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Laser Micro-Texturing and AI-Driven Optimization for Thermal Management of Photovoltaic Systems

Aswin Karkadakattil

Purpose. Photovoltaic (PV) and other renewable systems suffer efficiency and reliability losses from overheating. This review emphasizes the need for scalable, integrated thermal management solutions. **Design / Method / Approach**. The paper evaluates recent advances in laser-based surface micro-texturing as a promising strategy for thermal regulation. Controlled micro/nano-scale structures enhance heat dissipation, expand surface area, and tune wettability. The study also explores the role of artificial intelligence (AI) in predicting, designing, and optimizing laser-induced textures for simultaneous improvements in thermal, optical, and mechanical durability. **Findings**. Laser-processed surfaces provide multifunctional benefits such as enhanced convective cooling, anti-reflection, and self-cleaning, but most demonstrations remain confined to laboratory scale. AI methods including neural networks, evolutionary algorithms, and reinforcement learning show strong predictive capability and multi-objective optimization potential, offering pathways for industrial adoption. **Theoretical Implications**. The review establishes links between surface morphology, thermo-fluid dynamics, and optical behavior, and shows how AI-enabled digital twins can extend these relationships into predictive, generalized models. It also highlights opportunities for modelling coupled thermo-optical effects and advancing data-driven surface engineering. **Practical Implications**. Integrating laser texturing with AI-driven optimization could embed thermal regulation directly into device structures, reducing reliance on external cooling systems and improving field durability. **Originality / Value**. Unlike prior reviews, this work unites laser surface engineering and AI optimization into a roadmap for renewable energy devices, highlighting digital twins and techno-economic assessment as enablers for scale-up. **Research Limitations / Future Research**. Challenges include scalability, durability under harsh environments, limited AI training datasets, and insufficient lifecycle analyses, requiring cross-disciplinary collaboration. **Article Type**. Review Paper.

Keywords:

laser micro-texturing, renewable energy devices, photovoltaic cooling, thermal management, artificial intelligence, optimization

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Мета. Фотоелектричні (PV) та інші відновлювані енергетичні системи втрачають ефективність і надійність через перегрів. У цьому огляді наголошується на необхідності розробки масштабованих інтегрованих рішень для теплового керування. **Дизайн / Метод / Підхід**. Розглянуто останні досягнення лазерного мікротекстурування поверхонь як перспективного підходу до регулювання тепла. Контрольовані мікро- та наноструктури підвищують відведення тепла, збільшують площу поверхні та впливають на змочуваність. Досліджено також можливості штучного інтелекту (ШІ) для прогнозування, проєктування та оптимізації лазерних текстур з метою одночасного покращення теплових, оптичних і механічних властивостей. **Результати**. Лазерно оброблені поверхні забезпечують конвективне охолодження, анти-відбивання та самоочищення, але переважно демонструються на лабораторному рівні. Методи ШІ, включно з нейромережами, еволюційними алгоритмами та підкріплювальним навчанням, ефективні для прогнозування та багатокритеріальної оптимізації, відкриваючи шляхи для промислового застосування. **Теоретичне значення**. Огляд встановлює зв'язки морфології поверхні з тепло- та гідродинамікою і оптикою, показуючи, як цифрові двійники на основі ШІ перетворюють їх у прогнозовані та узагальнені моделі. Виділено перспективи моделювання взаємопов'язаних термооптичних ефектів і розвитку методів поверхневої інженерії на основі даних. **Практичне значення**. Інтеграція лазерного текстурування з оптимізацією на основі ШІ дозволяє вбудувати терморегуляцію в конструкцію пристроїв, зменшуючи потребу у зовнішньому охолодженні та підвищуючи надійність. **Оригінальність / Цінність**. Робота об'єднує лазерну обробку поверхні та оптимізацію за допомогою ШІ в єдину дорожню карту для пристроїв відновлюваної енергетики, виокремлюючи цифрові двійники та техніко-економічну оцінку як ключові фактори масштабування. **Обмеження дослідження / Майбутні дослідження**. Основні складнощі пов'язані з масштабуванням, довговічністю в жорстких умовах, обмеженістю навчальних наборів даних для ШІ та недостатністю аналізу життєвого циклу, що вимагає міждисциплінарної співпраці. **Тип статті**. Оглядова стаття.

Ключові слова:

лазерне мікротекстурування, пристрої відновлюваної енергетики, охолодження фотоелектричних систем, теплове керування, штучний інтелект, оптимізація

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The accelerating global shift toward renewable energy has firmly positioned photovoltaic (PV) technologies as a cornerstone of sustainable power production. Nevertheless, their operational efficiency remains highly vulnerable to thermal stress. Elevated module temperatures diminish power conversion efficiency, hasten material degradation, and reduce service lifetime. It is well established that each degree Celsius rise beyond the optimal range can lower PV efficiency by approximately 0.4–0.5% illustrating the pressing demand for advanced thermal regulation. Comparable issues are evident in other solar-based devices, such as photovoltaic–thermal (PV/T) hybrids and solar thermal collectors, where inadequate heat dissipation significantly restricts performance reliability and overall energy yield. To overcome these thermal bottlenecks, multiple cooling strategies have been investigated over the past two decades. Passive approaches including heat sinks, natural convection channels, and phase change materials (PCMs) are cost-effective and maintenance-friendly but frequently lack scalability and stable performance under fluctuating weather conditions. Active cooling methods, such as forced air or liquid circulation, provide superior thermal control yet impose additional energy demands, higher costs, and increased system complexity. Hybrid techniques, combining passive and active measures, have shown promise in boosting efficiency; however, challenges related to economic feasibility, system integration, and long-term durability still remain. These constraints underscore the urgent need for innovative, multifunctional, and economically viable cooling strategies for next-generation renewable devices.

The novelty of this review lies in its systematic synthesis of two disruptive frontiers: laser-based micro-texturing and artificial intelligence (AI). Laser surface texturing has recently attracted attention as a transformative solution. By introducing controlled micro- and nano-scale patterns, laser texturing improves heat dissipation through enhanced convective transfer, enlarged surface area, and engineered wettability. Moreover, such surfaces provide multifunctional advantages including anti-reflection, self-cleaning, and dust-repellent properties attributes highly desirable in outdoor energy harvesting systems. However, the true significance of this approach extends beyond these individual benefits; it represents a paradigm shift from add-on cooling components to integrated, multifunctional surface engineering. Despite these benefits, practical implementation of laser-engineered textures in PV and solar thermal devices is still at an early stage, with most evidence limited to laboratory-scale trials rather than industrial deployment. This gap highlights the critical relevance of a complementary innovation: the integration of artificial intelligence (AI). Traditional trial-and-error methods of optimizing surface patterns are resource-intensive and often yield suboptimal outcomes. AI-based models such as artificial neural networks, genetic algorithms, and reinforcement learning enable predictive mapping of the intricate relationships between texture geometry, heat transfer mechanisms, and device efficiency. Through multi-objective optimization, AI offers the capacity to simultaneously maximize thermal performance, mechanical durability, and optical behaviour, potentially accelerating the industrial adoption of laser-engineered solutions. The interdisciplinarity of this convergence is a core theme of this review, bridging materials engineering, thermal science, laser physics, and computational intelligence. The present review aims to provide a comprehensive account of laser-assisted micro-texturing for thermal management in renewable energy systems, with particular emphasis on AI-driven design and optimization strategies. The discussion begins with an overview of laser–material interactions and mechanisms underlying texture formation, followed by an assessment of current applications in PV, PV/T, and solar thermal collectors. Subsequently, the role of AI in predictive modelling and performance enhancement is critically examined. The paper concludes with an exploration of existing challenges, unresolved research questions, and a strategic roadmap to guide future work. By integrating these perspectives, this review highlights the transformative potential of laser — AI synergy in enabling high-efficiency, durable, and sustainable renewable energy technologies.

Objectives and Tasks

The objective of this review is to consolidate and critically examine current research on enhancing the thermal management and durability of photovoltaic (PV) and renewable energy systems through laser-based micro-texturing and artificial intelligence (AI)–driven optimization. To achieve this, the following tasks are addressed:

1. Summarize the fundamental principles of laser micro-texturing and its influence on heat transfer, wettability, and optical properties of energy-harvesting surfaces.
2. Compare reported laboratory-scale demonstrations and modelling studies to highlight correlations between texture morphology, thermal regulation, and device performance.
3. Analyse the role of AI and machine learning in predicting, optimizing, and designing multifunctional textures for improved cooling efficiency, optical absorption, and durability.
4. Identify existing limitations, including scalability, environmental durability, data scarcity, and integration with commercial PV and hybrid systems.
5. Outline future research directions, emphasizing digital twins, adaptive AI algorithms, and techno-economic assessments to enable reliable, scalable, and sustainable deployment of laser AI-enabled renewable devices.

The limitations of existing cooling strategies are summarized in Table 1.

Table 1 – Comparison of conventional cooling approaches for photovoltaic (PV) systems (Source: author)

Cooling Approach	Typical Techniques	Reported Efficiency Gain	Cost & Complexity	Key Limitations
Passive	Heat sinks, natural convection channels, fins, phase change materials (PCMs)	2–5% (heat sinks, fins); 4–7% (PCM-based)	Low to moderate cost; simple design; minimal maintenance	Limited scalability; PCM suffers from leakage and long-term stability issues; effectiveness declines under fluctuating solar loads
Active	Forced air cooling, liquid circulation, water spraying, refrigerant-based loops	5–12% (air/liquid); up to 15% (water spray, evaporative)	Higher cost; requires pumps/fans; added energy consumption	Reduced net energy gain due to parasitic power use; increases system complexity; higher operational and maintenance costs
Hybrid	PCM + heat sinks, liquid + PCM, thermoelectric modules + cooling	8–12% (PCM + heat sink); 10–15% (PCM + liquid); up to 18% (thermoelectric hybrids in prototypes)	Moderate to high; requires integration of multiple components	Integration challenges; increased weight; reliability and durability concerns; cost-effectiveness at large scale remains unproven

Fundamentals of Laser Micro-Texturing

Principles of Laser-Material Interaction

Laser micro-texturing relies on the precise interaction of photons with a solid surface, producing effects such as localized melting, ablation, or photochemical modification. The process is governed by laser wavelength, fluence, and pulse duration, along with the optical-thermal properties of the substrate (Toyserkani & Rasti, 2015; Bonse, Kirner, & Krüger, 2020).

Nanosecond lasers operate primarily in the thermal regime. For instance, Liu et al. (2022) reported that ns pulses produced grooves and dimples on stainless steel, but with heat-affected zones (HAZ) up to 20 μm and frequent microcracking. Their advantage lies in cost-effectiveness and scalability, but precision is limited.

Picosecond lasers partly suppress electron–phonon coupling, enabling cleaner ablation. Wang et al. (2019) demonstrated that ps pulses reduced the HAZ to <1 μm on titanium alloys, yielding smoother ripple patterns and improved uniformity.

Femtosecond lasers deliver ultrafast, non-thermal energy deposition through multiphoton ionization and Coulomb explosion. Vorobyev and Guo (2013) observed ripple periodicities of 400–700 nm on silicon with negligible collateral damage, while Sugioka and Cheng (2014) demonstrated defect-free nanochannels in glass. Such precision makes fs systems especially promising for photovoltaics (PV), where surface quality directly affects optical absorption and long-term durability (Singh & Guo, 2022).

Significance. While ns systems remain attractive for large-area, low-cost processing, ps and fs lasers offer the precision and reliability essential for PV and semiconductor devices.

Mechanisms of Micro/Nano-Texture Formation

Different physical pathways contribute to texture development.

Laser-induced periodic surface structures (LIPSS). Arise from interference between incident and scattered light. Bonse et al. (2020) demonstrated sub-wavelength ripples (~500 nm spacing) that improve anti-reflective properties of metallic surfaces.

Capillary flow and resolidification. Molten material can reflow and freeze into grooves or ridges. Sierra, Edwardson, and Dearden (2018) generated ~10 µm channels on titanium, improving surface wettability.

Micro-explosions and plasma expansion. At fluences above ~1 J/cm², rapid vaporization produces craters or pits. Such features enhance nucleation sites for boiling and improve heat transfer efficiency (Toyserkani & Rasti, 2015).

Photochemical modification. Particularly relevant in polymers. Obilor et al. (2022) showed that fs-laser texturing alters polymer chemistry, enabling transitions between hydrophilic and hydrophobic states for tailored self-cleaning behavior.

Significance. These mechanisms can be selectively activated through parameter tuning, offering application-specific benefits such as improved cooling, light trapping, or dust repellence in PV devices (Andueza et al., 2021).

Key Processing Parameters

Surface features are highly sensitive to laser parameters and their interplay.

Fluence. Defines whether energy is below the ablation threshold (surface modification) or above (material removal). For silicon, fs ablation begins at ~0.2 J/cm², while ns systems require ~1 J/cm² (Vorobyev & Guo, 2013).

Wavelength. Shorter UV wavelengths penetrate less deeply, enabling high-resolution structuring of polymers and semiconductors (Wang & Wang, 2022).

Pulse duration. fs–ps pulses minimize heat diffusion. Sugioka and Cheng (2014) observed that fs pulses produced nanochannels free of thermal defects, while ns pulses caused micrometer-scale HAZ.

Repetition rate. Enhances throughput but risks cumulative heating. Kalinowski et al. (2023) reported that >500 kHz repetition rates in ps lasers led to local remelting.

Scan speed and hatch distance. Govern pulse overlap. Joe et al. (2017) demonstrated tunable micro-patterns in polymers by optimizing scanning strategies.

Processing atmosphere. Inert gas environments suppress oxidation and plasma shielding. Yilbas et al. (2018) showed improved finish on Inconel 718 surfaces when processed in argon compared to air.

Significance. For PV devices, fs–ps pulses at optimized fluence and repetition rates offer a balance between precision, processing speed, and industrial scalability.

Types of Laser-Induced Surface Textures

Laser micro-texturing enables a wide range of functional morphologies:

Grooves and channels. Promote liquid spreading and enhance convective cooling (Vorobyev & Guo, 2013).

Dimples and pits. Serve as nucleation sites for phase-change cooling, reducing thermal resistance (Liu et al., 2022).

Hierarchical micro/nanostructures. Replicate lotus-leaf topographies, achieving hydrophobicity and dust repellence (Guo, Zhang, & Hu, 2022).

LIPSS. Sub-wavelength ripples that improve light absorption and reduce reflectance in PV devices (Bonse et al., 2020; Andueza et al., 2021).

Significance. These multifunctional textures allow surfaces to simultaneously improve thermal management, optical efficiency, and durability key requirements for next-generation renewable energy systems. The different pulse-regime mechanisms are summarized in Figure 1.

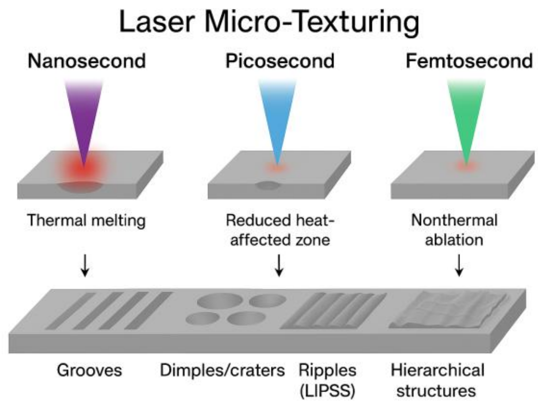

Figure 1 – Schematic of laser micro-texturing across pulse regimes (Authors own elaboration)

Nanosecond pulses induce melting and resolidification, forming dimples and grooves. Picosecond pulses minimize heat-affected zones for controlled ablation, while femtosecond pulses enable ultrafast non-thermal ablation and LIPSS, creating hierarchical micro/nano-textures. Surface morphology depends on fluence, wavelength, pulse duration, and scan speed. As summarized in Table 2, different material classes require tailored laser parameters to achieve desired functionalities.

Table 2 – Typical laser parameters used for micro-texturing of different materials (Source: author)

Material Type	Common Laser Sources	Pulse Duration	Wavelength Range, nm	Fluence Range, J/cm²	Representative Surface Features	Relevant Applications
Metals (Al, Cu, Ti, Stainless Steel)	Fiber (Yb), Nd: YAG, Femtosecond Ti: Sapphire	ns–fs	355–1064	0.2–5.0	Grooves, dimples, LIPSS, hierarchical micro/nano patterns	Heat transfer enhancement, anti-fouling, biomedical coatings
Semiconductors (Si, GaAs)	Femtosecond Ti: Sapphire, Excimer (KrF, ArF)	fs–ps	193–800	0.1–1.0	Nano-ripples, micro holes, super hydrophilic textures	PV anti-reflection layers, enhanced light trapping
Polymers (PMMA, PET, PDMS)	Excimer, CO_2, Femtosecond Fiber	ns–fs	193–10600	0.05–0.5	Smooth ablation zones, micro-channels, hierarchical patterns, chemical modifications	Microfluidics, wettability tuning, optical films
Ceramics & Composites (ZrO_2, Al_2O_3, SiC)	Femtosecond Fiber, CO_2, Nd: YAG	fs–ns	532–10600	0.2–2.0	Nano-porous surfaces, micro-channels, controlled cracks	Thermal barrier coatings, structural components, optical devices

Applications of Laser Micro-Texturing in Renewable Energy Devices

Photovoltaic Panels

Photovoltaic (PV) modules are constrained by two persistent challenges: optical reflection losses, which prevent full utilization of incident solar radiation, and thermal accumulation, which accelerates material degradation and lowers conversion efficiency (Joo et al., 2023; Khan et al., 2025). Addressing both simultaneously is essential for long-term, high-efficiency solar power generation.

Laser micro-texturing has emerged as a multifunctional solution to these problems. By fabricating sub-wavelength ripples and hierarchical surface patterns, textured layers suppress broadband reflection, thereby enhancing light absorption without the need for external coatings (Bonse, Kirner, & Krüger, 2020; Andueza et al., 2021). This optical tailoring translates directly into higher electrical output under real operating conditions.

Beyond optical control, engineered surface morphologies influence heat and contamination behavior. Increasing the effective surface area enhances convective heat transfer, while wettability modification enables self-cleaning functionalities. For instance, hydrophobic and superhydrophobic laser-textured surfaces minimize dust deposition and facilitate rain-assisted removal, a critical advantage for large-scale solar farms operating in dusty or humid environments (Guo, Zhang, & Hu, 2022; Fillion, Riahi, & Edrisy, 2014). Conversely, hydrophilic regions can promote thin water films that boost evaporative cooling under high irradiation.

Experimental studies validate these benefits. Nižetić et al. (2021) and Xu et al. (2021) reported 3–7% improvements in power conversion efficiency when PV modules were integrated with laser-textured layers, with even greater potential when combined with hybrid cooling approaches such as phase-change materials.

As illustrated in Figure 2 (Author's own elaboration), laser-textured PV surfaces deliver a triple benefit: reduced optical reflection, enhanced heat dissipation, and improved self-cleaning. Together, these effects provide an integrated strategy to overcome multiple bottlenecks that limit the performance and durability of current PV technologies.

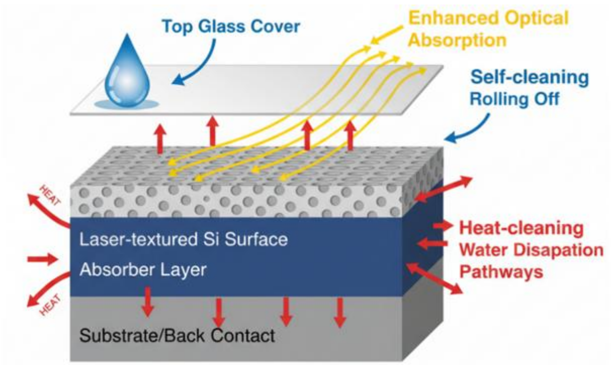

Figure 2 – Schematic of a laser-textured PV cell showing reduced reflectance, enhanced cooling, and self-cleaning for improved performance (Author's elaboration)

Solar Thermal Collectors

In solar thermal systems, the absorber plate is the primary component responsible for harvesting incident radiation and transferring heat to the working fluid. Conventional flat absorbers, however, often suffer from low wettability and modest heat transfer coefficients, particularly under fluctuating thermal loads (Gupta & Tiwari, 2016; Al-Shamkhee et al., 2022). These limitations reduce overall system efficiency and contribute to long-term performance degradation.

Laser micro-texturing has emerged as a promising strategy to overcome these drawbacks. By introducing grooves, dimples, and hierarchical features, laser-modified surfaces promote stronger fluid–surface interactions and enlarge the effective heat transfer area. Such engineered topographies enhance convective heat transfer while simultaneously reducing fouling and scaling tendencies, thereby improving both efficiency and durability (Toyserkani & Rasti, 2015; Liu et al., 2022). Experimental studies support these advantages. For example, nanosecond-laser-fabricated micro-dimpled copper absorber plates have shown up to an 18% increase in heat transfer efficiency compared with untreated surfaces, attributed to turbulence intensification and improved wettability (Sierra, Edwardson, & Dearden, 2018; Wang & Wang, 2022). Similar enhancements have been reported for micro-grooved and ripple-textured absorbers, which provide capillary-driven liquid spreading and localized boiling sites (Bonse, Kirner, & Krüger, 2020). Practical significance: These improvements directly contribute to higher thermal yields in both concentrating solar power (CSP) systems and low-temperature solar heating applications, where durability and sustained performance are critical. As solar thermal collectors continue to expand into industrial and residential markets, laser texturing offers a scalable pathway to achieve higher energy output with reduced maintenance demands.

Hybrid Energy Systems

Hybrid solar technologies, which integrate multiple energy-harvesting functions into a single platform, are increasingly recognized as a pathway toward higher efficiency and resource utilization. Among these, photovoltaic–thermal (PV/T) collectors and solar-assisted desalination units have gained particular attention. Both stands to benefit substantially from the multifunctional properties imparted by laser micro-textured surfaces.

In PV/T collectors, laser-structured absorber plates and heat exchangers facilitate enhanced thermal removal while maintaining electrical performance by regulating module temperature. Xu et al. (2021) demonstrated that coupling PV/T systems with advanced thermal regulation strategies such as phase-change materials can significantly improve energy conversion. Incorporating micro- and nano-textures further strengthens this effect by simultaneously boosting convective heat transfer and reducing surface reflection losses (Andueza et al., 2021; Bonse, Kirner, & Krüger, 2020). Preliminary reports suggest that PV/T units with textured absorbers can achieve 10–15% higher combined efficiency compared to conventional flat-plate designs (Nižetić et al., 2021).

Beyond PV/T systems, solar desalination devices also benefit from laser-enabled surface engineering. Wettability-controlled microtextures accelerate evaporation and mitigate salt scaling, two of the primary bottlenecks in long-term operation (Liang et al., 2023; Chen et al., 2022). For example, picosecond-laser-textured aluminum surfaces have been shown to enhance photothermal water evaporation while resisting fouling, thereby improving freshwater yield under continuous use.

Practical significance. By embedding heat-transfer enhancement, optical tuning, and scaling resistance into the device architecture, laser micro-texturing provides hybrid solar systems with sustained performance improvements and reduced maintenance requirements. This multifunctional approach broadens the role of solar technologies beyond electricity generation, enabling reliable co-production of power, heat, and clean water. Reported improvements in thermal efficiency based on literature are summarized in Table 3.

Table 3 – Reported improvements in thermal efficiency of renewable energy devices using surface texturing (Source: author based on literature)

Renewable Device	Texturing Strategy	Reported Thermal Efficiency Improvement	Additional Functional Benefits	Remarks
Photovoltaic (PV) Panels	Micro-dimples, grooves on Si surface	6–12% reduction in operating temperature; ~4–7% efficiency gain	Anti-reflection, hydrophobicity	Laboratory-scale demonstrations; scalability remains a challenge
Solar Thermal Collectors	Laser-textured absorber plates	8–15% higher heat transfer coefficient	Enhanced absorptivity, reduced fouling	Effective under fluctuating solar flux conditions
PV/T Hybrid Systems	Hierarchical textures on absorber/heat exchanger	10–18% improvement in combined thermal + electrical output	Dust repellence, wettability control	Integration complexity and cost factors
Solar Desalination Units	Textured evaporation surfaces	12–20% increase in evaporation rate	Enhanced solar absorption, salt-crust mitigation	Promising for off-grid and arid-region applications
Concentrated Solar Systems	Textured metallic receivers	5–10% improved heat absorption efficiency	Improved spectral selectivity	Long-term durability under high flux must be validated

Thermal Management Enhancement via Laser-Induced Surface Structures

Effective thermal regulation is one of the most critical factors influencing the efficiency and long-term durability of renewable energy devices. Overheating not only decreases power conversion efficiency in PV modules but also accelerates material degradation and failure in hybrid systems (Joo et al., 2023; Khan et al., 2025). Traditional cooling strategies whether passive or active often require bulky external components or consume additional energy (Nižetić, Papadopoulos, & Giama, 2017; Alao et al., 2025). In contrast, laser-induced surface texturing embeds thermal management directly into the device architecture by modifying surface geometry, altering fluid–surface interactions, and enabling tailored wettability (Bonse, Kirner, & Krüger, 2020; Liu et al., 2022).

Enhanced Convective Heat Transfer

Laser-generated grooves, dimples, and hierarchical roughness intensify fluid motion at the surface by disrupting the thermal boundary layer. This promotes turbulence in both air and liquid environments, improving convective heat transfer. Studies on textured silicon surfaces have demonstrated up to a 15% increase in local heat transfer coefficients relative to untreated substrates (Andueza et al., 2021; Nižetić et al., 2021). Similar results have been reported for textured metallic absorbers in hybrid PV/T systems, where groove-induced turbulence enhances thermal exchange without sacrificing electrical performance (Xu et al., 2021).

Significance. Embedding such microtextures into PV modules reduces surface temperature, directly slowing efficiency losses linked to heat buildup.

Increased Effective Surface Area

A fundamental advantage of laser texturing is the substantial increase in surface-to-volume ratio. Nanostructures such as laser-induced periodic surface structures (LIPSS) and conical features can nearly double the available heat-dissipating area (Bonse et al., 2020). Expanded interfaces enhance conduction into the working fluid and radiation into the ambient environment. For instance, PV cells coated with laser-fabricated micro-dimples have been shown to operate 3–5 °C cooler, corresponding to a 3–5% gain in power conversion efficiency (Andueza et al., 2021; Nižetić et al., 2021).

Significance. Such passive cooling eliminates the need for external fins or fans, reducing maintenance and energy penalties.

Wettability Control and Phase-Change Heat Transfer

Laser structuring also allows precise tuning of wettability. Hydrophilic surfaces encourage thin-film spreading of water, enhancing evaporative and phase-change cooling, while hydrophobic textures enable droplet roll-off, preventing dust accumulation that often creates thermal hotspots (Guo, Zhang, & Hu, 2022; Fillion, Riahi, & Edrisy, 2014).

This dual-mode wettability control is particularly useful in hybrid devices. For example, in solar desalination systems, hydrophilic laser-textured absorbers accelerate evaporation while simultaneously reducing salt scaling, leading to improved thermal efficiency and freshwater yield (Liang et al., 2023; Chen et al., 2022).

Significance. Wettability engineering provides both cooling enhancement and contamination resistance, extending operational lifetime in harsh outdoor conditions.

Case Studies in Renewable Devices

Applications of laser-induced surface structures have been explored across several renewable energy platforms.

Photovoltaic panels. Micro- and nano-structured silicon layers lower cell operating temperature by up to 10 °C while simultaneously improving light absorption (Andueza et al., 2021).

Solar thermal collectors. Laser-textured copper absorber plates demonstrate higher heat flux transfer and greater stability under fluctuating solar conditions (Sierra, Edwardson, & Dearden, 2018; Wang & Wang, 2022).

Hybrid PV/T systems. Hierarchical grooves at absorber–exchanger interfaces balance thermal removal with electrical stability, extending device lifespan (Xu et al., 2021).

Cooling fins and heat sinks. Laser-textured metallic fins show enhanced convection in both natural and forced flow, supporting integration in compact renewable energy modules (Nižetić et al., 2021).

As summarized in Figure 3 (Author's own elaboration), laser texturing enhances heat dissipation by promoting convective airflow or liquid motion, increasing effective surface area, and enabling targeted wettability control.

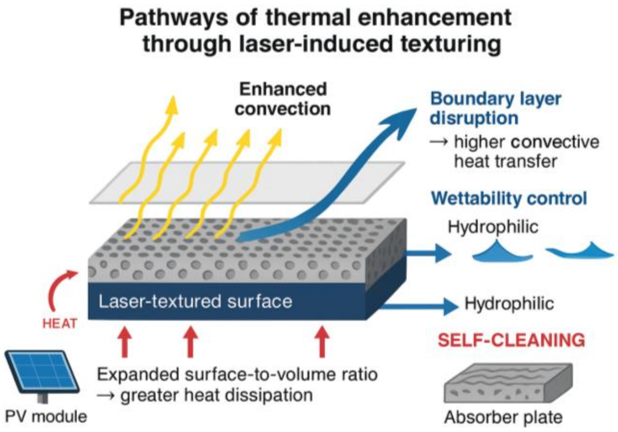

Figure 3 – Thermal management mechanisms of laser-textured surfaces: enhanced convection, higher heat dissipation, and wettability-driven cooling/self-cleaning (Author's elaboration)

Performance comparison between conventional and laser-textured thermal management approaches in photovoltaic systems is shown in Table 4.

Table 4 – Performance comparison between conventional and laser-textured thermal management approaches in photovoltaic systems (Source: author based on literature)

Cooling Strategy	Surface Condition	Typical Temperature Reduction, °C	Relative Efficiency Gain, %	Key Functional Features	Long-Term Stability
Passive Natural Cooling	Smooth absorber surface	2–3	~1–2	Relies solely on ambient convection; limited control	Moderate (degrades with dust/soiling)
Fin-based Cooling	Extruded metal fins	5–7	3–4	Increased surface area; no wettability control	High (mechanically robust, but adds bulk)
Liquid Immersion Cooling	Encapsulated with coolant fluid	8–10	4–6	Direct heat extraction via high thermal capacity fluid	Moderate (risk of leakage, maintenance needed)
Laser-Textured Surface Cooling	Micro/nano-grooved Si surface with tailored wettability	10–15	6–9	Expanded surface-to-volume ratio; induced micro-convection; enhanced evaporative cooling; hydrophobic rolling for self-cleaning	High (surface stability if protected with coating)
Hybrid Laser-Textured + Fins	Textured Si with attached cooling fins	15–18	8–12	Synergistic enhancement of conduction, convection, and evaporation	High (robust under outdoor cycling)

AI-Driven Optimization of Laser Micro-Texturing

The integration of artificial intelligence (AI) with laser surface engineering is transforming the way micro- and nano-scale textures are designed for renewable energy applications. Conventional trial-and-error experimentation is resource-intensive and slow, whereas AI frameworks enable predictive modelling, multi-objective optimization, and adaptive control, significantly reducing experimental overhead while accelerating innovation (Sohrabpoor et al., 2019; Ji et al., 2024).

Role of AI

Different AI paradigms provide complementary strengths.

Artificial neural networks (ANNs). Capture nonlinear relationships between laser parameters (e.g., fluence, pulse duration, scanning speed) and resulting surface features such as groove depth, roughness, or wettability (Sohrabpoor et al., 2019).

Deep learning architectures (CNNs, RNNs). Extract hidden correlations from large process datasets, enabling accurate prediction of texture morphology and energy-related performance outcomes (Sharma et al., 2022).

Evolutionary algorithms (genetic algorithms, particle swarm optimization). Efficiently explore wide parameter spaces and converge on optimal strategies that balance thermal, optical, and mechanical performance (Ji et al., 2024).

Significance. These approaches allow researchers to predict and refine laser processing outcomes before experimentation, saving cost and time while uncovering novel texture designs.

Predictive Modelling

AI frameworks are increasingly used for end-to-end prediction of functional outcomes.

Inputs. Pulse regime, fluence, wavelength, scanning speed, ambient environment.

Outputs. Heat transfer coefficient enhancement, absorptivity gain, self-cleaning potential, durability under thermal cycling.

Validation. Predictions are cross-checked with finite element modelling and experimental techniques such as SEM, AFM, and profilometry (Sohrabpoor et al., 2019; Ji et al., 2024).

Significance. By integrating modelling and experiments, AI ensures predictive reliability, enabling faster scale-up for industrial PV and hybrid systems.

Multi-Objective Optimization

Renewable energy devices demand simultaneous optimization of thermal, optical, and durability-related functions.

Thermal. AI identifies groove and dimple geometries that maximize convective and evaporative cooling (Sharma et al., 2022).

Optical. Models optimize LIPSS periodicity for broadband anti-reflection and light trapping (Bonse et al., 2020).

Durability. Forecasts surface degradation under UV exposure, dust deposition, and humidity cycling (Jordan et al., 2019).

Multi-objective optimization platforms often employ Pareto-front analysis, allowing designers to select parameter sets that achieve balanced trade-offs tailored to specific device requirements (Kenfack et al., 2025).

Cross-Domain Case Studies

Lessons from other engineering domains demonstrate the versatility of AI-guided laser texturing.

Tribology. AI-predicted dimple arrays on bearing surfaces reduce wear, analogous to optimizing micro-textures for thermal transport (Sohrabpoor et al., 2019).

Biomedical devices. ANN-guided femtosecond texturing enhances wettability and osseointegration; similar strategies can be used for hydrophilic coatings in evaporative PV cooling (Sharma et al., 2022).

Aerospace coatings. Deep learning frameworks optimize drag-reducing ablation patterns, showing parallels to optical absorption tuning in PV collectors (Ji et al., 2024).

More directly, AI has already penetrated renewable energy optimization.

PV/T collectors with nanofluids. ML models improved thermal prediction accuracy by >10% over traditional regression (Sharma et al., 2022; Jakhar et al., 2023).

Hybrid ANN–GA approaches. Genetic algorithms tuned neural networks to optimize channel geometries, lowering PV/T operating temperatures by 8–12 °C (Kenfack et al., 2025; Zayed et al., 2023).

Reinforcement learning. Adaptive AI controllers regulate PV output under fluctuating irradiance, reducing parasitic power penalties and improving stability (Xu & Gong, 2023; Kavousi-Fard et al., 2024).

Significance. Embedding AI within laser-assisted surface texturing frameworks enables dual optimization: (i) precise micro-scale texture design, and (ii) system-level thermal management under dynamic operating conditions. This synergy positions AI as a catalyst for scalable, intelligent, and durable renewable energy devices.

Figure 4 illustrates AI-driven loop optimizing laser-textured surfaces for thermal, optical, and durability performance.

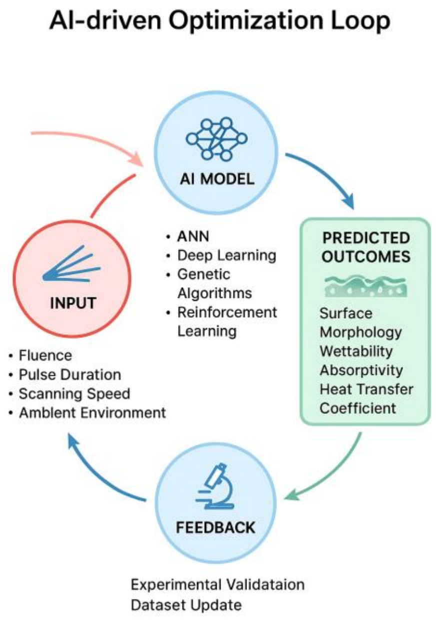

Figure 4 – AI-driven loop optimizing laser-textured surfaces for thermal, optical, and durability performance (Author's elaboration)

Table 5 – AI methods applied in laser texturing and thermal optimization (Source author)

AI Method	Application Scope	Input Dataset	Predicted/Optimized Outcome	Relevance to Renewable Devices
Artificial Neural Networks (ANNs)	Mapping nonlinear process–response	Laser fluence, pulse width, scan speed	Groove depth, surface roughness, wettability state	Prediction of cooling efficiency and optical gain in PV cells
Convolutional Neural Networks (CNNs)	Image-based morphology recognition	SEM/AFM images of textures	Classification of periodic structures (LIPSS, dimples, grooves)	Enables autonomous quality assurance of textured PV/T absorbers
Genetic Algorithms (GA)	Multi-objective optimization	Parameter ranges + constraints	Pareto-optimal solutions for thermal vs. optical trade-offs	Identifies balanced texturing strategies for PV/T collectors
Particle Swarm Optimization (PSO)	Rapid global parameter search	Continuous parameter space	Converges on high-performance settings with fewer iterations	Suitable for real-time adaptive laser control in PV panels
Reinforcement Learning (RL)	Closed-loop adaptive process control	Real-time sensor feedback (temperature, reflectance)	Dynamic adjustment of laser power/speed	Maintains optimal texture under variable solar flux
Hybrid AI–FEM Models	Data-driven + physics-based synergy	FEM simulations + experimental inputs	Predicts heat transfer enhancement and stress resilience	Ensures durability of laser-textured absorbers in outdoor cycling

Challenges and Research Gaps

Although laser-based micro-texturing shows strong potential for improving the thermal management of renewable energy devices, several unresolved challenges continue to limit its translation from laboratory-scale demonstrations to industrial deployment. These challenges span technical, environmental, computational, and economic dimensions, and addressing them is essential to unlock scalable applications. Research gaps and future opportunities for laser-textured renewable energy devices is illustrated in Figure 5.

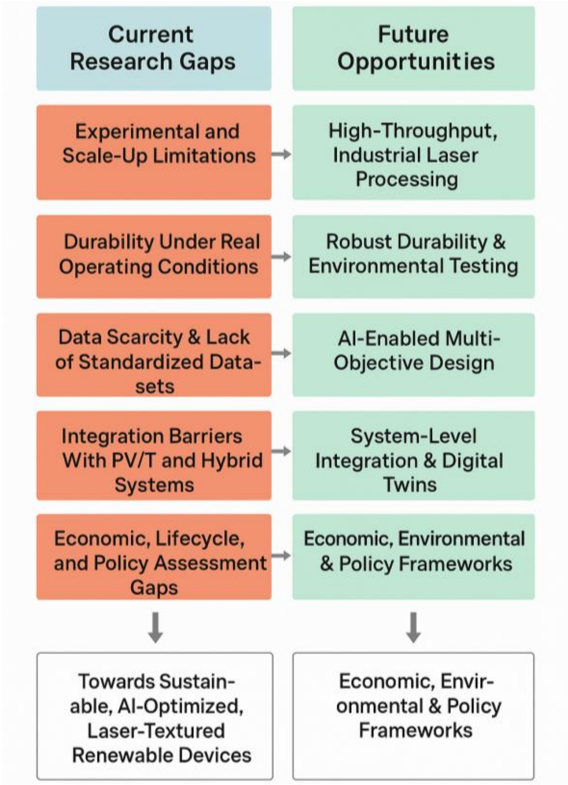

Figure 5 – Research gaps and future opportunities for laser-textured renewable energy devices, highlighting scalability, durability, data, integration, and economic challenges (Author's elaboration)

Experimental and Scale-Up Limitations

Most studies on laser micro-texturing have been performed on small laboratory samples under controlled conditions. Scaling these textures to large-area photovoltaic (PV) modules or solar thermal collectors introduces significant engineering barriers. Current laser systems struggle with high processing times, power consumption, and alignment precision when applied to meter-scale surfaces (Toyserkani & Rasti, 2015; Pfleging, 2020). Achieving uniform micro/nano-features over such areas remains unresolved. Promising directions include high-throughput techniques, such as multi-beam splitting, roll-to-roll laser processing, or hybrid lithography–laser approaches, but these remain at the prototype stage.

Significance. Without breakthroughs in scalability, laser texturing will remain restricted to niche or high-value applications rather than broad PV deployment.

Durability Under Real Operating Environments

Another critical gap is the long-term durability of textured surfaces in harsh outdoor conditions. PV and hybrid systems operate under UV exposure, thermal cycling, humidity, and abrasion from airborne dust. While laboratory experiments confirm enhanced wettability or cooling effects, few studies evaluate stability over years of operation. For example, hydrophilic textures designed for evaporative cooling may degrade through fouling or corrosion, while hydrophobic textures can lose functionality due to abrasion (Conradi et al., 2019; Fillion, Riahi, & Edrisy, 2014). Field studies in desert regions have shown that dust accumulation alone can reduce PV output by 20–30% annually if unmitigated (Kahoul et al., 2014). The interaction of such soiling with textured geometries remains poorly understood.

Significance. Systematic accelerated aging tests and long-term field trials are urgently needed to quantify durability and guide texture designs tailored to real-world environments.

Data Scarcity for AI Model Development

AI frameworks hold strong potential to accelerate laser-texturing design; however, their impact is currently constrained by limited and fragmented datasets. Most reported studies use small, single-laboratory datasets with narrow parameter variation (Sohrabpoor et al., 2019; Sharma et al., 2022). The absence of open-access databases combining laser inputs, material properties, and functional outcomes prevents generalization and cross-validation. Other fields, such as materials genomics and tribology, have shown that collaborative data-sharing platforms can drive rapid progress (Agostinelli et al., 2021).

Significance. Without robust shared datasets, AI models risk overfitting, limiting their ability to reliably guide industrial-scale texture optimization.

Integration with Existing Renewable Energy Systems

The compatibility of textured surfaces with commercial device architectures is another underexplored area. In PV modules, laser processing must avoid damaging encapsulation layers, transparent conductive oxides, or electrical pathways. In hybrid PV/T systems, textures must simultaneously enhance both optical absorption and thermal dissipation without creating trade-offs (Xu et al., 2021; Andueza et al., 2021). Achieving this balance requires holistic design approaches that couple surface engineering with device-level modelling.

Significance. Integration challenges highlight the need for multidisciplinary collaboration across materials science, device engineering, and renewable system design.

Economic and Lifecycle Assessment Gaps

Even if technical performance is improved, the economic viability of laser texturing remains uncertain. High capital costs for fs–ps lasers, coupled with slow processing times per unit area, raise concerns about scalability (Pfleging, 2020). Equally important, lifecycle assessments (LCAs) that account for energy payback, embodied carbon, and long-term maintenance are scarce (Nižetić, Papadopoulos, & Giama, 2017; Hemeida et al., 2022). Without these assessments, the true sustainability benefits of laser texturing cannot be quantified.

Significance. Future work must combine techno-economic analysis with environmental LCA to evaluate whether laser texturing provides net-positive sustainability outcomes at scale.

Future Prospects and Roadmap

The integration of laser-based surface engineering with artificial intelligence (AI) offers a disruptive roadmap for advancing the thermal management and durability of renewable energy systems. However, bridging the gap between laboratory demonstrations and commercial adoption requires a combination of technological, economic, and policy-driven strategies.

Digital Twins for Renewable Devices. The deployment of digital twin frameworks provides a powerful opportunity to replicate and predict the real-time behavior of laser-textured devices. By combining high-fidelity simulations with continuous sensor-driven feedback, digital twins can model degradation pathways, optimize surface properties dynamically, and extend device lifetimes (Xu & Gong, 2023; Kavousi-Fard et al., 2024). Such approaches are particularly relevant for PV and hybrid PV/T systems, where operational conditions fluctuate across climatic zones.

Self-Adaptive AI for Real-Time Optimization. Current AI models often depend on static datasets, limiting their applicability to dynamic field environments. Future progress will depend on reinforcement learning and transfer learning frameworks that allow surface functionalities such as wettability, absorption, and convective cooling capacity to be tuned in real time (Sharma et al., 2022; Ji et al., 2024). This adaptability will be essential for ensuring performance stability in regions with high dust loads, humidity, or temperature swings.

Coupling with Nanofluids, PCMs, and Hybrid Cooling. Laser texturing alone cannot fully overcome thermal bottlenecks. Combining micro-grooved or dimpled surfaces with nanofluids (Mahian et al., 2013; Ghalandari et al., 2020) or phase change materials (PCMs) (Jo et al., 2022; Xu et al., 2021) offers synergistic cooling strategies. Hybrid active–passive configurations, integrating advanced fluids, PCMs, and textured absorbers, could deliver superior thermal buffering and ensure resilience under peak irradiance.

Industrial Scaling and Cost–Benefit Analysis. Scalability remains a major challenge. The next generation of high-throughput laser systems, leveraging beam-shaping optics and multi-beam arrays, will be necessary to texture large-area PV modules cost-effectively (Pfleging, 2020; Coblas et al., 2015). In parallel, techno-economic assessments and lifecycle analyses (Qi et al., 2021; Hemeida et al., 2022) must quantify return on investment, carbon payback, and long-term durability to drive industrial acceptance.

Policy and Sustainability Implications. For laser–AI-enabled devices to gain traction globally, research progress must align with energy policy frameworks. International collaboration is required to set technical standards and certification protocols (Grillo et al., 2024; Van de Kaa & Greeven, 2017). Policy incentives, such as targeted funding for sustainable manufacturing and requirements for lifecycle assessments, will ensure that deployment is not only technologically feasible but also environmentally responsible.

Strategic Outlook. Figure 6 presents a staged roadmap:

Short term (1–3 years). Proof-of-concept validation and open-access dataset development.

Medium term (3–7 years). Industrial pilot systems, techno-economic validation, and digital twin integration.

Long term (7–15 years). Large-scale commercialization, policy harmonization, and global deployment.

Table 6 further outlines research directions with anticipated technical, economic, and environmental impacts, serving as a reference point for academia, industry, and policymakers. Figure 6 illustrates Strategic roadmap for laser-textured renewable energy devices.

Table 6. Suggested research directions and potential impacts for laser-textured renewable energy devices (Source author)

Research Direction	Technical Impact	Economic / Environmental Impact
Digital twin integration for PV and hybrid systems	Enables real-time monitoring, predictive degradation modelling, and adaptive performance optimization.	Reduces maintenance costs; extends device lifetime; lowers lifecycle carbon footprint through predictive fault prevention.
Self-adaptive AI (reinforcement and transfer learning)	Real-time optimization of surface properties (wettability, absorptivity, heat transfer coefficient) under dynamic weather conditions.	Improves energy yield across diverse climates; reduces need for manual reconfiguration; enhances resilience in extreme environments.
Hybrid cooling integration (laser textures + nanofluids/PCMs)	Enhances convective and conductive heat transfer; stabilizes module temperature during peak irradiation.	Cuts energy losses from overheating; improves levelized cost of electricity (LCOE); reduces material wastage by mitigating thermal fatigue.
High-throughput industrial laser systems (beam-shaping, multi-beam arrays)	Scales micro/nano-texturing to industrial PV/T module dimensions; ensures reproducibility and durability.	Reduces per-unit manufacturing cost; accelerates commercialization; enables widespread adoption in utility-scale solar projects.
Lifecycle and techno-economic assessments	Provides rigorous benchmarks for performance, durability, and recyclability under real-world conditions.	Informs investment decisions; ensures compliance with sustainability goals; supports green certification and market competitiveness.
Integration with energy storage and smart grids	Optimizes thermal and electrical balance through coupling with PCMs and AI-driven load management.	Enhances energy security; supports decentralized renewable systems; reduces dependence on fossil backup.
Policy-driven standardization and incentives	Establishes durability, testing, and performance standards for textured renewable devices.	Encourages industry adoption; lowers investment risks; accelerates global deployment with equitable access.

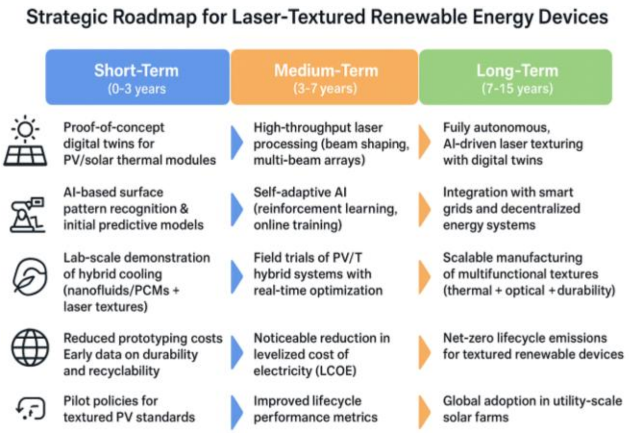

Figure 6 – Strategic roadmap for laser-textured renewable energy devices, outlining short-, medium-, and long-term milestones in technology, economics, and sustainability (Author's elaboration)

Conclusion

This review highlights the emerging paradigm of laser micro-texturing integrated with artificial intelligence (AI) as a disruptive strategy for overcoming thermal management challenges in renewable energy devices. Laser-induced surface structures provide unprecedented control over morphology, wettability, and heat transfer pathways, while AI frameworks enable predictive modelling and multi-objective optimization that extend beyond conventional trial-and-error approaches. Together, these domains pave the way toward scalable, adaptive, and durable cooling solutions capable of enhancing the performance and operational lifespan of photovoltaic (PV), solar thermal, and hybrid energy systems.

Beyond their technical value, these innovations represent an important step in interdisciplinary convergence. Advances in laser–matter interaction, materials science, and thermal engineering must be combined with data-driven approaches such as deep learning, genetic algorithms, and reinforcement learning to fully realize the potential of textured renewable devices. This integration not only improves device-level efficiency but also contributes to broader sustainability goals through reduced lifecycle costs, extended durability, and minimized environmental impact.

Moving forward, progress will require collaborative engagement across multiple domains. Mechanical engineers, materials scientists, and AI researchers must jointly address scale-up barriers, generate standardized open-access datasets, and develop robust digital twins that capture coupled thermal, optical, and environmental dynamics. Equally critical are industry–academia–policy partnerships to ensure that laboratory-scale innovations can be translated into utility-scale deployment.

In conclusion, laser micro-texturing empowered by AI-driven optimization offers a transformative roadmap for renewable energy thermal management. By fostering interdisciplinary collaboration and aligning with sustainability imperatives, this approach holds the potential to accelerate the transition toward high-efficiency, resilient, and environmentally responsible energy systems.

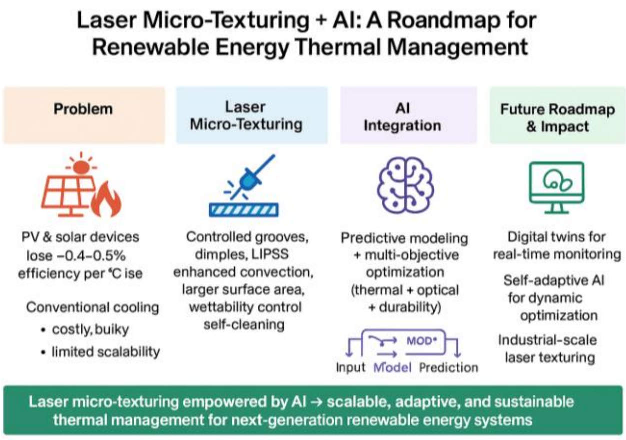

Figure 7 – Graphical summary of laser micro-texturing and AI integration for renewable energy thermal management, highlighting challenges, mechanisms, and future roadmaps (Author's elaboration)

Key Takeaways

– Overheating remains a critical barrier to efficiency and durability in renewable devices, particularly PV systems.

– Conventional cooling methods (passive, active, hybrid) face challenges of cost, durability, and scalability.

– Laser micro-texturing enables controlled surface features that enhance heat dissipation, wettability, and optical absorption.

– Experimental studies report measurable efficiency improvements in PV and solar thermal devices using textured surfaces.

– AI frameworks (ANNs, genetic algorithms, deep learning) accelerate the design and optimization of textured morphologies.

– Cross-sector evidence (tribology, biomedical, aerospace) demonstrates successful integration of surface engineering and AI, offering transferable lessons.

– Major gaps remain, including scalability, environmental durability, dataset availability, and lifecycle assessment.

– Future directions: development of digital twins, real-time adaptive AI, integration with hybrid cooling systems, and policy-supported industrial adoption.

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