# Ingenuity for El Ingenio: Resilient and Sustainable Housing Design Concept for Displaced Communities in Puerto Rico

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***Abstract*– Ingenuity for El Ingenio is a case study to address the challenges that marginalized communities in Puerto Rico suffer, mostly from natural hazards, due to settlements in high-risk areas and deteriorating infrastructure. The case study was developed by an interdisciplinary group of students from the University of Puerto Rico - Río Piedras School of Architecture and students from the Department of Civil Engineering and Surveying and the Department of Electrical Engineering at the University of Puerto Rico - Mayagüez, as part of the course "Design-Build Project Delivery" in the RISE-UP program. The project contemplated spaces for a family/group of four people, in the neighborhood Ingenio in Toa Baja, Puerto Rico, which is a community exposed to multiple natural hazards including hurricanes, earthquakes, and floods. The design parameters for the project included a set budget of $40,000 USD for the construction of four temporary housing units, requirement to withstand the impact of multiple natural hazards, as well as being simple to build and be able to operate independent to power and water grids during an emergency. The resulting design provides 270 sq ft. of usable space and can partially function off the grid due to solar energy generation and water storage. Local materials were implemented, and a manual of components and suggested construction methods was developed. This experience showcases the benefits that an interdisciplinary-integrated approach to infrastructure design can have on producing rapid and efficient design solutions to challenges caused by natural hazards, in resilient and sustainable ways.***
***Keywords—Sustainable Design, Case Study, Design Project***

## I. Introduction

The aftermaths of Hurricane María in 2017 and the January 2020 earthquake swarm shed light on a concerning problem for Puerto Rico, which is the settlement of marginalized communities on areas prone to natural hazards and deteriorating infrastructure. After Hurricane María, many individuals and families were either required to perform temporary repairs for their damaged homes and/or displaced from their homes entirely [1-2]. Everyday life was interrupted due to lack of basic necessities such as electricity and potable water [3]. Of the affected, the most vulnerable of these homeowners either lived in structures with simple light metal and wooden roofing which suffered wind damage or lived in areas with high flooding or storm surge risk. Similarly, the most affected homes by the 2020 earthquake swarm were reinforced concrete homes of one and two stories either designed with outdated codes or lacking design guides entirely. It is known that applying resilient and sustainable design aspects to infrastructure allows for better performance to withstand natural hazards, nonetheless, these design practices are mostly not made accessible to marginalized communities such as the elderly and low-income families and individuals. This is worrying because Puerto Rico is exposed to many types of natural hazards [4-5]. To address this problem, the Resilient Infrastructure and Sustainability Education Program (RISE-UP) focused its final course to design temporary housing solutions for displaced communities after natural disasters. RISE-UP is a National Science Foundation (NSF) [6] funded program at three campuses of the University of Puerto Rico: Mayagüez, Rio Piedras and Ponce, which teaches resilient and sustainable design for infrastructure in an interdisciplinary setting which includes students from Architecture, Civil Engineering, Surveying, and Electrical Engineering [7]. In the RISE-UP coursework, the final course is the application of skills learned throughout the several classes into a collaborative design project. This work contains the design considerations, steps taken, and results of one of the three groups who participated in the RISE-UP final design course.

## II. Methodology

The project was divided into three phases throughout the semester, each with its own set of challenges and deliverables which will be explained in detail.

### *Phase 1. Analysis and Evidence*

The design problem addressed was to design emergency housing of four units, each one for a family/group of four people either located in areas or structures vulnerable to natural disasters and/or displaced from their homes due to one of those events. The final design was required to be scalable, meaning that housing arrays could be expanded in sets of four units, and must incorporate sustainable and resilient design practices.

The project contemplated an initial analysis of the area using Geographic Information System (GIS) tools. The analysis examined the soil types around the neighborhood, flooding risk, seismic risk, average annual rainfall, ventilation, and illumination. The process to select the site used was the Best Value Procurement method. The established criteria were: (a) land ownership public or private, (b) access to roads, (c) flooding risk, (d) greenery (flora), and (e) closeness to facilities such as markets, schools, and community centers that could contribute to daily life activities in the shelter.

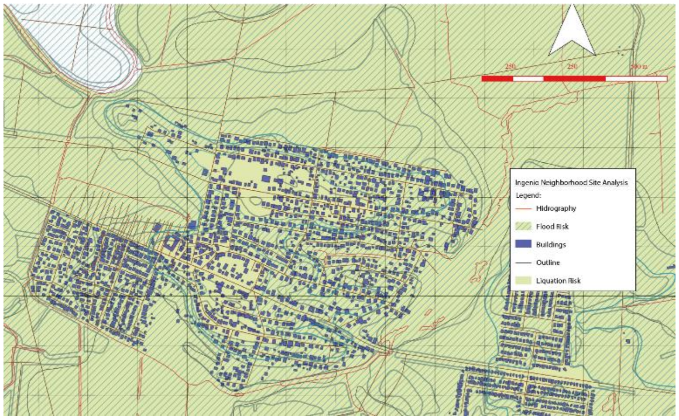


*Figure 1: GIS map of Barrio El Ingenio, Puerto Rico*

During this initial phase, several goals were set to be accomplished in the design. These goals included: (a) keeping the project construction under the $40,000 budget, (b) compliance with ASCE-7 building code [8], particularly considering hurricane wind and earthquake loads, (c) implementation of solar power with sufficient storage for three days without sun exposure, (d) enough water storage for four days of use, and (e) having a usable area of 200-350 square feet per unit.

To organize the interdisciplinary group, the roles and responsibilities were divided using the criteria of Responsible, Accountable, Consulted, and Informed, known as the RACI chart [9]. These were assign taking into consideration the area of expertise of each group member. Since the project was handled as Design-Build, every member was informed of decisions to maintain integrity and consistency of the design.

*Figure 2: Close-up view of selected lot for the project*

*Phase 2. Preliminary Design*

The preliminary design phase of the project involved building around the goals determined in the initial phase. This meant the team researched on possible designs and technologies that could supply the necessary commodities for the occupants of the shelter. The design spatial configuration focused on maximizing space. In addition, it considered an inclusive design using the American Disabilities Act (ADA) codes [10]. A space was designated to store batteries for the solar power array as well as the water storage tank. Various roof designs were considered for this phase including flat, gable, and hybrid roof. Aspects of the roof design taken into consideration were height, potential for cross-ventilation, and optimum solar panel positioning.

The spatial configuration's biggest challenges were tied to maximizing space and budget. This led to investigating ways to accommodate bedroom area, dining tables and kitchens. The bathroom area was estimated to be large enough to comply with ADA codes, and the openings for windows and doors were studied to determine the most economic material as well as the most favorable positioning to allow cross-ventilation. The material selection heavily depended on the budget and requirement to reduce complexity of the construction. The materials considered were wood and prefabricated cement panels, as they could be locally sourced and required less labor-intensive construction.

The solar power equipment configuration predesigns included solar panels, an inverter, a controller, batteries, and a circuit breaker. The system was required to power a fridge, small washing machine, LED lighting, and other miscellaneous items. Daily water use per person was estimated to determine the capacity of the water storage tank. Wind and earthquake loads were obtained from the ASCE-7 design standard and the structural system for the building was determined to be a lightweight wood frame with structural panels rated for shear resistance. The material and labor costs were calculated according to the guides from Puerto Rico *Oficina de Gerencia y Permisos* (Management and Permits Office) (OGPE) [11] and RS Means data: Construction Estimating Software.

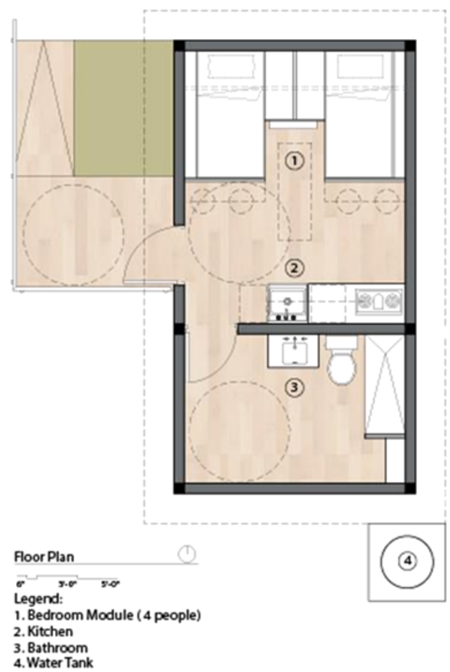


*Figure 3: Floor plan view of housing unit (illustration by the authors)*

*Phase 3. Final Design*

For the final phase, the complete architectural and structural designs were presented as well as a completed solar power system, water storage details, and a completed cost estimate for construction materials and labor. These will be discussed in detail in the Results section.

## III. RESULTS

*Architectural Design*

The unit design responded the initial goals set by the team. An elevation of one foot was designed between the house floor and the ground to increase flood protection and remove excess heat generated inside. A ramp was also designed to access the floor elevation in compliance with the ADA codes. The spatial configuration maximized space and the bunkbed-style furniture designed for the sleeping quarters also serves as personal storage and retractable table. The kitchen design includes a 48-in table, a small fridge, and a compact washing machine. The sink and table have adjustable leg height and the kitchen area's open space complies with ADA codes. A gas-powered countertop stove was also included, and shelving units were proposed instead of cabinets for ease of use and to lower costs. The gable roof was selected to allow rainwater drainage and it positions the rooftop solar panels in the most efficient angle to capture sunlight. A skylight was added on the roofs to allow natural light inside and lower energy consumption during the day. The battery storage area can be accessed from the outside of the house and is placed away from direct sunlight (North side) that could cause overheating. The construction materials for the roof are roof tile, insulation blanket, and paint. Materials for the walls and structure are gypsum, faced insulation, pine pressure treated plywood, pine lumber, premium southern, and Golden Virola Plywood.

*Figure 4: Housing unit front view (illustration by the authors)*

*Figure 5: Interior view of kitchen/living space (illustration by the authors)*

*Figure 6: Interior view of sleeping quarters and storage (illustration by the authors)*

*Placement and Orientation:*

The housing units designed were planned to be versatile enough to be placed on different locations with minimum changes to their structure and/or materials. This is useful when dealing with risks from natural disasters in different areas of Puerto Rico such as seismic hot spots or land prone to flooding. The gable roof was also selected to position the skylight and solar panels at an appropriate orientation to maximize the solar power. Having the four units act as an independent module also allows for expandability and the creation of a sustainable community.

*Figure 7: Top view of housing array (illustration by the authors)*

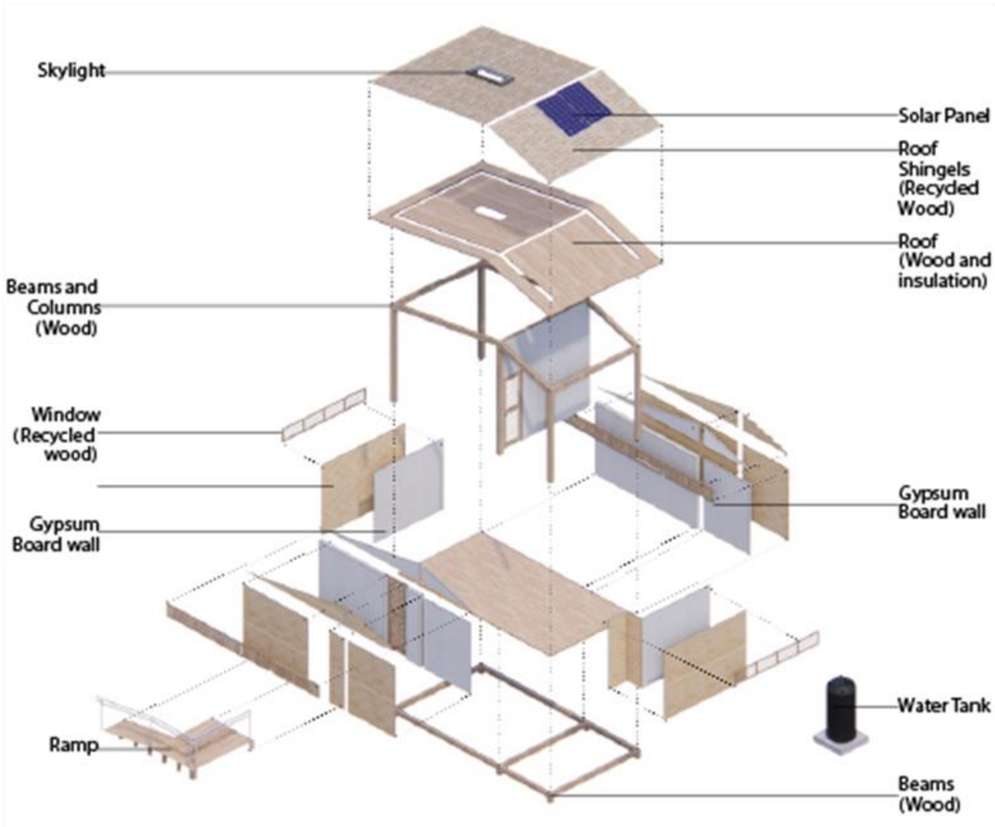


*Figure 8: Housing unit assembly and materials (illustration by the authors)*

*Structural Design*

The final structural design consisted of a Douglas Fir frame with cement board walls and plywood floors with 2x4 inch studs spaced at 24 inches on-center. The roof consists of plywood sheathing with 2x4 inch studs spaced at 48 inches on-center. The loading applied to the structural model included the dead load, live loads, wind loads, and earthquake loads calculated using the ASCE-7 design standard. The housing unit was designed to be bolted to concrete footings which were to be installed prior to construction of the structure. Details for this connection, among others, were provided using information from the American Wood Council [12].

*Electric and Water Storage Design*

The design of the rooftop PV system starts defining the use of electricity in the house, the potential irradiance in the location, and the need for storage systems. An evaluation of the solar potential using PV Watts calculator [13], a tool from National Renewable Energy Laboratory (NREL), and the house rooftop area shows that a PV system of 2.2kW provides in average 11.28KWh of energy per day. An energy balance together with the load profile in house and the PV system allows to define a need of at least 1KWh of storage system. The final electric design included the use of the following equipment: (a) 415-Watt solar panels, (b) 1,500-Watt, 24 Volt DC to AC inverters, (c) 100 Volt, 30 Amp charge controllers, (d) 6 Volt, 235 Amp-Hour batteries, and (e) 15-, 20-, and 30-Amp circuit breakers. The system provides a total capacity of 11.28 KWh, and it supplies power to all the necessary home appliances while being completely independent of the electric grid. For water storage, a 200 Gallon tank was placed in each home which supplies about four days of use if the water grid were to fail. This was based on an average consumption of 50 Liters per-person per-day.

*Project Construction and Cost Estimates*

After considering the cost of materials, labor, and equipment, the final estimate resulted in a total of $40,000 USD for the entire project, or $37 USD per square foot. Cost of construction materials and accessories were estimated using local store pricing, and labor costs were estimated using information from the Puerto Rico Office of Permit Management (OGPE) and RS Means [14]. Categories included in the cost estimate were: (a) construction of structure, (b) accessories and appliances, (c) electric system, (d) plumbing, and (e) miscellaneous. For this work, the anchorage system, earthwork, maintenance, and permit costs were not considered in the analysis. These exceptions were made by the course faculty and applied for all three participating groups.

## IV. Conclusions

This case study functioned as evidence of the benefits of working as an interdisciplinary group when developing integrated projects that involve sustainability and resiliency goals, as well as design and construction. By working in an integrated manner, many of the inefficiencies of traditional design and construction procedures such as lack of communication between designers (architects and engineers) and builders (construction engineers and workforce) could be overcomed. In this experience, every discipline contributed to the best strategies to create a sustainable and resilient design for Ingenuity for Ingenio, as well as collaborated in important decision making which benefited everyone. RISE-UP was a tool that brought the team together to experience interdisciplinary work and its benefits while in an undergraduate setting, and the lessons learned can be used by everyone in their future careers. This project served as inspiration to the team, as it enabled us to experience firsthand that designing resilient and sustainable housing in Puerto Rico at a low cost is achievable, and we can trust that future generations of students and professionals, with the right tools and interdisciplinary attitude, can also contribute to making a future Puerto Rico is not only safer, but sustainable, resilient, and more socially equitable.

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## References

[1] Meléndez, E., & Hinojosa, J. (2017). Estimates of post-hurricane Maria exodus from Puerto Rico. *Centro Voices*.

[2] Martín, Y., Cutter, S.L., Li, Z. *et al.* Using geotagged tweets to track population movements to and from Puerto Rico after Hurricane Maria. *PopulEnviron* **42,** 4–27 (2020). https://doi.org/10.1007/s11111-020-00338-6

[3] Kwasinski, A. & Andrade, Fabio & Castro-Sitiriche, Marcel & O'Neill-Carrillo, E.. (2019). Hurricane Maria Effects on Puerto Rico Electric Power Infrastructure. IEEE Power and Energy Technology Systems Journal. PP. 1-1. 10.1109/JPETS.2019.2900293.

[4] Palm, Risa, and Michael E. Hodgson. "Natural Hazards in Puerto Rico." *Geographical Review*, vol. 83, no. 3, [American Geographical Society, Wiley], 1993, pp. 280–89, https://doi.org/10.2307/215730.

[5] William R. McCann; On the earthquake hazards of Puerto Rico and the Virgin Islands. *Bulletin of the Seismological Society of America* 1985;; 75 (1): 251–262.

[6] National Science Foundation - Where Discoveries Begin. NSF. (n.d.). Retrieved March 17, 2022, from https://www.nsf.gov/

[7] Lopez del Puerto, C., Cavallín, H., Perdomo, J., Muñoz, J., Suárez, M., and Vázquez, D., RISE-UP: An Interdisciplinary Learning Tool to Generate Sustainable and Resilient Infrastructure, RIDNAIC (2021). Vol. 19-20, 17 URL https://www.scipedia.com/public/Puerto_et_al_2021b

[8] Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers (ASCE) (2021).

[9] Miranda, D., 2022. *What Is A RACI Chart? Everything You Need To Know About This Project Management Tool*. [online] Forbes.com. Available at: <https://www.forbes.com/advisor/business/raci-chart/#:~:text=What%20Is%20a%20RACI%20Chart%3F%20A%20RACI%20chart%2C,with%20the%20letters%20R%2C%20A%2C%20C%20or%20I.> [Accessed 17 March 2022].

[10]Ada.gov. 2022. *2010 ADA Standards for Accessible Design*. [online] at: <https://www.ada.gov/regs2010/2010ADAStandards/2010ADAStandards.pdf> [Accessed 17 March 2022].

[11]Sbp.ogpe.pr.gov. 2022. *OGPe – Oficina de Gerencia de Permisos*. [online] Available at: <https://sbp.ogpe.pr.gov/> [Accessed 17 March 2022].

[12]Details for Conventional Wood Frame Construction, American Wood Council (2001).

[13]Pvwatts.nrel.gov. 2022. *PVWatts Calculator*. [online] Available at: <https://pvwatts.nrel.gov/> [Accessed 17 March 2022].

[14]RSMeans Data Online. (n.d.). [online] Available at: https://www.rsmeansonline.com/Content/RSMOnline_Product_Sheet.pdf [Accessed 17 Mar. 2022].