White Paper on Prefabricated Active Modules for Façades and Roofs or Key Enabling Technologies for Active Building Skins

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Contents

List of acronyms

AI	Artificial Intelligence
IAQ	Indoor Air Quality
IoT	Internet of Things
IWG	Implementation Working Group
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
PV	Photovoltaics
SoA	State of Art
TRL	Technology Readiness Level

1. Executive Summary

This white paper provides an in-depth analysis of active module systems for building envelope, focusing on their development, challenges, and potential targets for future implementation. The paper examines the current landscape of active modules, reviews best practice projects from 2018 to 2023, and identifies gaps and barriers within the industry. By adopting a comprehensive methodology, this study aims to redefine the concept of active modules and propose strategies for their advancement in the construction sector.

The analysis of active module projects over the past six years reveals significant advancements in design, manufacturing, and testing capabilities. The integration of digital tools and parametric design tools has enhanced the accuracy and flexibility of active facade system design and furthermore, digital fabrication techniques have enabled more precise customization and cost-effectiveness in manufacturing active modules. Material science advancements have led to the development of lightweight and high-performance materials, offering improved durability, insulation properties, and aesthetic possibilities. Additionally, the integration of sensors, actuators, and control systems has enabled real-time monitoring and adaptive responses to changing environmental conditions.

Despite these advancements, several challenges and barriers exist in the widespread adoption of active modules. Decision-making complexity in multicriteria analysis, integration with existing building systems, technological maturity and reliability, cost and economic viability, standardisation and quality frameworks, regulatory and permitting challenges, maintenance and serviceability, and the lack of end-of-life analysis are identified as key challenges. These barriers require collaborative efforts among architects, engineers, manufacturers, regulators, and researchers to overcome.

To address these challenges, the white paper proposes specific targets and actions for the active module sector. This includes further research and development, improved standardisation, cost reduction, performance validation, and the establishment of clear guidelines and regulations. The document emphasises the importance of collaboration between stakeholders to drive innovation and ensure the long-term performance and reliability of active module systems.

In conclusion, while active module systems have made significant progress in recent years, there is still work to be done to fully realise their potential in the construction industry. This white paper provides a comprehensive overview of the current landscape, identifies gaps and barriers, and outlines specific targets and actions for advancing active module systems. By addressing these challenges and fostering collaboration, the industry can promote sustainability, energy efficiency, and occupant comfort in building design and construction.

2. Introduction

Energy Efficiency in Buildings (EEB) is of strategic importance in EU energy policies, contributing to improved energy security and reduced CO_2 emissions. New buildings with high energy performance offer potential energy savings, but the refurbishment of existing buildings holds even greater promise due to their larger numbers and higher energy demand. Active technologies play a critical role in achieving energy savings, accounting for over half of the final energy demand, primarily met by fossil fuels. The widespread implementation of active technologies could significantly contribute to CO2 emission reduction.

The European Union has established a robust regulatory framework to support EEB, including directives such as the Energy Performance of Buildings Directive (EPBD), Energy Efficiency Directive (EED), and Ecodesign. EEB is closely interconnected with subjects like the circular economy and efficient resource utilisation. Additionally, EEB is a focal point in the EU's Research, Development, and Innovation (RDI) policy, with significant contributions from projects funded by Framework Programme 7 (FP7), Horizon 2020, and Horizon Europe, particularly the Energy-efficient Buildings (EeB) and Public-Private Partnership (PPP).

Within this R&I framework, the Strategic Energy Technology Plan, along with the Temporary Working Group 5 on Energy Efficiency Solutions for Buildings, has played a coordinating role since 2018 in advancing energy efficiency solutions for buildings through low-carbon research and innovation activities among EU Member States and participating countries. The Implementation Plan outlines the actions required to achieve ambitious energy efficiency targets in buildings[1], identifies ongoing projects, and proposes new activities to address existing gaps and support R&I cooperation within the ecosystem.

The white paper issued by the Implementation Working Group 5's Task Force on active module aims to monitor the progress and understand the impacts achieved by active modules R&I activities in the last 5 years. It supports the update of the Implementation Plan and ensures the successful implementation of the outlined targets leading to the marketability of active module products. Strategic issues such as the **digitalization of construction, industrialization and standardisation, energy poverty, energy security, and sustainability** through circular economy principles are crucial to comprehend. Developing active module products requires a systematic integrated approach to advance their adoption for energy efficiency and responsive buildings.

A comprehensive understanding of the existing challenges can greatly benefit researchers, practitioners, policymakers, and industry stakeholders. This paper offers insights into the development, challenges, and opportunities associated with prefabricated active modules, providing targets and proposing actions. It serves as a valuable resource for the construction industry, ultimately paving the way for a future of energy-efficient, sustainable, and economically viable buildings.

[1] Target 5.1-T2: Develop and demonstrate market ready solutions to reduce the construction and maintenance costs of Nearly Zero Energy Buildings (NZEB) or positive energy buildings by at least 10% compared to their costs in 2015 with a view to reach a cost reduction of 15%.
Target 5.1-T3 Develop and demonstrate market ready solutions to reduce the average duration of energy-related construction works by more than 20% for renovation and for new buildings compared to current national standard practices.

3. Description of topic

The “active module” [1] is defined as a “prefabricated active modules for façades and roofs or Key Enabling Technologies for active building skins” with the expected targets to “develop and demonstrate market ready solutions to reduce the construction and maintenance costs of Nearly Zero Energy Buildings (NZEB) or positive energy buildings” and to “develop and demonstrate market ready solutions to reduce the average duration of energy-related construction works”.

Based on this definition, the active modules is hereafter furtherly defined. In the context of facade and roof solutions, active modules refer to technological and construction components or systems within a building envelope that are equipped with dynamic, interactive and adaptive features and capabilities. Unlike passive facade elements that remain static, active modules can respond and adapt to changing environmental conditions or user needs. These modules incorporate various technologies, sensors, and control systems to actively control and optimise aspects such as energy efficiency, thermal comfort, glaring, daylighting, ventilation, and aesthetics. They can be integrated into different types of building envelope components, such as windows, louvres, shades, glazing, cladding systems, as well as renewable energy sources and systems to facilitate easy integration in the building.

Over the last 10 years, active module systems have undergone significant advancements in design and manufacturing capacities, while processes, standardisation frameworks, and market expectations have also evolved. Here are some of the main evolutions in each of these areas:

- Regarding design, the integration of Building Information Modeling (BIM) has become more sophisticated, allowing architects and engineers to design and simulate active facade systems more accurately. BIM enables the integration of various design disciplines and facilitates collaborative design processes. The use of parametric design tools has gained popularity, enabling designers to create complex and dynamic facade systems, making the process more flexible. The reinforcement of advanced simulation software now allows designers to precisely predict and analyse the performance of active module systems under different environmental conditions. The combination of parametric design and simulation capacities allows for the optimization of factors such as solar heat gain, daylighting, and ventilation based on specific system requirements.
- In terms of manufacturing capacities, the use of digital fabrication techniques, such as Computer Numerical Control (CNC) machining, laser cutting, and 3D printing, has increased in the manufacturing of construction components, including active modules. These techniques offer greater precision, customization, and cost-effectiveness. Advancements in material science have resulted in the development of lightweight and high-performance materials for active module systems. These materials offer improved strength, durability, insulation properties, and aesthetic possibilities. Lastly, manufacturing capacities have evolved to incorporate smart technologies into active module systems. This includes the integration of sensors, actuators, and control systems that enable real-time monitoring, automated adjustments, and adaptive responses to changing environmental conditions.

- Standardisation frameworks and energy performance standards are boosting new solutions, and active modules can be among them. Various countries and regions have introduced or updated energy performance standards that encourage the use of active facade systems to improve the energy efficiency of buildings. These standards provide guidelines and requirements for design, installation, and performance assessment, particularly for active modules integrating renewable sources such as photovoltaic or solar collectors. Certifications and rating systems, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), have included specific criteria for active facade systems. These frameworks promote sustainable building practices and provide recognition for buildings with high-performance facades.
- Testing methods is an ongoing international process that standardisation organisations and industry associations are undertaking also to develop and harmonise testing methods, including those for active module systems. In the near future, this will ensure consistent performance evaluation, facilitate comparison between different systems, and promote innovation in the field.

Thanks to the boost coming from public funding for research and innovation programs, the active module context has witnessed advancements in active facade design, manufacturing, testing, and building applicability over the last 10 years. These developments have contributed to the integration of active module systems in the available construction solutions for contemporary building design, fostering sustainability, energy efficiency, and occupant comfort. However, active modules, at this moment, do not seem fully ready to disrupt the construction industry as expected. While the integration of single active systems such as energy production, particularly with PV products, has been successful, further improvements are needed for the wider applicability of active modules. Indeed, more complete and complex solutions that embed multiple technologies, pushing the active module concept beyond its limits, need to be analysed to identify specific insights and address further research and market actions to be adopted.

Active modules typically have the following characteristics:

- **Embedding and Integration of active technologies** – active modules combine multiple active technologies into a single prefabricated construction component. Commonly integrated technologies include mechanical ventilation, photovoltaic systems, solar tech, actuators for vents, and IoT technologies. Additionally, energy storage, heating/cooling systems, and onboard algorithms for active module management can also be incorporated.
- **Dynamic Adaptability** – Active modules can dynamically adjust their position, orientation, transparency, or other properties based on external factors, such as sunlight, temperature, wind, or user preferences. This adjustability allows for the optimization of energy performance, daylight penetration, privacy, and visual comfort.
- **Sensor Integration** – Active modules incorporate sensors that collect data on environmental conditions, occupancy or user inputs. These sensors provide real-time feedback, allowing the modules to respond and adapt accordingly. For example, sensors can detect excessive heat gain and trigger the activation of shading devices to reduce solar heat and glare.
- **Control Systems** – Active modules are controlled through intelligent control systems that receive data from sensors and apply algorithms to make decisions. These control systems regulate the behaviour of the active modules, enabling automated or manual adjustments based on predefined settings or user inputs.

- **Integration with Building Management Systems –** Active modules can be integrated into the building's overall management system, allowing for centralised control and coordination with other building systems. This integration facilitates the optimization of energy consumption, indoor comfort, and overall building performance and may enable grid integration capability.
- **Role in sustainability (environmental, social, economic)** – Throughout its functionalities, active modules can play a crucial role to lower sustainability impacts in its declinations. Its adaptability to user experience, improvement of occupant comfort, overall energy efficiency and enhanced control integrate in a LCC and LCA design framework can dramatically improve its impact.

4. Scope of the white paper

The scope section outlines the specific areas and aspects covered within this white paper. It provides a breakdown of the key topics addressed, summarising the current landscape of active modules through an extensive methodology. It includes thematic workshops among task's members and an analysis of best practice projects in active facades over the past six years (2018-2023) [2–15] and a thorough revision and update of project references. Additionally, the methodology involves the identification of the Technology Readiness Level (TRL) for each project analysed to determine whether it is still in the research phase or ready for the market. Furthermore, the methodology encompasses the identification of the targeted market, distinguishing between new and existing buildings, as well as residential and tertiary buildings.

The evaluation process includes an assessment of the gaps and barriers encountered, covering technological, non-technological, social, and environmental aspects. Technological aspects encompass considerations such as eco-design, Design for Assembly/Disassembly (DfA/D), and the integration, installation, and validation of various technologies. Non-technological aspects include economic factors (e.g., cost reduction for construction and maintenance, return on investment), social factors (e.g., architectural acceptance, minimal disruption during construction), and environmental factors (e.g., greenhouse gas emissions, carbon neutrality, use of eco-design principles and bio-based materials). Within these activities, gaps and barriers are identified and then clustered based on a classification framework that facilitates the analysis of the results, leading to the identification of specific targets and actions for active facades.

In line with the adopted methodology, this white paper supports the redefinition of the active module based on the latest achieved results. It supports the identification of current gaps and barriers that hinder its promotion. Evaluating these missing points within the active module allows for the identification of specific actions and strategies to continue implementing the active module concept and better understand its overall impact and the expected targets by 2030 within the building sector.

5. Implementation

In line with the methodology defined in section 4 and the synthesised analysis of the active module projects and products, this implementation section is divided into two main subsections: Gaps and Barriers, and Possible Targets and Actions.

a. Gaps and barriers

The Gaps and Barriers subsection explores the challenges and obstacles currently faced in the development and implementation of active modules with the objective to identify the main gaps in research, the potential technological limitations, regulatory hurdles, and market barriers. The development of active modules for building envelopes faces several barriers and challenges. Some of the key challenges include:

- **Complexity of decision-making in multicriteria analysis –** Designing and selecting the appropriate active modules for a specific system involves considering multiple criteria, such as energy efficiency, cost-effectiveness, occupant comfort, aesthetics, and maintenance requirements. Balancing these criteria and making informed decisions can be complex, as optimising one aspect may have trade-offs in another. It is necessary to adopt active module practices that can break down the evaluation of module adoption into multiple impacts, involving decision-makers and players in the value chain.
- **Integration with in-place systems** – The integration with existing building systems is key to further use active modules for the retrofitting of existing buildings as it needs to be adapted to the building's infrastructure and systems, from mechanical to IT components. Ensuring compatibility and seamless integration with existing electrical, mechanical, and control systems may require additional coordination during the design phase.
- **Technological maturity and reliability** – Active module technologies are relatively new and rapidly evolving, and they need to demonstrate built experience and robustness over repeated installations. The maturity and reliability of these technologies can be a concern for developers and designers. Ensuring the long-term performance, durability, and maintenance of active modules is essential to gain stakeholders' trust and confidence. The acceptance by stakeholders is also related to the challenge of architectural design, appearance, and aesthetics, which are key aspects to allow the full adoption of active modules within the building construction sector in order to have a customised solution based on architectural design.
- **Cost and economic viability** – The initial costs associated with active modules can be higher compared to conventional passive facade elements. The economic viability of incorporating active modules depends on factors such as energy savings, operational costs, and the payback period. Achieving cost-effectiveness and demonstrating a positive return on investment can be crucial for wider adoption. At present, the cost is far from being competitive for commercialization. While the European framework expects the cost to be competitive with traditional solutions (e.g., ETICS, ventilated facades), currently, only a short range of products is competitive on the market with traditional solutions (price <250€/sqm). This is also demonstrated by the fact that, despite demonstrations of active modules being conducted in 65% of the surveyed projects (11 projects out of 17), only 6 will be on the market by 2025.
- **Standardisation and quality framework** – As active modules are diverse and incorporate advanced technologies, there is a need for standardised procedures and

quality frameworks to ensure safety, performance, and interoperability. Developing industry standards, testing protocols, and certification processes specific to active modules can provide a quality assurance framework and support market acceptance.

- **Regulatory and permitting challenges** – Integrating active modules in a building project may involve navigating through complex building regulations and obtaining permits. As active modules often deviate from traditional building practices, establishing clear guidelines and regulations that address safety, energy efficiency, and other concerns is necessary to support their widespread implementation. The fact that nZEB buildings and positive buildings have wide definitions at the international level and multiple numeric thresholds multiply the reference regulations and standards, negatively affecting the application and market entry of active modules.
- **Maintenance and serviceability** – Active modules may require specialised maintenance and service procedures due to their technical complexity. Ensuring access, ease of maintenance, and the availability of skilled technicians for repairs and replacements is essential for the long-term performance and reliability of active modules. The active module suppliers often stop at the installation stage, demanding that other players along the value chain provide the maintenance service.
- **Missing end-of-life analysis** – Considerations for active modules in building facades are gaining importance as the principles of circularity and sustainability become integral to the construction industry, but currently, they are lacking. The integration of multiple technologies in prefabricated systems needs to consider the end-of-life step since the design stage to enable such a strategy. The increased use of design for assembly and disassembly methodologies offers great potential.
- **Marketability issues** – All these aspects contribute to the current lack of marketability. The active modules analysed in the experiences are tested and validated, but they are not considered market-ready by 2027. While it is a common understanding that active modules can update building systems and their technical validation demonstrates this objective, the price is considered a key factor to be market-ready, as well as the scalability related to the market needs. Both aspects are necessary to allow mass customization of prefabricated solutions, as well as standardisation (achieved performances, construction practices, local norms) for different buildings and climates.

Addressing these barriers and challenges requires collaboration among architects, engineers, manufacturers, regulators, and researchers. Continued research and development, improved standardisation, cost reduction, and performance validation are crucial to advancing the development and adoption of active modules in building envelope.

b. Possible targets and actions

The Possible Targets and Actions subsection proposes strategies and actions to address the identified gaps and barriers. It includes recommendations for research and development, policy interventions, industry collaboration, and standardisation efforts.

In this framework, specific actions to better frame active modules and understand their impact in the overall building life can be conducted:

- **Define Multiple evaluation parameters** – Establish new standardised parameters for active modules' norm compliance and applicability, considering all the impacts and building aspects they address. Parameters such as thermal transmittance, heat transfer, energy production, adaptability, and data insights should collaborate to evaluate a common active module parameter, providing a better understanding of their overall impact on the building beyond the typical building envelope parameters. This could involve setting a standard based on the contribution to a percentage of heat loss or gain in the building envelope area where active modules are applied. Examining existing case studies, experiences, and conducting specific simulations can help determine this percentage ratio.

- **Develop Multi-Criteria decision matrix and analysis** – Promote the understanding of active modules' complex systems by adopting Multicriteria analysis techniques and tools within soft computing approaches. This approach can accurately evaluate and compare different active module options. Integrated design is a major challenge for active modules, and by fostering interdisciplinary collaboration, coordinated efforts, and iterative analysis, design options can be enhanced with a comprehensive perspective. However, it is important to note that this approach may take longer and be more expensive than current design practices on the market, which may be a consideration for designers and employers.
- **Adopt Life Cycle Assessment and anticipate end-of-life** – Introduce a new approach that considers the overall building life cycle, including enhancing material and products replacement and end-of-life strategies throughout all the stages of active modules' lifespan. Designing active modules with a focus on circularity, thinking about replacement and disassembly is crucial to extend active modules lifecycle while minimise waste generation and maximise material recovery. Strategies such as Ecodesign and Design for Disassembly (DfD) ensure that active modules can be easily maintained and optimized for their environmental performances throughout the whole life cycle, so for the end-of-life dismantling, allowing for the recovery and reuse of valuable components and materials. Considering replacement and disassembly strategies during the design phase might lead active modules to adopt standardised connections and fasteners that facilitate easy separation and replacement of individual components, it also enables increased modularity. This approach enables efficient maintenance, upgrades, and replacements while reducing the environmental impact associated with active module service life as well as disposal. Embracing circular design principles throughout the life cycle of active modules promotes resource conservation, reduces landfill waste, and fosters a more sustainable and environmentally responsible approach to building construction and renovation.
- **Adopt Cost-Benefit Analysis** – Integrating multiple technologies makes active modules a complex solution that may have higher costs. To address this, a Cost-Benefit Analysis (CBA) for a 30-year period of performance can change perspectives on costs in relation to already installed solutions, as well as more traditional and passive systems. It is particularly relevant to consider the adaptability of active modules to outdoor and indoor conditions, as well as users' needs, taking advantage of environmental data and occupancy scenarios. Such active modules can improve the durability of buildings and the health of the occupants which should be valorised. The result of the CBA should be compared with well-established baselines for both conventional strategies and the cost and time of intervention.
- **Identify Standardisation of norms** – Active modules have a wide range of applicability and embeddable technologies, requiring a common framework and norms to define testing procedures, target parameters, and comprehensive definitions. International understanding on the topic is necessary to avoid mismatching among national norms and support the scaling up of active modules at the EU level. Standardisation should be guided by the vision of having a holistic approach to active module practices during its stages of implementation.

- **Define Financial schemes and business models –** Active modules introduce a level of complexity that requires a financial and business effort to enter the market. Implementing financial schemes such as tax reductions and premiums can boost the uptake of active modules in the market. Additionally, there is a necessity to develop and promote new business models within the construction industry beyond the current practice of selling active modules as products. Investigating and investing in life cycle business models with revenue models based on enabled services, achievable performances, and end-of-life economic valorisation can drive innovation and adoption.
- **Define communication standards** – Active modules need to be supported by standardised protocols and interfaces for communication between the modules and building management systems. This ensures interoperability, seamless integration, and efficient operation of the modules within the building ecosystem. Common communication standards enable easier monitoring, control, and optimization of energy performance.
- **Define methods for formulating data-driven digital twins –** Active modules require full commissioning and informed decisions during their service lives. Developing methodologies for creating data-driven digital twins of active modules can enhance their performance monitoring, predictive maintenance, and optimization. By collecting real-time data from sensors and combining it with advanced analytics, digital twins can provide valuable insights into the functioning and efficiency of the modules. This information can then be used to identify areas for improvement and optimise energy consumption, comfort, and environmental impacts.
- **Create synergies among actors** – active modules require continuous and efficient collaboration among disciplines and actors involved. Establishing a knowledge sharing and training ecosystem can create a network capable of providing appropriate and sufficient capability to manage active modules. These synergies should promote training/education programs for highly skilled professionals and the workforce, facilitate connections among universities, research and technology organisations, startups, and industrial actors, and support the validation of active modules in Living Labs to accelerate market readiness.

These actions will contribute to the advancement of active module technologies, promoting further research and widespread market adoption, and achieving results for energy-efficient and responsive buildings.

Based on these actions and on the targets of the Implementation Plan defined in 2018, are suggested to be updated as follows:

- **Target 5.1-T2 - Update 01** – Moving from "construction and maintenance costs reduction" to "Cost-Benefit Analysis in building life stages (construction, maintenance, commissioning, end-of-life)". The costs should also include cost opportunities for the long-term implementation of subjective aspects such as thermal comfort, lighting comfort, and Indoor Air Quality.
- **Target 5.1-T2 - Update 02** – Define new targets for buildings that are the focus of interventions with active modules. Possible targets include:
    - Energy savings due to interaction among embedded and automated technologies: -35%.
    - Reduction of CO_2 levels in parts per million (ppm) due to mechanical and natural ventilation: -20%.
    - Increase in hours of thermal comfort due to optimised energy utilisation: +15%.
    - Energy production based on total building energy demand: 10%.

- **Target 5.1-T3 - Update 01 –** Extend the time analysis from “average duration of energy-related construction works” to “average duration of the construction process (decision-making, design, manufacturing, construction, maintenance, commissioning, end-of-life)”.

A new target is suggested for active modules:

- **Target 5.1-T5** – Develop and demonstrate market-ready solutions to reduce the environmental impact of buildings towards the 2050 Carbon Neutrality and Circularity targets in the EU by achieving:
    - A carbon-neutral building in 12.5 years (an average of 8% reduction in overall building eqCO2 emissions each year for 12.5 years).
    - 80% of materials reusable or recyclable after end-of-life.

6. Synergies with other topics and objectives

This section highlights the potential synergies between active modules and other related topics and objectives, fostering collaboration and knowledge exchange to accelerate progress in the field.

Active modules are designed to be transversal to disciplines, integrating technologies and covering a wide range of responsiveness scenarios. This aligns with activities and initiatives:

- Sustainable Development Goals (SDGs) by the United Nations [16]: active modules contribute to several SDGs, including:
    - Goal 7: Affordable and Clean Energy: active modules promote energy efficiency and reduce carbon emissions in buildings through advanced technologies and renewable energy integration.
    - Goal 9: Industry, Innovation, and Infrastructure: active modules drive innovation in the construction industry, introducing sustainable building practices and digitalization.
    - Goal 11: Sustainable Cities and Communities: active modules enable the development of energy-efficient, environmentally friendly buildings, supporting sustainable urban development.
    - Goal 13: Climate Action: active modules play a vital role in reducing greenhouse gas emissions and promoting the transition to low-carbon buildings.
- Revision of the Energy Performance of Buildings Directive (EPBD) [17]: active modules align with the EPBD by enhancing energy efficiency in buildings. They offer integrated solutions for insulation, ventilation, and energy management, reducing energy consumption and improving overall building performance.
- EU Mission: Climate-Neutral and Smart Cities [18]: active modules contribute to this mission by enabling the construction of energy-efficient and smart buildings. They incorporate technologies for energy optimization, indoor environmental quality, and digital connectivity, supporting climate-neutral and smart city development.
- Driving Urban Transitions (DUT) to a Sustainable Future [19]: active modules play a significant role in driving urban transitions by offering sustainable building solutions. They facilitate the integration of renewable energy sources, optimize energy consumption, and enhance the environmental performance of buildings, contributing to sustainable urban development.
- New European Bauhaus [20]: active modules align with the principles of the New European Bauhaus, which promotes sustainability, aesthetics, and inclusivity in the built environment. Active modules integrate sustainable design elements, renewable energy technologies, and innovative construction methods, exemplifying the principles of the New European Bauhaus.
- Horizon Europe, Cluster 4: Digital, Industry and Space [21]: active modules contribute to Cluster 4 by embracing digitalization in the construction industry. They incorporate digital technologies, such as IoT and AI systems, to optimise building performance, enhance productivity, and improve resource efficiency.
- Horizon Europe, Cluster 5 [22]: Climate, Energy and Mobility: active modules support Cluster 5 by addressing climate and energy challenges in the built environment. They promote energy efficiency, renewable energy integration, and sustainable mobility solutions, contributing to the goals of the cluster.
- European Union Circular Economy Action Plan [23]: active modules can contribute to the principles of the circular economy by incorporating reusable and recyclable

materials, promoting resource efficiency, and reducing waste generation in the construction sector.

- European Green Deal [24]: active modules align with the objectives of the European Green Deal, which aims to make Europe the world's first climate-neutral continent. By enhancing energy efficiency, reducing greenhouse gas emissions, and promoting sustainable construction practices, active modules support the goals of the Green Deal.
- EU Renovation Wave Strategy [25]: The EU Renovation Wave Strategy aims to double the renovation rate of buildings in the European Union, thereby improving energy efficiency and reducing carbon emissions. Active modules can play a crucial role in this strategy by offering innovative and sustainable solutions for building refurbishment and retrofitting.
- EU Biodiversity Strategy for 2030 [26]: active modules can contribute to the EU Biodiversity Strategy by integrating nature-based solutions into building design and construction. By incorporating green roofs, living walls, and other ecological features, active modules can enhance biodiversity, support ecosystem services, and promote sustainable urban development.
- EU Digital Decade [27]: The EU Digital Decade seeks to promote digitalization and interoperability across various sectors, including construction. Active modules, with their integration of digital technologies, can align with this strategy by facilitating data exchange, improving communication between building systems, and enabling smart building management.
- Energy Agency Energy Consumption in Buildings and Communities program [28]: Active modules are highly relevant to the Energy Agency's program as they offer innovative solutions to improve energy consumption in buildings and communities. By integrating technologies like photovoltaics, energy storage, and smart controls, active modules optimize energy usage, reduce electricity demand, and contribute to overall energy efficiency. Additionally, their adaptability and dynamic features enable better management of energy consumption based on environmental conditions and user preferences, further enhancing their impact on energy savings and sustainable building practices.

By addressing these European norms and policies, active modules can play a significant role in advancing sustainable construction practices, reducing environmental impacts, and promoting the overall goals of the European Union, demonstrating their potential to create positive impacts, fostering a more sustainable and resilient future and driving sustainable development, improve energy efficiency and contribute to the transition towards a low-carbon future.

7. Conclusion

The active modules have the potential to enhance energy-efficient and sustainable construction practices, but specific actions and investments are necessary to promote the widespread adoption of these solutions in buildings. The white paper also emphasises the importance of collaboration among stakeholders and urges them to act upon the proposed strategies and recommendations in order to overcome barriers and unlock the full potential of active modules. The suggested actions and updated targets align with key aspects of EU strategies where active modules can contribute, such as cost reduction, energy efficiency, energy load management, and environmental sustainability. By focusing on these targets, the Implementation Plan can drive innovation and advancements in the development of energy-efficient and environmentally friendly buildings.

In particular, the following topics need to be addressed:

- **Synergy among different construction players** to trigger market adoption of active modules. It is crucial to establish a common understanding and facilitate knowledge sharing among all disciplines involved in the deployment of active modules throughout all stages, ensuring an effective, efficient, responsive, dynamic, and resilient product. This synergy guarantees better management and quality control of results, while respecting the holistic approach underlying active module development.
- **Holistic analysis of the costs and benefits** of active modules is complex but necessary to determine the overall impact. Only with comprehensive insights can active modules enter the market with a clear and quantifiable analysis aligned with market targets. Active modules are the result of multiple interactions and should be quantified using measurable and verifiable parameters that collectively contribute to the achievable results.
- **Exploiting digital opportunities** is crucial to leverage the advantages of digitization in the decision-making and design processes and enable data-driven approaches through IoT and AI systems connected to building management. This digitization ensures the deployment of monitoring and optimization capabilities across the value chain, promoting quality, time, and cost control during the process, as well as energy efficiency, multidomain comfort, and well-being in the building. As a complex system delivered throughout its life cycle, active modules can harness digital opportunities to understand and track their sustainable impacts in economic, social, and environmental domains.
- **Engagement from the entire construction value chain ecosystem** is fundamental and only through tight collaboration can market-ready solutions be achieved. The challenges for active modules involve merging multidisciplinary skills into a knowledge base that can only be accomplished through joint programs and activities among stakeholders. Open innovation approaches facilitated by collaborative platforms and European programs play a crucial role in accelerating progress by enhancing the cooperation necessary to meet the expected targets for active modules. However, despite ongoing efforts in research activities, such as R&I European funding schemes and dissemination events, it is essential to investigate how construction industry actors, including startups, SMEs, and large enterprises, can adopt active modules effectively.

The need for concerted efforts, collaboration, and embracing digitalization to drive the successful implementation of active modules and pave the way for a future of energy-efficient and sustainable buildings for applicable market ready solutions.

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