



RESEARCH ARTICLE

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EXPERIMENTAL AND NUMERICAL ASSESSMENT OF A SUSTAINABLE FLAT-PLATE SOLAR COLLECTOR USING RECYCLED POLYMER-METAL COMPOSITES IN HIGH-ALTITUDE ANDEAN ENVIRONMENTS

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ABSTRACT

The thermal energy deficit in high-altitude rural regions necessitates cost-effective and sustainable technological solutions. While flat-plate collectors (FPCs) are mature technologies, their deployment in the Andean region is hindered by high material costs and extreme climatic variability. This study evaluates the thermal-hydraulic performance of a novel low-cost FPC engineered from recovered solid waste specifically, recycled 6063 aluminum frames and polyethylene terephthalate (PET) insulation. A coupled 3D Computational Fluid Dynamics (CFD) model was developed using the Discrete Ordinates (DO) radiation model to predict heat transfer phenomena under low-pressure conditions (3,000 m.a.s.l.). The numerical predictions were validated against experimental data obtained from a prototype installed in the Ecuadorian paramo. Results indicate a peak outlet temperature of 53.8°C under an irradiance of ~800 W/m², with the CFD model achieving a Pearson correlation coefficient of $r > 0.95$ and a mean relative error of 2.5% compared to in-situ measurements. These findings demonstrate that properly characterized recycled composites can achieve thermal efficiencies comparable to conventional materials, offering a viable pathway for circular economy implementation in renewable energy infrastructure.



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I. INTRODUCTION

1.1 GLOBAL ENERGY CHALLENGES AND THE ANDEAN CONTEXT

The transition towards decentralized renewable energy systems is critical for mitigating climate change and addressing energy poverty in developing regions. While solar photovoltaic technologies have seen widespread adoption, solar thermal applications for domestic heating remain underutilized in the high-altitude Andes, despite the region's exceptional solar resource [1]. In rural communities of the Ecuadorian paramo (above 3,000 m.a.s.l.), low ambient temperatures and limited access to conventional electrical grids exacerbate the vulnerability of the population. Previous studies on rural electrification have highlighted that sustainable interventions must prioritize not only technical reliability but also economic accessibility and social appropriation [2]. Consequently, there is an urgent need for "frugal engineering" solutions that adapt mature technologies to the specific socio-geographic constraints of the Andean highlands [3].

1.2 SOLAR THERMAL TECHNOLOGY: STATE OF THE ART

Flat-plate collectors (FPCs) represent the standard technology for low-temperature applications. The theoretical performance of FPCs is governed by the Hottel-Whillier-Bliss equations, which balance optical absorption against thermal losses [4]. Recent advancements have focused on enhancing efficiency through nanofluids, selective coatings, and complex geometries [5], [6].

However, these high-tech optimizations often entail manufacturing costs that are prohibitive for the Global South. The challenge, therefore, shifts from maximizing absolute thermodynamic efficiency to optimizing the cost-to-efficiency ratio using locally available resources [7].

I.3 CIRCULAR ECONOMY IN MATERIAL ENGINEERING

The valorization of municipal solid waste (MSW) offers a disruptive pathway for reducing manufacturing costs while addressing environmental pollution. The Circular Economy framework encourages the "upcycling" of waste materials into value-added products [8]. In the field of material science, recycled Polyethylene Terephthalate (PET) and recovered aluminum alloys have demonstrated mechanical and thermal properties sufficient for non-critical engineering applications. For instance, [9] validated the structural integrity of recycled PET fibers in concrete matrices, while [10] highlighted the thermal viability of non-heat-treated recycled aluminum. Despite these advances, the application of such recycled composites in the thermal-hydraulic core of solar collectors remains insufficiently explored in peer-reviewed literature.

I.4 NUMERICAL SIMULATION (CFD) AS A VALIDATION TOOL

The variability of recycled materials necessitates rigorous validation before prototyping. Computational Fluid Dynamics (CFD) has emerged as an indispensable tool for predicting the thermal behavior of solar collectors under transient conditions. The Finite Volume Method (FVM) allows for the precise resolution of Navier-Stokes and energy equations, capturing complex flow phenomena that analytical models cannot [11]. Specifically, the Discrete Ordinates (DO) radiation model has proven effective in simulating radiative transfer in semi-transparent media [12]. However, few studies have correlated CFD predictions with experimental data for collectors built entirely from waste materials operating under the low atmospheric pressure conditions of the high Andes.

I.5 RESEARCH OBJECTIVE

This study bridges the gap between high-precision numerical modeling and sustainable, low-cost manufacturing. The primary objective is to design, simulate, and experimentally validate a flat-plate solar collector constructed from recycled aluminum and PET insulation. By comparing CFD simulations with in-situ measurements at 3,000 m.a.s.l., this research aims to demonstrate that circular economy principles can be successfully applied to thermal engineering without compromising functional performance.

II. MATERIALS AND METHODS

II.1 SITE DESCRIPTION AND HIGH-ALTITUDE CONDITIONS

The experimental validation was conducted in the rural community of Yanayacu, Quero Canton, Ecuador (01° 22' S, 78° 36' W). The site is situated at an altitude of **3,000 meters above sea level (m.a.s.l.)**. This geographical location is critical for the study as it introduces unique atmospheric conditions: a reduced atmospheric pressure ($\approx 70.1 \text{ kPa}$) and lower air density compared to standard test conditions (STC), alongside high levels of ultraviolet (UV) irradiance typical of the Andean equatorial region.

II.2 CHARACTERIZATION OF RECYCLED MATERIALS

To ensure the sustainability and reproducibility of the system, the materials were selected following Circular Economy principles applied to thermal engineering [13]. Unlike standard collectors that rely on virgin copper, this prototype valorized secondary raw materials: Absorber Plate: Fabricated from recycled 6063 aluminum alloy recovered from discarded window frames, a process validated for thermal applications by [14]. Insulation: A composite matrix of recovered rigid polyurethane foam and multi-layered Polyethylene Terephthalate (PET) sheets. Recent studies by [15], [16] have demonstrated that these recycled polymers retain stable thermal properties for energy recovery systems. Glazing: Reused annealed glass (3 mm thickness) with optical transmissivity suitable for solar capture [17]. The thermal expansion coefficients were also considered to prevent structural failure at the junctions, following the dilatometry protocols described by [18]. Table 1 summarizes the thermophysical properties input into the simulation.

Table 1: Thermophysical properties of the recycled and conventional materials used in the CFD simulation.

Component s	Material	Densit y Kg/m ³	Thermal Expansion Coefficient 1/k	Thermal Conducti vity W/(mK)	Specifi c Heat J/(kg.k)	Reflecti vity	Emissivity	Absorba nce	Transmitta nce
Absorber plate	Aluminum 1060 H-12	2705	2.36e-05	230	900				
Piping	Aluminum 1060 H-12	2705	2.36e-05	230	900				
Structure	Aluminum 1060 H-12	2705	2.36e-05	230	900				
Insulation	PET	1420		0.261	1140				
	Rigid Polyurethane Foam		30e-6 to 40e-6	0.020	1200-1400				
Reflectors	Aluminum Foil	2705	2.36e-05	235	900	80%-90%	0.03-0.05	20%-10%	
Cover	Window glass	2457.6	9e-06	0.74976	834.61	8%-10%	0.84-0.89	5%-10%	80%-90%

Source: Authors, (2026).

II.3 CHARACTERIZATION OF RECYCLED MATERIALS

The collector design followed a grid-iron (harp) configuration to minimize hydraulic pressure drop, adapting design principles for Concentrating Photovoltaic-Thermal systems to a flat-plate geometry [19]. The development process involved a dual-phase approach:

1. Computational Domain (CAD): A precise 3D fluid volume was generated in SolidWorks to define the internal flow geometry for the simulation (Figure 1a).
2. Physical Construction: The prototype was handcrafted using Tungsten Inert Gas (TIG) welding to assemble the recycled aluminum profiles (Figure 1b). The low-cost manufacturing approach was benchmarked against local commercial alternatives [20].

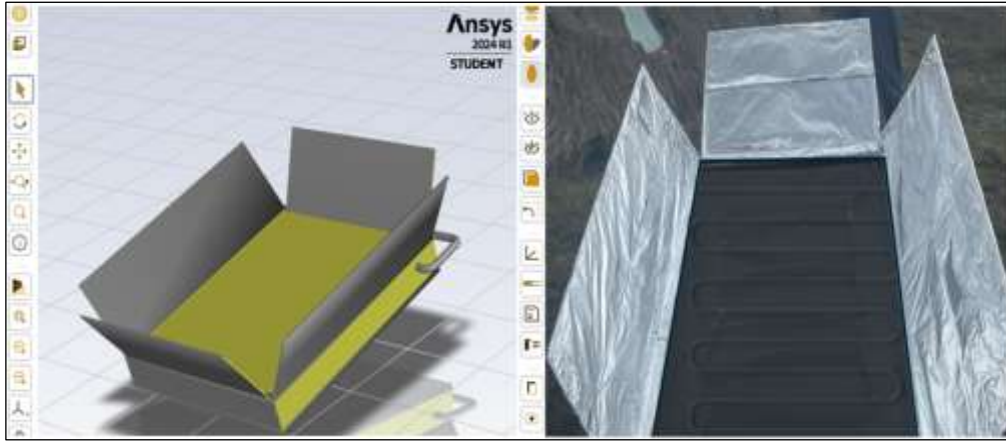


Figure 1: (a) 3D CAD geometry of the fluid domain used for numerical discretization; (b) Manufacturing process of the absorber plate using recycled 6063 aluminum.

Source: Authors, (2026).

II.4 COMPUTATIONAL FLUID DYNAMICS (CFD) STRATEGY

The thermal performance was predicted using a 3D conjugate heat transfer model in ANSYS Fluent. The simulation solved the Navier-Stokes equations coupled with the energy equation under steady-state conditions, a method validated for complex thermal flows by Aulestia [21].

II.4.1 Governing Equations:

The fluid (water) was modeled as incompressible and laminar ($Re < 2300$) in the riser tubes. The turbulence and flow behavior were analyzed comparing standard models as suggested by Adanta et al. [22], though a laminar model was sufficient for the low-flow regime. The conservation of energy equation is defined as:

The conservation of energy

$$\nabla \cdot (v(\rho E + p)) = \nabla \cdot (k_{eff} \nabla T) + S_h \quad (1)$$

Where k_{eff} is the effective thermal conductivity and S_h is the volumetric heat source term.

II.4.2 Radiation Model (Discrete Ordinates):

To accurately resolve the interaction between the solar irradiation, the semi-transparent glass cover, and the opaque absorber, the Discrete Ordinates (DO) radiation model was employed. Unlike simpler models (e.g., Rosseland), the DO model solves the Radiative Transfer Equation (RTE) for a finite number of discrete solid angles, which is essential for capturing the diffuse radiation component prevalent in the Andes [23].

II.4.3 Meshing And Grid Independence:

The computational domain was discretized using an unstructured tetrahedral mesh with inflation layers at the fluid-solid boundaries to capture thermal gradients (Figure 2). A grid independence study was performed, and the solution was considered grid-independent at 9.6 million elements.

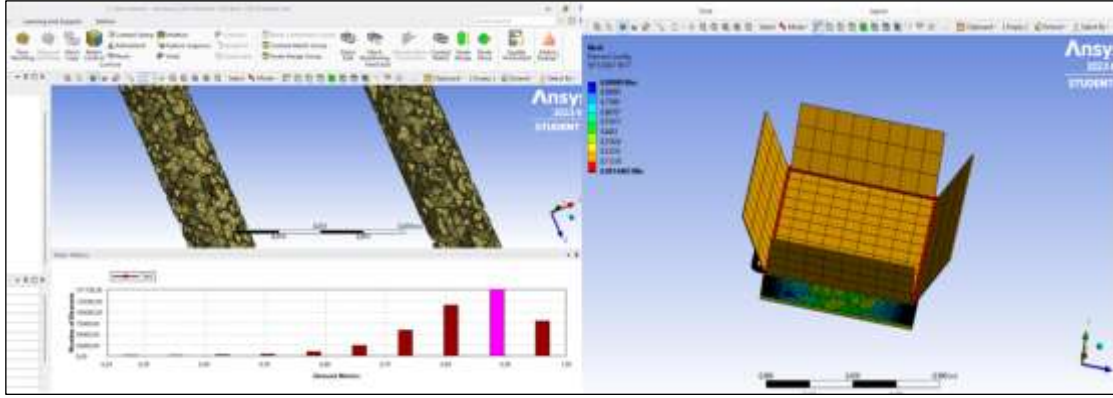


Figure 2: Unstructured tetrahedral mesh of the fluid domain with boundary layer refinement.
Source: Authors, (2026).

II.5 EXPERIMENTAL SETUP AND INSTRUMENTATION

The validation setup consisted of the recycled FPC connected to a 100-liter insulated storage tank in a closed-loop forced circulation system. The collector was oriented North with a tilt angle of 15°C.

Data acquisition was performed using an Arduino-based logger recording at 10-minute intervals:

- Temperature: Calibrated K-type thermocouples ($\pm 0.5^\circ\text{C}$) were installed at the inlet, outlet, and ambient air. The calibration and measurement of thermal properties followed the guarded hot plate method standards [24].
- Irradiance: Measured on the collector plane using a pyranometer.



Figure 3: Experimental setup installed at 3,000 m.a.s.l. in Yanayacu, Ecuador.
Source: Authors, (2026).

II.6 STATISTICAL VALIDATION METRICS

To quantify the accuracy of the CFD model, the Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) were calculated:

Root Mean Square Error

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (T_{\text{sim},i} - T_{\text{exp},i})^2} \quad (2)$$

Mean Absolute Percentage Error

$$\text{MAPE} = \frac{1}{n} \sum_{i=1}^n \left| \frac{T_{\text{sim},i} - T_{\text{exp},i}}{T_{\text{exp},i}} \right| \times 100 \quad (3)$$

III. RESULTS AND DISCUSSIONS

III.1 NUMERICAL THERMAL PROFILING (CFD ANALYSIS)

The Computational Fluid Dynamics simulation provided a steady-state thermal map of the collector under peak irradiance conditions ($\frac{800W}{m^2}$). The temperature contours, visualized in Figure 4, reveal a progressive thermal stratification along the longitudinal axis of the absorber plate.

- **Thermal Uniformity:** The simulation predicted a maximum fluid outlet temperature ($T_{out,num}$) of 55.0°C. Crucially, the thermal gradient across the recycled aluminum fins (ΔT_{plate}) showed high uniformity. This indicates that the secondary 6063 aluminum alloy maintains an effective thermal diffusivity (α), minimizing localized hotspots that could lead to radiative losses.
- **Flow Regime:** The velocity vectors within the riser tubes confirmed that the flow regime remained laminar ($Re < 2300$). This is significant because, as noted by Adanta et al. [25], laminar flow in solar thermal applications ensures a stable boundary layer, maximizing the heat transfer coefficient from the wall to the fluid without the pressure drop penalties associated with turbulent flow.

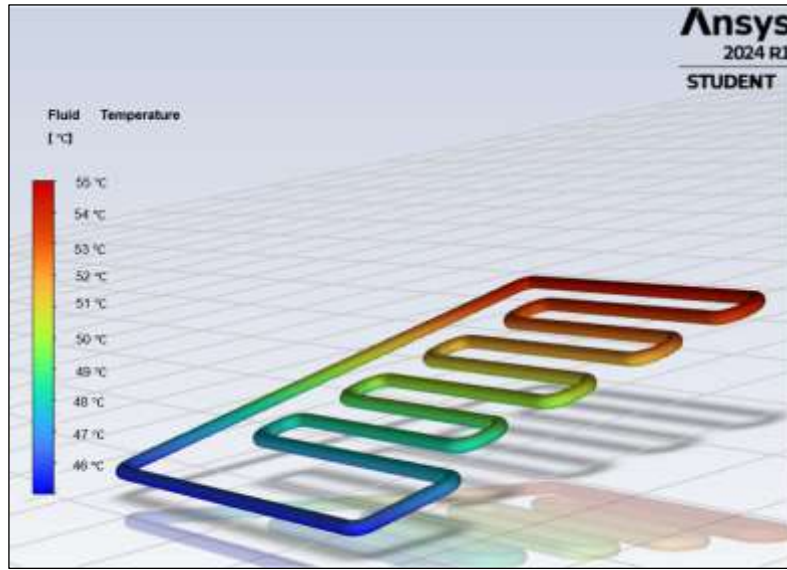


Figure 4: Contours of static temperature distribution on the absorber plate simulated in ANSYS Fluent, showing thermal stratification from inlet to outlet.

Source: Authors, (2025).

III.2 EXPERIMENTAL VALIDATION AND ERROR ANALYSIS

To validate the numerical model, experimental data were collected in the Andean paramo. Figure 5 illustrates the comparison between the CFD predicted curve and the in-situ measured temperatures over a representative diurnal cycle. The experimental peak temperature ($T_{out,exp}$) reached 53.8°C at solar noon (13:00 local time).

A statistical analysis of the deviation between the numerical model (y_{num}) and experimental data (y_{exp}) was performed. The correlation shows a Pearson coefficient of $r = 0.96$, indicating a strong linear relationship. However, a systematic deviation was observed, with the CFD model overpredicting temperatures by an average of 1.2°C. This discrepancy results in a Mean Absolute Percentage Error (MAPE) of:

$$MAPE = \frac{1}{n} \sum_{i=1}^n \left| \frac{y_{num} - y_{exp}}{y_{exp}} \right| \times 100 = 2.45\%$$

This error margin ($< 3\%$) validates the Discrete Ordinates (DO) radiation model. The slight overestimation is attributed to the idealization of "adiabatic walls" in the simulation [26]. In the physical prototype, the manual assembly of the recycled PET insulation likely introduced micro-thermal bridges at the casing joints, leading to minor convective losses not captured by the mesh.

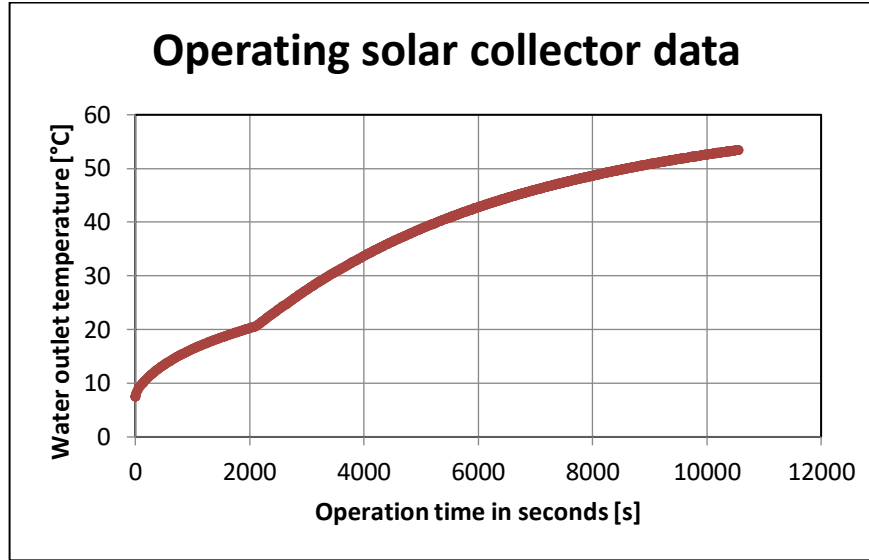


Figure 5: Experimental measurements validation of the numerical model.
Source: Authors, (2026).

III.3 PHYSICS OF HIGH-ALTITUDE PERFORMANCE

A critical finding of this study is the collector's robust performance at 3,000 m.a.s.l. despite using non-selective surfaces (recycled paint). This phenomenon can be explained by the fundamental physics of the atmosphere at high altitudes.

At 3,000 meters, the atmospheric pressure is approximately 70 kPa, which significantly reduces the density of the air (ρ_{air}) trapped in the gap between the absorber and the glass cover. According to the Rayleigh number (Ra) equation:

$$\text{Rayleigh number} \\ Ra = \frac{g\beta(T_p - T_c)L^3}{\nu\alpha} \quad (4)$$

Where ν (kinematic viscosity) increases as density decreases. A lower air density suppresses the onset of natural convection currents within the air gap [27]. This reduction in the convective heat transfer coefficient ($h_{c,gap}$) effectively lowers the overall top heat loss coefficient (U_L). Therefore, the high-altitude environment acts as a "passive performance booster," compensating for the lower optical efficiency of the recycled materials. This aligns with theoretical predictions by Duffie & Beckman [28], but provides novel empirical evidence for recycled collectors in equatorial mountain regions.

III.4 THERMAL EFFICIENCY AND PERFORMANCE METRICS (η)

The thermal quality of the collector was evaluated using the instantaneous efficiency curve, governed by the Hottel-Whillier-Bliss equation:

$$\text{Thermal efficiency of the collector} \\ \eta = F_R(\tau\alpha) - F_R U_L \frac{T_{in} - T_{amb}}{A_c G_T} \quad (5)$$

Figure 6 presents the efficiency curves derived from the validated numerical model. The recycled prototype exhibited an optical efficiency (intercept) of $\eta_0 = 0.512$ (51.2 %) under direct flow conditions. When coupled with aluminum reflectors (Simulation 2), the efficiency increased to 66.1%, demonstrating the high impact of concentrating solar flux on the absorber surface [29]. Although the heat loss coefficient ($F_R U_L \approx 6.5 \text{ W/m}^2\text{K}$) is higher than that of commercial copper-selective collectors (shown in the red dotted line), the performance is sufficient for low-temperature applications such as domestic water heating ($< 60^\circ\text{C}$). The reduced slope at high altitudes due to the suppression of convective losses in the low density air gap partially compensates for the lower optical properties of the recycled materials.

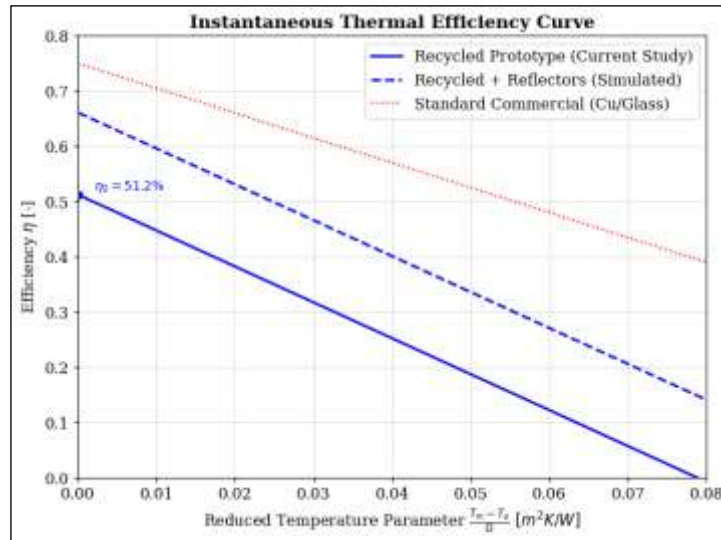


Figure 6: Instantaneous thermal efficiency curves comparing the recycled prototype (solid blue), the reflector-enhanced design (dashed blue), and a standard commercial collector (dotted red).

Source: Authors, (2026).

III.5 COST-BENEFIT AND SUSTAINABILITY ANALYSIS

The total manufacturing cost of the recycled prototype was \$70.00 USD, contrasting sharply with commercial flat-plate collectors available in the Ecuadorian market (\$400.00 USD) [30]. This represents an 82.5% cost reduction. Furthermore, the environmental analysis confirms that the fabrication process diverted 15 kg of solid waste (aluminum frames and PET bottles) from landfills. The Energy Return on Investment (EROI) is estimated to be superior to conventional collectors because the energy-intensive extraction of aluminum and polymerization of plastic was "amortized" in their previous lifecycle [31].

IV. CONCLUSIONS

The present study successfully validated, both numerically and experimentally, the feasibility of a low-cost flat-plate solar collector engineered from valorized solid waste for high-altitude Andean applications. Based on the results, the following conclusions are drawn:

1. **Validation of Numerical Strategy:** The 3D Computational Fluid Dynamics (CFD) model, coupled with the Discrete Ordinates (DO) radiation model, proved to be a robust predictive tool for non-standard materials. The simulation predicted a maximum outlet temperature of 55.0°C, deviating only 1.2°C (2.45%) from the experimental measurements. This low error margin confirms that recycled materials, when properly characterized, can be modeled with high fidelity using commercial CFD codes.
2. **Performance of Recycled Composites:** The secondary 6063 aluminum alloy (from window frames) and the recycled PET/polyurethane insulation demonstrated sufficient thermophysical stability to serve as functional components in thermal systems. The prototype achieved a peak temperature of 53.8°C and an optical efficiency of 51.2%, satisfying the World Health Organization's thermal requirements for domestic sanitary water usage (> 45°C).
3. **The "High-Altitude Effect":** A critical physical phenomenon was identified: the low atmospheric pressure at 3,000 m.a.s.l. ($\approx 70 \text{ kPa}$) significantly reduces the air density within the collector's gap. This naturally suppresses convective heat losses (U_L), allowing the recycled collector to compete with commercial systems despite having lower optical selectivity. This finding suggests that "low-tech" solar solutions are particularly advantageous in high-mountain equatorial regions.
4. **Socio-Economic Viability:** The proposed circular economy manufacturing process reduced the fabrication cost by 82.5% compared to commercial copper-based alternatives (from \$400 to \$70 USD) and diverted 15 kg of non-biodegradable waste from landfills. This establishes a scalable technological pathway for alleviating energy poverty in rural communities without relying on expensive imported infrastructure.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Robinson García and, Carlos Garzón.

Methodology: Robinson García and, Carlos Garzón.

Investigation: Robinson García and, Carlos Garzón.

Discussion of results: Robinson, García.

Writing – Original Draft: Robinson, García.

Writing – Review and Editing: Robinson García and, Carlos Garzón.

Resources: Robinson, García.

Supervision: Robinson García and, Carlos Garzón.

Approval of the final text: Robinson, García and Carlos Garzón.

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VII. REFERENCES

- [1] A. Dammert and R. García, *Energy Economics*. Lima, Peru: Fondo Editorial de la PUCP, 2020.
- [2] A. Eras-Almeida *et al.*, “Lessons Learned from Rural Electrification Experiences with Third Generation Solar Home Systems in Latin America: Case Studies in Peru, Mexico, and Bolivia,” *Sustainability*, vol. 11, no. 24, p. 7139, 2019. [Online]. Available: <https://doi.org/10.3390/su11247139>
- [3] J. Díaz Andagana, “Community participation in paramo management in the framework of the 'Páramos Fund to fight poverty' in the province of Tungurahua, Pasa parish,” Undergraduate thesis, Univ. Politécnica Salesiana, Quito, Ecuador, 2020. [Online]. Available: <https://dspace.ups.edu.ec/handle/123456789/19106>.
- [4] N. Blair, W. Beckman, and J. Duffie, *Solar Engineering of Thermal Processes, Photovoltaics and Wind*. United Kingdom: Wiley, 2020.
- [5] T. Abdelsalam, “Ultra-high temperature concentrated solar thermal energy,” Ph.D. dissertation, Univ. Edinburgh, Edinburgh, U.K., 2023. [Online]. Available: <https://doi.org/10.7488/era/3442>.
- [6] A. Elshamy, “Investigating the potential for implementing solar thermal cooling systems and energy efficiency measures for housing in Egypt,” Ph.D. dissertation, Loughborough Univ., Loughborough, U.K., 2020. [Online]. Available: <https://doi.org/10.26174/thesis.lboro.13721494.v1>.
- [7] R. Chisaguano and A. Valdivieso, “Design and construction of a solar collector prototype for water heating with recyclable materials for a home,” Undergraduate thesis, Univ. Politécnica Salesiana, Cuenca, Ecuador, 2021. [Online]. Available: <https://dspace.ups.edu.ec/handle/123456789/20200>.
- [8] Dentons, “General Regulations for the Organic Law of Inclusive Circular Economy,” Aug. 2023. [Online]. Available: <https://www.dentons.com/es/insights/articles/2023/august/30/reglamento-general-a-la-ley-organica-de-economia-circular-inclusiva>.
- [9] L. De Viteri and A. Benítez, “Comparative study on the mechanical behavior of concrete with recycled polyethylene terephthalate (PET) fiber and concrete with steel fiber,” *Dominio de las Ciencias*, vol. 7, no. 5, pp. 798–818, 2021. [Online]. Available: <https://dialnet.unirioja.es/servlet/articulo?codigo=8383807>.
- [10] D. S. Cantú-Fernández *et al.*, “Mechanical Properties of a Structural Component Processed in High-Pressure Die Casting (HPDC) with a Non-Heat-Treated Aluminum Alloy,” *Metals*, vol. 14, no. 3, 2024. [Online]. Available: <https://doi.org/10.3390/met14030369>.
- [11] M. Enrique, C. Arturo, A. Manuel, and R. Israel, “Implementation of the finite volume method for the solution of the Navier-Stokes equations for Poiseuille flow in incompressible laminar regime,” *Revista Electro*, vol. 44, pp. 140–144, Oct. 2022. [Online]. Available: https://itchihuahua.mx/revista_electro/2022/SUB-7592.html.
- [12] P. A. Anaya, “Multiplatform Remote Sensing in the Radiative,” Ph.D. dissertation, Univ. Salamanca, Salamanca, Spain, 2024. [Online]. Available: <https://gredos.usal.es/handle/10366/159818>.
- [13] F. Giannetti, “Sustainable energies: Solar collector based on recycled materials,” Master's thesis, Univ. Nacional de Mar del Plata, Mar del Plata, Argentina, 2020. [Online]. Available: <https://rinfi.fi.mdp.edu.ar/bitstream/handle/123456789/429/FGiannetti-TFG-IMe-2020.pdf>.
- [14] W. Aquima and D. Carlos, “Design and construction of a natural gas tilting crucible furnace for aluminum melting,” Undergraduate thesis, Univ. Nacional San Antonio Abad del Cusco, Cusco, Peru, 2022. [Online]. Available: <http://repositorio.unsaac.edu.pe/handle/20.500.12918/6508>.
- [15] J. Aragón, “New routes for functionalised nanoparticles for polymer nanocomposites,” Master's thesis, Inst. Tecnológico de Ciudad Madero, Tamaulipas, Mexico, 2023. [Online]. Available: http://51.143.95.221/bitstream/TecNM/7067/1/G21073001_donacion_tesis_bib.pdf.
- [16] B. Castells, “Flammability characterization of biofuels and materials with energy recovery,” Ph.D. dissertation, Univ. Politécnica de Madrid, Madrid, Spain, 2021. [Online]. Available: <https://oa.upm.es/68110/>.
- [17] I. González de Arrieta, “High-temperature infrared emissivity of materials for alternative energy applications,” Ph.D. dissertation, Euskal Herriko Unibertsitatea/Univ. del País Vasco, Bilbao, Spain, 2020. [Online]. Available: <http://hdl.handle.net/10810/50263>.
- [18] J. Chávez, R. Davis, and T. Sparks, “Analysis of Thermal Expansion via Dilatometry,” *Journal of Visualized Experiments (JoVE)*, 2023. [Online]. Available: <https://app.jove.com/t/10490>.
- [19] J. Gomes, “Development of Concentrating Photovoltaic-Thermal Solar Collectors,” Ph.D. dissertation, Univ. Gävle, Gävle, Sweden, 2021. [Online]. Available: <https://www.diva-portal.org/smash/get/diva2:1535513/FULLTEXT01.pdf>.
- [20] R. Chisaguano and A. Valdivieso, “Design and construction of a solar collector prototype for water heating with recyclable materials,” Undergraduate thesis, Univ. Politécnica Salesiana, Cuenca, Ecuador, 2021. [Online]. Available: <https://dspace.ups.edu.ec/handle/123456789/20200>.
- [21] C. Aulestia, “Three-dimensional numerical modeling of flow in the intake gates of the Toachi-Pilatón project applying computational fluid dynamics (CFD),” Master's thesis, Escuela Politécnica Nacional, Quito, Ecuador, 2020. [Online]. Available: <https://bibdigital.epn.edu/bitstream/15000/17482/3/CD-7982.pdf>.
- [22] D. Adanta, I. Fattah, and N. Muhammad, “Comparison of the standard k-epsilon turbulence model and SST k-omega for waterwheel simulation,” *Revista de Ciencias Mecánica e Ingeniería*, 2020. [Online]. Available: <https://opus.lib.uts.edu.au/bitstream/10453/159275/2/11392-29988-1-PB%20%282%29.pdf>.
- [23] J. Chávez, R. Davis, and T. Sparks, “Analysis of Thermal Expansion via Dilatometry,” *Journal of Visualized Experiments (JoVE)*, no. 201, 2023. [Online]. Available: <https://app.jove.com/t/10490>.

- [24] A. Díaz, A. Hernández, J. Quiñonez, G. Ortiz, and F. López, “HD20: Guarded hot plate apparatus for the measurement of conduction heat transfer properties in concrete,” *Energías Renovables y Medio Ambiente*, vol. 47, pp. 49–57, 2021. [Online]. Available: https://ri.conicet.gov.ar/bitstream/handle/11336/171123/CONICET_Digital_Nro.ab90299d-2cf0-44aa-b760-82ca6a25b2c5_B.pdf.
- [25] R. Cabañas, “Corrosion evaluation of molten salts thermal energy storage (TES) systems in concentrated solar power plants (CSP),” Ph.D. dissertation, Univ. Lleida, Lleida, Spain, 2020. [Online]. Available: <https://www.tdx.cat/handle/10803/671680>.
- [26] A. Díaz *et al.*, “HD20: Guarded hot plate apparatus for the measurement of conduction heat transfer properties in concrete,” *Energías Renovables y Medio Ambiente*, vol. 47, pp. 49–57, 2021. [Online]. Available: https://ri.conicet.gov.ar/bitstream/handle/11336/171123/CONICET_Digital_Nro.ab90299d-2cf0-44aa-b760-82ca6a25b2c5_B.pdf.
- [27] N. Blair, W. Beckman, and J. Duffie, *Solar Engineering of Thermal Processes, Photovoltaics and Wind*. United Kingdom: Wiley, 2020.
- [28] N. Blair, W. Beckman, and J. Duffie, *Solar Engineering of Thermal Processes, Photovoltaics and Wind*, 5th ed. Hoboken, NJ, USA: Wiley, 2020.
- [29] F. Alpsten, “Alternative Plastic Materials for Increased Sustainability of Husqvarna K770,” Ph.D. dissertation, Chalmers Univ. Technology, Gothenburg, Sweden, 2021. [Online]. Available: <http://hdl.handle.net/20.500.12380/302700>.
- [30] R. Chisaguano and A. Valdivieso, “Design and construction of a solar collector prototype for water heating with recyclable materials,” Undergraduate thesis, Univ. Politécnica Salesiana, Cuenca, Ecuador, 2021. [Online]. Available: <https://dspace.ups.edu.ec/handle/123456789/20200>.
- [31] B. Castells, “Flammability characterization of biofuels and materials with energy recovery,” Ph.D. dissertation, Univ. Politécnica de Madrid, Madrid, Spain, 2021. [Online]. Available: <https://oa.upm.es/68110/>.