Data-Driven Design for Off-Grid Systems: Electricity in the Navajo Nation

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Engineering for Change Webinar

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Henry Louie, PhD

Dr. Henry Louie received his B.S.E.E. degree from Kettering University in 2002, his M.S. degree from the University of Illinois at Urbana-Champaign in 2004 and his PhD in Electrical Engineering from the University of Washington in 2008. He is a Professor in the Department of Electrical and Computer Engineering at Seattle University.

In 2015 Dr. Louie was Fulbright Scholar to Copperbelt University in Kitwe, Zambia. He is the President and Co-founder of KiloWatts for Humanity, a non-profit organization providing off-grid electricity access and business opportunities in sub-Saharan Africa. Dr. Louie is an Associate Editor *for Energy for Sustainable Development* and is a founding member of the IEEE PES Working Group on Sustainable Energy Systems for Developing Communities. Dr. Louie is recognized as an IEEE Distinguished Lecturer for his expertise on energy poverty. He is a Senior Member of the IEEE and has been a registered professional engineer in Zambia. He previously served as Vice President of Membership & Image of the IEEE Power & Energy Society. He is was the inaugural chair of the IEEE PES/IAS PowerAfrica Conference Steering Committee. He is the 2022 recipient of the IEEE Region 6 Award for Outstanding IEEE Member who Promoted Global Humanitarian Projects or Activities.

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Derrick Terry, Navajo Tribal Utility Authority

Mr. Derrick Terry is a Renewable Energy Specialist for Navajo Tribal Utility Authority (NTUA). He assists in managing the Off-grid solar program for NTUA as well as the On-grid Distributed Generation Program, where he maintains, monitors and operates over 600 off-grid systems with the assistance of 30 qualified personnel located throughout the NTUA service area. Mr. Terry has over 16 years of experience of working on and around photovoltaic systems. He is dedicated to optimizing off-grid photovoltaic systems for people that don't have grid power. His background is rooted in sustainable building and sustainable development on the Navajo Nation for the past 22 years.

Mohammed Ba-Aoum

Mohammed Ba-Aoum is a Ph.D. candidate in Industrial and Systems Engineering at Virginia Tech (VT). His research is at the forefront of the intersection between data science and dynamic modeling to inform design of sociotechnical systems and develop data-driven policy. Mohammed serves as a fellow in the Global Engineering Academy at VT and a senior fellow in E4C. In these roles, he contributes to projects that bridge engineering and global development. Mohammed worked as a lecturer in Industrial and Systems Engineering at King Fahd University as well as an electrical engineer at ARAMCO in Saudi Arabia before joining VT.

Energy Poverty

Energy Poverty is:

the lack of access to modern fuels

2.4 billion people rely on solid biomass for cooking/heating

733 million people do not have access to electricity

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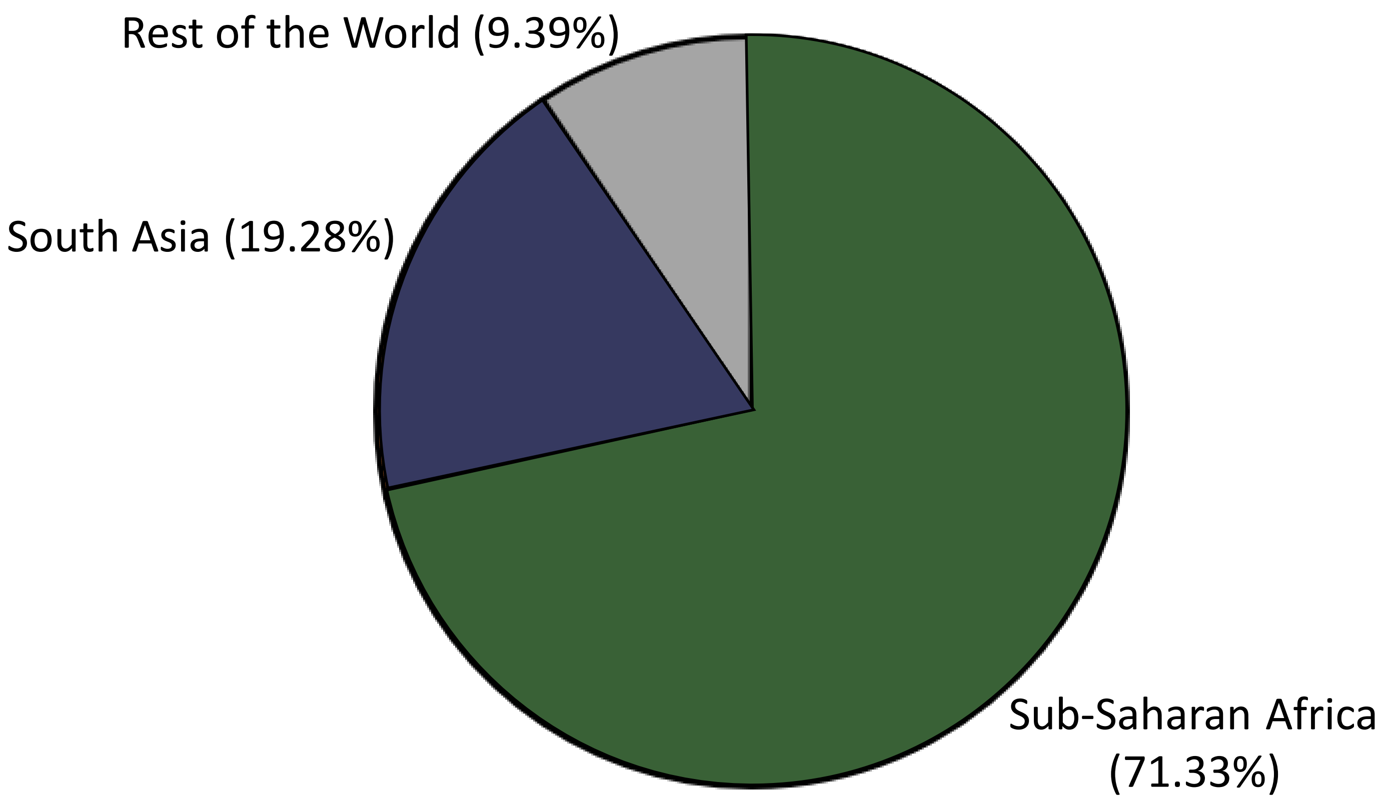
Distribution of Population without Electricity Access



Zambia

Navajo Nation

Electricity Access on the Navajo Nation

- Navajo Nation was overlooked by U.S. Government's Rural Electrification Act and efforts
- Grid extension cost $20,000 to $40,000/mile
  - Remote areas (some homes are 40 miles from the grid)
  - Low population density (~6 people/square mile)
- +10,000 homes on Navajo Nation are not grid connected
  - Least electrified of all U.S. reservations

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Navajo Tribal Utility Authority (NTUA)

An Enterprise of the Navajo Nation

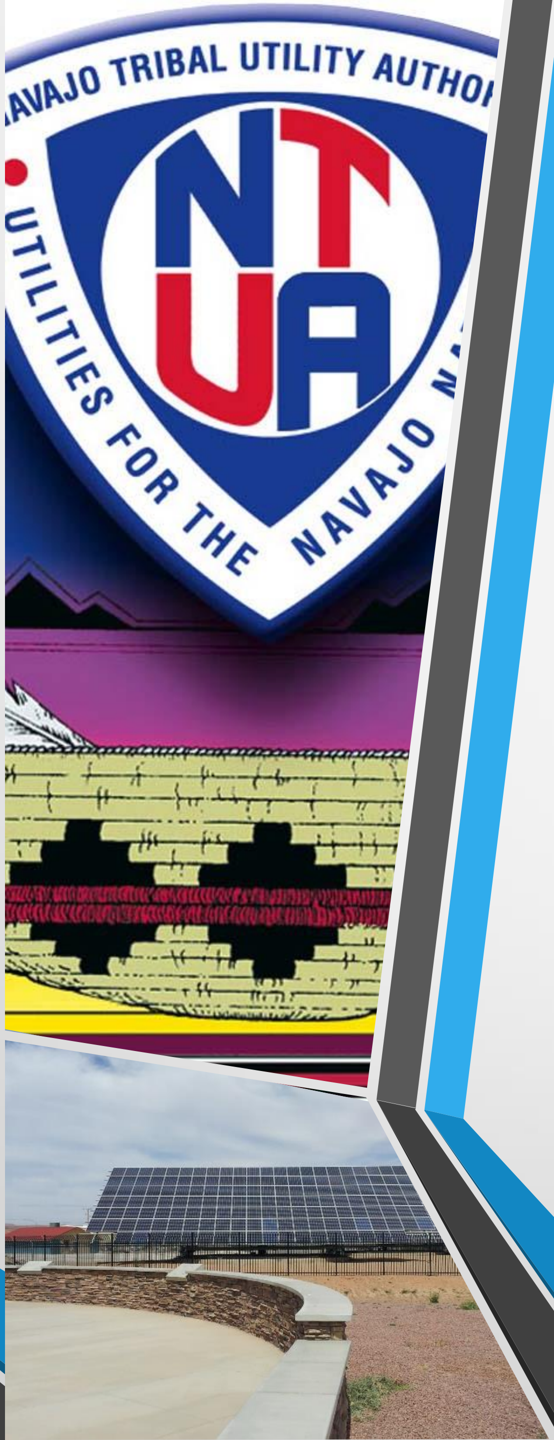
The NTUA is organized for the operation, maintenance and expansion of:

- Electric distribution and transmission
- Communications
- Natural Gas
- Water
- Wastewater
- Power Generation- Photovoltaics
- Photovoltaic Systems
- It is estimated that 31% of all homes lack complete plumbing, 28% lack kitchen facilities, 38% lack water services, 32% lack electricity, 86% lack natural gas services, and 60% lack landline telephone services.

The Navajo Nation consist of approximately 17,939 square miles in Arizona, 7,493 square miles in New Mexico and 1,981 square miles in Utah. According to the 2010 U.S. Census 156,823 Navajos live on the Navajo Nation.

Navajo Tribal Utility Authority (NTUA)

Renewable Energy Program



- Promote the use of Renewable Energy.
- Be an example for other Native Communities.
- Increase energy efficiency in our daily lives.
- Stress the importance of energy efficiency

Off-Grid Residential Power and Refrigeration Program

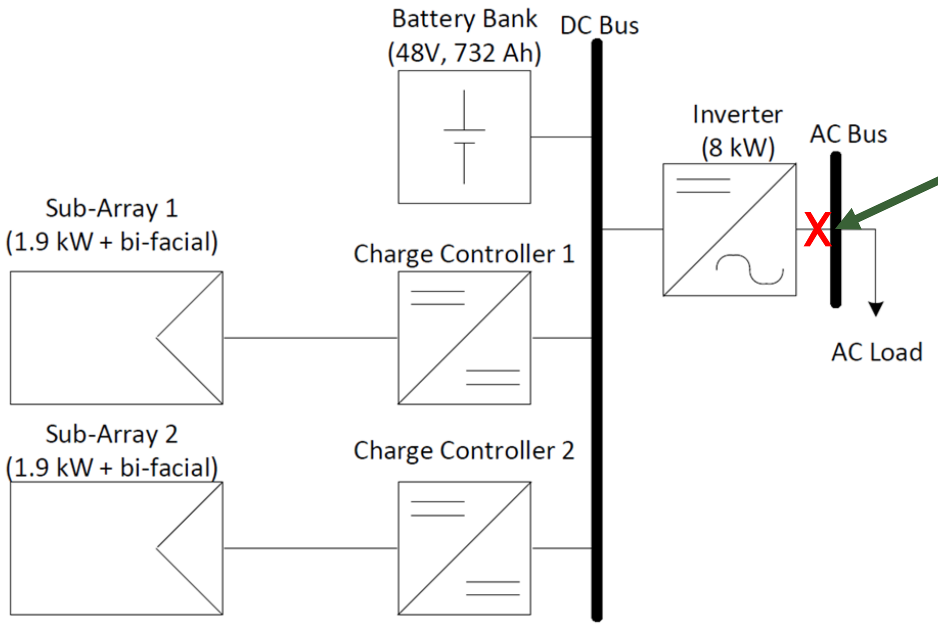
- Solution for families that live far from the NTUA electrical system
- NTUA has the ability to install these systems virtually anywhere on the Navajo Nation
- NTUA currently has 502 installed photovoltaic systems
- Larger PV systems come with refrigerators to a solution to minimize traveling distances to the grocery stores. Have the capacity to power personnel electronic devices, small kitchen appliances and lights in the home.
- 3 days of autonomy to cover long days of no sun events
- Customers have power when traditional grid power experiences an outage.
- Customers are completely energy dependent
- Keeping our environment clean and natural

Off-Grid Systems

450 systems with Samsara industrial monitoring data acquisition systems installed

- 300 Sol-Ark
- 150 Outback

System Schematic



Measurement point

Data sampling rates between <1 min to 10 min, then converted to daily energy values

1 Jan. 2021 to 31 Dec. 2022 (or to 7 Mar. 2023)

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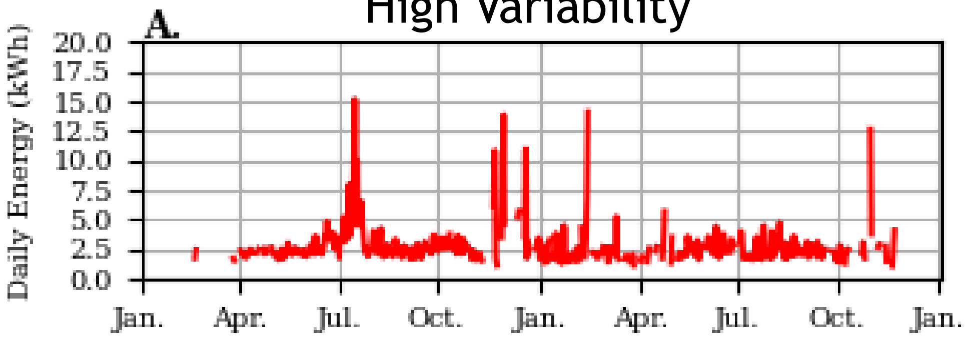
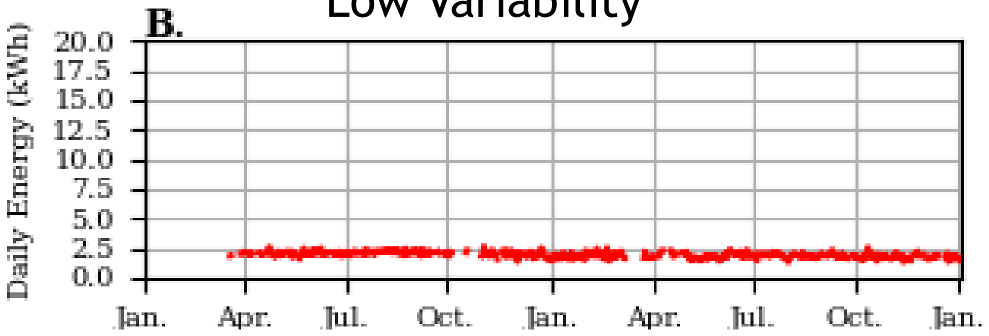
Energy Consumption Characteristics

Daily Consumption: Example Profiles

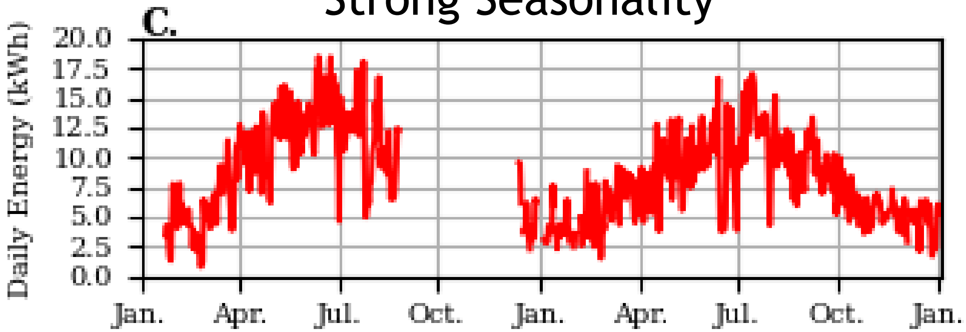
High Variability



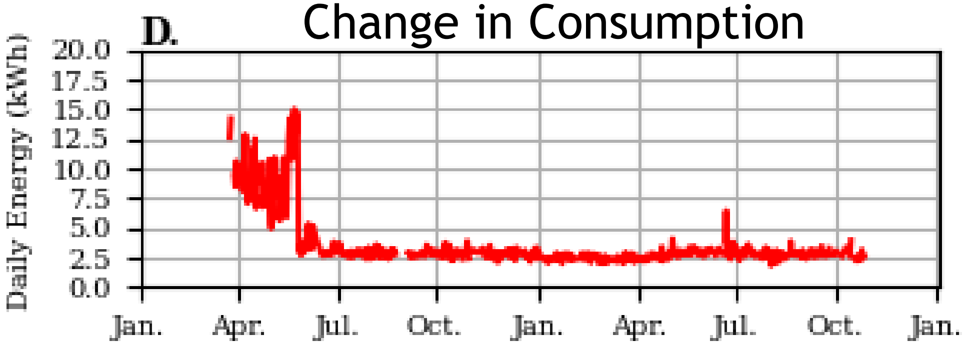
Low Variability



Strong Seasonality



Change in Consumption



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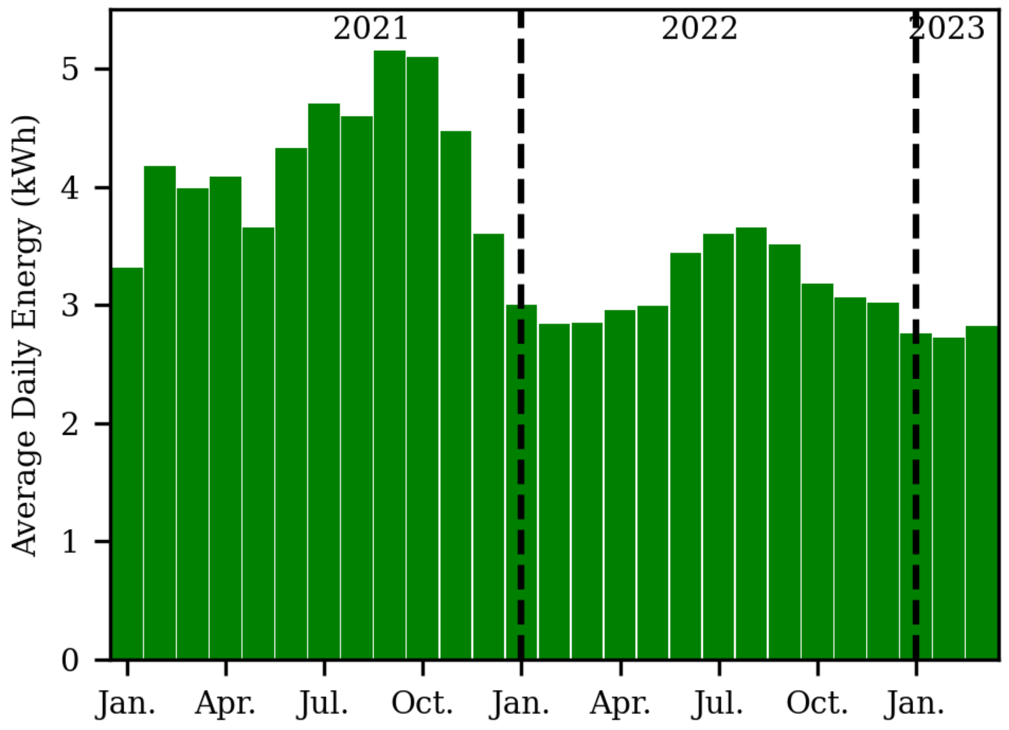
Annual Consumption Pattern

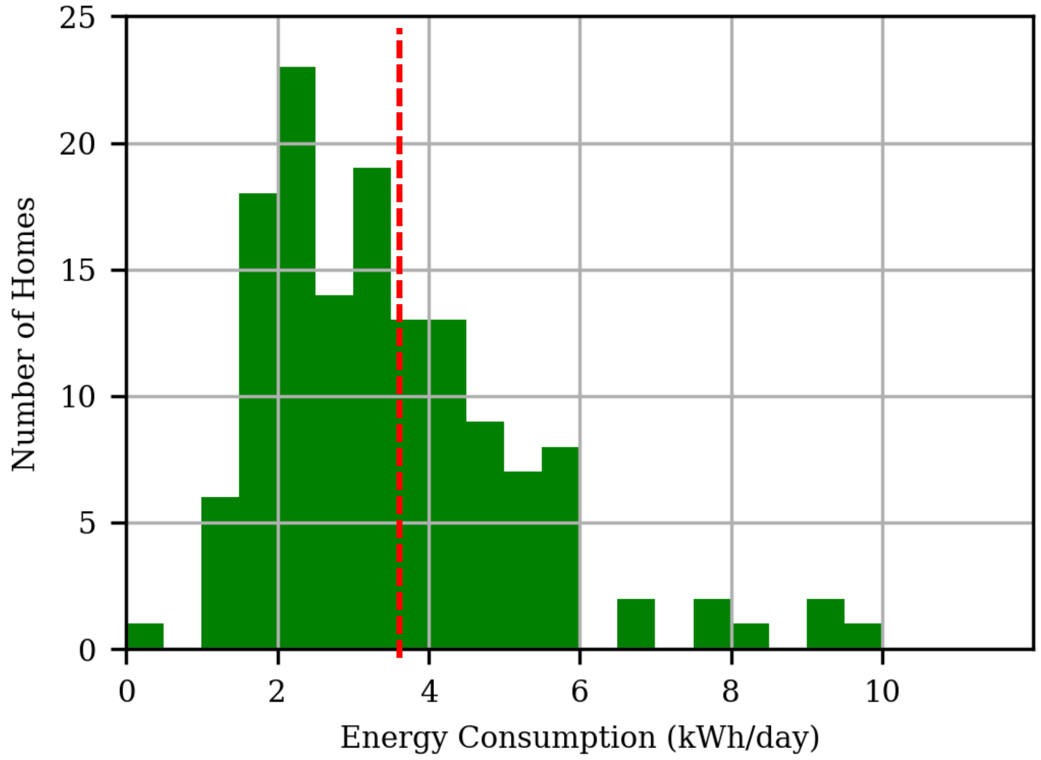


Summer peaking profile
Potential causes:
- Cooling load
- Seasonal work/school patterns
- Energy availability

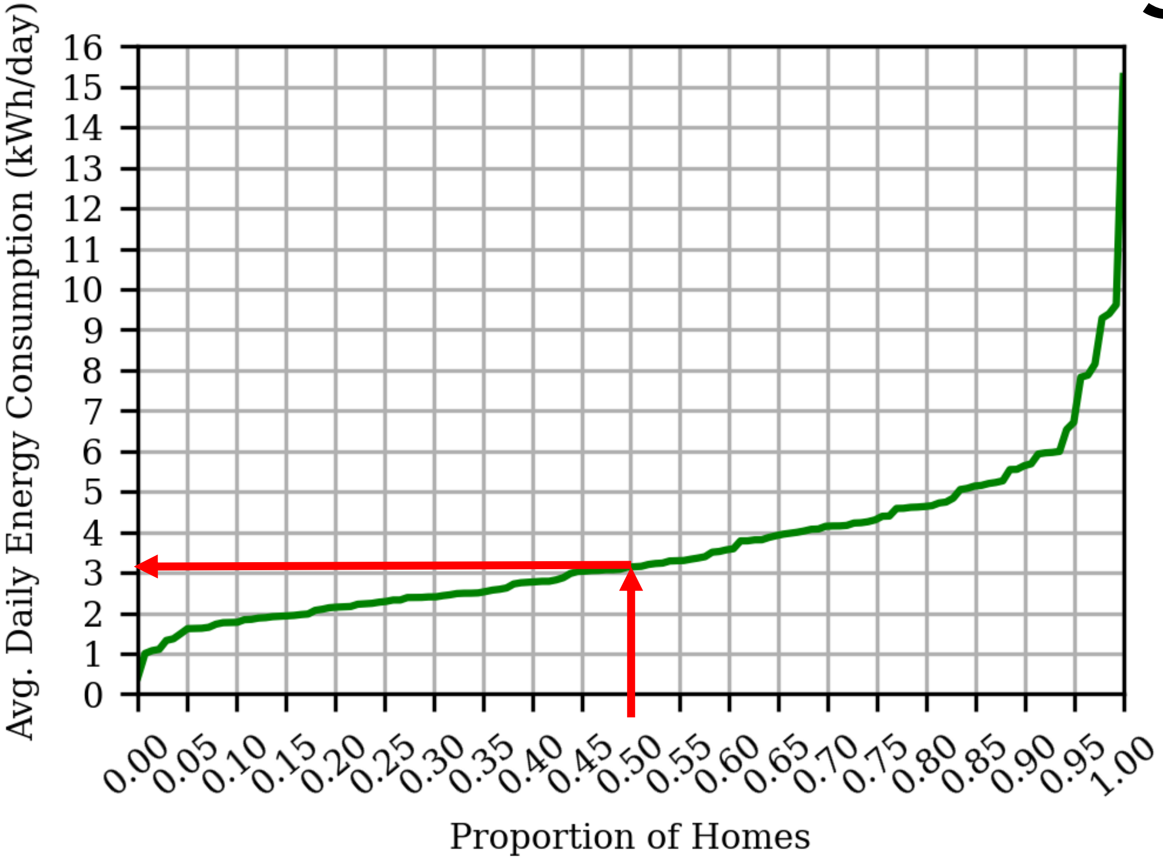
Year-over-Year *decrease* (~10%)
Potential causes:
- COVID-19 restriction changes
- Component degradation

Distribution of Average Consumption

- Average AC consumption: 3.58 kWh/day
  - Estimated DC consumption: 5.01 kWh/day (based on inverter standby losses)
- Wide range of average daily consumption among the homes



Distribution of Average Consumption



Statistic	Avg. (kWh/day)
Maximum	15.26
Q(0.975)	8.75
Q(0.95)	6.77
Q(0.90)	5.64
Mean	3.58
Q(0.50)	3.14
Q(0.10)	1.77
Q(0.05)	1.61
Minimum	0.42

95% of homes consumed no more than 6.77 kWh/day

50% of homes consumed no more than 3.14 kWh/day

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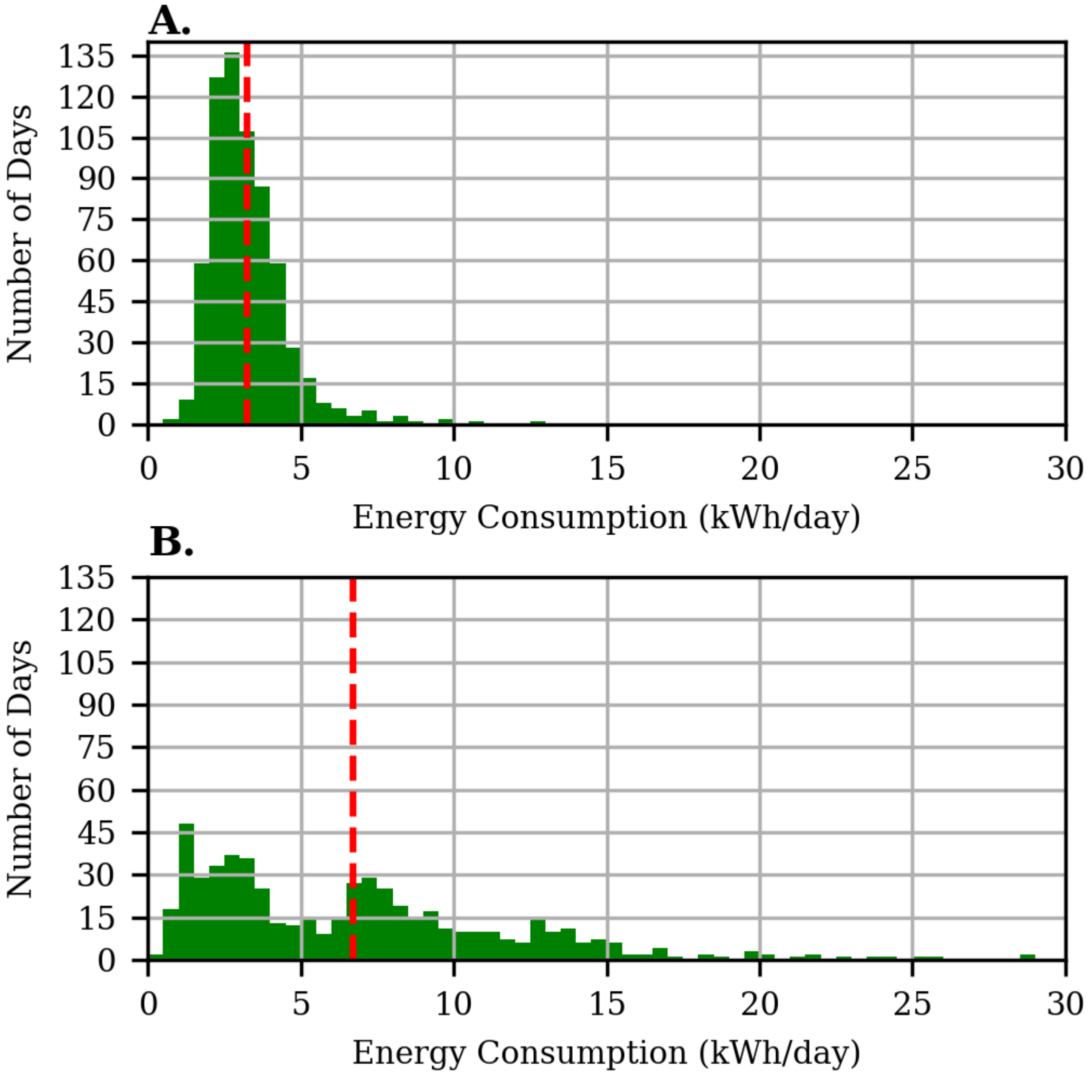
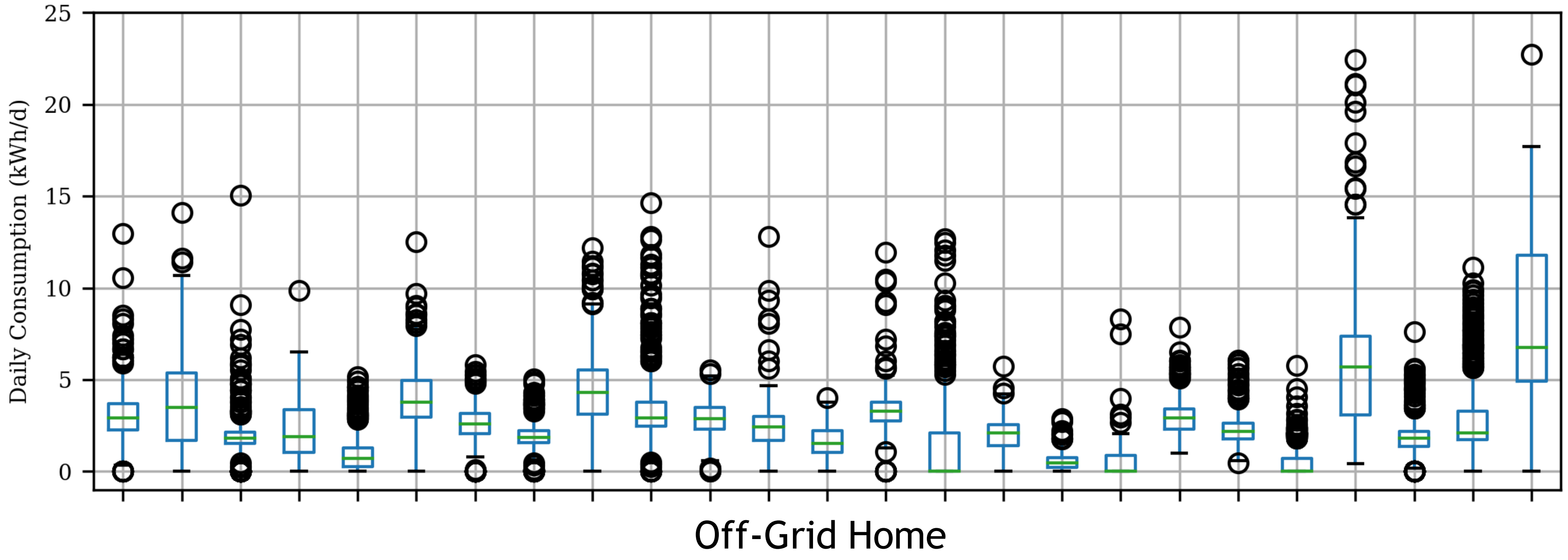
Daily Variation

- Even within the same home, there can be large variation of daily energy use
- Variation in energy use is important in sizing battery bank and reliability



Daily Energy Use Variation

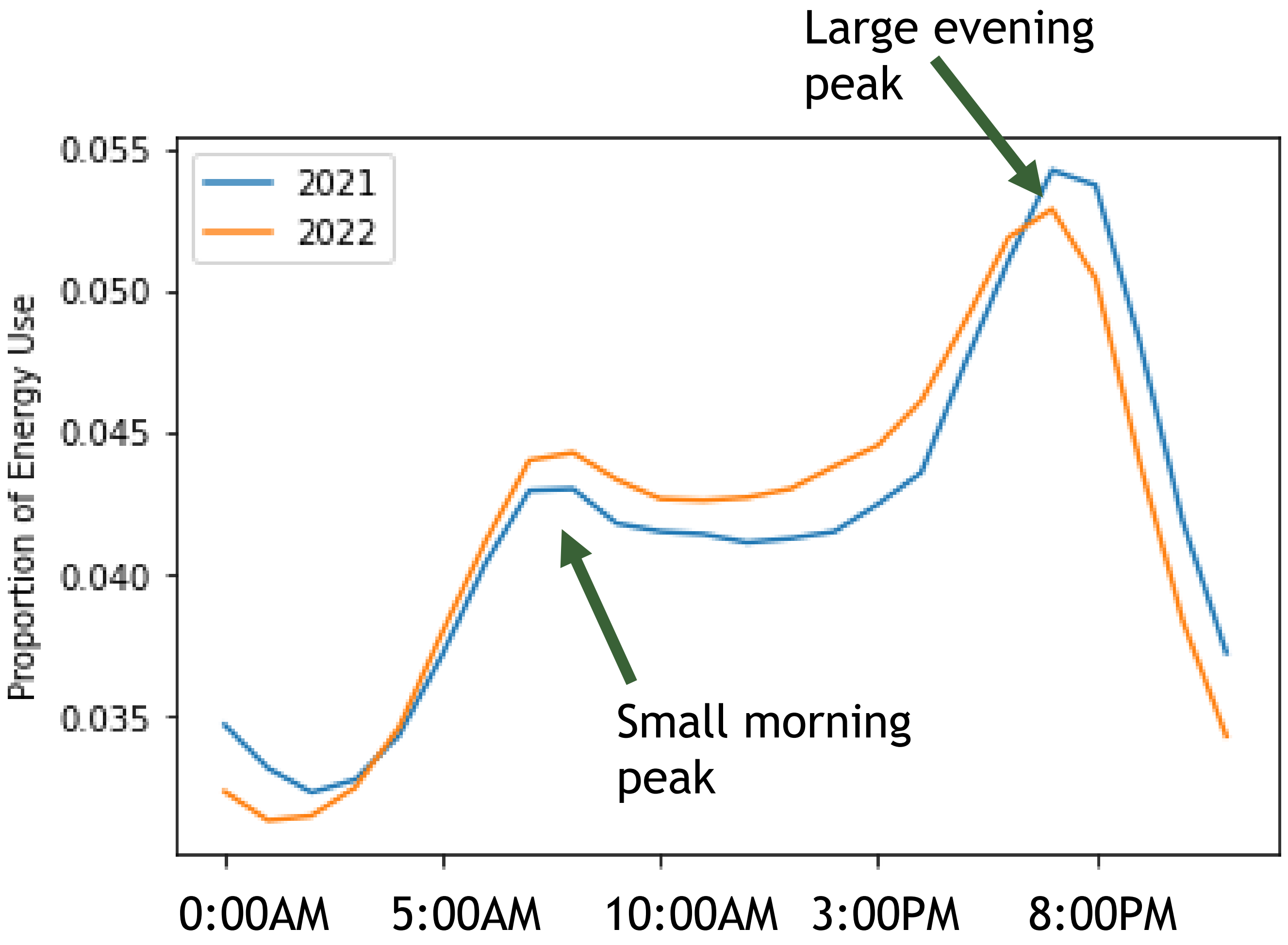
Note:
Non-Gaussian
distribution



Load Profiles

Load Profiles

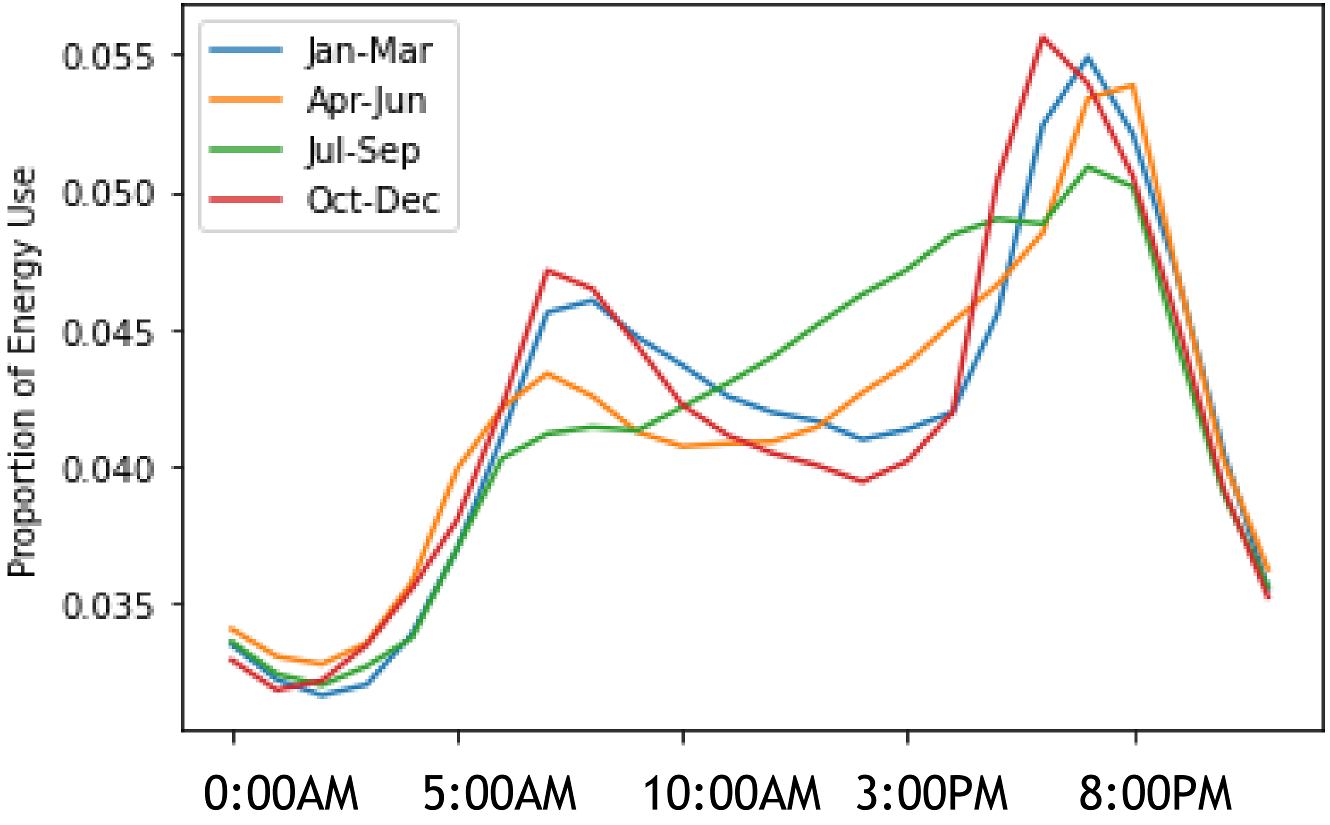
- Load profiles tell us what time of day energy is used
- Similar profiles in 2021 and 2022
- Consumption co-incident with sunlight hours is preferred
- Based on 73 homes with the fewest missing days



*Mountain Standard Time (UTC -7 Hours)

Seasonal Load Profiles

- Some seasonal differences, but general pattern is apparent
- Summer use is more consistent during daylight hours



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Design Considerations

PV Array Sizing

How Much Energy Can Be Produced?

PV Energy Potential

Energy production potential can be estimated as:

$$\tilde{E}_{\text{PV}} = P_{\text{rated}} \times \bar{I} \times (1 - L)$$

- P_{rated}: rated PV array capacity, in kW
- $\bar{I}$: average insolation, set at 4.5 kWh/m^2/day (lowest month average)
- L: losses, assumed to be 25 percent

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PV Energy Potential

Average daily DC-side load that can be served by a given amount of daily PV energy:

$$\bar{E}_{\mathrm{DC}} = \frac{\tilde{E}_{\mathrm{PV}}}{A}$$

A: array-to-load ratio, assumed to be 1.3

PV Energy Potential

Combining $\tilde{E}_{\mathrm{PV}} = P_{\mathrm{rated}} \times \bar{I} \times (1-L)$ and $\bar{E}_{\mathrm{DC}} = \dfrac{\tilde{E}_{\mathrm{PV}}}{A}$ shows the required PV array rating to serve an average daily DC-side load:

$$P_{\mathrm{rated}} = A \times \frac{\bar{E}_{\mathrm{DC}}}{\bar{I} \times (1-L)}$$

Each 1kWh of DC-side load requires a PV capacity of:

$$P_{\mathrm{rated}} = 1.3 \times \frac{1\ \mathbf{kWh}}{4.5 \times (1-0.25)} = 0.385\ \mathbf{kW}$$

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PV Array Sizing

Statistic	DC Load (kWh/day)	Required PV Capacity (kW)
Maximum	16.70	6.43
Q(0.975)	10.19	3.92
Q(0.95)	8.21	3.16
Q(0.90)	7.09	2.73
Q(0.75)	5.77	2.22
Mean	5.02	1.93
Q(0.50)	4.58	1.76
Q(0.10)	3.21	1.24
Q(0.05)	3.05	1.18
Minimum	1.87	0.72

Existing array is 3.8 kW
+ bi-facial

Half of homes could
be served with a 1.76 kW array

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Battery Bank Sizing

Battery Sizing

- Battery banks are often designed to provide a targeted Days of Autonomy (DoA)
- Days of Autonomy: the number of days a battery can supply the average DC-side load (with zero PV input) before being depleted to a pre-defined state-of-charge
- NTUA targeted three Days of Autonomy

Days of Autonomy

Days of Autonomy: $DoA = \dfrac{E_{\mathrm{B}} \times EoL \times DoD \times C}{\bar{\bar{E}}_{\mathrm{DC}}}$

- E_{B}: battery bank energy capacity (Ah x Nominal Voltage)
- EoL: battery end-of-life capacity adjustment, set to 0.80
- DoD: maximum depth-of-discharge, set to 0.70
- C: Capacity adjustment for losses, etc., set to 0.87

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Days of Autonomy

Battery energy capacity to supply a given DC load with a targeted DoA:

$$E_B = \frac{DoA \times \bar{E}_{DC}}{EoL \times DoD \times C}$$

To supply 3 Days of Autonomy for each 1 kWh of DC-side load requires battery capacity of:

$$E_B = \frac{3 \times 1\ \mathbf{kWh}}{0.80 \times 0.70 \times 0.87} = 6.15\ \mathbf{kWh}$$

Implications for Battery Bank Sizing

Statistic	DC Load (kWh/day)	Required Battery Cap. for 3 DoA (kWh)
Maximum	16.70	102.9
Q(0.975)	10.19	62.8
Q(0.95)	8.21	50.6
Q(0.90)	7.09	43.7
Q(0.75)	5.77	35.5
Mean	5.02	30.9
Q(0.50)	4.58	28.2
Q(0.10)	3.21	19.8
Q(0.05)	3.05	18.8
Minimum	1.87	11.5

Serving all homes would require more than doubling battery bank

Existing battery bank
35.1 kWh (~75% of homes served)

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Appropriate Design

Remember, it isn't just technical considerations:

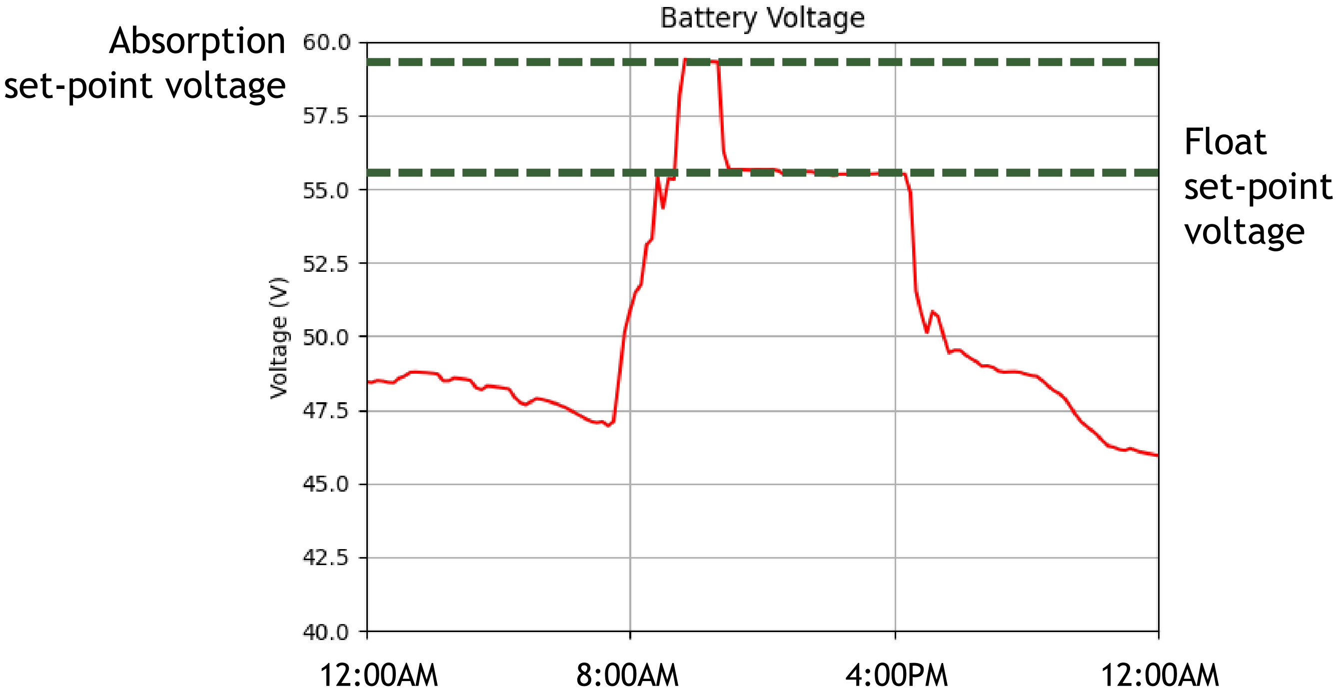
- Estimating user load for off-grid systems is extremely difficult without historical data
- NTUA was less concerned about capital costs
- Had to quickly deploy units: "one size fits all"
- Service costs are high, preferred to over-size systems

Future Analyses

Future Work: Battery Voltage Profiles

What can battery bank voltage profiles tell us about the performance and reliability of the systems?

Can the time that the absorption stage is reached predict reliability?



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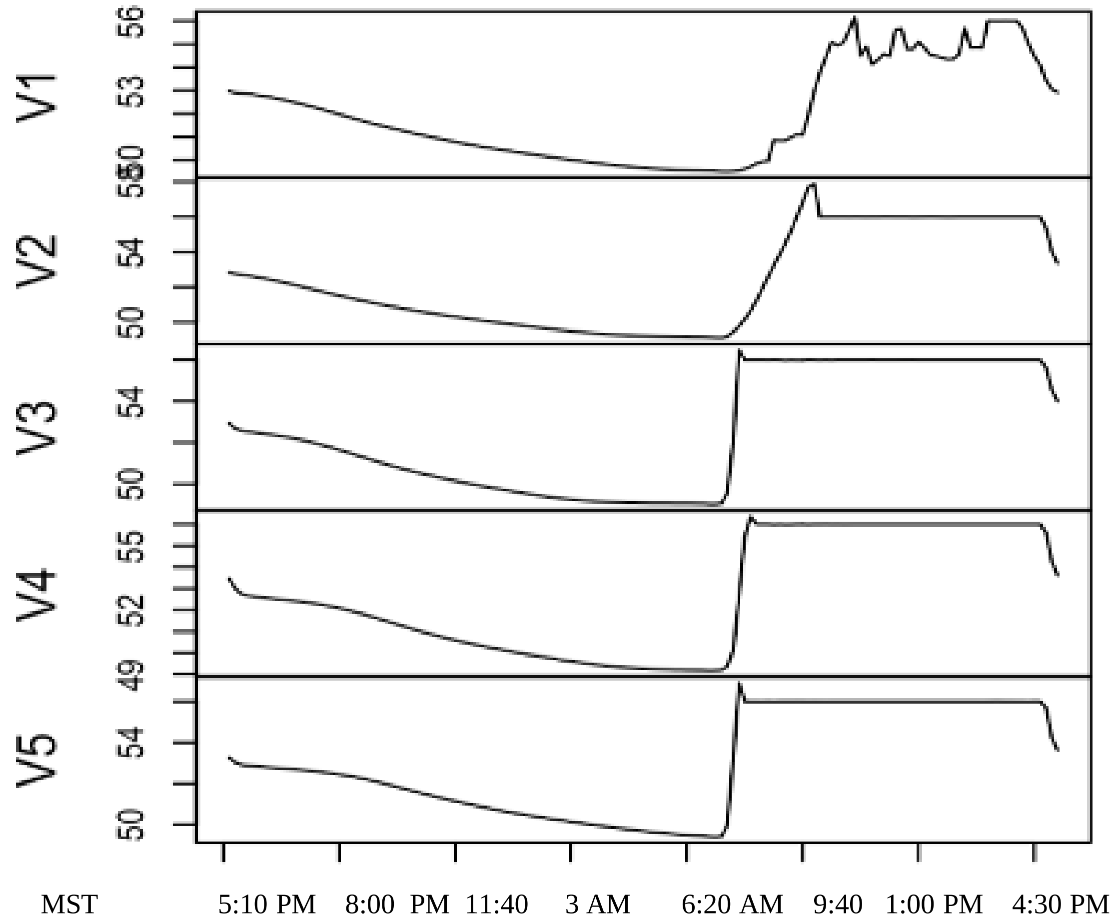
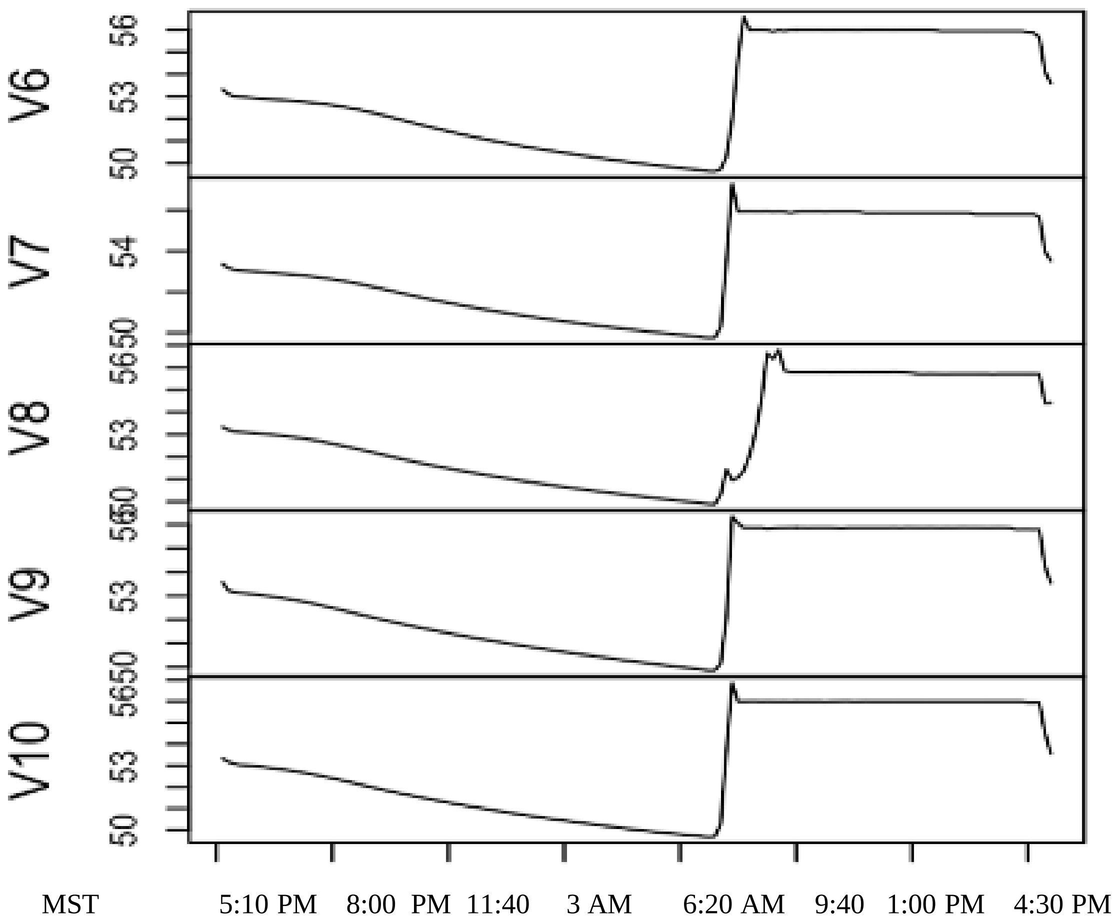
EXAMPLE VOLTAGE PROFILE UNIT 1110, JAN 1- 10, 2023





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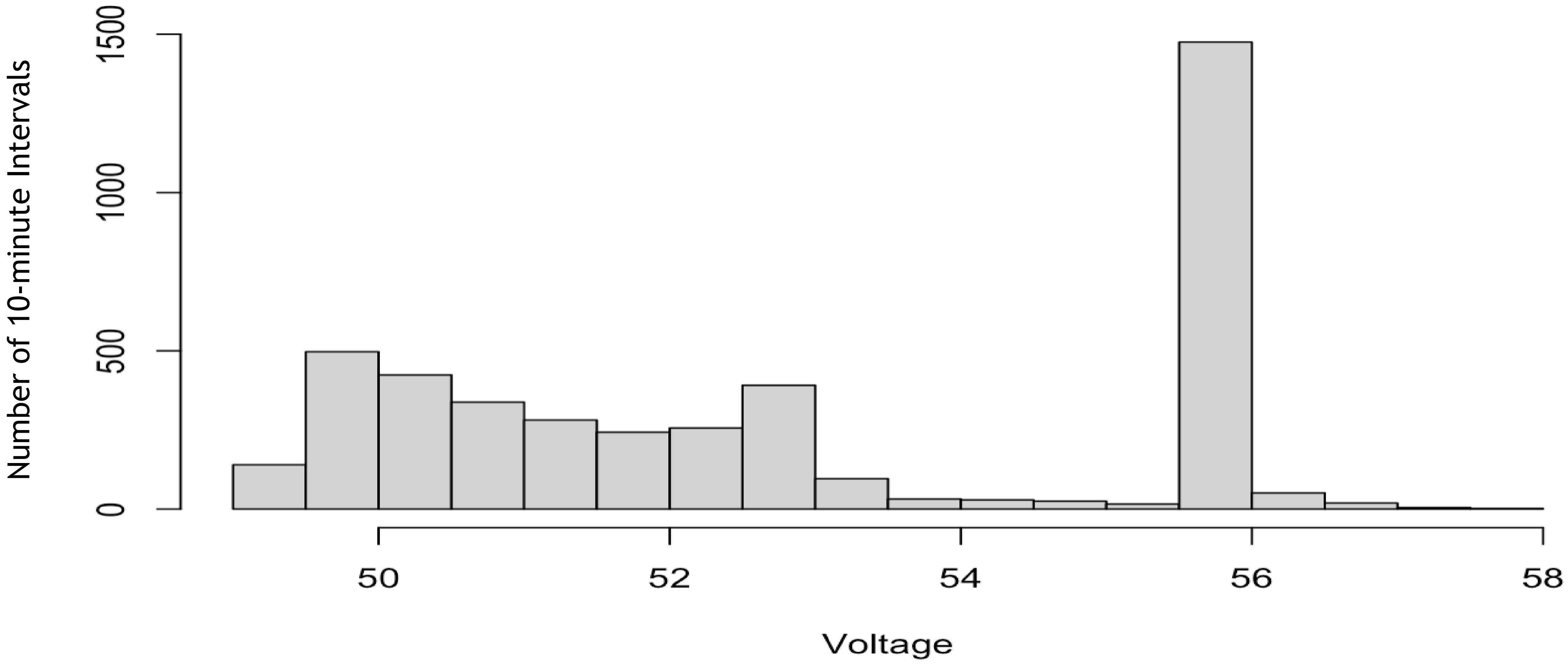
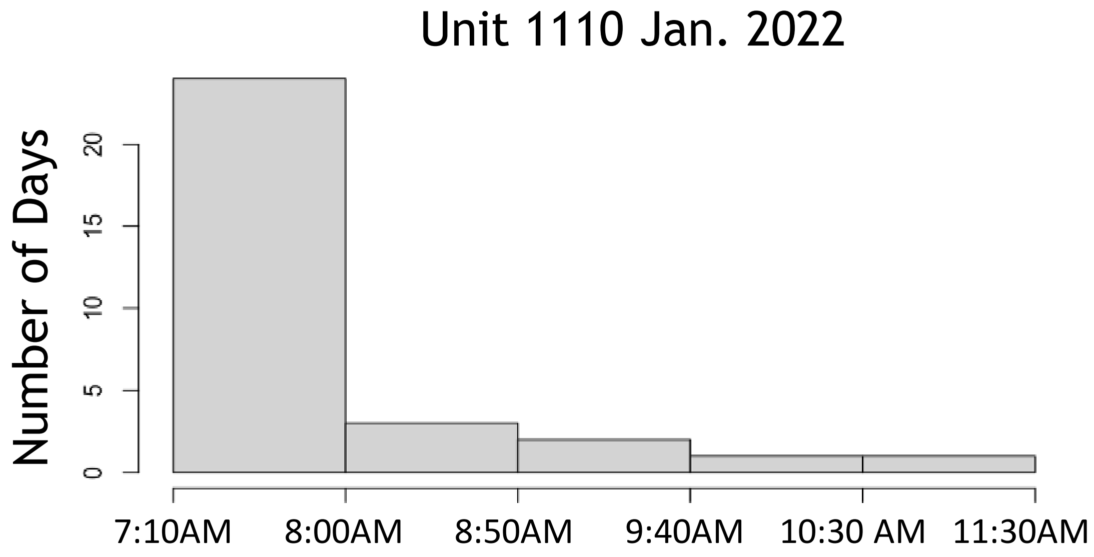
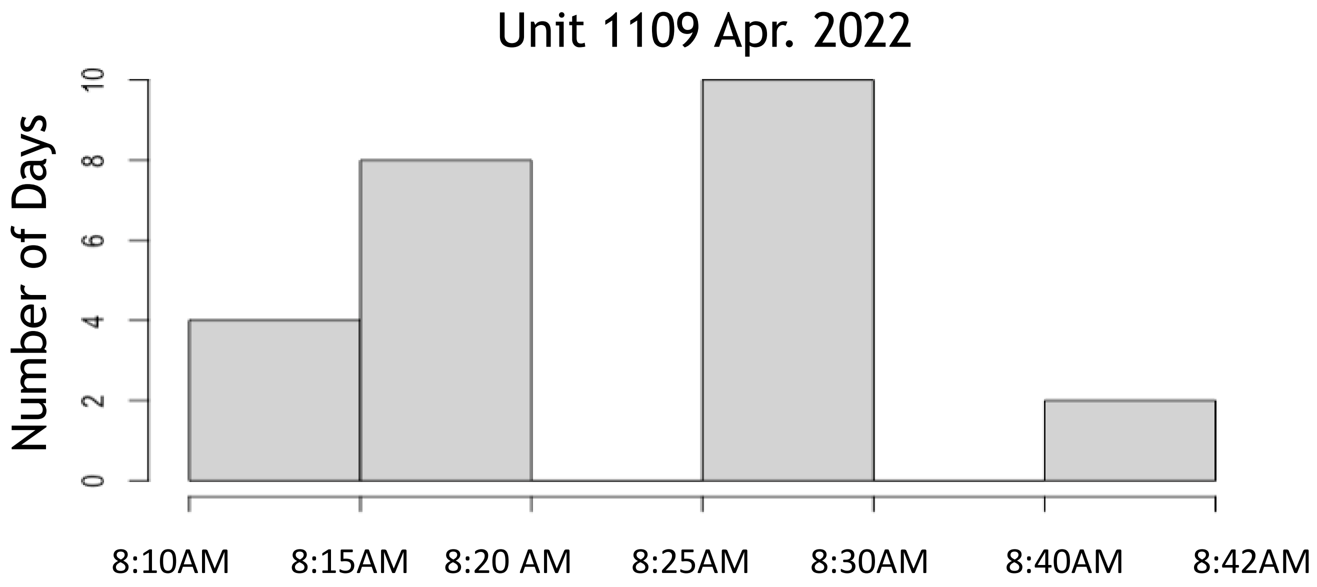
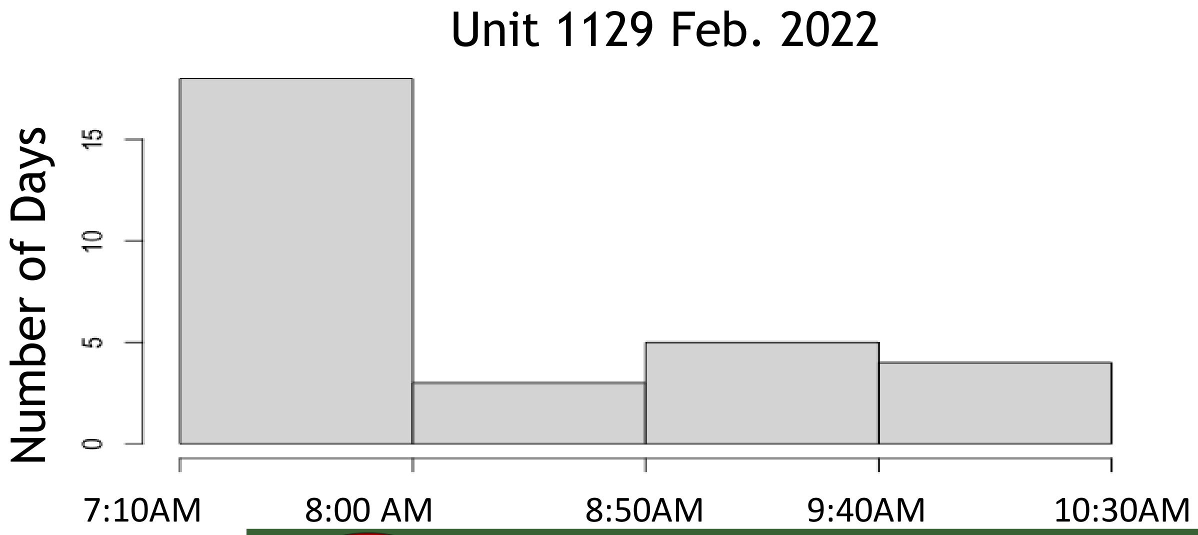
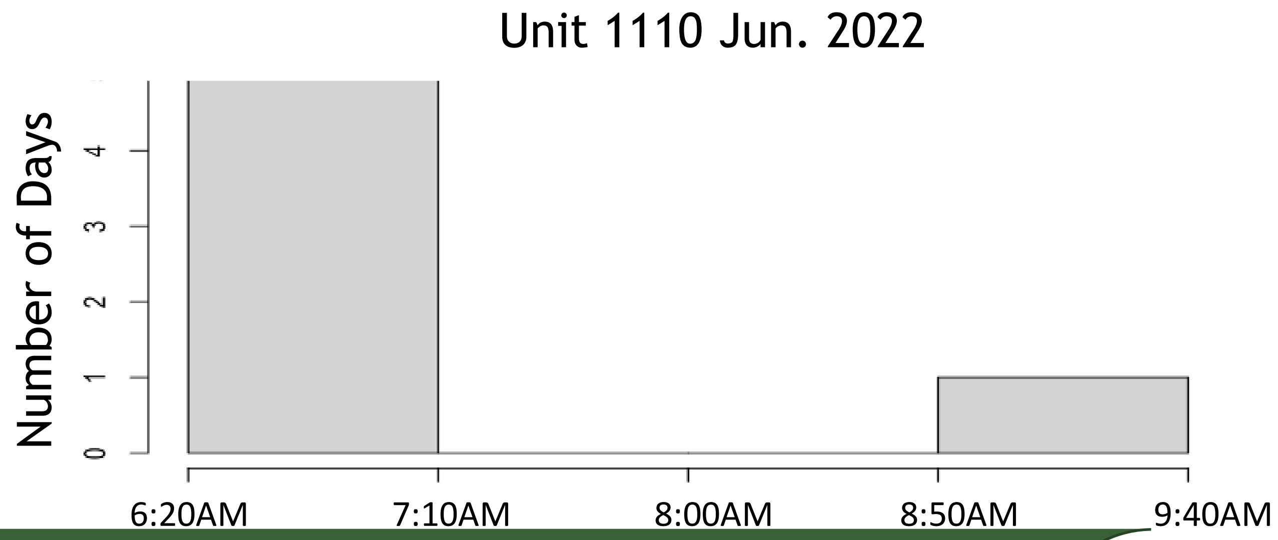

Number of 10-minute Intervals
0
500
1000
1500
50
52
54
56
58
Voltage


Unit 1110 Jan. 2022
Number of Days
0
5
10
15
20
7:10AM
8:00AM
8:50AM
9:40AM
10:30 AM
11:30AM


Unit 1109 Apr. 2022
Number of Days
0
2
4
6
8
10
8:10AM
8:15AM
8:20 AM
8:25AM
8:30AM
8:40AM
8:42AM


Unit 1129 Feb. 2022
Number of Days
0
5
10
15
7:10AM
8:00 AM
8:50AM
9:40AM
10:30AM


Unit 1110 Jun. 2022
Number of Days
0
1
2
3
4
6:20AM
7:10AM
8:00AM
8:50AM
9:40AM

Conclusions

- Over 100 million inverter AC-side power consumption data points analyzed from off-grid homes on the Navajo Nation
- Average consumption was 3.58 kWh/day---far lower than grid-connected homes in the region, but far higher than incipient off-grid users in Sub-Saharan Africa
- Wide range of energy-use characteristics among the homes
- PV and inverter sizes could be reduced (or demand stimulated); segmented approach used
- Battery bank supplies 75% of homes with targeted DoA

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Next Steps

- Utilize battery voltage to gain further insight on system operation and reliability
- Survey users to understand appliance ownership/usage and demographics
- Collect irradiance data from systems
- Develop high-resolution load profiles
- Reliability analysis

Acknowledgements

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Additional Collaborators and Contributors

Dr. Stanley Atcitty (Sandia National Laboratories)

Dr. Peter Romine (Navajo Technical University)

Mr. Darrick Lee (Navajo Technical University)

Mr. Scott O’Shea (KiloWatts for Humanity)

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