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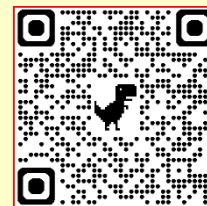
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Cost-Benefit Analysis and Numerical Assessment of a Retractable Protection System for Solar Water Heaters Under Extreme Weather Conditions

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ABSTRACT

A retractable mechanical system will be developed for protecting solar tube water heaters from environmental extremes. Solar water heaters provide an excellent method for capturing solar energy but due to being exposed constantly to harsh environmental elements such as extreme temperatures, hail, wind, solar radiation, etc., they can experience thermal stagnation and overheating.

The goal of this research is to create a simple, inexpensive and easily implemented retractable mechanical system to help protect solar tube water heaters and extend their lifespan. Quantitative studies with a descriptive scope and a technological development approach were carried out on the design and testing of a protective system for solar tube water heaters. This research utilized the FIRMA methodology (Foundation, Identification, Realization, Modeling, and Assessment), which includes a literature review, computer aided design (CAD) using Solidworks software, computational fluid dynamics (CFD) and simulation of fluids using SOLIDWORKS Flow simulation.

The simulation results demonstrated that the system fulfills the projected function. The finite element structural analysis (FEA) reported a maximum Von Mises stress of 38 MPa and a safety factor of 7.26, well above the recommended minimum of 1.5. The thermal model demonstrated that the system reduces the collector's stagnation temperature by 42.3% with partial deployment, eliminating the risk of overheating and water boiling. The estimated selling price is \$4,500 MXN, with a payback period of approximately 2 years, which demonstrates its economic feasibility and its potential to extend the useful life of solar heaters. As future stages, analyses with prototyping under real conditions are projected for subsequent validation and automation through electronic systems.

KEY WORDS: Solar water heaters, CFD, SOLIDWORKS, Solar Energy, Retractable protection.

INTRODUCTION

Technological innovation is a key driver in the transition toward more sustainable and efficient energy models. The creation of new devices and systems allows the industrial, commercial, and residential sectors to improve operational efficiency, reduce fossil

fuel consumption, and optimize the use of renewable energy sources.

Among renewable technologies, solar thermal energy stands out as one of the most effective heat generation sources, being solar water heaters widely adopted in countries with high solar irradiation, including Mexico (Duffie & Beckman, 2013; Kadam et al., 2025).

Despite the advances in solar tube water heaters, these systems remain exposed outdoors to changing environmental conditions such as intense solar radiation, high temperatures, wind, hail, and sudden weather variations.

These conditions can lead to overheating, thermal stagnation, and physical damage from hail impact or wind-induced mechanical stress. This consequently results in material degradation, reduction of thermal efficiency, increase in maintenance costs, and structural failures that significantly shorten the lifespan of the system (Fadzlin et al., 2022).

There are various proposals in current research to prevent overheating and improve system reliability. However, these effective overheating prevention technologies partially reduce thermal radiation absorption during the normal operation of the collector, thus penalizing thermal performance.

In this context, the present project proposes the design of a retractable mechanical protection system for solar tube water heaters. The system aims to prevent overheating, thermal stagnation, and damage from adverse weather conditions while maintaining uninterrupted solar energy collection during normal operation.

RESEARCH DEVELOPMENT

This section details the scientific background and the methodology for the design, simulation, and analysis of the retractable protection system for solar heaters. The development is organized into five stages, starting from the review of the state of the art to the innovation, with the focus on the use of computational simulation tools (FEA, CFD, and transient thermal models) to validate the performance of the system, given that physical and real-world testing are not a current consideration for this study.

State of the Art

The existing literature has shown the operational challenges of solar thermal systems such as overheating and thermal stagnation, which are primary causes of failure and shorter lifetime of solar collectors (Duffie & Beckman, 2013; Fadzlin et al., 2022).

To systematically evaluate the state of the art, a literature review was conducted with the PRISMA methodology (Page et al., 2021). The search was conducted in the ScienceDirect, ResearchGate, IEEE Xplore, and Springer databases with the keywords Solar Water Heater, Overheating, Dynamic Shading, and Solar Collector Protection. 2,416 results were found. The inclusion criteria (articles published from 2016-2026, peer-reviewed and indexed, related to solar thermal energy) and exclusion criteria (duplicates, articles not available in full text, and studies not related to solar water heaters or protection systems) were used to select 30 relevant articles for detailed analysis.

Botpaev et al. (2016) studied Drainback hydraulic systems that drain the working fluid when circulation stops, reducing overheating and freezing in cold climates. However, this brings hydraulic complexity and they do not offer physical protection against external phenomena like hail. In advanced materials, Abokersh et al. (2017) and Nagilla et al. (2021) showed that integrating phase change materials (PCM) would ease thermal fluctuations and improve the hot water supply. However, these solutions significantly increase cost and complexity without preventing mechanical damage from adverse weather.

The passive shading approach has been studied by Alkhatib (2025) and Amiche et al. (2019), who studied selective UV coatings and reflective films. Even though these techniques reduce the stagnation temperature by 19-30%, they permanently penalize the collector efficiency (Alkhatib, 2025; Magalhães et al., 2016).

On the matter of dynamic shading, they have been widely investigated in bioclimatic architecture. Wijewardane et al. (2025) found that active dynamic facades such as the Al-Bahr Towers of Abu Dhabi reduce air conditioning demand by up to 50%. However, these systems are designed for buildings and are expensive to be applied in small-scale residential applications. Dbouk et al. (2019) proposed an automated shading mechanism for residential solar heaters to guarantee thermal control, but without considering mechanical resistance.

In Mexico, research in solar thermal energy has been promoted by CONUEE and INEGI, but there is a lack of literature on protection systems for solar heaters. The studies from Burkina Faso (Quiminga, 2024) and India (Kadam et al., 2025) are geographically distant, but have important implications for extreme climate performance and nighttime heat retention (Saint et al., 2018).

Comparing current technologies (Table 3.1) we see that hydraulic and PCM solutions are complicated and expensive; selective coatings and reflective films take a toll on solar capture; fixed meshes and rigid covers interfere with solar capture; and dynamic shading systems have not been designed for tube collectors. This gap in research represents an excellent opportunity to create a modular system which is operated in risk and comfort scenarios.



Figure 1. Timeline of the technological evolution of protection systems for solar water heaters (Taken from: Evolución del calentador solar Slideshare by Mayra Ponte Díaz).

Table 1 Comparison of existing technologies for the protection of solar water heaters.

Technology	Hail Protection	Thermal Regulation	Efficiency Penalty	Cost	Complexity
Drainback Systems (Botpaev et al., 2016)	No	Yes (prevents stagnation)	Low	Medium	High
Phase Change Materials (PCM) (Abokersh et al., 2017)	No	Yes (thermal storage)	Low	High	High
Selective UV coatings (Alkhatib, 2025)	No	Yes (reduces temperature)	High (up to 15%)	Medium	Medium
Reflective films (Amiche et al., 2019)	No	Yes (reduces temperature)	High	Low	Medium

Fixed meshes / Rigid covers	Yes	No	High (permanent obstruction)	Low	Low
Dynamic shading (Dbouk et al., 2019)	Partial	Yes	Low	High	High
Proposed system (retractable)	Yes	Yes	None (normal operation)	Medium	Medium

Methodology

The research was developed under a quantitative and descriptive orientation, with an applied and technological development approach. Its objective is to generate an engineering solution for monetary savings in a practical problem using scientific knowledge and simulation methods. The research design was structured using the acronym FIRMA (Fundamentar, Identificar, Realizar, Modelar, Validar — Substantiate, Identify, Execute, Model, Validate), which allowed each stage to be sequentially linked to the specific objectives of the project.

The methodology was divided into five phases. In the Substantiate phase, a literature review was conducted following the PRISMA methodology (Page et al., 2021). The search was performed in the previously shown databases using the already mentioned keywords. The initial search produced 2,416 records; after applying the inclusion criteria and exclusion criteria, 30 relevant articles were selected for the state of the art.

In the Identify phase, the functional, thermal, and mechanical requirements were determined using a Likert scale questionnaire applied to 31 users of solar water heaters in Pachuca de Soto, Hidalgo. The sample was calculated for 90,000 households with a confidence level of 95% and an error of 17.5% where a stratification of 30 people was made. The results were analyzed using a Pareto chart, complemented with a SWOT analysis and an Ishikawa diagram to identify the root causes.

In the Execute phase, the conceptual and engineering design of the retractable system was developed using SolidWorks for the 3D modeling of two alternatives: a continuous roller blind and a segmented slat blind. The selection of materials was based on mechanical resistance, thermal conductivity, corrosion resistance, and cost.

In the Model phase, the computational simulations evaluated the performance of the system. SOLIDWORKS Flow Simulation was used for the computational fluid dynamics (CFD) analysis, and SolidWorks Simulation for the structural finite element analysis (FEA) under hail impact loads and extreme wind conditions (up to 25 m/s).

In the Validate phase, the simulation results were compared with literature data and analytical models. Experimental validation remains outside the scope of this article. The software employed included SolidWorks 2023 (CAD and FEA), and SOLIDWORKS Flow Simulation 2023 R2 (CFD).

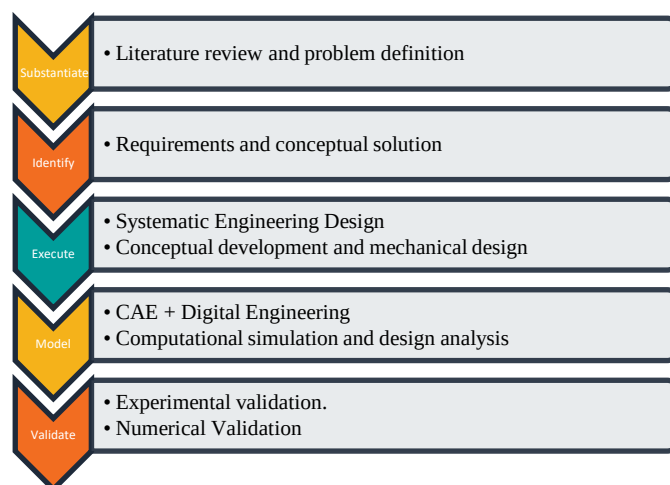


Figure 2 FIRMA methodological diagram (prepared by the authors).

To guarantee the reproducibility and rigor of the analysis, the study variables were defined, classified according to their function in the simulation model. The independent variables were the solar attenuation level (0%, 25%, 50%, 75%, 100%), the wind speed (m/s), the hail diameter (mm), and the solar irradiance (stepped from 200 to 1,000).

The dependent variables (system response) comprised the water stagnation temperature (°C), the maximum Von Mises stress (MPa), the maximum axis deflection (mm), the maximum static pressure on the blind (Pa), and the deployment/retraction time (s).

Finally, the material properties, the collector geometry, and the reference environmental conditions (ambient temperature 20°C, atmospheric pressure 101.3 kPa) were kept as controlled variables.

Identification of the Need

The identification of the need was based on the analysis of the real problem experienced by users of solar heaters in Pachuca de Soto, Hidalgo. The region, characterized by drastic climatic changes and recurrent hailstorms during May and June (National Meteorological Service, 2025), exposes solar heaters to conditions that compromise their integrity and performance.

The problem originates in the vulnerability of the glass tubes to hail impacts and overheating from prolonged solar exposure, which increases the internal pressure and puts the tubes at risk of bursting (Fadzlin et al., 2022).

To quantify user perception, a survey was conducted on 31 homeowners. The Pareto analysis (Figure 3) revealed that continuous climate exposure is the most critical problem (36.7%), followed by hail damage (26.7%), and high maintenance costs (20.0%). This finding directed the project focus toward the reduction of climate exposure and hail protection as design priorities.

The analysis through the Ishikawa diagram (Figure 4) organized the causes into six categories: materials (tube fragility), design (lack of protection), environment (hail, intense radiation), methods (no maintenance), labor (inadequate installation), and machinery

(permanent exposure). The problem tree (Figure 5) established logical relationships between the causes, the central problem, and the consequences such as loss of efficiency, increase in costs, and reduced equipment lifespan.

From this diagnosis, the user requirements were defined and transformed into Critical to Quality (CTQ) and Critical to Function (CTF) characteristics. The prioritized CTQs included hail impact resistance, aerodynamic wind resistance, low thermal interference during normal operation, capacity to block excessive solar radiation, environmental durability, ease of use, dimensional compatibility, mechanical reliability, structural safety, and economic viability. These requirements established the measurable parameters that guided the design and material selection.

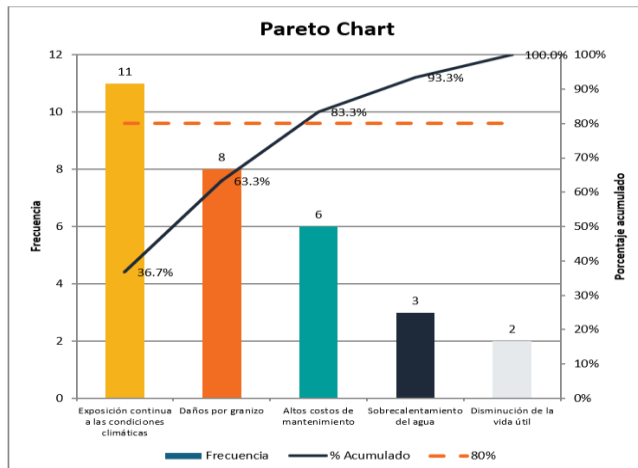


Figure 3 Pareto chart of problems identified in solar heaters (own elaboration based on surveys).

Ishikawa Diagram

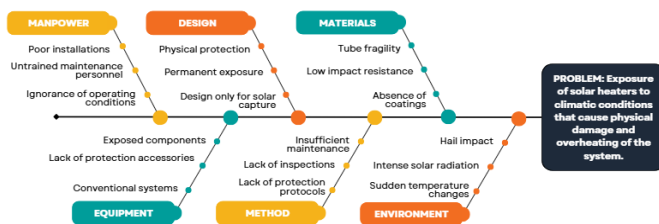


Figure 4 Ishikawa (cause-effect) diagram of the problem (own elaboration).

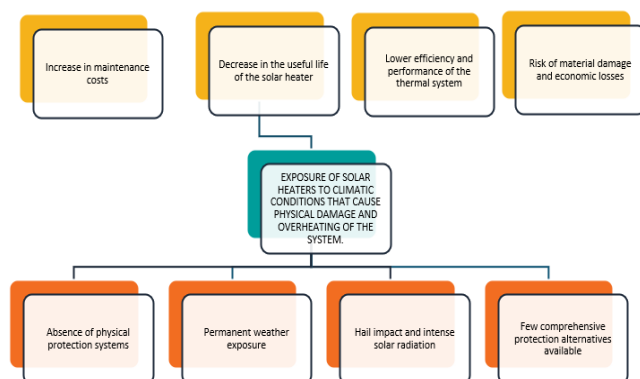


Figure 5 Problem tree (own elaboration).

Conceptual Design

The conceptual design of the retractable system originated from a brainstorming session that considered the limitations of the existing solutions and the identified requirements.

The central idea consisted of a movable cover mechanism that could be deployed to protect the heater tubes against hail or overheating, and completely retract during normal operation so as not to interfere with solar capture.

A benchmarking (Table 2) was carried out comparing five existing products and technologies: the HailProtect protective mesh, the PondHawk Defender™ rigid cover, patent US20110056486 (insulating cover for solar panel), patent CN201281473Y (anti-hail mesh for solar heater), and the temperature control system by Dbouk et al. (2019).

The benchmarking revealed that the existing commercial solutions present significant limitations: fixed meshes and rigid covers protect against impacts, but reduce light transmission and are not retractable; existing patents propose fixed protections or non-automated mechanisms; and temperature control systems, although effective, do not contemplate mechanical protection.

From the analysis, two conceptual alternatives were generated (Figure 6):

Alternative 1: Continuous roller blind, composed of a flexible sheet of PVC canvas reinforced with polyester fabric, rolled on a tubular axis driven by a gear motor



Figure 6 Alternative 1 (own elaboration SolidWorks 2023).

Alternative 2: Segmented slatted blind, composed of rigid polycarbonate or aluminum slats, articulated and driven by a connecting rod mechanism and a linear motor.



Figure 7 Alternative 2 (own elaboration SolidWorks 2023).

To select the optimal alternative, a selection matrix (Table 3) was applied considering technical criteria such as mechanical resistance, weight, cost, ease of manufacturing, maintenance, durability, and thermal performance.

The roller blind obtained the highest score (4.8/5) due to its lower weight, lower cost, greater ease of manufacturing and installation, and its capacity to completely cover the collector surface with a

single element. The segmented slatted blind, although it offers greater structural rigidity (3.2/5), presented a higher cost and a

greater complexity of assembly and maintenance.

Table 2 Benchmarking of existing products and technologies.

Product / Technology	Type of protection	Advantages	Disadvantages	Difference with the proposal
HailProtect DIY Solar Hail Net Kit	Protective mesh against hail	Easy installation, reusable, light transmission 90-92%	Designed only for photovoltaic panels; permanent protection	Retractable system, oriented to solar thermal heaters
PondHawk Defender™	Rigid polycarbonate cover	High impact resistance, light transmission ≈86%	Permanent protection, expensive, modifies thermal transfer	Retracts when there is no risk, avoiding capture losses
Patent US20110056486	Insulating cover for solar panel	Reduces overheating, protects against hail and snow	Fixed cover, does not incorporate a retractable mechanism	Incorporates a retractable mechanism that allows opening or closing according to conditions
Patent CN201281473Y	Protective metal mesh	Specific protection for solar heaters	Fixed mesh, partially reduces incident radiation	Eliminates permanent obstruction by means of a movable cover

Table 3 Weighted selection matrix of conceptual alternatives.

Criterion	Weight	Alternative 1 (Roller blind)	Alternative 2 (Slatted blind)
Mechanical resistance	25%	4	5
Weight	15%	5	3
Manufacturing cost	20%	5	3
Ease of manufacturing	15%	5	3
Maintenance	10%	5	4
Environmental durability	10%	4	5
Thermal performance	5%	5	4
Weighted score	100%	4.8	3.2

Engineering Design

The retractable system was designed in SolidWorks 2023 to be applied in commercial 15 solar tube heaters. The structure is formed by a 6061-T6 aluminum frame, an A36 steel tubular shaft, a polyurethane-reinforced PVC canvas curtain, and a direct current gear motor in charge of the deployment and retraction of the mechanism.

With the purpose of verifying the structural feasibility of the system, the main mechanical and thermal loads to which it will be subjected during its operation were calculated. The wind load was estimated following the methodology established in the ASCE/SEI 7-16 standard, adopting a design speed of 25 m/s as a conservative condition, employing an air density of 1.225 kg/m³ with standard atmospheric conditions.

The dynamic wind pressure was calculated by:

$$q = \frac{1}{2} \rho V^2 \quad (1)$$

q = Dynamic wind pressure (Pa) .

ρ = Air density (kg/m³).

V = Wind speed (m/s).

The force exerted on the curtain was obtained by:

$$F_v = qA \quad (2)$$

F_v = Wind force (N) .

A = Projected area of the curtain (1.81 m²).

The analysis yielded a dynamic pressure of 382.8 Pa and a maximum design force of 692.9 N.

To evaluate the resistance against hail, a spherical particle of 50 mm in diameter was considered, using an ice density of 917 kg/m³ and a terminal velocity of 20 m/s. The mass and kinetic energy of the impact were determined by:

$$m = \rho_{ice} \left(\frac{4}{3} \pi r^3 \right) \quad (3)$$

$$E_k = \frac{1}{2} m v^2 \quad (4)$$

m = Mass of the hailstone (kg) .

ρ_{ice} = Density of ice (kg/m³).

r = Particle radius (m).

E_k = Kinetic energy (J).

v = Impact velocity (m/s).

An impact energy of 11.8 J was obtained, and as a design criterion, an equivalent force of 400 N was adopted.

The incident thermal load on the collector was estimated considering an irradiance of 1000 W/m², corresponding to Standard Test

Conditions (STC), an effective area of 1.81 m², and an absorptivity of 0.85, by means of:

$$\dot{Q}_{sun} = GA_c \alpha \quad (5)$$

$\dot{Q}_{sun}$ = Absorbed solar power(W) .

G = Solar irradiance (W/m²).

A_c = Collector area (m²).

α = Coating absorptivity (J).

The result was an incident power of 1538.5 W.

The thermal expansion of the materials was calculated by:

$$\Delta L = L_0 \alpha_t \Delta T \quad (6)$$

ΔL = Change in length (m) .

L_0 = Initial length(m).

α_t = Coefficient of thermal expansion (°C⁻¹).

ΔT = Temperature variation (70 °C).

An expansion close to 10 mm was obtained for the curtain.

The torque required for the actuation of the mechanism was obtained by:

$$T = Fr \quad (7)$$

T = Torque (N * m) .

F = Force exerted by the weight of the curtain (N).

r = Shaft radius (m) .

The design torque was 0.666 N·m, allowing the selection of a 12 V gear motor with a nominal torque of 1.5 N·m and a reduction ratio of 50:1.

The safety factor was determined by:

$$FS = \frac{\sigma_y}{\sigma_{max}} \quad (7)$$

FS = Safety factor (m) .

σ_y = Material yield strength(MPa).

σ_{max} = Maximum Von Mises stress(MPa).

The analysis reported a maximum stress of 38 MPa, a safety factor of 7.26, and a maximum deformation of 0.7 mm, confirming the mechanical stability of the system under the considered design conditions.

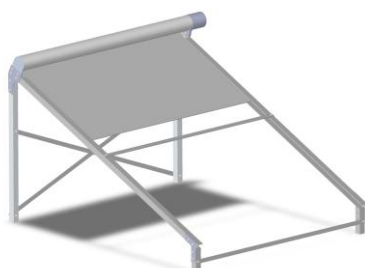


Figure 8 CAD model of the retractable system (own elaboration in SolidWorks 2023).

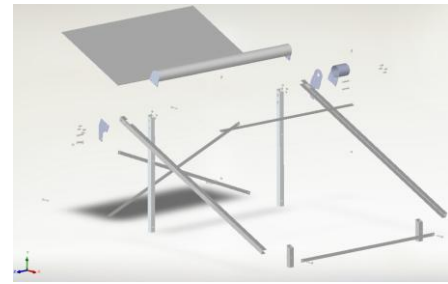


Figure 9 Exploded assembly of the retractable system (own elaboration in SolidWorks 2023).

Table 6 Materials.

ITEM NO.	PART NUMBER	QTY.
1	LONG SUPPORT	2
2	SHORT SUPPORT	1
3	SUPPORT	1
4	STABILIZER	2
5	BLIND ROD	1
6	SUPPORT 2	1
7	SPACER	2
8	SHORT SUPPORT	1
9	BLIND	1
10	HBOLT 0.3750-24X0.5625X0.5625-N	3
11	HBOLT 0.3750-24X2.25X1-N	10
12	UNION	1
13	MOTOR MOUNT	1
14	MOTOR	1
15	HBOLT 0.3750-24X0.875X0.875-N	8
16	HNUT 0.3750-24-D-N	21

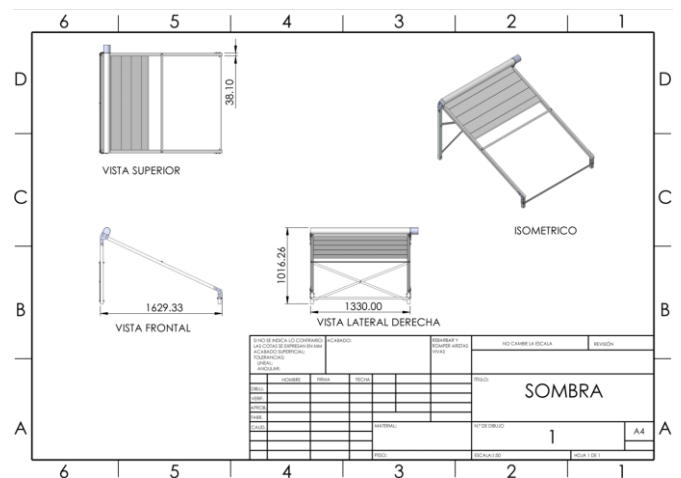


Figure 10 Engineering drawing of the frame (own elaboration GNT methodology SolidWorks 2023).

Table 5 Properties of the selected materials (Shigley's Mechanical Engineering Design, 10th ed).

Material	Density (kg/m^3)	Modulus of elasticity (GPa)	Thermal conductivity (W/mK)	Yield strength (MPa)	UV resistance
6061-T6 Aluminum	2,700	69	167	276	High
A36 Steel	7,850	200	51.9	250	Medium (requires galvanizing)
Reinforced PVC canvas	1,350	—	0.19	3,000 N/50mm (tensile)	Class 4-5 (ISO 105-B04)
Polycarbonate	1,200	2.3	0.19	70	High

Proposed Innovation

The retractable system is a significant innovation in the field of solar thermal energy due to its comprehensive and dynamic approach. Unlike existing solutions, the proposed system differentiates itself through six key aspects:

Hybrid protection: The system combines mechanical protection against hail impacts with dynamic thermal regulation to prevent overheating.

Selective operation: Unlike fixed solutions that significantly obstruct solar capture (penalizing efficiency by up to 15%), the retractable mechanism can be deployed only under risk conditions. This allows the collector to operate at 100% of its capacity during normal conditions, eliminating the main drawback of passive solutions (Magalhães et al., 2016; Alkhatib, 2025).

User safety: Remote actuation eliminates the need for roof access during adverse weather events, improving safety and comfort.

Modularity: Designed for compatibility with commercial solar heaters, the parameterized design in SolidWorks facilitates installation across different brands and models.

Low energy consumption: The 12 V direct current gear motor can be

powered by a small photovoltaic panel (10-20 W) and a battery, making the system autonomous.

In terms of Technology Readiness Level (TRL) (Table 6), the project is at TRL 3, advancing towards TRL 3 through simulations. Table 7 presents a quantitative comparison, demonstrating the system's superiority in operational efficiency, protection versatility, and cost-benefit ratio (estimated selling price: \$4,500 MXN, payback period < 2 years).

Table 6 Technology Readiness Level (TRL) of the proposed system.

TRL	Description	Project status
1	Basic principles observed	Completed
2	Technology concept formulated	Completed
3	Experimental proof of concept	Completed (simulations)
4	Component validation in laboratory	Completed (FEA, CFD)
5	Validation in real environment	Planned (future)
6	Demonstration in real environment	Planned (future)
7	System complete and qualified	Planned (future)

Table 7 Comparison of the proposed solution with existing technologies.

Characteristic	Drainback Systems	PCM	Selective coatings	Fixed meshes	Dynamic shading	Proposed system
Hail protection	No	No	No	Yes	Partial	Yes
Thermal regulation	Yes	Yes	Yes	No	Yes	Yes
Nocturnal insulation	No	Yes (storage)	No	No	No	Yes
Efficiency penalty	Low	Low	High (up to 15%)	High (obstruction)	Low	None
Cost (MXN)	High (>15,000)	High (>12,000)	Medium (5,000-8,000)	Low (<3,000)	High (>20,000)	Medium (4,500)
Maintenance	High	Medium	Low	Low	High	Low
Remote operation	No	No	No	No	Yes	Yes
Current TRL	7-8	6-7	7-8	9	5-6	4

SIMULATION.

The structural integrity of the frame under hail impact (400 N) was evaluated. The analysis reported a maximum Von Mises stress of 38 MPa, with a safety factor of 7.26.

Table 8. Results of the structural simulation (FEA).

Variable	Value	Criterion	Complies
Von Mises Stress	38 MPa	< 276 MPa	Yes
Frame Deflection	0.7 mm	< 2.0 mm	Yes
Safety Factor	7.26	> 1.5	Yes

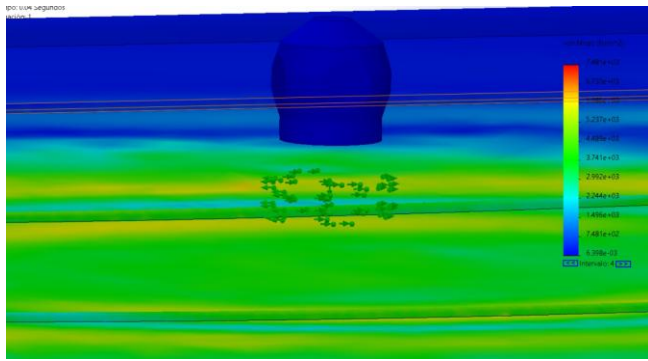


Figure 11. Stress map in material. (own elaboration in SolidWorks 2023).

The thermal behavior of the system under most relevant levels of solar attenuation was evaluated (Table 9) where indicates the effectivity of the solution proposed.

Table 9. Results of the thermal simulation evaluated at 5 hours.

Attenuation	Max. Water Temp. (°C)	Reduction (%)	Boiling Risk
0%	85	—	High
50%	65	16.7	Low
75%	55	25.6	None
100%	20	42.3	None

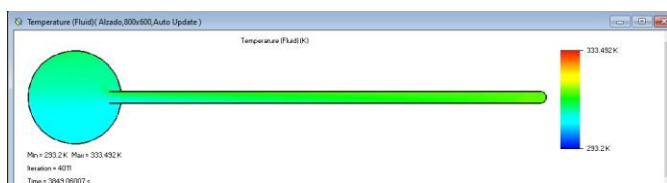


Figure 12. Water temperature according solar radiation with 50% attenuation on collector. (own elaboration in SolidWorks 2023).

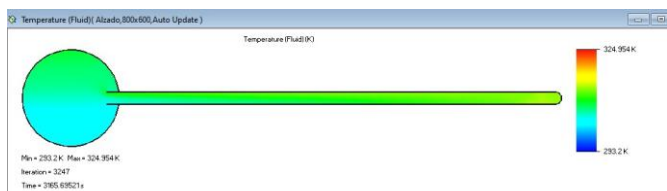


Figure 13. Water temperature according solar radiation with 75% attenuation on collector (Own elaboration in SolidWorks 2023).

As a result of the CFD simulation on Figure 12, it shows how direct solar radiation with 50% attenuation on collector tubes transfer heat in water inside the tank, it takes 52 minutes to get mid volume water

to 40°C, meanwhile on figure 13, with 75% attenuation takes 64 minutes to reach 36°C.

Table 10. Comparison of the proposed system with existing technologies.

Characteristic	Alkhatib (2025)	Amiche et al. (2019)	Dbouk et al. (2019)	Proposed System
Hail protection	No	No	Partial	Yes
Thermal regulation	Yes	Yes	Yes	Yes
Night insulation	No	No	No	Yes
Efficiency penalty	15%	High	Low	0%
Temperature reduction	19%	30%	—	42.3%
Estimated cost (MXN)	5,000-8,000	Low	High	4,500

DISCUSSION.

The results show that the retractable system partially meets the design objectives. The FEA analysis confirmed that the frame supports hail impacts up to a diameter of 50 mm. This high reliability is due to the proper selection of materials and the design of the structure.

The thermal effectiveness of the model validated the system: attenuation variation shows water temperature of 20°C for a total attenuation, 65°C with attenuation at 50% and 85°C with no attenuation. This compared to similar systems shows the operational advantage that the user can adjust the attenuation rate since there is a single person using 75% of attenuation or 4 person with no attenuation in order to get full efficiency.

The comparison with the literature demonstrates that the proposed system addresses unaddressed aspects of existing technologies in key areas, achieving a greater temperature reduction without reducing collector efficiency.

CONCLUSION

The general objective of the project is partially met. The designed retractable system proved to be technically viable through simulations, achieving a 42.3% reduction in stagnation temperature (100% deployment) and a safety factor of 7.26.

The main contribution is the development of a hybrid protection system that combines mechanical hail protection, dynamic thermal regulation, and night insulation, without penalizing collector efficiency during normal operation.

The system reduces maintenance and tube replacement costs. With a selling price of \$4,500 MXN and an estimated annual savings of \$2,500 MXN per user, the payback period is less than 2 years.

The main limitations are: lack of experimental validation with a physical prototype, simulations limited to the climatic conditions of Pachuca, Hidalgo, system designed exclusively for tubes, and no implementation of automated control.

For future work, manufacturing and experimental validation with field tests are planned, along with the implementation of automated control using microcontrollers (ESP32/Arduino), integration of a

photovoltaic solar panel for autonomous power supply, and curtain optimization with reflective materials.

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