ResThermoVR: Development and Assessment of VR Educational Tool

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ABSTRACT: Understanding building energy simulation poses a significant challenge due to the intricate nature of energy modeling principles, particularly among secondary school students who form the groundwork for addressing climate change. Raising awareness about energy consumption and wastage among students at an early educational stage holds paramount importance for the future environmental well-being. This stems from the fact that individuals commonly encounter difficulty in concretely grasping the extent of their energy usage. This research endeavor seeks to tackle this challenge by conceptualizing and assessing an educational tool in the realm of Virtual Reality (VR) named ResThermoVR. The central objective of ResThermoVR is to augment students' comprehension of diverse aspects, including building thermal behavior, operational and embodied energy of buildings, and the associated carbon footprint linked to environmental consequences. The meticulous development of ResThermoVR from the ground up aligns with the goals and aims of this study. It introduces a distinct VR environment that facilitates interaction with nine distinct simulation scenarios. These scenarios encompass a variety of factors influencing building performance, ranging from alterations in architectural design to modifications in construction materials. This prototype stands as an inventive pedagogical medium, plunging students into the intricacies of a building's energy usage and its ecological consequence. The immersive and captivating nature of this experience contributes to expounding complex concepts. The primary purpose of the prototype development revolves around exploring the high school architecture courses curriculums for refining the prototype with focus of delivering appropriate content for students' study which will assist the subsequent assessments, and evaluations of the prototype.

KEYWORDS: VR Simulation, VR Building Simulation, VR Energy, VR Education, VR Architectural Education

INTRODUCTION

There is a growing imperative to address the repercussions of climate change from an early phase of a student's educational journey. Secondary schools hold paramount significance as a channel for instilling in students a profound comprehension and awareness of key aspects, such as building thermal behavior, energy consumption, and environmental impact. There exists a pressing necessity to heighten consumer consciousness concerning energy utilization and waste. Often, individuals lack the mental capacity to envision the extent of their energy consumption (Haefner et al. 2014).

The far-reaching impacts of climate change are manifesting in the form of devastating natural catastrophes. As reported by the International Energy Agency (IEA) in 2020, buildings contribute to nearly 38% of the annual worldwide CO2 emissions. This contribution can be broken down into 28% stemming from building operations and an additional 10% attributed to building materials and construction, also referred to as embodied carbon (United Nations Environment Programme 2020). Consequently, energy-related carbon emissions in industrialized nations account for 36% of their total emissions (Metz et al. 2007). The escalating demands for energy are driven by a rapid rise in living standards and population growth (Hafeznia et al. 2017). Despite the widespread use of electrical energy to power various elements within buildings, energy remains an often overlooked and misunderstood aspect of construction. Unlike tangible components, energy lacks a physical presence, rendering its conservation less conspicuous. Notably, a substantial portion of a building's overall energy consumption can be attributed to the climate control processes required to meet occupants' desired thermal conditions ("U.S. Energy Information Administration - EIA - Independent Statistics and Analysis," n.d.). Given these circumstances, a transformative shift in energy management, with a primary focus on enhancing the energy efficiency of buildings, should stand as a paramount objective for future generations, both from economic and environmental standpoints (Lin et al. 2016).

In the building industry, concerted efforts are underway to minimize the life cycle energy (LCE) of structures, aimed at reducing their carbon footprint and mitigating adverse environmental impacts (Paleari, Lavagna, and Campioli 2013; Monteiro, Fernandez, and Freire 2016). The entirety of a building's life cycle energy can be categorized into two primary components: embodied energy and operating energy. Embodied energy denotes the energy expended during various stages, including raw material extraction, product manufacturing, transportation, on-site construction, fabrication, life cycle repair and maintenance, as well as eventual renovation and demolition processes (Manish K. Dixit 2017; Manish Kumar Dixit et al. 2010; Hernandez and Kenny 2011). On the other hand, operating energy encompasses the total energy consumption associated with the day-to-day operation of the building, including measures taken to maintain thermal comfort and uphold the indoor environment (Karimpour et al. 2014; Thormark 2002). This aspect can also be referred to as building consumption and usage within the context of this study.

1.0. WHY VIRTUAL REALITY...!

The intricacies of energy modeling principles, the diverse array of factors influencing the outcomes, and the interrelatedness and correlations among these components render building energy simulation a complex concept to grasp (Clarke 2007). Therefore, effectively imparting this level of information to high school students through conventional educational methods presents a considerable challenge. The term "embodiment" refers to "the identification of an abstract idea with a physical entity" (MacLachlan 2004). It can also be understood "the enactment of knowledge and concepts through the activity of our bodies." (Sawyer 2005). Embracing embodiment involves integrating physical, biological, phenomenological, and experiential aspects, giving rise to a unified body-mind perspective that encompasses cognition, actions, and interactions (Hocking, Haskell, and Linds 2001). The interactions between the human body and its physical environment form the basis for human cognition (Gallagher 2006; Wilson 2002). Within the interdisciplinary framework of embodied learning, which consolidates phenomenology and cognitive sciences, it has been demonstrated that cognition is inherently connected to the body and intricately linked to the interplay between perception and action (Varela, Thompson, and Rosch 1993; Clark 2008). Embodied learning breaks down and erases the traditional hierarchy between the brain and the body, as it emphasizes the vital role the body plays in meaning construction and creative processes (MacLachlan 2004).

The current literature across various fields of study, such as linguistics (Lakoff and Johnson 2008), neuroscience and mirror neurons (Decety and Grèzes 2006), mathematics (Noice and Noice 2006), cognitive psychology (Glenberg 2010), and social psychology (Niedenthal et al. 2005), strongly supports the notion that embodiment plays a pivotal role in cognition. From physical and intellectual development to the composition of creative artifacts and engagement in social and emotional contexts, learning processes encompass a diverse range of human actions and mental mechanisms that can benefit from an embodied learning environment (Lindgren and Johnson-Glenberg 2013). The physical embodiment forms the fundamental underpinning of all cognitive learning processes, including the development and comprehension of concepts. Immersive technologies facilitate the type of interaction essential for an embodied learning environment (Lindgren and Johnson-Glenberg 2013; Alhazzaa, Dixit, and Yan 2023). Virtual reality (VR) technologies have the potential to create controlled environments that enable users to physically interact with content and systems. This immersive setting can serve as a platform for exploring and articulating both fundamental and advanced ideas (Lindgren and Johnson-Glenberg 2013).

1.1. VR in education

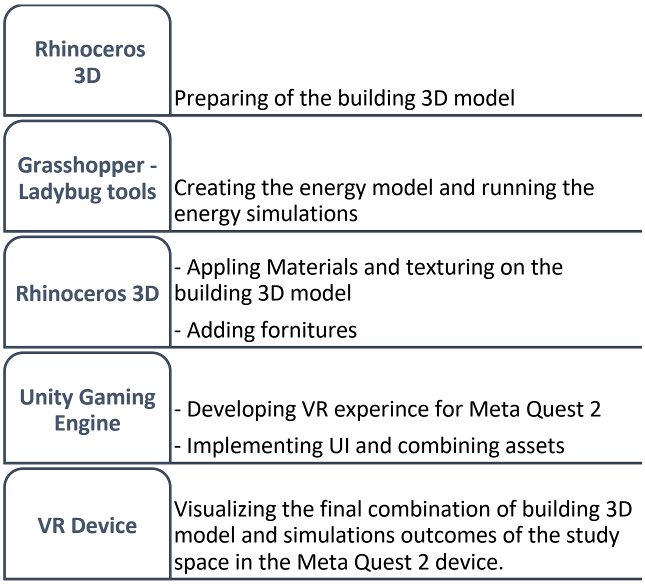
The Immersive Virtual Reality Learning Environment (IVRLE) offers a sophisticated 3D representation, real-time motion tracking, natural navigation and communication, immediate control, as well as personalized and repetitive learning experiences (Tacgin 2020). This approach shows promise in enhancing education through various means, such as providing multiple viewpoints, facilitating situational learning, and promoting knowledge transfer (Dede 2009). By employing IVRLE, learners' sense of presence is positively impacted, leading to overall improvements in learning achievements (Dalgarno and Lee 2010; Lenz et al. 2015). The potential applications of VRLEs are diverse and include simulating costly and time-consuming safety training exercises (Andersen et al. 2020; Jung and Ahn 2018; Buttussi and Chittaro 2017), conducting field tests in STEM subjects that may pose risks in real-world scenarios (Bennett and Saunders 2019; Lynch and Ghergulescu 2017), and enabling the exploration of three-dimensional (3D) models from multiple perspectives, a feat not easily attainable on 2D monitors (Doak et al. 2020; Zinchenko et al. 2020). The utilization of VRLEs has demonstrated positive effects on student motivation and engagement in the classroom (Buttussi and Chittaro 2017; Olmos-Raya et al. 2018; Stepan et al. 2017). Researchers have also observed that students exhibit increased focus while using VRLEs, which subsequently contributes to improved academic performance and knowledge retention (Alhalabi 2016; Krokos, Plaisant, and Varshney 2019; Kwon 2019).

2.0. PROJECT DEVELOPMENT

This research centers on the conception of an educational VR tool aimed at augmenting students' comprehension of building thermal behavior, energy consumption, and environmental impact. The study encompasses two primary phases. The initial stage involves the meticulous development of a VR environment, tailored to attain the research objectives and goals. The subsequent phase involves demonstrating the proposed prototype to teachers showing how VR technology can be effectively used as an educational tool for complex topics, encouraging its future adoption.

2.1. ResThermoVR prototype

The ResThermoVR application utilizes a diverse array of platforms and software technologies. Figure 1 illustrates the entire development process, which starts with the creation and construction of a 3D model of the building. To construct the energy model, the study employs Grasshopper - Ladybug tools and the EnergyPlus simulation engine, integrated with the Rhinoceros 3D software interface and its Grasshopper visual programming extension. The integration of materials and textures for the production of a VR experience is facilitated in this research through the utilization of Rhinoceros 3D. The central platform utilized for VR content creation is the Unity game engine, which effectively handles both asset generation and the user interface. Particular emphasis is placed on verifying compatibility with the well-known Meta Quest 2 VR headset throughout the development process, as it is widely recognized for its standalone functionalities and superior adaptability. At present, the Meta Quest 2 VR headset ranks among the most financially viable choices within the VR market.



Rhinoceros 3D	Preparing of the building 3D model
Grasshopper - Ladybug tools	Creating the energy model and running the energy simulations
Rhinoceros 3D	- Appling Materials and texturing on the building 3D model - Adding fornitures
Unity Gaming Engine	- Developing VR experince for Meta Quest 2 - Implementing UI and combining assets
VR Device	Visualizing the final combination of building 3D model and simulations outcomes of the study space in the Meta Quest 2 device.

Figure 1. The development workflow. Source: (Alhazzaa 2024)

The VR experience occurs within a digitally simulated traditional American house, featuring two bedrooms and two bathrooms, as illustrated in the floor plan (Figure 2), spanning an area of 110.78 m^2 (1192.43 ft^2). The construction of the digital representation encompasses various aspects, including the layout and arrangement of furniture, the specific furniture types utilized, the physical attributes, and textures, along with the external surroundings (Figure 3). As a result, users can establish a stronger emotional connection to the environment owing to the familiarity of the design and style of the space.

Figure 2. Floor plan. Source: (Alhazzaa 2024)

Figure 3. Interior picture of the VR environment base case living room and bedroom. Source: (Alhazzaa 2024)

2.1.1. Energy simulation setup & scenarios

The ResThermoVR simulation's baseline conforms to the guidelines set forth by The International Energy Conservation Code (IECC) 2006, which has been adopted by the City of Houston, specifically concerning the thermal properties of building materials (City of Houston 2022). The base case entails a wooden framed wall with a thermal resistance of 2.876 m^{2}K/W (16.329 Ft²·°F·h/BTU) and a single window with a U-factor of 2.120 W/m^2·K (0.373 BTU/h·ft^2·°F). The Window to Wall Ratio (WWR) for the base case is approximately 20%. The calculation of WWR is focused on the living and main bedroom spaces, as these areas have been subjected to comprehensive thermal analysis and visualization as part of the overall building energy simulation. These two spaces exhibit distinctive characteristics attributed to differences in their orientation and usage. The thermal properties of the materials employed in this building simulation are sourced from EnergyPlus materials library. ResThermoVR offers users a platform to engage with nine alternative simulation scenarios. These scenarios encompass a wide array of conditions that can influence building performance, including aspects such as manipulation of building geometry (figure 4 shows the building orientation and figure 5 illustrates the window to wall ratio) and utilization of diverse construction materials. The nine simulation scenarios are as follows:

- 90 Degree Rotation
    - Walls and windows are all constructed with the base case materials, but the building's orientation changed by 90 degrees clockwise.
- 180 Degree Rotation
    - Walls and windows are all constructed with the base case materials, but the building's orientation changed by 180 degrees clockwise.
- 270 Degree Rotation
    - Walls and windows are all constructed with the base case materials, but the building's orientation changed by 270 degrees clockwise.
- Exterior Walls R 23
    - Walls are made with wooden framed construction that has with 3.932 m^2K/W (22.329 $Ft^2 \cdot °F \cdot h/BTU$) R-value. The windows are made with base case materials.
- Exterior Walls R 32
    - Walls are made with wooden framed construction that has with 5.517 m^2K/W (31.329 $Ft^2 \cdot °F \cdot h/BTU$) R-value. The windows are made with base case materials.
- Double Glass U 0.24
    - The windows are made with double glass window assembly that has 1.362 $W/m^2 \cdot K$ (0.239 $BTU/h \cdot ft^2 \cdot °F$) U factor. Walls are made with base case materials.
- Triple Glass U 0.19
    - The windows are made with triple glass window assembly that has 1.224 $W/m^2 \cdot K$ (0.215 $BTU/h \cdot ft^2 \cdot °F$) U factor. Walls are made with base case materials.
- WWR 40%
    - Walls and windows are all constructed with the base case materials, but the building's WWR increased to 40%.
- WWR 60%
    - Walls and windows are all constructed with base case materials, but the building's WWR increased to 60%.

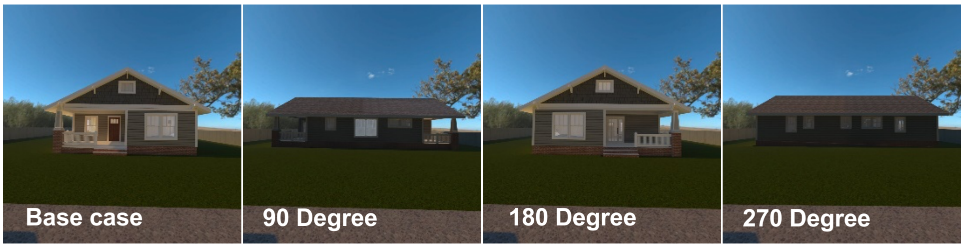


Figure 4. Building orientation simulation alterations that has 360 Degree rotation. Source: (Alhazzaa 2024)

Figure 5. Window to wall ratio design alterations which range from about 17-20% in the base case to 60%. Source: (Alhazzaa 2024)

ResThermoVR generates a comprehensive set of eleven simulation results for each simulation condition which are as follows:
Building Operational energy consumption
Embodied energy (Associated with building materials construction)

Embodied Carbon (Associated with building materials construction)
Summer – interior wall temperature map
Summer – Energy Flow
Summer – Vertical map
Summer – Volumetric map
Winter – interior wall temperature map
Winter – Energy Flow
Winter – Vertical map
Winter – Volumetric map

The computation of the building's operational energy consumption relies on the aggregate yearly energy consumption, with reference to the meteorological data specific to Houston, Texas (EnergyPlus, n.d.). The summer simulation includes the months of June, July, and August, while the winter simulation comprises December, January, and February. The interior wall temperatures correspond to the surface temperatures of the inner layer of walls, which have been effectively visualized using individualized single surfaces. The Energy Flow refers to the quantified energy transfer measured in kWh/m^2 from the external to internal regions of the building, which has been visually rendered through colored surfaces signifying the magnitude of energy flow across each wall. The vertical interior temperature maps consist of an array of 216 sensors strategically positioned within the living room, arranged in a vertical stack to form a continuous surface. In contrast, the volumetric interior temperature maps comprise 250 sensors within the living room and 72 sensors within the bedroom, evenly distributed throughout the respective spaces. Each sensor in these maps is graphically represented by a distinct box, visually floating in its designated location within the room. The calculation of indoor temperature employs the Ladybug plugin integrated with the Grasshopper spatial thermal map tool, employing a combination of three spatial thermal map simulation methods (Webb 2012; Brandan and Alejandra 2012; Arens et al. 2015). Extensive validation of the Ladybug simulation method has demonstrated its reliability, exhibiting a satisfactory level of consistency when compared to both ENVI-met software and field measurements (Ibrahim, Kershaw, and Shepherd 2020; Elwy et al. 2018). As for the simulation of energy consumption and walls' temperatures, the EnergyPlus engine is utilized. To provide data on embodied energy and carbon, a specialized economic model known as an input-output-based hybrid (IOH) macroeconomic model, tailored specifically to the United States economy, serves as the data source (M. Dixit, Culp, and Fernandez-Solis 2015; Venkatraj et al. 2020; Kumar, Venkatraj, and Dixit 2022).

2.1.2. User interface (UI)

The UI in VR possesses a distinctive characteristic wherein it lacks constraints on display size (Bastug et al. 2017). This attribute allows for unparalleled flexibility in presenting information from various directions. While the capacity to showcase abundant content within the VR environment is advantageous, it is equally imperative to ensure that spatial relationships between elements and the user are effectively delineated to achieve optimal legibility and comprehension. In the context of virtual reality (VR), the presentation distance of text carries equal significance to the font size of individual characters. At Google IO 2017, engineers from Google introduced the concept of the distance-independent millimeter (dmm), which serves as a novel unit for gauging perceived size in VR. Specifically, dmm represents a character with a height of 1 mm when situated at a distance of 1 m. To ensure legibility and user comfort, the ResThermoVR UI is designed based on the dmm standard. ResThermoVR incorporates two distinct user interfaces. The primary UI (Figure 6) remains anchored to the user's head, enabling users to observe the interface from various vantage points while maintaining an appropriate distance between the UI and the user. On the other hand, the secondary UI, located on the left controller (Figure 7), serves merely as an information display and is not interactable by the user. This secondary UI is conveniently attached to the user's hand, facilitating easy access for reading, analyzing, and correlating the visualized components represented by distinct colors with their relevant data.

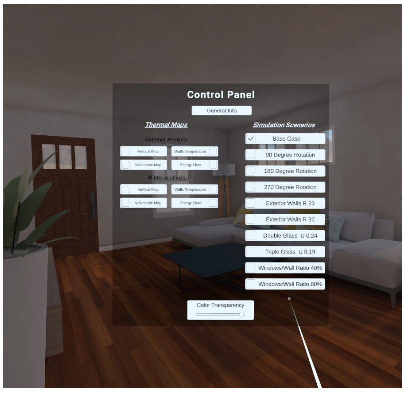


Figure 6. Main UI. Source: (Alhazzaa 2024)

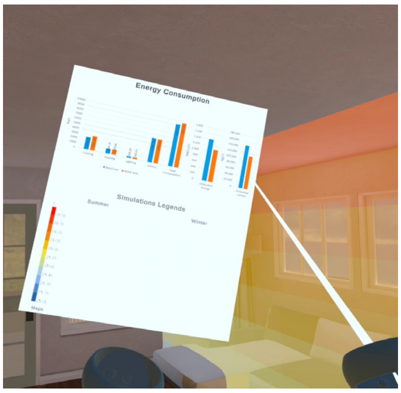
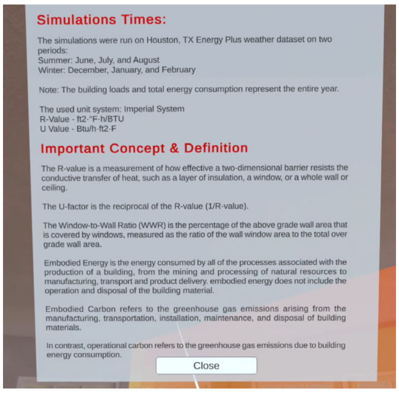


Figure 7. Secondary display mounted to left controller, Energy Consumption Graph, and maps' legend. Source: (Alhazzaa 2024)



Simulations Times:

The simulations were run on Houston, TX Energy Plus weather dataset on two periods:
Summer: June, July, and August
Winter: December, January, and February

Note: The building loads and total energy consumption represent the entire year.

The used unit system: Imperial System
R-Value - ft2·°F·h/BTU
U Value - Btu/h·ft2·F

Important Concept & Definition

The R-value is a measurement of how effective a two-dimensional barrier resists the conductive transfer of heat, such as a layer of insulation, a window, or a whole wall or ceiling.

The U-factor is the reciprocal of the R-value (1/R-value).

The Window-to-Wall Ratio (WWR) is the percentage of the above grade wall area that is covered by windows, measured as the ratio of the wall window area to the total over grade wall area.

Embodied Energy is the energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery. embodied energy does not include the operation and disposal of the building material.

Embodied Carbon refers to the greenhouse gas emissions arising from the manufacturing, transportation, installation, maintenance, and disposal of building materials.

In contrast, operational carbon refers to the greenhouse gas emissions due to building energy consumption.

Figure 8. General info panel. Source: (Alhazzaa 2024)

The primary UI comprises three integral components. Firstly, the "General Info" button serves as the initial component, granting access to a window containing informative descriptions of key terms such as "R-Value," "solar heat gain coefficient," "embodied energy," "embodied carbon," and "simulation time" (Figure 8). Secondly, the UI incorporates simulation scenario toggles (as shown in Figure 6). Each condition toggle is linked to an energy consumption graph that presents comprehensive data, including overall energy consumption, embodied energy, embodied carbon, cooling load, heating load, and a comparative analysis of the existing conditions (Figure 7). Furthermore, the thermal map menu, shown in Figure 6, plays a central role in the UI. This menu includes two submenus, namely, the summer and winter simulation periods. Within each simulation period, four distinct options are available: vertical maps (Figure 9), volumetric maps (Figure 10), wall temperature (Figure 11), and energy flow (Figure 12). Upon selecting any of these options, the corresponding color legend is activated on the secondary display (Figure 7). Lastly, the fourth component of the primary UI enables users to control the transparency of the map's colors, affording them the ability to fine-tune transparency levels and facilitate improved differentiation of individual color tones.

Figure 9. The existing condition vertical map. Note: The same visualization is applied for all simulation conditions. Source: (Alhazzaa 2024)

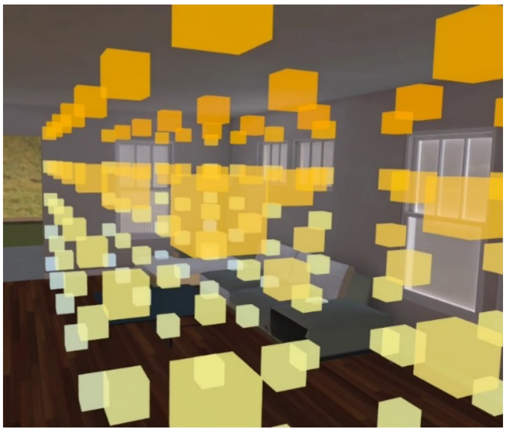


Figure 10. The existing condition volumetric map. Source: (Alhazzaa 2024)

Figure 11. The existing condition wall temperatures. Source: (Alhazzaa 2024)

Figure 12. The existing condition energy flow. Source: (Alhazzaa 2024)

2.2. Prototype demonstration

The prototype was Demonstrated to high school teachers who teach architecture courses through a guest lecture on energy consumption in the built environment. The lecture sequence was methodically organized, starting with a presentation demonstrating fundamental principles and facts concerning embodied energy, carbon footprint, and operational energy within buildings. This presentation also underscored the role of building design and material choices in global energy consumption and climate change, spanning a duration of approximately 30 to 45 minutes. Following the presentation, teachers were offered the opportunity to engage with the presented topic in a VR environment. By immersing themselves in the VR scenario, they could visually grasp the concepts discussed during the presentation. This approach facilitated comprehension by enabling teachers to interact physically with the subject matter, as it effectively translated the lecture concepts into tangible visualizations within an immersive environment.

CONCLUSION & FUTURE WORK

The effectiveness of VR for energy simulation and visualization is demonstrated through ResThermoVR, which transforms abstract energy data into comprehensible visual outputs. By linking simulation outcomes to real-world scenarios, it enhances users' understanding of building operations, including embodied energy and carbon impacts throughout the building lifecycle. The VR environment integrates construction materials, geometry, and orientation, allowing users to explore how these factors influence energy performance. Visual tools like spatial thermal maps and color-coded temperature depictions help users intuitively grasp the relationship between design inputs and energy outputs, addressing common learning challenges. A subset of numerical data is presented alongside these visuals to bridge qualitative insights with quantitative outcomes.

Future development will include expanded features and refined visualizations tailored to high school curricula. After successful feedback from teachers, a more comprehensive study with students will evaluate the prototype's impact on learning, engagement, and retention of key energy concepts.

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