Driven Design of a Stand-Alone PV System to Support Residential Loads on the Navajo Nation

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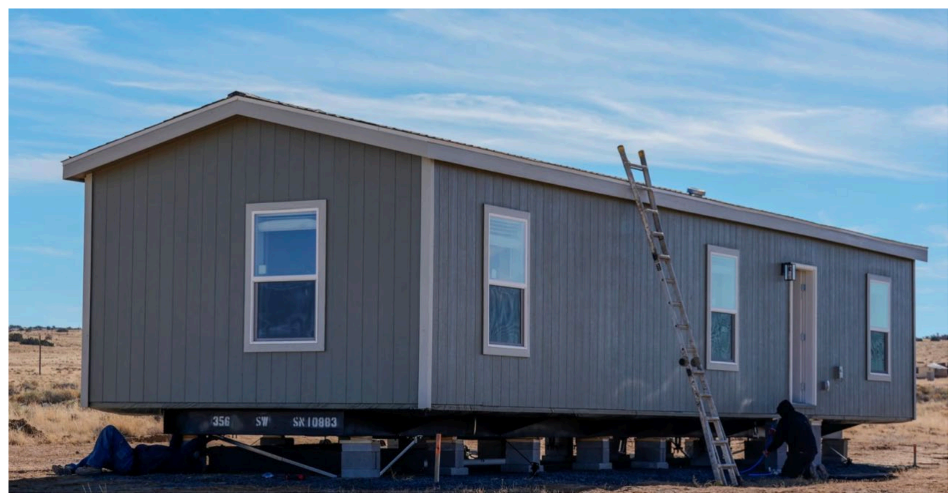
IEEE Rural Electric Power Conference (REPC)
April 2026

Problem Statement

Many Navajo homes are located in remote, rural areas where grid access is limited or unavailable.

- Lack of reliable electricity
- High cost of generator fuel
- Environmental pollution
- Limited access to modern appliances
- Reduced quality of life

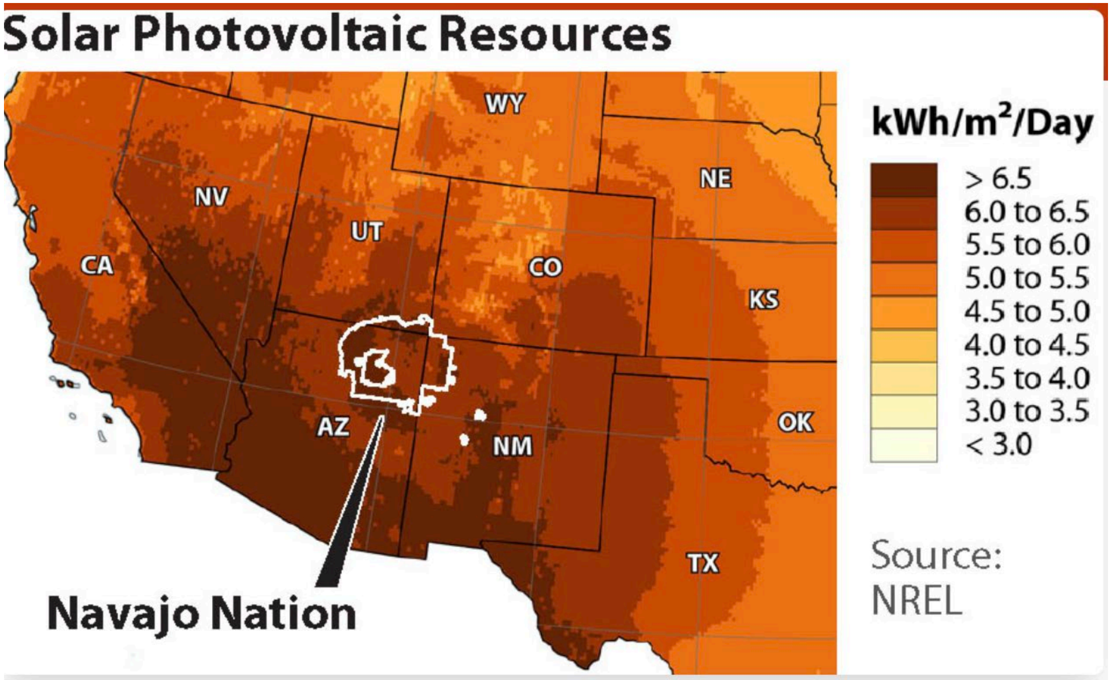


Research Objective

Main Goal

- Design a stand-alone photovoltaic (PV) system capable of supplying:
  - **16 kWh/day household load**
- Develop a 4 kW PV array, a 42–45 kWh $LiFePO_4$ battery bank, a 60–80 A MPPT charge controller, and a 4–5 kW pure sine wave inverter.
- Developed to match **local solar conditions**, load characteristics, and national electrical standards.

Solar Energy Potential



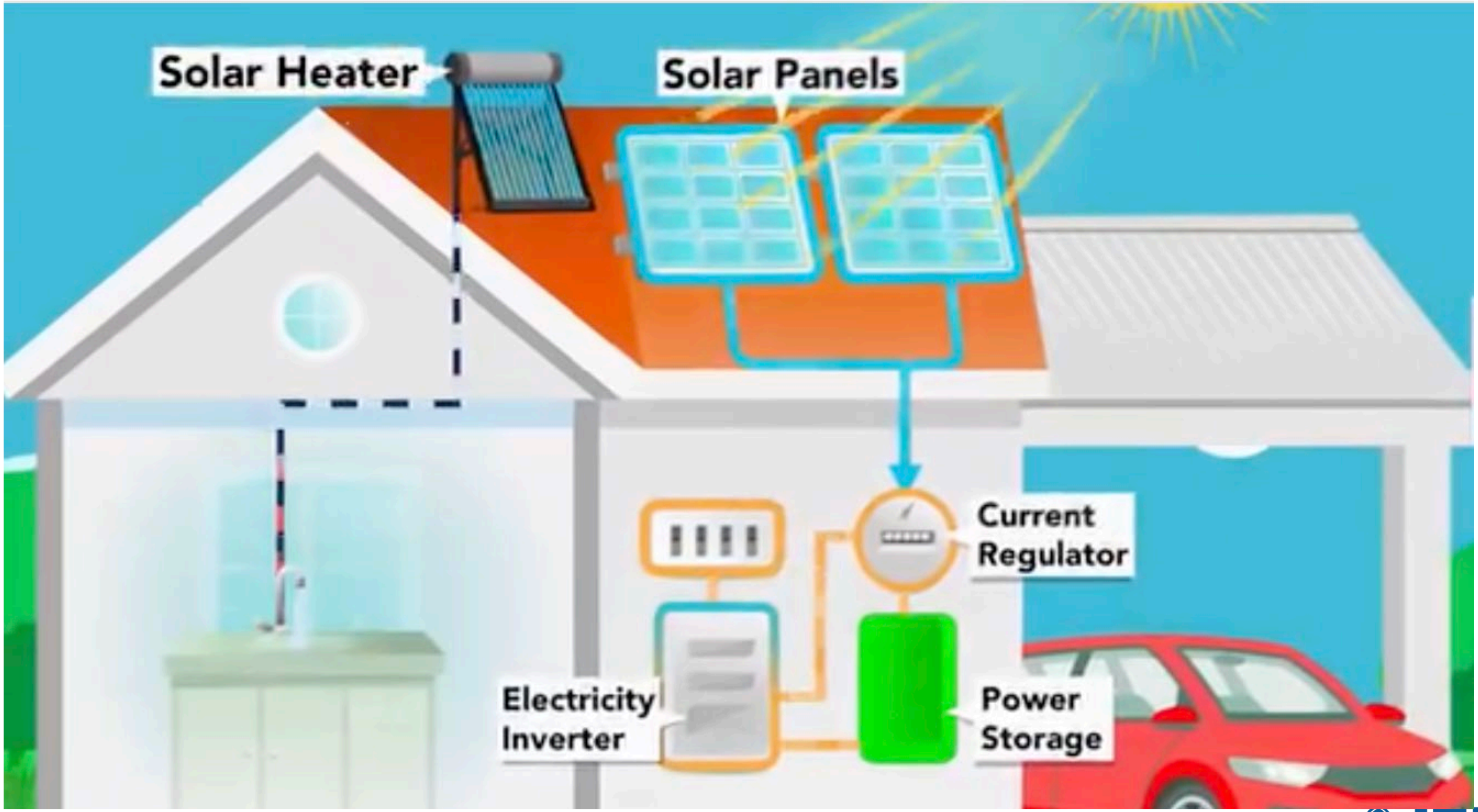
Solar Resource in Navajo Nation

The Navajo Nation covers nearly 27,000 square miles across Arizona, Utah, and New Mexico, making it the largest Native American reservation in the United States. Average solar irradiance:

- 5.5 – 6.5 $kWh/m^2/day$

Navajo Nation House

Design Consideration



Electrical Load Estimation

Table I. SUMMARY OF DAILY LOADS

Appliance	Power Rating (W)	Quantity	Hours Used per Day	Daily Energy Consumption (kWh)
LED Lights	10	10	5	0.5
Refrigerator	150	1	24	3.6
Electric Stove	1,500	1	1.5	2.25
Microwave Oven	1,200	1	0.5	0.6
Washing Machine and Dryer	500	1	1	1.0
Television	100	1	4	0.4
Laptop Charger	65	2	4	0.52
Water Pump	750	1	1	0.75
Space Heater	1,500	1	4	6.0
Phone Charger	10	2	3	0.06
Total Daily Consumption				15.68kWh

Seasonal Variations in Energy Consumption

- Winter: Higher usage due to space heaters, heated blankets, and increased lighting
- Spring/Fall: Moderate appliance use with stable lighting needs
- Summer: Increased fan use and reduced lighting needs; Usage of AC.

TABLE II. SEASONAL ENERGY CONSUMPTOION ESTIMATES

Season	Primary Additional Loads	Estimated Daily Consumption (kWh)
Winter	Space heater (6 hrs), additional lighting	18 – 20 kWh
Spring/Fall	Moderate appliance use, stable lighting needs	13 – 15 kWh
Summer	Increased fan use, reduced lighting needs	12 – 14 kWh

Orientation and Angle for better Irradiance

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Orientation and Angle for Maximum Irradiance

- PV modules achieve maximum irradiance when oriented due south (180° azimuth).
- Optimal fixed tilt angle ≈ site latitude (36°–38°) for Navajo Nation.
- Tilt-angle formulas:
  - $\theta_{opt} \approx \phi$
  - Winter: $\theta_{winter} = \phi + 15°$
  - Summer: $\theta_{summer} = \phi - 15°$

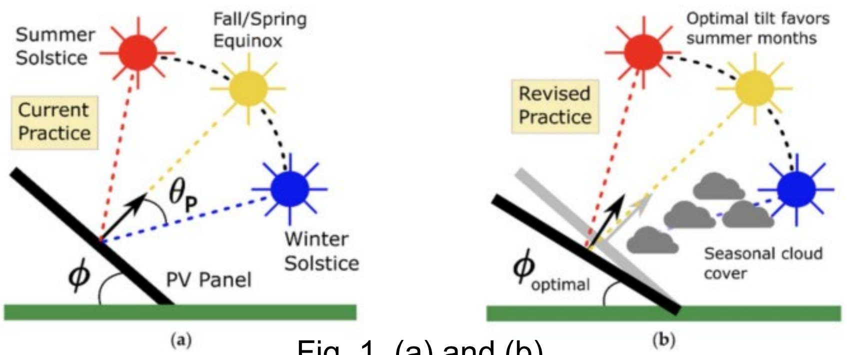

Fig. 1. (a) and (b)

- Seasonal adjustments increase exposure to low-angle winter sun and high-angle summer sun.
- Structural considerations:
  - Minimal shading
  - Strong, wind-resistant mounting
  - Adequate ventilation for cooling

Optimal Tilt Angle

- **Recommended Tilt Angle for PV Panels**
  - **Navajo Nation Latitude:** 36° – 38°
  - **General Rule:** $\theta_{opt} \approx \phi$
    Optimal tilt angle ≈ **local latitude**
  - **Fixed System Recommendation:**
    Tilt Angle: ~37°
- **Seasonal Adjustment (if adjustable mounting is available):**
  - **Winter:** $\theta = \phi + 15°$
    Latitude + 10° to 15° → 47° – 52° (to capture lower winter sun)
  - **Summer:** $\theta = \phi - 15°$
    Latitude – 10° to 15° → 22° – 27° (to capture higher summer sun)
- **Key Benefit:**
  Improves annual energy production and winter performance for off-grid systems.

Solar Panel Calculation

- Series and parallel wiring change array voltage and current.
- Series wiring: Voltage adds with each panel; current equals one panel. Useful to reach higher DC bus voltages for MPPTs and inverters and to reduce conductor current and **I^2R losses**.
- Parallel wiring: Current adds with each string; voltage equals one panel. Useful when a **lower DC voltage is required**, but it increases conductor size and protection requirements.
- Design impacts: Wiring choice affects **MPPT/controller** voltage window, conductor gauge, overcurrent protection, and cold-temperature Voc checks.
- Site context: High irradiance (≈5.5–6.5 kWh/m²/day) often favors series-dominant stringing to reduce current losses, provided cold-temperature Voc and controller voltage limits are respected.

Solar Panel Calculation

- Series wiring increases array voltage while parallel wiring increases array current.

TABLE III. COMPARISON OF SOLAR PANEL RATING IN SERIES AND PARALLEL

Panels Connected in Series	Panels Connected in Parallel
The output voltage of a series-connected string is the sum of all individual panel voltages: $V_{total=} V_{Panel} \times N$ $V_{Panel} = 20$ $N = 20$ $V_{total=} 20\text{ V} \times 10 = 200\text{ V}$	In a parallel configuration, all panels share the same Voltage $V_{total} = V_{Panel}$ $V_{panel} = 20\text{ V}$ $V_{total} = 20\text{ V}$
Current in a series array remains equal to the current of one panel: $I_{total} = I_{Panel}$ $I_{Panel} = 20\text{A}$ $I_{total} = 20\text{ A}$	Total current in parallel $I_{total} = I_{Panel} \times N$ $I_{panel} = 20\text{A}$ $N = 10\text{ panels}$ $I_{total} = 20\text{ A} \times 10 = 200\text{ A}$
Total Power Output $P_{total=} V_{total} \times I_{total}$ $P_{total} = 200\text{ V} \times 20\text{ A}$ $P_{total} = 4000\text{ W} = 4.0\text{ kW}$	Total Power output $P_{total} = V_{total} \times I_{total}$ $P_{total} = 20\text{ V} \times 200\text{ A}$ $P_{total} = 4000\text{ W} = 4.0\text{ kW}$
high voltage, same current	same voltage, high current

Preferred Connection

- **Series or series-parallel connections are preferred** in the Navajo Nation due to:
  - High solar irradiance and long sun hours → higher DC voltage, lower current
  - Reduced line losses over long wire runs in remote areas
  - Higher MPPT efficiency when array voltage far exceeds battery voltage
  - Improved energy extraction in desert/semi-arid conditions
- **Parallel-only arrays are less efficient** for off-grid systems with long distances.
- **Chosen configuration**:
  - 2 strings × 5 panels each (Series-Parallel)
  - Delivers high voltage, low current, and greater efficiency for rural homes.

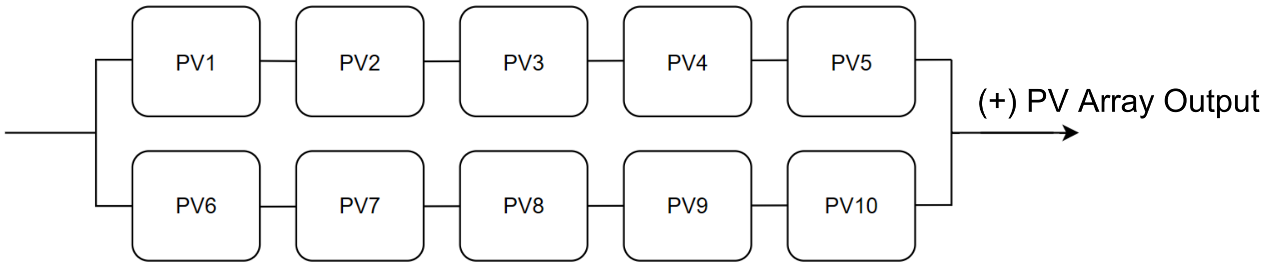

Fig 2. Series parallel combination (String 1 + String 2)

Battery Capacity for a Stand-Alone PV System with a 16 kWh/Day Load

- **System Configuration**
  - Nominal Voltage: 48 V DC (efficient, smaller cables)
  - Required Capacity:
    - $Ah = 44{,}000/48 \approx 917\ Ah$
  - Practical bank: 48 V, 900–950 Ah $LiFePO_4$
  - Modular rack-mount or outdoor units
- **Why it Works**
  - Two-day energy reserve for cloudy/snowy periods
  - Long service life & high temperature tolerance
  - Meets IEEE off-grid design guidelines
  - Ensures reliable, resilient, year-round power for remote Navajo homes

Charge Controller Sizing

- Purpose: Regulates charging of 48 V $\mathrm{LiFePO_4}$ battery bank; prevents overcharging, overcurrent, and voltage instability.
- System Context
  - PV Array: 10 x 400 W = 4 kW
  - Configurations: 5S x 2P (five in series, two in parallel)
  - Array current(Standard: 40 A
- IEEE 1562 & NEC 690 safety factor: 1.25 x 1.25 = 1.56
- Calculation
  - $I_{controller} = I_{array} * 1.56 = 62.4\ A$
- Satifies:
  - Required rating ≥ 63 A
  - PV input voltage ≥ 100V

5-module series string → ≈ 200 V nominal; compatible with 48 V systems using MPPT

Recommended MPPT Charge Controller

- Why MPPT?
  - **94-99% efficiency**
  - Higher yield under varying sunlight and temperatures
  - Extracts more power in mornings/evenings
  - Works with high-voltage PV strings
  - Recommended by NREL/SEIA for off-grid systems
- Benefits
  - **Meets IEEE 1562 & NEC 690 guidelines**
  - **Operates safely above 62.4 A load**
  - Supports expansion & cold-weather voltage spikes
  - Proven reliable in remote Navajo installations

Parameter	Recommended Value
Type	MPPT
Input Voltage	150 V DC
Output Voltage	48 V nominal
Max Output Current	60-80 A
Efficiency	> 98 %

Inverter Surge & Efficiency

- **Surge Requirement:**
  - $P_{surge} = P_{continuous} * SF = 3\ kW * 2 = 6\ kW$
  - Inverter must handle ≥ 6 kW surge
- **Efficiency factor:**
  - $E_{required} = Eload/\eta_{inverter} = \frac{16}{.09} \approx \frac{17.8kWh}{day}$
  - Battery bank (42-45 kWh) easily supports this demand
- **Recommended inverter:**
  - 4-5 kW pure sine wave, 48 V DC input, 6-8 kW surge, ≥ 90% efficiency

Inverter Summary

- **Specifications:**

Parameter	Recommended Value
Type	Pure Sine Wave
Continuous Power	4–5 kW
Surge Power	6–8 kW
DC Input	48 V nominal
Efficiency	≥ 90 %
Standards	IEEE 1562 / NEC 690

- **Benefit:**
  - Stable AC supply
  - Reliable for off-grid Navajo homes

Results Summary

System Performance Findings

Component	Specification	Key Notes
PV Array	4 kW (10 × 400 W) 5S2P	200 V approx
Battery Bank	42–45 kWh (48 V) $LiFePO_4$	2-day autonomy
Controller	60–80 A, 150 V input MPPT	>98 % efficiency
Inverter	4–5 kW PSW, 48 V input	6–8 kW surge
Orientation	36–38° tilt, South (180°)	Year-round optimization
Lifetime	PV 15–20 yr, Batt 10–15 yr	High reliability

Conclusion

- **Key Takeaways**
  - 4 kW PV Array + 48 V $LiFePO_4$ Battery (42-45 kWh) delivers reliable off-grid power.
  - 60-80 A MPPT Controller + 4-5 kW Pure Sine Wave Inverter meet IEEE 1562 & NEC 690.
  - System provides 2 days autonomy, high efficiency, and robust winter performance
- Outcome:
  - Sustainable, self-reliant clean energy solution for remote Navajo households
  - Model for wider Indigenous community adoption

Selected References

[1] U.S. Census Bureau, *American Community Survey: Navajo Nation*, 2021.

[2] Navajo Tribal Utility Authority, *Service Area Annual Report*, 2020.

[3] M. Anderson et al., "Solar electrification strategies for U.S. tribal communities," *IEEE Access*, vol. 8, pp. 221982–221995, 2020.

[4] U.S. Dept. of Energy, *Tribal Energy Atlas*, 2021.

[5] J. D. McKenzie, "Energy poverty in Native American reservations," *Energy Res. Soc. Sci.*, vol. 74, 2021.

[6] NREL, *Solar Resource Data*, 2021.

[7] IEEE Std 1526-2019, *Recommended Practice for Testing the Performance of Stand-Alone PV Systems*.

[8] NFPA, *National Electrical Code (NEC) Article 690: Solar Photovoltaic Systems*, 2023.

[9] M. Petri et al., "$LiFePO_4$ battery performance for remote solar systems," *J. Power Sources*, vol. 327, 2016.

[10] NREL, *PV System Design Principles*, 2021.

- *Full reference list available upon request.*


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Achievements of EE Students and Faculty

U.S. Department of Energy's - Solar Decathlon Competion

- Electrical student Edwina Lesli Presented the design paper in the completion.
- **With Martin Keller, The director of National Renewable Energy laboratory**
- **David M.Turk Deputy Secretary of the US Department of Energy**.

Achievements of EE Students and faculty

Four Corners Energy & Water Innovation, Student Symposium

- Strawberry Livingston presented a paper titled
- “ Off-Grid Solar Powered system implementation on the Navajo Nation” conducted at San Juan College School of Energy, Farmington

Achievements of EE Students

The National Renewable Energy Laboratory (NREL)

- Determining the best ways to convert biomass into sustainable aviation fuel.

- In still another, scientists explore the pathway to integrating various technologies onto the nation's electrical grid.

Achievements of EE Students and Faculty

MSIPP (Minority Serving Institution Partnership Program (MSIPP

- Radiation Detection on Abandon Uranium Mines on the Navajo Nation.

- **International Journal of Electrical and Computer System.** https://ijecsd.com/index.php/archive?id=114

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Achievements of EE Students and Faculty

Formula SAE racing car lab at UNM

- Met with Dana C.Wood at UNM .
- Understanding the Wiring Diagram of racing cars.

Achievements of EE Students and Faculty

<u>Tribal Colleges and University Program Research Symposium Feb 2024</u>

- NTU students presented posters on various research topics.

Achievements of EE Students and Faculty

NTEC Navajo Mines A3 Farmington, NM

- The students were introduced to energy availability for a sustainable future, financial stability, and strategic assets.

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Achievements of EE Students and Faculty

NTEC Navajo Mines A3 Farmington, NM

- **Evaluation of Smart Portable Cooling System for Temperature-Sensitive Medicine Delivery in Remote Regions of the Navajo Nation**
- **International Journal of Engineering Research & Technology (IJERT)**
- https://www.ijert.org/evaluation-of-smart-portable-cooling-system-for-temperature-sensitive-medicine-delivery-in-remote-regions-of-the-navajo-nation

Achievements of EE Students and Faculty

<u>Utha State University</u>

- **Evaluation of Smart Portable Cooling System for Temperature-Sensitive Medicine Delivery in Remote Regions of the Navajo Nation**
- **International Journal of Engineering Research & Technology (IJERT)**
- https://www.ijert.org/evaluation-of-smart-portable-cooling-system-for-temperature-sensitive-medicine-delivery-in-remote-regions-of-the-navajo-nation

Achievements of EE Students and Faculty

50th IECON – IEEE conference

- **Improving Indoor Air Quality Using a Box Fan Filter in a Navajo Nation Home-Healthy Hooghan Project.**

- **IEEE Publication**

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Achievements of EE Students and Faculty

AIHEC 2025

- **First price on NASA Rower Competion**

Achievements of EE Students and Faculty

<u>Energozed WaterShed Panel member</u>

- One of the key contributors to the symposium

Achievements of EE Students and Faculty

Learning from the Land at Rio Grande Community Farm

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Learning from the Land at Rio Grande Community Farm

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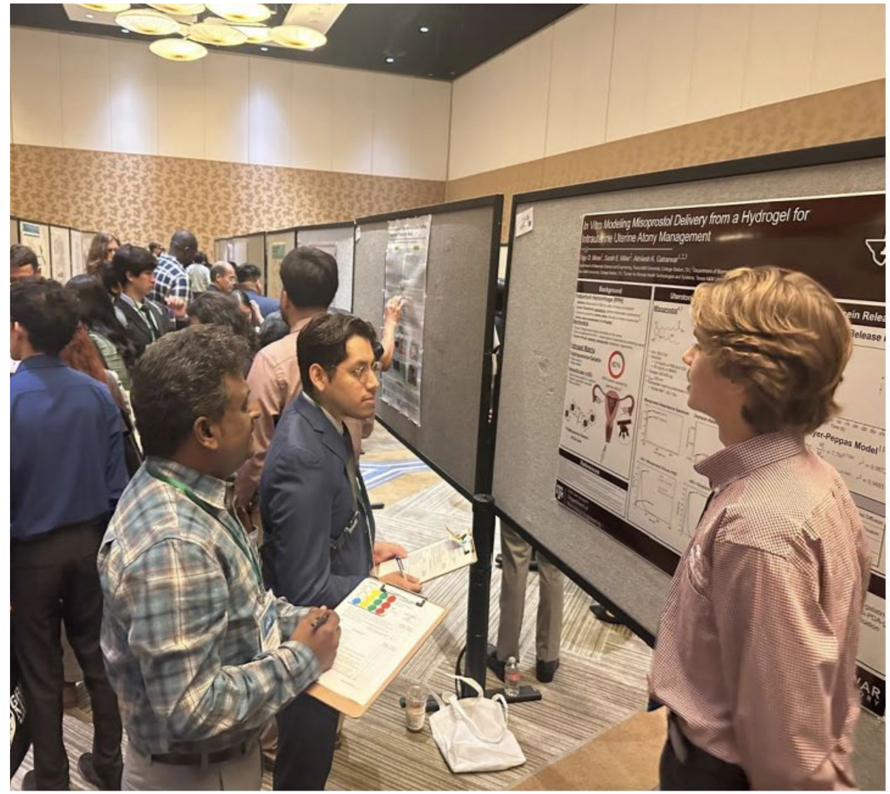
Presentation at the GMIS Conference



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Recent Conference papers by EE students

- 1. Navajo Healthy Hooghan Project: Reducing Household Air Pollution and Asthma Symptoms in Navajo Nation Children - NTU Testing, SJUIT international Conference, Tanzania. July 2023.
- 2. Radiation Detection on Abandoned Uranium Mines on the Navajo Nation, SJUIT international Conference, Tanzania. July 2023.
- 3. Characterization of Radiation Detectors: Uranium Mines Monitoring on the Navajo Nation Utilizing an Aerial Drone. SJUIT international Conference, Tanzania. July 2023.
- 4. Modeling a Box Fan Filter for Navajo Healthy Hooghan Project: Reducing Household Air Pollution and Asthma Symptoms in Navajo Nation Children. SJUIT international Conference, Tanzania. July 2023.

- 5. “The rise of AI driven BMS: Revolutionizing Li-ion Battery Performance”, S. Karthik kumar, A. Deenu Mol, Sundaram Arumugam; V. Gowri Shankar; S. Sharmila; S. Subashini, Published in: 2024 Third International Conference on Electrical, Electronics, Information and Communication Technologies (ICEEICT), Date of Conference: 24-26 July, DOI: 10.1109/ICEEICT61591.2024.10718508, Date Added to IEEE Xplore: 23 October 2024, Publisher: IEEE

- 6. “Improving Indoor Air Quality Using a Box Fan Filter in a Navajo Nation Home - Healthy Hooghan Project” in the 50th IECON (Institute of Electrical and Electronics Engineers) conference – IEEE conference held in Chicago November 3rd to 7th. 2024

Achievements of EE Students and Faculty

Thank you