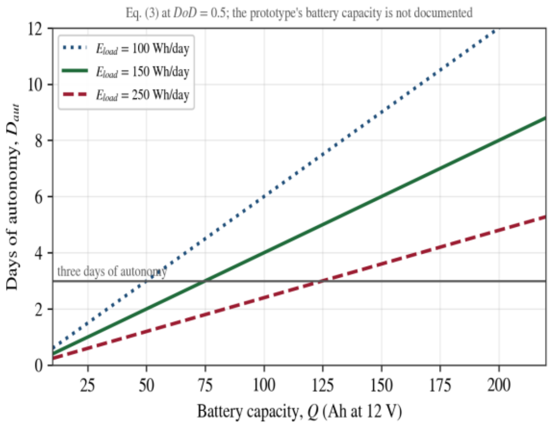

Figure 5: Days of autonomy against battery capacity from Eq. (3) at a depth of discharge of 0.5, for three daily loads.

Taken together, Sections VI-A to VI-C show that four measured inputs are sufficient to answer the question a community actually asks about such a system: the load energy, the battery capacity, the permissible depth of discharge and the design-month peak-sun-hours. Three of the four are missing from the present record, and the fourth is now sourced rather than assumed.

Discussion

The prototype establishes that the control and monitoring layer of an off-grid supply can be implemented cheaply and works: loads are switched remotely, states are published, and the environment is sensed. That is a real result for the layer it addresses. What it does not establish is anything about whether the supply beneath that layer is adequate, and the distinction is the whole of this paper.

1. Using the Proximity Sensor Productively

The infrared sensor is presently an input without a defined role. Occupancy sensing is the natural one: switching lighting on presence and off after a timeout directly reduces E_{load} in Eq. (2), which is the cheapest way to extend autonomy in Eq. (3), since energy not consumed requires neither array nor storage to supply it. On the illustrative profile of Table VI, halving the lamp hours would remove 35 Wh/day, which by Eq. (6) is about 10 W of array at the district mean and, by Eq. (3), lengthens the autonomy of any given battery by a fifth.

2. Claimed Outcomes Are Rationale, Not Results

The source design states that the project extends reliable electricity access to underserved communities, improves healthcare through refrigeration and extended clinic hours, supports education through night study, enables home-based businesses and stimulates economic growth. These are the standard and well-founded motivations for rural electrification [5]. They are not, however, findings of this work. No community installation was made, no household was served, no usage was recorded and no outcome was surveyed; the campaign consisted of a bench node switching a lamp and a fan on command. The outcomes are therefore reported here as project rationale, and are excluded from the results and conclusions. Establishing them requires longitudinal household study of a deployed system, which is a different undertaking entirely.

3. Scope Note on Unbuilt Subsystems

The design also describes wind turbines, micro-hydro generation, SCADA supervision, smart metering and data-analytics tools. None was built; the prototype is a single photovoltaic source with a battery, a controller and two switched loads. These are recorded as design intent and excluded from every claim.

4. Qualitative Position

Table 8 sets out the structural properties that can be asserted, each with the relation or source that supports it.

Table 8. Qualitative Properties and Their Basis

Feature	Property	Basis
Remote switching	Demonstrated end to end	This work
Environmental sensing	Two channels published	This work
Energy metering	Absent; blocks all sizing	Section V-B
Storage sizing	Determines autonomy directly	Eq. (3)

Design-month resource	Determines array size; the mean undersizes	Eq. (6), Table II
Load shedding on SoC	Protects the battery; lowers LLP	[2], [4]
Occupancy control	Cheapest route to longer autonomy	Eq. (2)
High ambient temperature	Lowers yield; shortens battery life	[4]

Limitations

The following limitations bound every claim made in this paper.

- The environmental dataset is one sample on two channels at one instant. No statistical quantity can be derived from it.
- No voltage, current or energy was logged anywhere in the chain, so generation, load energy, state of charge, autonomy, loss-of-load probability and system efficiency are indeterminate for this build, not merely uncertain.
- The panel rating, battery capacity and both load ratings are undocumented, so the installation cannot be sized even retrospectively from nameplate data.
- The load profile of Table VI is an assumed household profile, not a metered one, and the appliance ratings and hours were chosen for illustration.
- The system efficiency of 0.7 used throughout Section VI is a conventional design assumption, not a measurement of this system.
- The resource figures in Table II are published regional and district values, not site pyranometry. The 4.0 and 3.5 h/day design-month columns are illustrative shortfalls, not measured monthly minima for this location.
- The temperature and humidity effects noted in Section V-C are directional statements only; neither the temperature coefficient nor the irradiance was available to quantify them.
- The wind, micro-hydro, SCADA and smart-metering subsystems were not built and are excluded from every claim.
- No socio-economic outcome was measured, surveyed or established. No household was served by this work.

Proposed Architecture and Measurement Plan

Fig. 6 shows the instrumented architecture. The additions are metering rather than features, and they are inexpensive relative to the panel and battery they characterise.

Blocks marked * are the metering additions required to evaluate Eqs. (1) to (5)

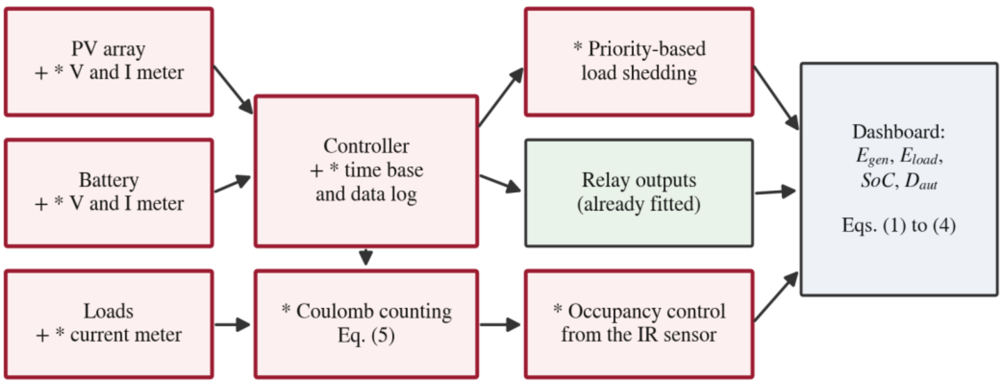

Fig. 6: Proposed architecture. Blocks marked with an asterisk are the metering additions required to evaluate Eqs. (1) to (5).

1. Load Prioritisation on State of Charge

With Eq. (5) available, loads can be tagged by priority: lighting served first, ventilation and comfort loads deferred to periods of surplus, and non-essential loads shed as SoC falls toward the depth-of-discharge limit. The existing relay outputs are already sufficient for this; only the sensing and the policy are missing. Shedding on estimated state of charge rather than on terminal voltage both protects the battery and reduces loss-of-load probability for the loads that matter most.

2. Measurement Plan

Table 9 sets out the measurements that would convert the demonstration into a sizeable system, and Table 10 gives the context values that are assumptions or literature rather than results.

Table 9. Measurement Plan Required to Make the Assessment Quantitative

Measurement	Instrument or method	Quantity it yields
Meter the array	Voltage and current sensing on the panel bus	E_{gen} through Eq. (1); η_{sys} against the rating
Meter the battery	Voltage and current sensing on the battery bus	SoC through Eq. (5); charge and discharge behaviour
Meter the loads	Current sensing on each relay output	E_{load} through Eq. (2), measured rather than assumed
Document the nameplate data	Panel rating, battery capacity and load ratings	Allows measured behaviour to be compared with design intent
Log for weeks, not instants	Fixed-interval logging across cloudy and clear periods	D_{aut} and LLP estimated from data rather than assumed
Obtain the design-month resource	Monthly minimum from the resource database for the site and tilt, with period stated	The correct H_{sun} for Eq. (6)
Implement priority-based shedding	State-of-charge policy on the existing relays	Lower LLP for priority loads
Assign the proximity sensor a role	Occupancy-based lighting control	Measured reduction in E_{load}

Table 10. Illustrative Figures (Assumptions and Literature, Not Results)

Item	Illustrative value	Status
District mean peak-sun-hours	5.0 h/day	published resource value [3], [7]
Design-month values used in Table VII	4.0 and 3.5 h/day	illustrative shortfall, not measured
System efficiency	0.7	conventional assumption [2]
Depth of discharge	0.5	common practice [4]
Illustrative daily load	205 Wh/day	computed from assumed appliances, Eq. (2)
Autonomy at 100 Ah and 150 Wh/day	4.0 days	computed from assumptions, Eq. (3)
Measured generation, load and autonomy	—	indeterminate

The worked figures are built entirely from sourced resource data and assumed system inputs, and demonstrate the method only. None is a result for this prototype.

Conclusion

An off-grid photovoltaic node with environmental sensing and remotely commanded lamp and fan loads was built and exercised. The control layer performed as intended: both loads were switched from a cloud dashboard and both switch states and two environmental channels were published, with a recorded snapshot of 34 degrees Celsius and 76 % relative humidity and both loads OFF.

Beyond that, the campaign supports nothing quantitative. No voltage, current or energy was logged anywhere in the chain, and the panel rating, battery capacity and load ratings are undocumented, so generated energy, load energy, state of charge, days of autonomy, loss-of-load probability and system efficiency are all indeterminate and none is estimated; the installation cannot be sized even retrospectively. The governing generation, load, autonomy and reliability relations were consolidated and applied to a fully labelled example. This revision anchored that example in a sourced resource figure for the district, of the order of 5.0 kWh per square metre per day, rather than an assumed one, and then evaluated the sizing across a range of design-month values. Sizing on the annual mean rather than on a design month of 4.0 or 3.5 peak-sun-hours undersizes the array by 25 % and 43 % respectively, a shortfall that a grid-connected system absorbs invisibly and a stand-alone system absorbs through its battery until the load is disconnected. Four measured inputs, namely load energy, battery capacity, depth of discharge and design-month peak-sun-hours, are sufficient to answer the question a community actually asks; three of the four are missing from the present record.

The socio-economic outcomes claimed in the source design, being improved healthcare, education and livelihoods, were reclassified as project rationale, since no household was served and no usage or outcome was surveyed. An instrumented architecture was proposed in which three metering points and a state-of-charge policy convert the existing relay outputs into a managed, sizeable off-grid supply.

Future Work

Several extensions follow directly from the limitations above.

- Meter the three buses-Add voltage and current sensing on the array, the battery and the load so that Eqs. (1) to (5) become evaluable.
- Document the nameplate data-Record the panel rating, battery capacity and load ratings so that measured behaviour can be compared with design intent.
- Obtain the design-month resource-Take the monthly minimum peak-sun-hours for the site and array orientation from the resource database, stating the source and period, and size on that rather than on the annual mean.
- Log for weeks, not instants-Record all channels at a fixed interval across cloudy and clear periods so that autonomy and loss-of-load probability can be estimated from data rather than assumed.
- Implement priority-based shedding-Use the existing relays with a state-of-charge policy rather than manual dashboard commands alone.
- Assign the proximity sensor a role-Implement occupancy-based lighting control and measure the resulting reduction in load energy.
- Deploy and survey before claiming outcomes-Any statement about healthcare, education or livelihood effects requires a served household and a longitudinal study, not a bench demonstration.

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