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Review paper

INNOVATIVE NANOMATERIALS AND BUILDING ENERGY EFFICIENCY

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Abstract

This paper examines how selected nano-related technologies can be used in energy-efficient new buildings and retrofit, with emphasis on the point at which material-scale performance becomes relevant to architectural and engineering design. The review distinguishes regulatory nanomaterials from nano-enabled composites/products and from advanced functional systems, and groups the selected technologies by four building functions: (1) thermal resistance, (2) thermal storage, (3) optical and surface control, and (4) structural/durability enhancement. Reported performance values are retained only where they can be linked to identifiable evidence and are interpreted in relation to the complete building assembly. Silica aerogel and VIPs are most convincing where available thickness is limited; nano-enhanced PCMs depend on an appropriate phase-change range and verified cycling behaviour; nano-coatings and smart glazing depend strongly on exposure and control conditions; and nano-modified cementitious materials contribute mainly through durability and added functionality. The paper also considers EU-aligned governance, occupational exposure, life-cycle assessment, product transparency, public procurement and the need for testing under Western Balkan conditions. The resulting design-and-verification framework supports selective use of these technologies where their specific function can be demonstrated at building scale.

Key words: *nanomaterials, nano-enabled systems, building envelope, energy efficiency, life-cycle assessment*

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1. INTRODUCTION

durability of the built stock. Buildings account for about 30% of global final energy demand, while the wider buildings and construction sector remains a major source of energy-related emissions and material consumption [1,2]. However, the term "nanomaterial" must not be used as a blanket label: under the European Commission recommendation, regulatory classification depends on the number-based particle-size distribution and specified particle dimensions [3]. Across the reviewed technologies, nanoscale pores, particles and interfaces can alter heat transfer, radiation, latent storage, surface chemistry and cementitious microstructure [4-13]. A building product may therefore contain a nanomaterial without the complete product itself meeting the regulatory definition.

The purpose of the review is to translate the available material evidence into criteria that can be used in architectural and engineering decisions. Three questions guide the assessment: what function is expected from the technology; which measurable indicator demonstrates that function; and which conditions at component or building scale may reduce the laboratory or catalogue performance. Organising the discussion by function, rather than by product label, also makes it possible to compare technologies against the same design constraints: heat and solar transfer, moisture and fire compatibility, durability, installation, safety and life-cycle consequences.

2. METHODOLOGICAL FRAMEWORK AND CLASSIFICATION BOUNDARY

The paper uses a targeted narrative review combined with comparative analysis. Peer-reviewed reviews and representative studies with a clear building application were considered together with relevant EU institutional documents. Preference was given to evidence that connects a nanoscale mechanism with a measurable property of a product, component or assembly. Because the reviewed studies differ in materials, test conditions and reporting units, the analysis is not treated as a statistical meta-analysis. Numerical values are used as source-specific indicative ranges; they should not replace product declarations, project-specific testing or the applicable harmonised test methods in design practice.

Four functional groups are adopted: (I) thermal-resistance systems; (II) thermal-storage systems; (III) optical and surface-control systems; and (IV) structural/durability-enhancement systems. The classification boundary is deliberately separated from function. Silica aerogel is a nanoporous/nanostructured insulating material, but regulatory nanomaterial status must be demonstrated for the specific material against the particle criteria in the European Commission definition [3-5]. A VIP is an evacuated product whose high performance commonly relies on a nanostructured fumed-silica core and a gas-barrier envelope [6]. A conventional PCM is not a nanomaterial, whereas a nanoparticle-enhanced PCM is a nano-enabled composite [7,8]. TiO2 nano-coatings contain nanoscale constituents when nano-TiO2 is used [9,10]; smart glazing is an advanced functional system whose electrochromic layers may be nanostructured [11]; and nano-modified cementitious composites contain deliberately introduced nanoscale additions [12,13].

3. FUNCTION-BASED ASSESSMENT OF SELECTED TECHNOLOGIES

3.1. Group I - Thermal resistance: aerogel and VIP

Silica aerogels suppress solid and gaseous heat transfer through a highly porous nanoscale network. Reviews report thermal conductivity of approximately 0.010-0.020 W/(m K), with values around 0.013-0.014 W/(m K) frequently reported for silica aerogels [4,5]. Their main architectural advantage is high resistance at low thickness, especially where envelope geometry constrains conventional insulation [4,5]. Transparent or translucent aerogel glazing can also preserve a substantial fraction of daylight; reported visible-light transmittance reaches approximately 0.75 in reviewed systems, although haze, moisture compatibility, mechanical protection and cost remain design constraints [5].

VIPs provide even lower centre-of-panel conductivity but are more dependent on factory integrity and detailing. A state-of-the-art review reports approximately 0.002-0.004 W/(m K) at delivery, with typical performance around 0.008 W/(m K) after 25 years of ageing [6]. The panel cannot normally be cut on site, and perforation, edge effects and vacuum degradation can dominate the realised U-value. VIPs are therefore best treated as dimensionally coordinated components for roofs, terraces, prefabricated panels and other space-constrained details, not as a direct like-for-like substitute for conventional insulation.

3.2. Group II - Thermal storage: nano-enhanced PCM

PCMs buffer temperature by storing and releasing latent heat; the base PCM itself is not necessarily nanoscale. Nano-enhancement uses graphene, graphite, carbon nanotubes, metal oxides or other nanoscale phases to improve heat transfer or shape stability [7,8]. For building-oriented organic PCMs, literature reports phase-change temperatures commonly within about 19-29 degrees C and heats of fusion around 120-280 kJ/kg, illustrating why transition range and latent capacity must be specified together rather than by material name alone [7]. Nano-addition can increase conductivity but may reduce latent heat per unit mass or increase viscosity; dosage and cycling stability must therefore be experimentally verified [8]. In buildings, the useful indicator is not only conductivity but the matched melting range, enthalpy, number of stable cycles and reduction of peak temperature or load under the relevant climate and operating schedule.

3.3. Group III - Optical and surface control: nano-coatings and smart glazing

TiO2 nano-coatings can provide photocatalytic activity and photo-induced changes in surface wettability [9,10]. Building-scale performance is exposure- and substrate-dependent: irradiance, pollutant type, TiO2 dispersion, binder/substrate characteristics, abrasion, washing and ageing influence retained activity [10]. Therefore, specifications should report the relevant test metric - for example pollutant-removal efficiency, contact-angle/wetting response or optical properties - together with the exposure

protocol and post-ageing retention, rather than relying on a generic "self-cleaning" claim [10].

Smart glazing should likewise be classified as an advanced functional building system, not automatically as a nanomaterial. Electrochromic technologies use thin functional layers to vary the transmission of visible light and solar energy under an applied electrical potential [11]. For building design, U-value, solar factor/g-value, visible transmittance, switching range, switching time and cycle durability are more meaningful than the term "smart" alone. Annual performance also depends on orientation, shading, control logic and occupancy, so dynamic glazing requires whole-building simulation and commissioning rather than assessment from an isolated material property [11].

3.4. Group IV - Structural and durability enhancement: nano-modified cementitious materials

Nano-SiO2, TiO2 and carbon-based nanoscale additions can influence hydration, nucleation, pore structure, cracking, durability and, in selected systems, conductivity or sensing [12,13]. These materials usually do not reduce wall U-value directly; their energy relevance is principally indirect through durability, maintenance reduction, moisture resistance or thinner high-performance components. For nano-SiO2, review evidence indicates that beneficial mechanical and durability effects are often reported at additions of about 2-3% in the studied cementitious systems, but the optimum is mixture-specific and cannot be treated as a universal dosage [13]. Because agglomeration and poor dispersion can negate benefits, every quantitative claim should identify nanoparticle dosage, particle form, dispersion protocol, reference mixture, curing regime and statistically reported comparison [12,13].

Table 1. Functional classification, status and evidence-traceable performance indicators

Function	Technology	Classification	Quantitative indicator / evidence source
I Thermal resistance	Silica aerogel	Nanoporous/nanostructured material; regulatory status product-specific [3]	λ ≈ 0.010–0.020 W/(m K); glazing τv up to ≈ 0.75 [4,5]
I Thermal resistance	VIP	Advanced evacuated product; commonly nano-enabled by fumed-silica core	λ ≈ 0.002–0.004 W/(m K) initial; service-life ageing must be declared [6]
II Thermal storage	Nano-enhanced PCM	Nano-enabled composite	Report Tm and ΔH; organic building PCMs ≈ 19–29 °C; 120–280 kJ/kg [7,8]
III Optical/surface	TiO2 nano-coating	Nanomaterial-containing functional layer [9]	Repor catalytic/wetting/optical metric before and after defined ageing/exposure [9,10]

III Optical/surface	Smart glazing	Advanced functional system; may use nanostructured layers [11]	Report U, g, τv, switching range/time and cycle durability [11]
IV Structure/durability	Nano-cementitious composite	Nano-enabled composite [12,13]	Report dosage/dispersion and change vs reference; nSiO2 often beneficial ≈ 2–3% in reviewed systems [12,13]

4. BUILDING-SCALE INTEGRATION AND SELECTION

Material properties become useful to the designer only after they are translated to the assembly in which the product will operate. For aerogel and VIP systems, joints, edge losses, moisture, ageing and workmanship may substantially reduce the advantage suggested by centre-of-product values [4-6]. We therefore consider selective, hybrid use more defensible than blanket substitution: aerogel or VIP at thickness-critical details [4-6]; PCM where the expected daily temperature cycle activates the selected transition range [7,8]; photocatalytic or electrochromic systems where exposure and control conditions are known [9-11]; and nano-modified cementitious materials only against a defined reference mixture and durability target [12,13]. In heritage retrofit the decision is narrower still, because reversibility, vapour/capillary compatibility, facade geometry and daylight must be preserved. Thin high-performance materials are consequently most useful at carefully diagnosed details rather than as automatically preferable envelope solutions [4,5].

Table 2. Building-scale decision and verification matrix

Design problem	Candidate technology	Required performance evidence	Principal risk	Verification route
Thickness-limited detail	Aerogel / VIP	U-value and ψ-value, including edge effects; hygrothermal check	Perforation; condensation; ageing	Full-scale detail / validated simulation
Summer overheating	NePCM; smart glazing	Peak operative T; cooling peak; g; switching schedule	Inactive PCM; glare; control failure	Climate-specific annual simulation + monitored pilot
Polluted/exposed facade	TiO2 nano-coating	Aged optical / wetting / catalytic response	Wash-off; abrasion; uneven ageing	Weathering + release/leaching assessment
Durability-critical element	Nano-modified cementitious composite	Reference-normalized strength/durability; service life	Agglomeration; worker exposure	Documented mix/dispersion + standard tests

5. EU-ALIGNED GOVERNANCE, SAFETY, LIFE CYCLE AND WESTERN BALKANS

For nano-related construction products, traceability is not only a matter of citation; it also affects regulatory and occupational-safety decisions. REACH and CLP apply within

the existing substance framework, while registered nanoforms are subject to explicit information requirements for nanoform characterisation and chemical safety [14]. Exposure is especially relevant when handling, spraying, cutting, grinding, maintenance or demolition can release airborne particles. EU-OSHA recommends a precautionary approach and a hierarchy of controls where hazard information remains incomplete [15]. In specification practice, the physical form and the life-cycle stage should therefore be stated: a constituent bound in a finished product does not present the same exposure situation as a dry powder or an abraded coating. The technical file should accordingly include safety information, engineering and organisational controls, PPE for residual risk, maintenance procedures and end-of-life handling [14,15].

The same caution is required in environmental assessment. Operational energy savings alone are not sufficient for comparing technologies with different production routes, service lives or replacement needs. Building-level LCA should use a consistent functional equivalent, system boundary, service-life assumptions and life-cycle model, following the principles formalised in EN 15978:2026 [16]. Product transparency is also becoming more explicit in EU construction-product policy. Regulation (EU) 2024/3110 establishes the framework for a construction digital product passport and requires the passport information to be accurate, complete and up to date [17]. Directive 2014/24/EU also allows life-cycle costing in public procurement to include acquisition, use, maintenance, end-of-life and verifiable environmental externalities [18]. For a nano-related product, a technically credible procurement file should therefore request declared performance, information on nanoform/content where applicable, safety documentation, durability evidence, assumed service life and end-of-life information, rather than treating the word "nano" as evidence of superior performance.

For the Western Balkans, the immediate policy context is the continuing alignment of the green transition with EU legislation and policy. The Revised Green Agenda Action Plan (2025-2030) strengthens alignment with the European Green Deal and the EU acquis [19], but it does not create a separate regional regulatory regime for nanomaterials in construction. In our view, this makes local performance evidence more, not less, important. Validation programmes should reproduce representative summer solar exposure, winter operation, humidity and driving rain, as well as realistic construction tolerances, maintenance capacity and product availability. Pilot applications should report material properties together with assembly-level U-values and linear thermal transmittance ψ-values or optical indicators where relevant, hygrothermal response, ageing or cycling, installation deviations, occupational controls and monitored in-use behaviour. These items are proposed here as a regional research and verification agenda; they should not be read as an assumption that results obtained in other climates transfer unchanged to Balkan buildings.

6. PROPOSED DESIGN AND VERIFICATION MODEL

On the basis of the review, we propose a six-step design sequence. First, identify the dominant energy, comfort, moisture or durability problem. Second, establish whether the candidate is an intrinsic nanomaterial, a nano-enabled composite/product or an

advanced functional system. Third, select the relevant functional group and the quantitative indicators listed in Table 1. Fourth, test whether those indicators remain meaningful in the complete assembly through thermal-bridge, hygrothermal or annual energy analysis, as appropriate. Fifth, examine occupational exposure, life-cycle impacts, repairability, procurement documentation and end-of-life. Finally, verify the installed result through commissioning and monitoring. If the claimed benefit cannot be linked to an appropriate test, declaration or peer-reviewed evidence source, it should not be used as the basis for specification.

7. CONCLUSION

The technologies considered in this review should not be treated as a single material class. Silica aerogel is a nanoporous/nanostructured insulation technology whose regulatory status must be established for the specific material against the relevant particle criteria [3-5]. A VIP is an evacuated product that may use a nanostructured fumed-silica core [6]. Nanoparticle-enhanced PCMs and nano-modified cementitious materials are nano-enabled composites [8,12,13], while TiO2 coatings contain nanomaterials when nanoscale TiO2 is deliberately incorporated [9,10]. Smart glazing is better described as an advanced functional system that may include nanostructured electrochromic layers [11]. Keeping these categories separate is important because their mechanisms, exposure pathways and verification requirements are not interchangeable.

From an architectural-engineering standpoint, the evidence favours targeted use. Aerogel and VIPs have their clearest role where high thermal resistance must be achieved within limited thickness [4-6]. NePCMs are credible only when the transition temperature is matched to the climate and operation and cycling performance is documented [7,8]. Coatings and smart glazing require verification under the relevant exposure and control conditions [9-11], while nano-modified cementitious materials should be judged against a reference mixture with documented dispersion and durability [12,13]. EU-aligned practice adds traceability of nanoforms under REACH, precautionary occupational-safety management, building-level LCA, construction-product transparency and life-cycle-based procurement [14-18]. For the Western Balkans, closer alignment with the European Green Deal and acquis should be accompanied by locally validated evidence under regional climatic, construction and maintenance conditions [19].

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LITERATURE

[1] International Energy Agency. (2025). Buildings. In Energy Efficiency 2025. IEA. https://www.iea.org/reports/energy-efficiency-2025/buildings

[2] United Nations Environment Programme. (2026). Global Status Report for Buildings and Construction 2025/2026. UNEP and GlobalABC. https://www.unep.org/resources/report/global-status-report-buildings-and-construction-2025-2026

[3] European Commission. (2022). Commission Recommendation of 10 June 2022 on the definition of nanomaterial (2022/C 229/01). Official Journal of the European Union, C 229, 1-5. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022H0614(01)

[4] Cuce, E., Cuce, P. M., Wood, C. J., & Riffat, S. B. (2014). Toward aerogel based thermal superinsulation in buildings: A comprehensive review. Renewable and Sustainable Energy Reviews, 34, 273-299. https://doi.org/10.1016/j.rser.2014.03.017

[5] Buratti, C., Belloni, E., Merli, F., & Zinzi, M. (2021). Aerogel glazing systems for building applications: A review. Energy and Buildings, 231, 110587. https://doi.org/10.1016/j.enbuild.2020.110587

[6] Kalnæs, S. E., & Jelle, B. P. (2014). Vacuum insulation panel products: A state-of-the-art review and future research pathways. Applied Energy, 116, 355-375. https://doi.org/10.1016/j.apenergy.2013.11.032

[7] Cui, Y., Xie, J., Liu, J., Wang, J., & Chen, S. (2017). A review on phase change material application in building. Advances in Mechanical Engineering, 9(6). https://doi.org/10.1177/1687814017700828

[8] Li, J., Mo, S., Zhou, Z., Du, Y., Jia, L., & Chen, Y. (2025). Nanoparticle-enhanced phase change materials for thermal energy storage: A critical review. Renewable and Sustainable Energy Reviews, 223, 116040. https://doi.org/10.1016/j.rser.2025.116040

[9] Fujishima, A., Rao, T. N., & Tryk, D. A. (2000). Titanium dioxide photocatalysis. Journal of Photochemistry and Photobiology C: Photochemistry Reviews, 1(1), 1-21. https://doi.org/10.1016/S1389-5567(00)00002-2

[10] Bersch, J. D., Flores-Colen, I., Masuero, A. B., & Dal Molin, D. C. C. (2023). Photocatalytic TiO2-based coatings for mortars on facades: A review of efficiency, durability, and sustainability. Buildings, 13(1), 186. https://doi.org/10.3390/buildings13010186

[11] Granqvist, C. G. (2014). Electrochromics for smart windows: Oxide-based thin films and devices. Thin Solid Films, 564, 1-38. https://doi.org/10.1016/j.tsf.2014.02.002

[12] Sanchez, F., & Sobolev, K. (2010). Nanotechnology in concrete: A review. Construction and Building Materials, 24(11), 2060-2071. https://doi.org/10.1016/j.conbuildmat.2010.03.014

[13] Abhilash, P. P., Nayak, D. K., Sangoju, B., Kumar, R., & Kumar, V. (2021). Effect of nano-silica in concrete; a review. Construction and Building Materials, 278, 122347. https://doi.org/10.1016/j.conbuildmat.2021.122347

[14] European Chemicals Agency. (n.d.). Nanomaterials. https://echa.europa.eu/regulations/nanomaterials

[15] European Agency for Safety and Health at Work. (n.d.). Managing nanomaterials in the workplace. https://osha.europa.eu/other/emerging-risks/nanomaterials

[16] European Committee for Standardization. (2026). Sustainability of construction works - Assessment of environmental performance of buildings - Requirements and guidance (EN 15978:2026). CEN.

[17] European Union. (2024). Regulation (EU) 2024/3110 laying down harmonised rules for the marketing of construction products. Official Journal of the European Union. https://eur-lex.europa.eu/eli/reg/2024/3110/oj

[18] European Union. (2014). Directive 2014/24/EU on public procurement. Official Journal of the European Union, L 94, 65-242. https://eur-lex.europa.eu/eli/dir/2014/24/oj

[19] Regional Cooperation Council. (2025). Revised Green Agenda Action Plan (2025-2030). https://www.rcc.int/pubs/217/revised-green-agenda-action-plan-20252030