

IEEE Molokai Energy Equity Projects Using Nano-Grids & Mini-Grid With Internet Access Leads To Social Equity (Year 3 Update)

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Abstract— In 2023, we initiated the IEEE Molokai Energy Equity project to bring low-cost renewable energy (solar + battery) to low-income, most vulnerable Native Hawaiian families on Molokai. Agricultural-Homestead families must live off-grid without access to electricity from the utility (Hawaiian Electric), we replaced their high use of fossil fuel (gasoline for electric generators and propane gas for cooking and heating water) with solar + battery. The economic and social benefits were huge, saving a family of 4 on average \$750/month or \$91K over 10 years. This was life changing, improving Quality of Life through 100% electrification and family health/well-being by eliminating gas cooking the #1 cause of asthma in children. We also provided each family with reliable internet access using StarLink with WiFi sharing between Homesteads, bringing the World Wide Web into each home benefiting their children's education/learning, business and healthcare access. For most vulnerable grid-connected families requiring power 24/7 for home medical dialysis machine and oxygen breathing equipment, we provided safety & resilience to the numerous random power outages on Molokai with a Plug-n-Play solar + battery system reducing electricity costs 39-70%. This also provided local Molokai workforce jobs and new business opportunities for Social Equity.

Keywords— energy equity, social equity, resilience, solar + battery, ground mount solar, nano-grid, internet access, WiFi sharing, battery-only.

I. INTRODUCTION

The global mean temperature exceeded 1.5°C for the first time in 2024 (1.54°C) but decreased to 1.44°C in 2025 reported by Berkeley Earth shown in Fig.1 [1]. The atmospheric CO₂ levels on top of Mauna Loa observatory also saw its largest increase year to year up 3.6PPM reaching a new high of 430.5PPM in May 2025 shown in Fig.2 [2]. Fossil fuel usage still dominates United States (U.S.) electricity generation, and the generation level has been flat the past decade at ~4.0TWh/day or 1,500TWh/year [3]. But it will need to double in a few years driven by increased electricity demand from: 1) EV (Electric Vehicle) fast charging needs unless solar-battery cars become popular and 2) Super Data Centers rapid growth for AI (Artificial Intelligence) [4]. An nVIDIA Blackwell chip uses ~1kW of power and a Super Data Center has 500K-1M chips. If you add cooling power requirements you are at a mini nuclear power plant of 2GW power. Therefore, Fighting Climate Change and Global Warming will

require everyone to be Good Citizens of Earth and do their part by adopting renewable energy at home [5].

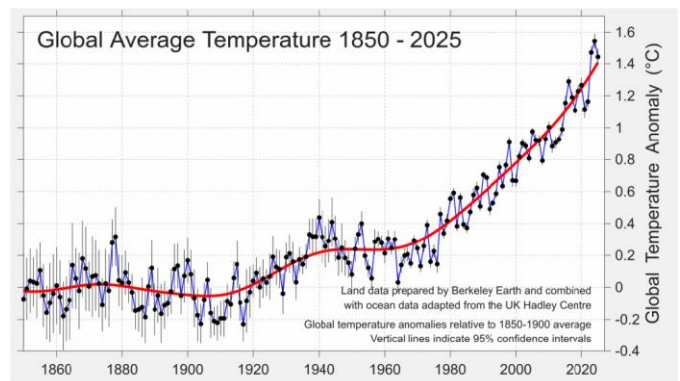


Fig.1: Global temperature rise for 2025 [1].

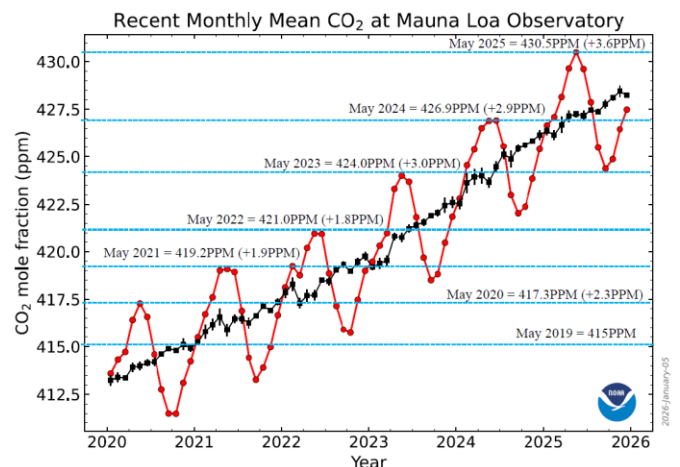


Fig.2: NOAA atmospheric CO₂ levels from 2020 to 2026 [2].

Rooftop solar adoption in Hawaii is at 40%, the “Haves”. The “Have Nots”, renters and those living in apartments or high-rise condos without access to rooftop solar can use indoor LFP (lithium-iron-phosphate) solar-battery generators with small ground mount, portable or balcony solar as Plug-n-Play systems. If there is no space for solar panels, then another option is “Battery-Only” as reported by Borland at PVSC-2022 [6]. Proper battery sizing is required to handle 100% of the overnight home electricity demands as an overnight household

appliance, this requires digitization for home energy use monitoring. High residential solar penetration markets like HI and CA have offered time-of-use (TOU) rates since 2017 to promote daytime load shifting and grid-buy of electricity when grid solar energy is abundant. Daytime electricity rates can be half the regular rates, reducing the monthly electricity bill by 50% as shown in Fig.3 for Molokai TOU electricity rates from 2017 to 2025. The National average electricity price increased 1.4x over 4 years from 13.5¢/kWh in 2021 to 19.0¢/kWh in 2025, while Molokai rates increased 2.3x over 2 years from 25.0¢/kWh in July 2020 peaking at 57¢/kWh in Aug 2022 then dropping 28% to 41¢/kWh by May 2025 (Fig.3). The volatility in Molokai electricity rates reflects changes in oil prices. In 2025, the average electricity rate was 42¢/kWh while daytime TOU rate was 20.5¢/kWh (9AM to 5PM), evening peak was 61.4¢/kWh (5PM to 10PM) and overnight was 40.9¢/kWh (10PM to 9AM). Low daytime TOU rates are very attractive for low-income families to significantly reduce their Energy Burden and end Energy Poverty but requires battery storage for nighttime home energy needs. Table 1 shows how “Battery-Only” with TOU daytime rates can reduce energy burden of low-income families compared to Community Solar based on usage [7].

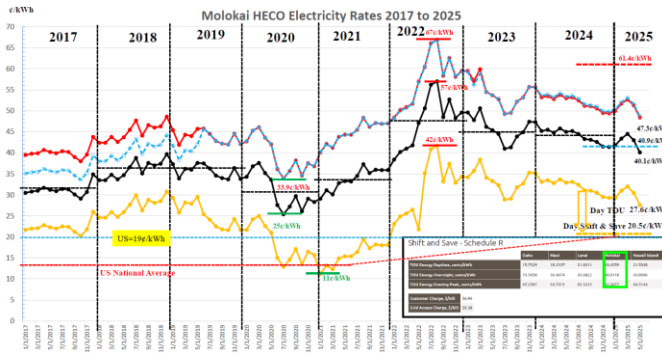


Fig.3: Molokai residential Hawaiian Electric electricity rates from 2017 to 2025.

Energy Burden	HI	HI	HI	HI	HI	HI
Family Energy Usage	No Solar	CSS	Battery Only	Battery +	Community	Community
Low Usage = 325kWh/month	/ (Savings)	/ (Savings)	/ (Savings)	Portable-Solar	Solar/Battery	Solar/Battery
High Usage = 1250kWh/month			100% (-20-35% Savings)	/ (Savings)	/ (0% Savings)	/ (25% Savings)
Affluent Low Usage (Molokai)	2.4% (0%)	0.3% (8%)	1.3% (4%)	1-0.3% (55-87%)	2.30%	1.80%
Affluent High Usage (Dahu)	6.6% (0%)	0.3% (95%)	3.3% (49%)	2.7-0.3% (58-95%)	5.90%	4.90%
LMI Low Usage (Molokai)	9.9% (0%)	1.3% (87%)	5.6% (43%)	4.3-1.3% (55-87%)	8.90%	7.40%
LMI High Usage (Dahu)	22.5% (0%)	1.3% (95%)	13.9% (49%)	11.5-1.3% (58-95%)	24.70%	20.40%

Table 1. Energy Burden analysis based on usage for Low-Income (<\$25K) versus Affluent (>\$100K).

II. MOLOKAI NATIVE HAWAIIAN FAMILIES

The greatest energy insecurity and social inequity in Hawaii is on Molokai Island where a Honolulu Civil Beat article by Teruya on 9/22/2021 reported many Native Hawaiian residents live without a connection to the grid because of the high electricity rates (45¢/kWh) and fees to bring powerlines varies between \$10-40K [8]. The article quotes “When the sun sets on Molokai, hundreds of homes go dark. ...forcing many families to choose between using power at night or feeding their children”. Similar off-grid living experiences were also reported for Navajo Nation in a CNN News report on 7-3-24 [9]. NPR reported off-grid Hopi Tribe solar funds cut 10-10-25 [10]. Molokai has a population of 7,350 residents

with 63% of Native Hawaiian ancestry (4,630). Molokai has frequent power outages (blackouts) and high volatile energy costs (Fig.3). Basic necessities includes housing, food, transportation and utilities. Currently about 11% (514) of the Native Hawaiians live on 129 agricultural homestead lots and this number is growing. Department of Hawaiian Home Lands (DHHL) on Molokai has a waitlist of 2,149 for 1,133 agricultural homestead lots and 815 residential homestead lots. DHHL awards “Raw Land” to fulfill the wait list, 5 acre lots for 99 year leases at \$1/year. Homesteaders are responsible for infrastructure, developing water, sewage, solid waste disposal, electricity and communication. Off-Grid homesteaders live like permanent campers [8].

The Office of Hawaiian Affairs (OHA) reported the 2024 median Molokai Native Hawaiian household income is \$30,603 [11]. To minimize cash expenses, subsistence is an economic necessity on Molokai, hunting, fishing and farming supports their families, not a cultural hobby, it’s a critical, non-cash economic activity essential for food security. Bartering between agricultural homesteaders for food and services is commonplace on Molokai due to high cost of living and close community where everyone knows each other. Preserving food, fish and game (deer meat) requires refrigeration capability 24/7, making off-grid electricity a matter of food security not a mere convenience. The average Molokai family uses 10kWh/day of electricity. Grid-connected families’ electricity expense is \$1,800/year for an energy burden of 5.9% while off-grid families’ fossil fuel expense is \$10,200/year for an energy burden of 33.3%.

III. OFF-GRID HOMESTEAD LIVING EXPENSES

A typical off-grid family consumes 88 gallons of gasoline per month to power their electric generator, gasoline price on Molokai is \$5.80/gallon costing \$510/month [12]. Six bottles of propane is used monthly for hot water heating and cooking costing \$240/month. Add purchase of a bag of ice for ice box/chest for cold food storage and medicine at \$50/month and coin operated laundry for clothes washing and drying at \$50/month. Total energy related costs is \$850/month or \$10,200/year, a 33.3% energy burden. Over a 10-year period the energy expense/payment for fossil fuel is \$102,000. Idling generators consumes gas, so this equates to \$28/day, or \$2.80/kWh based on 10kWh/day consumption.

A. Social Equity Economic Benefits:

Over a 10-year period, would it be cheaper to 1) remain off-grid using fossil fuel, 2) add solar + battery for Island Nano-Grid or 3) connect to the grid with overhead powerlines at an added expense between \$10-40K? The answer for these various options are shown in Fig.4 showing the estimated yearly energy costs (expense or net savings) at 10-years and 20-years with battery system replacement at year 15. This is similar to an analysis reported by Sadat and Pearce on the economic threat of Grid defection in the U.S. where utility rates are high [13]. For CA and HI with high electricity rates 30-60¢/kWh, they show residential Nano-Grid payback/breakeven is 6-10 years then “Free Electricity for Life” and the electricity net savings can be \$45,000 over a 25-year period with battery replacement every 8 years. In

Hawaii, the monthly grid connection fee is \$16/month with minimum bill of ~\$32/month for grid access. At 10kWh/day, the monthly utility bill is \$149/month, \$1,800/year for energy burden of 5.9% and 10-year total expense of \$18,000 or \$36,000 over 20 years. Even if you add the cost of powerline connection at \$10-40K, the net savings will be \$44-74K, compared to \$102K expense with fossil fuel, but grid-connection is not resilient and subject to grid blackouts. Community Solar also requires up front powerline connection expense between \$10-40K, electricity rate reduction/savings would be 20% reducing the monthly bill to \$119/month, or \$1,430/year for energy burden of 4.7% and total electricity expense over 10 years would be \$14K (no “Free Electricity for Life”). The best economic solution is Island Nano-Grid where you get “Free Electricity for Life” after the short payback period of 1 year based on a system cost of \$10K if cash ownership or 5 years for Rent/Lease-to-Own model. Energy burden is reduced from 33.3% to 1.9% and after 10 years, net savings would be \$91K for cash ownership or \$51K for Rent/Lease-to-Own. Note that only Nano-Grid provide safety/resilience and security to blackouts. For a large multigenerational Homestead (17 family members) living in 5 wooden hut homes and a mini-bus home shown in Fig.5, we had to design a Mini-Grid connecting them all via trench buried powerline in Oct 2023. They were spending \$2,100/month on fossil fuel expenses. During the winter rainy season, Hawaii can experience 3-4 consecutive days of rain without sunshine. We designed this Mini-Grid system with an 8kW ground mount canopy solar array, 8 feet tall that provides shading on sunny hot days with 30kWh Li-ion battery storage and a small 2kW gasoline generator for backup power. Cloud based monitoring of each home energy demand is critical to maintain Mini-Grid performance and prevent overload fault and battery overnight full discharge (dead battery) in case one of the 6 interconnected homes has an excessive energy use spike. This requires cooperation and energy balancing with daytime load shifting to minimize nighttime battery discharge using smart IoT devices.

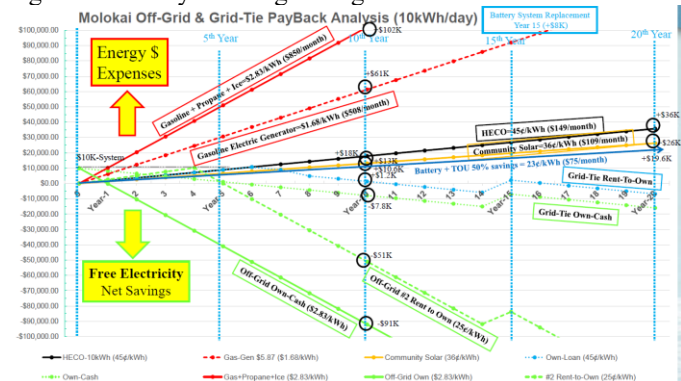


Fig.4: Off-Grid homestead yearly energy expense or net savings with Free Electricity for various sources of electricity (grid-connection to utility or community solar versus Nano-Grid) with battery replacement at year 15.

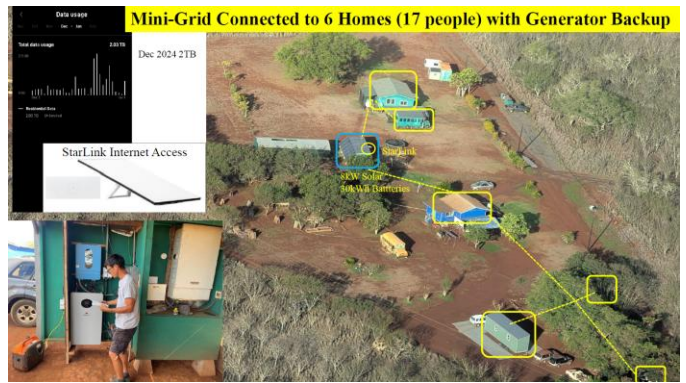


Fig.5: Mini-Grid solar + battery + generator for a large multigenerational Homestead (17 people) with 6 connected homes using trench buried powerlines and StarLink for internet access and WiFi sharing for energy ecosystem monitor and control to prevent dead battery.

B. Social Equity Environmental Benefits:

We replaced high usage of fossil fuel (88 gallons of gasoline/month and 6 bottles of propane/month) with 100% renewable clean energy from the Sun, achieving decarbonization for Zero Carbon Home. In 2023 we replaced fossil fuel usage at 2 homesteads (8-homes and 23 people), in 2024 at 2 more homesteads (2-homes and 9 people) and in 2025 at 3 homesteads (3-homes and 6 people), all shown in Fig.6. In Fig.7 we show an off-grid homestead farm (family of 2) with gasoline generator, propane gas cooking and water heating and ice chest. They have livestock and grow plants, spending \$400/month on fossil fuel. In Sep 2025 we installed a ground mount canopy solar array with battery to replace fossil fuel use.



Fig.6: Cluster of 6 Naiwa Homesteads and 3 Hoolehua Homesteads.

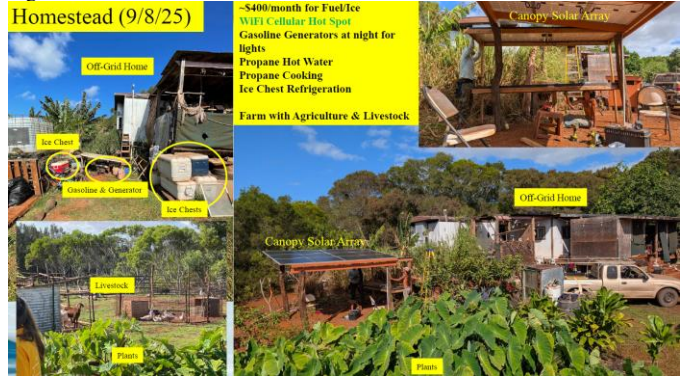


Fig.7: Off-Grid Homestead farm Sep 2025 showing a) before ice chests and gasoline containers and b) after ground mount canopy solar array.



Fig.11: Off-grid Plug-n-Play solar-battery generator with wind turbine.

A. Social Equity Economic Benefits:

The volatility of residential electricity rates for Molokai was shown in Fig.3. In Fig. 4 we showed the Molokai energy expense/saving cost analysis for both off-grid and grid-connected homestead families. Below in Fig.12, we show more details for various grid-connected options including “Battery-Only” for families without access to solar to reduce yearly payment expenses and energy burden. At 45¢/kWh, grid-connect monthly payment/expenses of \$149/month is \$1.8K/year and over a 10-year period will total \$18K for an energy burden of 5.9% using \$30,603 as the Molokai Native Hawaiian median annual income. Civil Beat reports since June 2023, Community Solar on Molokai has failed to gain traction with only 15 subscribers [17]. With a 20% savings the \$119/month is \$1.4K/year for an energy burden of 4.7% and 10-year total expense of \$14K, a savings of \$4K. However, homes with medical equipment, grid-connection does not provide safety/resilience to blackouts, this requires Nano-Grid technology. Battery-only Plug-n-Play system with daytime TOU rate of 23¢/kWh would be \$75/month or \$900/year for an energy burden of 2.9% and over 10-years a total payment of \$9K to Hawaiian Electric based on a \$1.6K battery system for a total savings of \$9K. The best option is cash ownership for a \$10K solar + battery system and “Free Electricity for Life” after payback period of 5.5 years and 10-year total savings of \$7.8K with an energy burden of 1.3%. The 2nd best option is Rent/Lease-to-Own with a 10-year expense/payment of \$1.2K and “Free Electricity for Life” after payback of 10.5 years. Hawaii has very favorable short payback periods because the utility electricity rates are very high (>40¢/kWh), 2-3x the National average of 19¢/kWh. In Hawaii residential rooftop solar LCOE is 4.5¢/kWh while battery storage is 14.5¢/kWh reported by Borland [18].

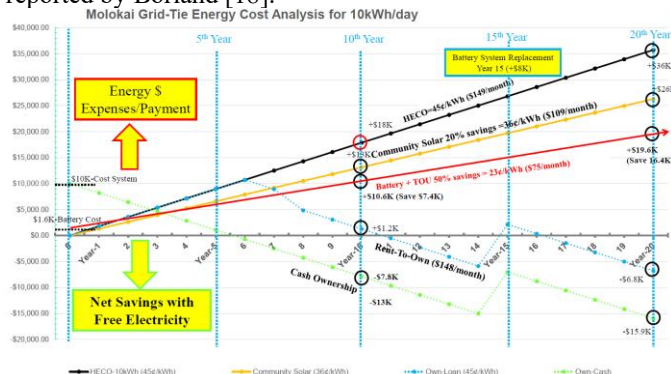


Fig.12: Options to reduce grid-connected yearly electricity payments from Community Solar→Battery-only→Rent/Lease-to-Own→Cash ownership.

B. Social Equity Home Digitization Benefits:

Digitization using Smart IoT devices for home energy monitor/audit to identify energy waste for corrective action is critical, as the saying goes “Out of Sight means Out of Mind”. We installed the smart IoT device at the section-8 renter who was disconnected from the utility (Hawaiian Electric) due to unpaid utility bills and was able to take corrective action and reduce the bill by 70% shown in Fig.13a. The Pareto Analysis showed top two energy wastes were AC (air conditioner) at 43% running 24/7 and electric water heater thermostat problems also at 43% in Fig.13b accounting for 86% of the daily home energy use. Reducing it from 17kWh/day to 7kWh/day, the bill went from \$251/month to \$75/month. With the money saved the renter started a home aquaponics farm business in the backyard (new business social benefit). A large section-8 family using 31kWh/day bill was \$400/month. The home energy monitor/audit device identified water heater issues with their solar thermal water system. Based on Pareto Analysis results and using behavioral Direct Load Control techniques, they reduced utility bill by 56% to 13kWh/day shown in Fig.14a. The solar thermal hot water heating system electricity demand was reduced from 12kWh/day to <1kWh/day shown in Fig.14b, saving \$220/month.

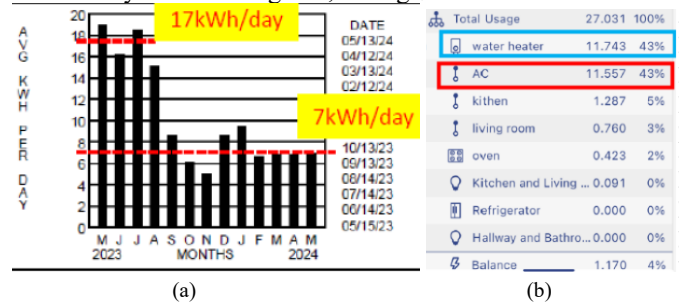


Fig.13: Reducing electricity bill by 70% with home energy audit using Smart IoT devices.

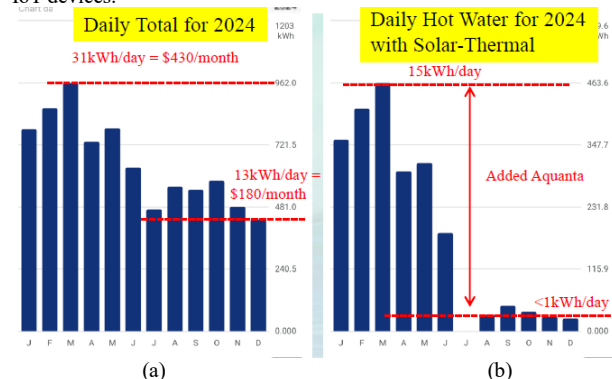


Fig.14: Smart IoT devices allows 56% reduction in energy waste: a) monthly total home energy usage and b) monthly water heater element load.

C. Social Equity Family Health & Well Being Benefits:

Grid-connected families with home lifesaving medical equipment requires safety/resilience to random blackouts. We first installed the home energy monitor, Smart IoT device (Sep 2023) to determine energy used over 1 week during each 4-hour home medical dialysis machine session shown in Fig.15. Each session starts at 3:30PM and ends at 7:30PM, the dialysis machine power is 150W and the room AC power is 460W for

610W total power and 2.4kWh/session. In Dec 2023 we installed a Plug-n-Play 3.6kWh LFP solar-battery generator with a 1.4kW ground mount solar array in the backyard, reducing utility bill by 39%. The family with a bedridden member, oxygen/humidifier equipment requires 250W power (5.8kWh/day) shown in Fig. 16. In May 2024 we installed an off-grid solar + battery system to provide 2-days of safety/resilience to blackout for <\$10K for “Proactive Loss of Life Prevention” [12].

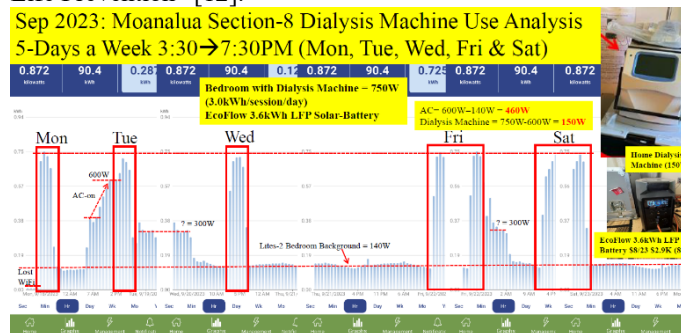


Fig.15 Monitor of dialysis machine session energy demands for 1 week.



Fig.16: Oxygen and humidifier equipment requiring 5.8kWh/day.

V. SUMMARY

The IEEE Molokai energy equity projects ended energy poverty for low-income Native Hawaiian families at 7 off-grid homestead sites and 4 grid-connected renters using ground mount solar array designs. Reliable off-grid internet access was required to monitor and control the solar + battery Nano-Grid and Mini-Grid systems using 3 StarLink systems. IEEE MTTs students using WiFi extenders enabled WiFi sharing between nearby homestead families bringing internet access to all. This had a huge impact on Social Equity benefiting children’s education/learning, jobs, business opportunity and healthcare access. The Hawaii PUC new energy equity docket (#2025-0284) released June 20, 2025 references the IEEE Molokai Energy Equity projects [19]. The Maui News reported Aug, 15, 2025 the IEEE Molokai projects inspired the Maui Rotary Club to model and use the best practices for their Lahaina fire victim recovery plan [20].

VI. ACKNOWLEDGEMENTS

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