Smart Home: Interactive Demonstration Tool for Engineering Education and Outreach

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***Abstract*— Outreach programs play a vital role in introducing engineering education and associated pathways to k-12 students. Specifically, opportunities in power and energy industry may be less visible to outsiders and need to be introduced to k-12 students as well as early engineering students. This is critical to promote power and education among future engineers. As such this work aims to develop an interactive demonstration tool that can be used for k-12 outreach and early engineering education. This proposed tool is themed around home energy management and focuses on illustrating the opportunities with renewable generation and home automation. This paper presents in detail the need, design, development and the capabilities of the tool. In brief, this interactive tool can take user prompts to simulate typical home energy consumption profile and roof top PV generation. This also includes energy cost estimation without solar, with solar and with solar & demand scheduling. This tool can be used for standalone demonstrations or as a part of any power and energy focused activities.**

***Index Terms*—Power engineering education, IoT, roof top solar, k-12 outreach, multidisciplinary, grid edge solutions, technological convergence.**

I. Introduction

The past decade has seen a sharp uptick in multitude of technologies that impact the power grid [1]. This includes renewable generation, transport electrification, cyber physical systems and the most recent being Generative AI and the associated datacenters. All of these bring new challenges and opportunities that require innovations to support grid integration and more importantly maximize the benefits by appropriate technological convergence [1] – [2]. This exemplifies the need for the future workforce to be able to design, build and implement these innovations. However, these opportunities do not reach engineering students or future engineers. This is supported by the decline in electrical engineering graduates [3] and firsthand experience of authors through high school outreach programs. This invisibility is due to the lack of introduction to these opportunities in an engaging/intriguing manner at an early stage. This work tries to address this by developing an interactive demonstration tool around a relatable problem. The relatable problem considered in this work is home energy management and sustainable development by leveraging renewable generation and smart IoT (Internet of Things) sensors. The objective of this work is presented in figure 1.

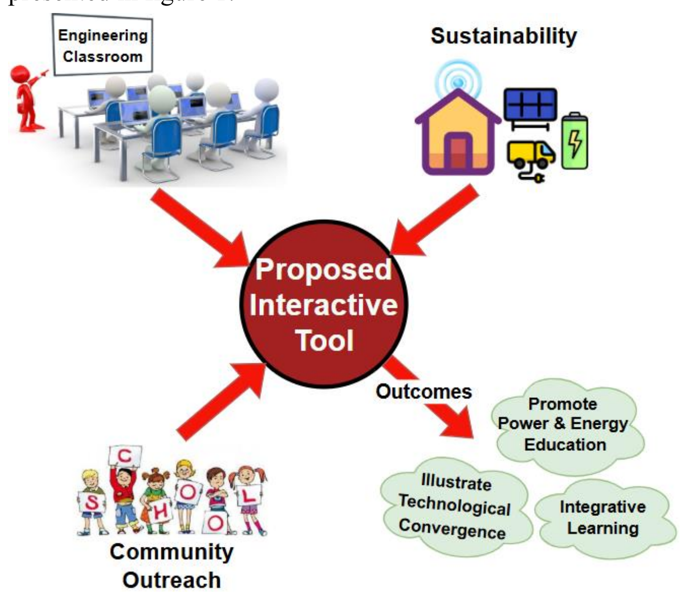

Figure 1. Intended Outcomes from the proposed tool

As shown in this figure, the proposed interactive demonstration tool aims at early introduction (k-12 outreach and Engineering Freshmen) of power and energy systems concepts such as renewable generation and demand side management and through the relatable problem of home energy management. Furthermore, this tool intends to show the technological convergence required at the grid edge to develop sustainable solutions and provides engineering students with an integrative learning opportunity.

Why this, why now: The early introduction of engineering applications through k-12 outreach [4] – [6] and in engineering curriculum through project-based and challenge-based learning (as early as freshmen level) is not new and their benefits have been well documented [7] – [10]. Works such as [4] and [5] provide detailed lessons to help k-12 teachers to introduce renewable generation and sustainability and other works such as [6] and [11] provide resources to introduce electricity generation and grid outside the curriculum through projects and camps. These efforts show the need and benefits of developing resources to introduce power and energy systems to k-12 students. Even among engineering students,

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the effectiveness of leading with context and application have been found to make a difference [7] – [10], i.e., starting with the end user requirements and real-world constraints before introducing engineering principles required for developing solutions. Furthermore, [8] supports the need to do the above at early levels in engineering. In this work the authors introduce electrical and electronic design through relatable applications (such as car's ant-theft circuit and heat sensing alarm) before introducing amplifiers or voltage dividers theoretically. Findings from this work and other recent studies [9] - [10] show that these new pedagogical approaches in engineering education are necessary given the evolution of learning styles and resources available to the new generation of engineering students.

Based on these existing works there are three critical phases for making an effective impact on students through early introduction of engineering problem, (i) ***intrigue*** them through relatable problem statement; (ii) ***involve*** them in requirement analysis and constraint formulation and (iii) through appropriate problem-solving process ***inspire*** them to explore further. Considering these and the observations and feedback received by authors prior work [11], it was clear that an interactive demonstration tool that illustrates sustainable development through user centric and grid aware home energy management would be an impactful way to introduce engineering problem solving and solution development. To the best of authors' knowledge no such tool has been proposed in existing literature for the purpose of outreach and engineering education.

The rest of the paper is organized as follows: section II presents the detailed design of the demonstration tool; section III presents the developed tool and its features and section IV concludes the paper.

II. Design of Smart Home Demonstration Tool

The authors of this work previously proposed summer camp activities themed around roof top PV sizing for residential buildings with the focus on design thinking and developing engineering solutions considering tradeoffs and economics driven design making [11]. Based on the feedback received during the review process and presentation of [11] at the 2025 General Meeting, it was clear that a gamified mock demonstration of demand response would be of great value for showcasing the benefits of synergy between distributed energy resources and grid operations. This will also highlight the sustainable development opportunity through grid edge solutions leveraging technological advancements in sensing, communication and control.

With the above motivation this work proposes a mockup tool that can illustrate the following, (i) remote appliance monitoring and control; (ii) Data acquisition and user interface through IoT sensors and microcontrollers and (iii) benefit of home energy management considering electricity price and user preferences. Figure 2 represents the different parts of this setup.

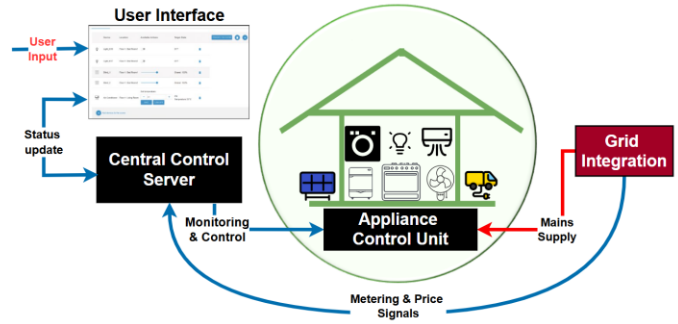

Figure 2. Proposed mock setup

As shown in this figure, this tool would have the following main components, (i) user interface: shows the status of appliances, overall consumptions and generation; takes user prompt to either control specific appliances or simulate the typical day to calculate the typical hourly energy consumption and generation; (ii) the Central control server: receives all the input setpoints and data and sends out the appropriate control signals to appliance control unit and status updates to user interface; enables seamless integration and produces all the decisions and has the logic to scale the meter readings from the mock setup to match the equivalent real-world system; (iii) smart home mock setup: physical setup with appliance dummies and the appliance control unit; mocks the appliance status by turning on the light associated with the corresponding appliance dummy.

The setup presented in figure 2 can operate in two different modes, *Mode 1: Appliance monitoring and control* mode that shows the status of the mock setup and its remote-control capabilities and *Mode 2: Simulator* mode that takes user input to simulate a typical daily routine and provide energy cost estimates with and without roof-top solar generation. In addition to the above the final setup will also have an LED arch that emulates the position of sun at different times of the day. The following subsections explain the details of the mock setup.

A. Appliance Level Monitoring and Control

Each large household appliance (e.g. oven, laundry machine, dryer) is represented with a 3D-printed miniature version with an embedded LED. Ceiling fans and HVAC are each represented with a motor and fan blades. The room lighting is modeled with LED chip bulbs. These mock appliance dummies are then controlled by the appliance control unit.

For appliance level control, each appliance dummies' LED is connected to the ESP32 microcontroller that acts as the appliance control unit. Through the general-purpose input/output (GPIO) pins pf ESP32, the "appliance" (LED) can be turned on or off. For appliances such as fans and HVAC the motors are controlled by PWM pins on the ESP32. All the connections including the appliance control unit are presented in figure 3. In this diagram the appliance controller implemented via the microcontroller ESP32 will control the LED/motor corresponding to the appliance being prompted via the user interface.

To measure household power usage, a system of power sensor is implemented at the appliance level. Appliance level monitoring is achieved using a power sensor breakout board.

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This sensor measures the voltage, current, and power drawn by the house. The effect of appliance operation, including house lighting, can be accurately measured with this sensor for visualization in the user interface (UI). During a simulation, the appliance monitoring data is used by the UI to calculate the energy cost, allowing the user to use the UI to try to optimize their appliance usage for lower energy cost.

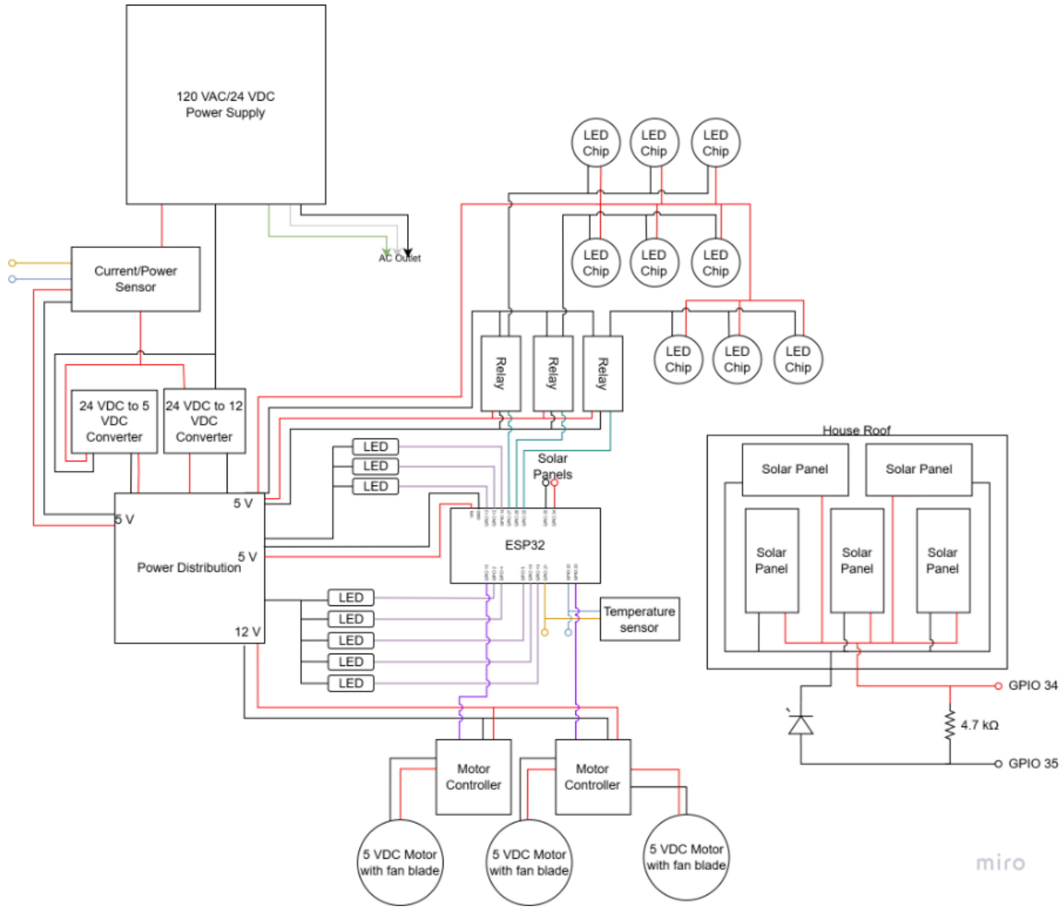

Figure 3. House hardware wiring diagram

B. *Central Controller\Server and User Interface*

For central data acquisition, decision making and control the Raspberry Pi microcontroller is used. The user interface is hosted on a Raspberry Pi which acts as the server as well. Raspberry Pi acts as the middleman between the user and the appliances and links with appliance monitoring and control. The operation of each appliance can be controlled through the UI. Any changes made in the UI are communicated back to the server on the Raspberry Pi. The Raspberry Pi then acts as the central controller and communicates with the ESP32 to control the appliances. In addition to this Raspberry Pi also houses the logic for converting the data from the mock setup to real life equivalent power consumption/generation that gets displayed in the UI. It also has the predefined seasonal solar generation profiles and time-of-use price of electricity required to operate in *Mode 2: Simulator*.

These implementations of the IoT system are done through MQTT (Message Queuing Telemetry Transport) and Node-RED as the core technologies for communication and automation. MQTT was selected because of its lightweight publish and subscribe model, which allows efficient, low-latency data transmission between devices, even on limited networks. Its minimal overhead compared to traditional HTTP protocols makes it ideal for ESP32 microcontrollers, enabling reliable communication with the Node-RED server. This ensures smooth data flow for telemetry and control across all connected devices.

Node-RED was chosen for orchestration and visualization due to its open-source accessibility and intuitive interface, which simplifies the creation of complex automation workflows without requiring advanced programming. The platform's extensive palette ecosystem, including tools like node-red-dashboard, node-red-contrib-ip, and node-red-contrib-ollama, allows for the integration of live dashboards and device discovery.

C. *Solar Generation and Sunlight Simulation*

The idea here is to emulate a residential solar photovoltaic (PV) system using small solar cells mounted to the roof of the mock house. The analog output from the solar is connected to one of the GPIO pins in the ESP32. This output voltage value will be sent to the Raspberry Pi central controller where it gets interpreted as an equivalent real size system output and represented in the UI. The output of the solar cells is also connected to an LED to show the working principle of the solar

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PV. This is in addition the mock values in the graph on the UI to help in case of hardware demonstrations.

In addition to emulating the Solar PV system, it will also be helpful if the sunlight incidence at different times of the day can be mocked. For this purpose, LED strips mounted on an arch (semicircle) can be used to indicate the position of sun at different times of the day. This is specifically utilized in *Mode 2: Simulator,* to illustrate a daily routine of appliance usage and solar generation. This LED arch is not shown in figure 3 and is controlled by a dedicated microcontroller that communicates with the Raspberry Pi central controller. This microcontroller uses a MOSFET driver to switch on the corresponding LED strip on the arch depending on the time of the day.

D. Implementation

The overall implementation of the system begins with breadboarding and testing each part individually before integration into the mock house. The individual parts that need testing include sensors, LED control, motor control, relay control, and solar PV monitoring. Once all are operating as expected and with accurate readings, communication with the central controller Raspberry Pi and the appliance controller ESP32 needs to be implemented. The connection can be tested with control of an LED first, sending a 1 or 0 based on the position of a toggle switch on the dashboard to indicate whether the LED should turn on or off respectively.

After all components are tested and communication between the microcontroller and central controller are established, the system can then be integrated into the mock house with the connections as specified in Figure 3. At this step the power distribution system is introduced. This system originates from 120 VAC outlet power which is converted to 24 VDC with a power supply. To meet the voltage requirements of the system, 12 VDC for the motor drivers and 5 VDC for all other components, two buck converters are used.

After the mock house is built, the lighting is added to each room by installing chip LEDs so the power wires could easily be connected to the front of the chip while the back was mounted to the ceiling. The chip LEDs are gathered into three groups, each group controlled by a relay. This connection method allowed for lighting control with limited pin usage while still accurately modeling lighting usage as groups would be adjacent rooms like stairwell and entryway lighting or a connected bedroom and bathroom. The wiring was routed to the same corner of the house and then out to the relays.

The appliances are 3D-printed, and an LED is installed on each of them. The appliances are printed from white PLA filament so that the LED light can be easily seen. The appliances are then placed in their proper rooms in the house and the LED in each is wired back to the same corner as the room lighting, then the LED anode is connected to its assigned GPIO pin and the cathode to ground. There are two motors mounted in the house to simulate ceiling fans and one motor mounted outside the house to simulate an HVAC. Each of the motors are connected back to the motor driver boards. The motor driver boards are powered by 12 V supply and controlled with a PWM signal from ESP32 based on the UI setpoint.

Once everything is wired and connected back to the ESP32 and power, the UI can be put to test. The UI features include ON/OFF control of appliances and speed control for fans and HVAC and the real-time monitoring of power consumption and generation. Once all these features are tested and verified, at this point, Mode *2: Simulator* that mocks a 24-hour day in 2 minutes can be tested and verified. This process would complete the implementation of the demonstration tool. More information and resources such as design descriptions, bill of materials, design files and manuals are made available online through GitHub repository and are free to download and use[1].

III. ILLUSTRATION OF DEVELOPED TOOL

The tool described in Section II was developed and is shown in figure 4. This figure captures the main components such as the physical mock setup, the LED arch to emulate the position of sun and the user interface. All of the circuitry represented in figure 3 is mounted on the acrylic panel next to the mock home setup and is shown in detail in figure 5.

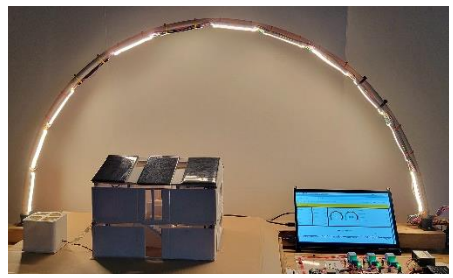

Figure 4. House hardware wiring diagram

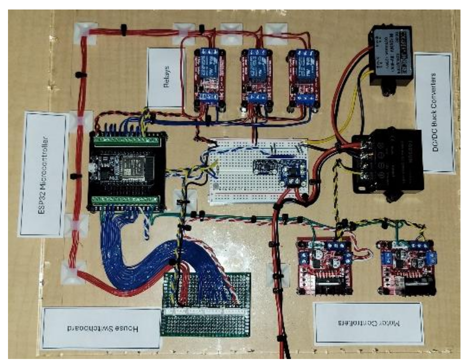

Figure 5. House hardware wiring diagram

On the front end the UI will provide access to three main tabs: Setup, Control Panel, and Simulator. The Setup tab allows users to generate a QR code linking to the web server for easy access and handles the initial distribution of Wi-Fi credentials to ESP32 devices via Bluetooth. The Control Panel and Simulator tabs represent operation modes 1 and 2 and are shown in figure 6. As shown in figure 6 (a) mode 1 enables real-time monitoring and control of appliances, displaying data such as power usage, temperature, and fan speed. The simulator tab takes necessary user input to simulate typical daily usage and generation and provides energy cost estimates

[1] More data can be found on https://github.com/Smart-Building-Energy-Management/

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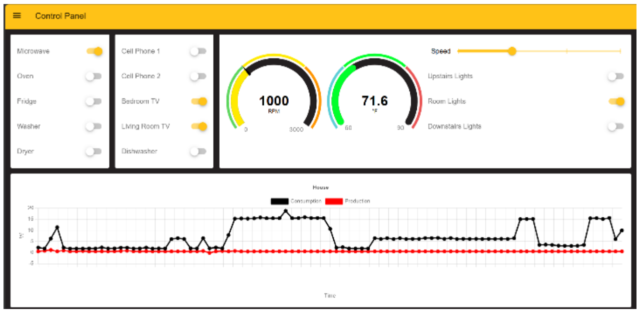
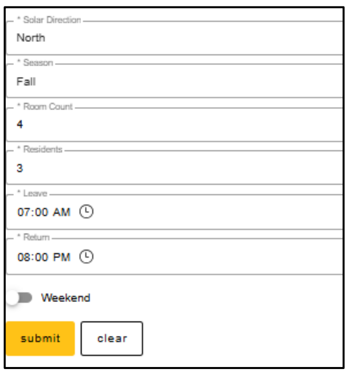
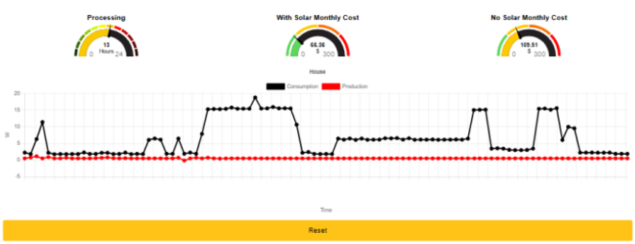
with and without solar generation. The advanced options in this mode enable scheduling appliances such as dishwasher, washer and dryer to simulate cost savings with demand response.



(a) User Interface set in Mode 1



(b) User input: Set points for simulation in Mode 2



(b) Simulation results in Mode 2

Figure 6. User Interface in Modes 1 and 2

Brief note on potential use cases: This tool as currently constructed can be used for standalone illustrations in modes 1 with the focus on home automation related engineering design and in mode 2 for solar PV sizing and demand response. Following is a brief note on lesson developed with mode 2.

Solar PV sizing and demand response activity: For this the students can be guided through the following steps towards. Necessary materials for this task can be found on the online repository mentioned in page 4 and in [11].

Step 1: Understanding Voltage, Current, Power and Energy
Step 2: Estimating Home Energy Profile
Step 3: NREL PV Watts Calculator for PV sizing
Step 4: Simulator mode for estimating energy cost savings

IV. Conclusion and Future Work

Early introduction to engineering problem solving and its impacts on daily human life through interactive demonstrations and hands-on activities can provide a new perspective towards engineering education to k-12 students and entry level engineering students. Especially for relatively less popular (among students) fields such as power and energy, it can be great way to attract more students and support the workforce development. Towards this goal, this work presents the design and development of an interactive smart home energy management tool that demonstrates the benefits of demand management. This tool also illustrates the necessary technological convergence required to develop grid edge applications that help maximize the benefits with renewable generation.

As a future work this tool can be further extended to a mock smart community that showcases grid impacts and pricing in presence of multiple smart homes. Based on our observations, this gamification will make an even better impression and further the interest in power and energy engineering.

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