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Advanced Materials and Nanotechnology to Improve Energy-Efficiency and Environmental Performance

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About the author

Dr. Marco Casini is a leading academic in the green and smart building sector with over 20 years' experience in building sciences.

He is an environmental engineer with a PhD in environmental engineering, and is a research fellow in architecture technology at Sapienza University of Rome, Department of Urban Planning, Design, and Architecture Technology. Since 2002 he has been professor of Architecture technology and of Environmental certification of buildings at the Faculty of Architecture of Sapienza University, where he also teaches in several masters', PhD, and graduate schools on subjects pertaining to energy and environmental sustainability for buildings.

Dr. Casini's research activities cover a wide spectrum of topics within sustainable architectural design and energy efficiency of buildings, focusing on advanced materials and nanotechnologies for smart building envelopes and integrated renewable energy systems. He has worked as scientific coordinator on major projects, including the development of "Italian regional system for the certification of environmental sustainability of buildings—Protocollo ITACA Lazio" (2014) and the preparation of the Sustainable Energy Action Plan of Rome within the European Covenant of Mayors for Climate and Energy (2012).

Dr. Casini's professional activity includes scientific and technical consultancy on technological, environmental, and energy aspects related to the design and construction of complex building structures worldwide, as well as training on green building and smart cities strategies and policymaking for Italian public authorities (Prime Minister's Cabinet, Ministry of Internal Affairs, Regione Lazio).

He has been a member of several public technical working groups (Italian Environment Protection Agency, UNI, Bank of Italy, and the Italian technical body of the Conference of Regions and Autonomous Provinces, Regione Lazio) for the development of specific standards on environmentally sustainable construction.

Dr. Casini is the scientific director of the editorial board of the Italian scientific journal *Ponte* and a member of the editorial boards of several other international scientific journals in the fields of engineering and architecture. He has authored over 70 scientific publications on energy and environmental efficiency of buildings.

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Introduction

The construction industry has been identified worldwide as one of the priority action areas in achieving the objective of a smart, sustainable, and inclusive development based on the efficient use of resources.

Because of their low energy efficiency, buildings are currently responsible for more than 30% of global world energy consumption and account for one-third of direct and indirect CO_2 and particulate matter emissions. Nevertheless, numerous studies show that the construction sector has the potential to improve energy efficiency with cost-effective interventions. An improvement of energy performance of buildings, along with reducing carbon emissions, would yield important benefits to building owners and occupants, such as improved durability, reduced maintenance, greater comfort, lower costs, higher property values, increased habitable space, increased productivity, and improved health and safety.

In this picture, the commitment of all countries to improving the energy efficiency of buildings has therefore greatly increased over the past decade, with the triple objective of significantly reducing the energy consumption of existing buildings, ensuring that all new buildings are characterized by high energy efficiency (very low-energy buildings), and using as much renewable energy as possible, instead of fossil fuels, to meet the energy needs of both new and existing buildings.

The challenge for the architecture of the new millennium focuses on several main areas of research in all phases of the building process, from planning through completion to final disposal of the building. Applications are in both new buildings and renovation or redevelopment of existing buildings.

The final objective is to provide a smart building, namely a building designed or renovated with intelligence (smart design) that uses the best typological (smart shape) and technological solutions, from both construction (smart envelope) and equipment (smart systems) points of view, able to interact intelligently with the environment and users (smart people) to provide, with a very low use of natural resources, an accessible, safe, comfortable, and healthy built environment, capable of improving the lives of all stakeholders involved (smart environment, smart living, smart economy, smart city).

In view of this strategic objective, the building envelope plays a key role and in recent years has undergone a thorough review of its features and requirements to find technological solutions that can guarantee continuous adjustment of environmental flows in relation to climatic conditions and other factors. The building envelope constitutes a complex system of barriers and filters that regulate the flow of heat, solar radiation, air, and steam, and can also convert radiation into energy (thermal and electrical), which is an essential element for the metabolism of the building.

The final goal is to provide a "smart envelope," capable of not only offering better performance compared to a traditional building shell, but also fulfilling new functions (power generation, light emission, image projection, air purification, self-cleaning surfaces, ability to self-repair, etc.) and adapting its characteristics in response to changes in external conditions (from transparent to opaque, from solid to liquid, from waterproof to permeable, etc.).

Thanks to huge progress in the field of materials science and nanosciences, technology solutions available today make it possible to accept this challenge of the new millennium architecture and take effective action, with more than satisfactory results, even in renovation of historical buildings subject to architectural restrictions.

Innovative insulation products (advanced insulating materials) that offer high thermal insulation performance with very low thickness along with dynamic glazing and building integrated renewable energy systems, are opening up important new possibilities in the fields of design and renovation of the building envelope to provide environment-adaptive skin facades. Examples are vacuum insulating panels (VIPs), nanoporous insulating materials (NIMs) like aerogel, transparent insulating materials (TIMs) that combine light transmission and thermal resistance in a few centimeters of thickness, special coatings to reflect infrared solar radiation (cool roofs), and active components and devices, so-called "smart materials," able to modify their characteristics in relation to different conditions imposed by climatic agents or users, such as phase-change materials (PCMs), chromogenic materials, and photocatalytic and organic photovoltaic materials.

The goal of this book is to provide readers with a state-of-the-art review of the latest advances in construction materials and building design. It takes into consideration both design and materials aspects, with particular focus on the next generation of construction materials and the most advanced products currently entering the market as high-priority, energy-efficient building envelope components.

The book is divided into three main parts.

In Part One, after an introduction about the issues concerning the design process in the third millennium and the differences between zero-energy buildings, green buildings, and smart buildings, the book addresses the issue of smart buildings, focusing on the envelope and how to make it "adaptive" thanks to the huge new possibilities offered by smart materials and nanotechnology.

Chapter 1 provides an overview of new issues related to building design, illustrating the design strategies to achieve maximum building efficiency, sustainability, and architectural quality. After an outline on the state of existing building stock and its role in energy consumption and global warming, an in-depth presentation of zero-energy, green, and smart building concepts and requirements is given, highlighting the main strategies and technical and technological design solutions. A new and inedited definition of smart buildings is introduced, responding fully to the needs of the architecture of the 21st century and in line with the new concept of a smart city. Particular attention is given to the envelope and how to make it "smart" by virtue of the new and extensive possibilities offered by nanotechnologies and smart materials. Lastly, an outlook on the importance of energy management systems and the "internet of things" to achieve a smart building is presented.

Chapter 2 gives an overview of the most advanced materials available today to reconcile the architectural features of buildings with the new challenges of energy and environmental efficiency. An in-depth analysis of nanotechnology and its application to the energy, environmental, and construction sectors is provided, focusing on innovative nanoproducts for architecture. The new class of highly innovative materials, so-called smart materials, is presented, addressing both property-changing and energy-exchanging materials, and illustrating their properties and application in the building sector. Lastly the chapter gives an overview of the enormous potential of three-dimensional (3D) printing technology for architecture, with particular focus on the realization of building components, structural elements, and entire buildings (3D house printing technology).

Part Two, devoted to the latest solutions for thermal insulation, the so-called smart insulation, presents the results of extensive and thorough research on the most innovative insulation materials, from nanotechnology to bioecological materials and PCMs, describing for each the technical characteristics, performance level, and methods of use. Also presented are the achievements in the field of green walls as a solution for upgrading the energy efficiency and environmental performance of existing buildings.

Chapter 3 focuses on the importance of the thermohygrometric characteristics of opaque closures in the energy efficiency of buildings. An overview of thermal insulation materials is presented, illustrating main thermal properties and heat transfer physics. Functional models and building application methods are described, highlighting the main differences in terms of energy performance, thermal comfort, and time and costs of realization.

Chapter 4 focuses on innovative solutions for thermal insulation of opaque closures in new and existing buildings, with an in-depth look at future prospect and developments. The most advanced thermal insulating materials, including NIMs such as aerogel and VIPs, are presented, providing a comprehensive analysis of different products available on the market, their advantages and disadvantages, their possible application in the building envelope, and their future developments. Different next-generation bio-based insulating materials (algae, mushrooms, wooden foam, etc.) are described, with particular attention to low environmental impact and reuse/recycle possibility. Main TIMs solutions and their applications are shown, comparing their performance to traditional insulating glass units.

Chapter 5 focuses on the importance of the heat capacity of the building envelope for energy efficiency and indoor thermal comfort, presenting the most innovative smart materials for latent heat storage in new and existing buildings. A thorough review of PCMs is given, explaining their classification, technical specifications, encapsulation methods, functional models, and application inside or outside the building, even combined with advanced insulating materials. Lastly, there is an in-depth look at future prospects and developments.

Chapter 6 provides an in-depth analysis of reflective coatings (cool roofs) available on the market, explaining their possible application for new and existing buildings and their potential to increase the energy efficiency of buildings and reduce urban heat island effect. Different technological solutions to integrate vegetable species as cladding systems for internal and external walls (green walls) are discussed, and the most innovative techniques are illustrated in detail. The last section looks at the state of research and future developments in environment-adaptive skin facades.

Finally, Part Three illustrates research on smart windows, with the assumption that transparent surfaces represent the most critical element in the energy balance of a building and simultaneously one of the most significant components of contemporary architectural quality. There is an extensive review of the technical features of transparent closures on the market or still under development, from so-called dynamic glazing up to bioadaptive and photovoltaic glazing, describing their esthetic potential and performance limits.

Chapter 7 focuses on the most innovative solutions to improve thermal transmittance of glazing, such as double and triple glazing, noble gas filling, low-emissivity coatings, suspended film glazing, vacuum insulated glass, monolithic aerogel, heating glazing, and glazed double-skin facades. It outlines different advanced insulating glazing solutions available on the market and their main characteristics and performance. Lastly, an outline of ETFE (ethylene tetrafluoroethylene) use for transparent closures is provided.

Chapter 8 illustrates the role of glazing in light and solar radiation control to achieve the maximum daylighting and energy efficiency levels by avoiding summer overheating and exploiting winter solar gain. Innovative solutions for enhancing and controlling visible light are shown, including self-cleaning glass, antireflective glazing, and light-redirection and optical systems. Main solutions for solar control are summarized, including advanced shading systems and static solar protection glazing, describing the main selective glazing available on the market and its performance and specifications.

Chapter 9 describes the most innovative high-performance dynamic glazing systems, aimed not only at reducing heat loss but also at controlling incoming solar radiation to maximize solar gain in winter and minimize it in summer, as well as ensuring the best natural lighting conditions with no glare. An analysis of the different types of dynamic glazing with both passive and active control is provided, illustrating their potential uses and the benefits achieved in terms of energy efficiency, environmental comfort, and architectural quality in both new constructions and existing building renovations. Particular attention is given to the different types of active dynamic glazing technologies (smart windows) available on the market or still in development, such as electrochromics, suspended particle devices, polymer-dispersed liquid crystals, and other emerging technologies. For each technology operation, performance, and feasibility are analyzed and compared.

Chapter 10 focuses on the role of glazed surfaces as an energy-generating component. The most advanced solutions to integrate photovoltaics into transparent surfaces are illustrated. Particular attention is paid to inorganic and organic semitransparent photovoltaic thin films, illustrating operation, performance, and feasibility for building applications. Emerging technologies such as spherical cell photovoltaic glazing, prismatic optical cell photovoltaic glazing, and transparent luminous solar collectors are also described. Lastly, innovative bioadaptive facades implemented with algae bioreactors are introduced, analyzing their operation, performance, and energy yield.

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