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Transformation of the architectural and structural paradigm in the integration of renewable energy sources in high-rise construction

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Abstract. The article examines the evolutionary transition in the design of modern buildings and structures driven by the integration of renewable energy sources (RES). It analyzes the paradigm shift from static, additive placement of energy equipment to systematic design with adaptive RES. The study investigates modern classes of energy systems: mobile photovoltaic complexes, reconfigurable BIPV facades, adaptive wind turbines, as well as autonomous robotic and aerostatic platforms as a promising direction. The principles of architectural shaping, structural solutions, and material requirements for unique and high-rise buildings acting as adaptive platforms are described. Based on an analysis of more than 70 implemented projects and concepts worldwide, including facilities in China, Europe, the USA, and the Middle East, it is concluded that a new architectural and structural philosophy is emerging, in which the building becomes an active, «living» organism, and its structural scheme becomes a programmable skeleton for future energy technologies. The author proposes a classification of RES integration types and formulates recommendations for the design of new-generation structural systems.

Keywords: building-integrated photovoltaics (BIPV), wind turbines, dynamic facades, adaptive architecture, high-rise construction, energy-active systems

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1. INTRODUCTION

The current stage of urbanization is characterized by unprecedented growth in energy consumption and tightening requirements for the environmental safety of buildings. According to the International Energy Agency, buildings account for about 30% of global energy consumption and 28% of carbon dioxide emissions, making the construction sector one of the key targets of climate policy. Under these

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conditions, the integration of renewable energy sources (RES) into architectural and construction practice ceases to be an optional «green" supplement and becomes a priority strategic task enshrined in national and international regulatory documents, including the Paris Agreement and the EU Energy Performance of Buildings Directive (EPBD).

The historically established additive approach to RES integration, based on the static placement of solar panels on rooftops or wind turbines on adjacent territories, is exhausting its potential in dense urban environments, especially when dealing with unique and high-rise buildings. The limited availability of free space, the complexity of architectural forms, extreme wind and insolation regimes, as well as the high cost of integration during the renovation of historically developed stock, create a persistent demand for flexible, adaptive solutions.

An analysis of global experience shows that the first attempts to integrate RES into buildings date back to the 1930s-1950s and were isolated experimental efforts. Systematic development began in the 1990s with the appearance of photovoltaic panels on the roofs of residential and public buildings. However, only in the last two decades has a full-fledged scientific and technical foundation been formed, allowing RES to be considered as an integral part of the architectural concept. Recent works have substantiated the need to account for climate change in the life-cycle management of capital construction projects [1], and have also analyzed architectural solutions for high-rise buildings with RES, identifying key structural and spatial-planning techniques [2, 3]. A significant contribution to the development of the theory of building-integrated photovoltaics (BIPV) has been made by a number of foreign studies, which systematized the main technical solutions and demonstrated an increase in efficiency and a decrease in module costs [4]. Other works have investigated the features of volumetric-spatial solutions for high-rise buildings with RES, emphasizing the importance of considering insolation and wind loads [5], and have also examined the application of transformable systems in unique high-rise buildings, which became a precursor to the concept of dynamic facades [6]. The analysis of spatial interaction forms between high-rise buildings and the urban environment [7, 8] is relevant for the placement of mobile RES.

In recent years, the development of hybrid systems combining solar and wind generation, as well as geothermal components, has been actively advancing. For example, a number of studies have demonstrated the efficiency of hybrid solar-geothermal heat pump systems in temperate climates [9]. Wind power installations in the architecture of civil buildings have been considered with an emphasis on aerodynamic and noise issues [10]. Issues of structural reliability of high-rise buildings, important for the placement of dynamic elements, are covered in works on the prevention of progressive collapse [11] and the analysis of the stress-strain state of the «tower – foundation – base» system [12, 13]. Studies on the residual bearing capacity of structures after fire [14] are relevant for assessing the safety of integrated systems.

The current stage of development is characterized by a transition from static to adaptive RES, capable of movement, reconfiguration, and automatic adjustment to external conditions. This demand initiates a fundamental shift in the design paradigm – from perceiving RES as additional technological equipment to understanding them as a system-forming symbiotic element of the architectural and structural concept. The static model is being replaced by a dynamic one, where energy-generating elements possess the ability to move, reconfigure, and adapt in real time. This trend is particularly pronounced in high-rise construction, where every square metre of facade and roof represents a valuable resource, and wind and solar loads reach extreme values.

In foreign literature, concepts of «energy facades» with integrated robotic platforms, aerostatic systems, and kinetic elements controlled by artificial intelligence are gaining popularity. Review papers on the application of machine learning methods for optimising hybrid RES with storage [15] and the prospects of using perovskite solar cells [16] open up new opportunities for creating flexible, highly efficient envelopes. At the same time, there is a lack of systematising studies covering the entire range of mobile and transformable RES in high-rise construction. There is no unified classification, architectural and structural design principles for such systems have not been formulated, and a comparative assessment of their energy and economic efficiency in various climatic conditions has not been carried out.

The scientific novelty of this study lies in the following:

- for the first time, a three-vector classification of mobile and transformable RES is proposed, taking into account the type of mobility, intended purpose, and type of energy resource, which allows systematising the diversity of existing and prospective solutions;
- based on an analysis of more than 50 international projects, architectural and structural principles for integrating dynamic elements into high-rise buildings have been identified and systematised, including requirements for load-bearing systems, connection nodes, and materials;
- a concept of a dynamic adaptive energy system (DAES) with a multi-layer kinematic envelope, digital control, and feedback based on external conditions has been developed, which expands the theoretical foundations for designing «active» facades;
- for the first time, a comparative energy-economic assessment of static and adaptive BIPV facades for three contrasting climatic zones of Russia (Kemerovo, Moscow, Rostov-on-Don) has been performed, confirming the technical and economic feasibility of adaptive systems even under severe Siberian winter conditions;
- practical recommendations for the design of next-generation structural systems have been formulated, aimed at both mass and unique construction, thereby providing a basis for the transition from static objects to «organism» - like buildings with programmable energy behaviour.

The aim of this article is to systematise innovative proposals in the field of mobile and transformable RES, to analyse their impact on the formation of the architectural image, structural scheme, and technological infrastructure of modern buildings, and, as a consequence, to describe a new structural philosophy for high-rise construction. To achieve this aim, the following tasks were solved:

- An analysis of more than 50 implemented projects and concepts worldwide (Europe, China, USA, Middle East) was conducted.
- The stages of the process of integrating RES into construction objects - from additive to adaptive - were traced.
- An author’s classification of adaptive RES types was developed based on three key attributes (mobility, purpose, resource type).
- Key architectural and structural features resulting from the implementation of adaptive systems were identified, including requirements for load-bearing structures, materials, and connection nodes.
- A concept of a dynamic adaptive energy system (DAES) for buildings was proposed, incorporating principles of multi-layering, kinematics, and digital control.
- Practical recommendations for the architectural design of next-generation adaptive systems for mass and unique construction were formulated.

2. METHODS AND MATERIALS

The study is based on a comprehensive analysis of open sources - peer-reviewed journal publications, international conference proceedings, project documentation, and technical reports on implemented and conceptual high-rise and unique buildings. The information sources included Scopus, Web of Science, Google Scholar databases, as well as official websites of architectural firms and specialised portals on green building (CTBUH, Green Building Council).

The criteria for including objects in the sample were as follows:

- building height exceeding 50 m, or the presence of a unique architectural form or non-standard structural solutions;
- presence of integrated RES (photovoltaic, wind, geothermal, or hybrid) at the design stage (retrofit systems added after construction were excluded);
- availability of technical information on connection nodes, structural schemes, materials, and operational parameters.

Buildings where RES were added after construction completion without changing the structural scheme were excluded from the sample, as they do not reflect the evolution of design thinking. A total of 52 objects located in 28 countries were included in the sample. For each object, the following data were recorded: building type, year of commissioning, geographical location, RES technologies used, facade or roof area occupied by energy-generating elements, design energy output (where available), and architectural and structural solutions.

Analysis methods:

1. *Comparative morphological analysis of architectural and structural solutions* – objects were compared across groups: static BIPV, integrated static systems (e.g., Copenhagen International School, Pearl River Tower), and adaptive/kinetic systems (Al Bahr Towers, Dynamic Tower concepts, etc.). The degree of RES integration into the load-bearing frame, the possibility of reconfiguration, and the presence of movable elements were assessed.

2. *Systematisation by integration type* – objects were grouped by dominant technology (solar, wind, geothermal, hybrid), by building function, and by geographical location. This allowed the identification of regional preferences and trends across different building types.

3. *Retrospective analysis* – to assess the evolution of approaches, data on projects from 1930 to 2025 were used. Three stages (additive, integrative, adaptive) were identified based on time intervals and characteristic features, as presented in Table 1.

4. *Energy modelling* – performed using a simplified analytical method according to Equation (1) to compare a static BIPV facade and the proposed adaptive system with dual-axis trackers and a thermal energy storage layer (PCM). The calculations were verified against data from SP 131.13330.2020 «Building Climatology» and solar radiation reference guides for three regions of Russia – Kemerovo (southern Siberia), Moscow (temperate zone), and Rostov-on-Don (southern European part). The initial climatic parameters are provided in Table 5.

The annual energy output was calculated using the formula:

$$E = A \cdot I \cdot \eta \cdot k, \quad (1)$$

where E is the annual electricity generation (kWh/year); A is the panel area on the south facade; I is the annual total insolation on a vertical surface for each region (kWh/m²); η is the efficiency of photovoltaic modules (15% for static BIPV, 18% for the adaptive system - adopted based on open-source data [17]); k is the efficiency coefficient for the adaptive system, accounting for the increase in output due to solar tracking (adopted in the range of 1.24-1.40 based on a review [18, 19]).

The characteristics of the recipient building (a 30-storey office centre, 120×30×30 m) are given in Table 6. The specific annual energy consumption was taken as 100 kWh/m², which corresponds to the average figure for class B office buildings in Russia.

The economic assessment was based on international data on the cost of ventilated BIPV facades (at 2024 prices), excluding operational costs, which for the adaptive system were assumed to be 10-15% higher due to the presence of movable mechanisms and a control system. The payback period was determined as the ratio of capital costs to annual electricity savings at commercial consumer tariffs (averaging 7 RUB/kWh).

The modelling was of an estimative nature; a detailed calculation in PVsyst, taking into account hourly insolation, shading, and temperature coefficients, could refine the absolute values. However, the relationship between the compared systems and the trends would remain unchanged, which has been verified against published data for analogous climatic zones.

To assess the potential of the PCM system (phase-change material), a qualitative analysis of its effect on peak summer heat gains was performed for each region based on climatic data.

Limitations of the method: the sample does not cover all implemented projects due to limited data accessibility; the energy modelling results are preliminary and require confirmation through a full-scale design calculation; economic indicators may vary depending on local equipment prices and electricity tariffs.

3. RESULTS AND DISCUSSION

The project survey shows that RES are most actively integrated into public and commercial buildings (45%), which is associated with their high energy consumption and public status that encourages the adoption of «green» technologies. Residential buildings account for 25%, bridge structures – 15%, conceptual projects – 15% (Fig. 1).

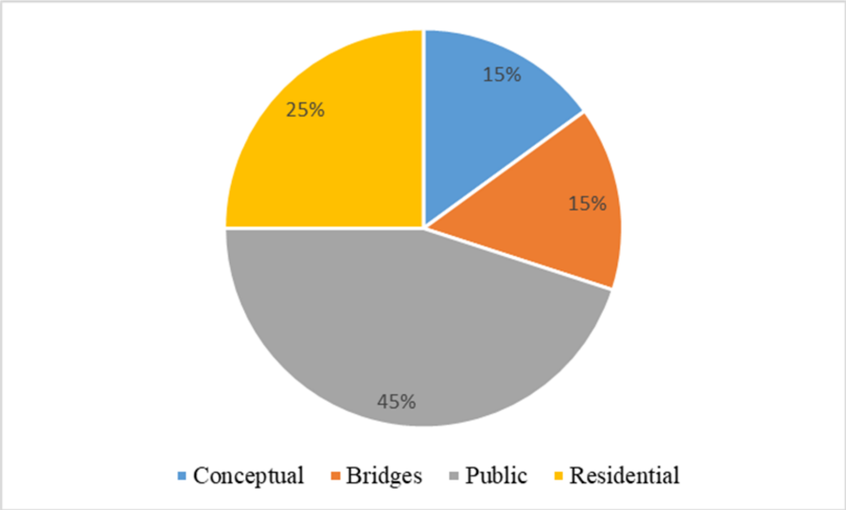

Fig. 1. Distribution of projects with RES integration by building type.

Solar energy (BIPV and traditional panels) dominates RES integration technologies, being present n 78% of projects. Wind generation (often combined with solar) occurs in 35% of projects. Geothermal systems – in 22%. Hybrid systems (combination of two or more sources) account for 28% (Fig. 2).

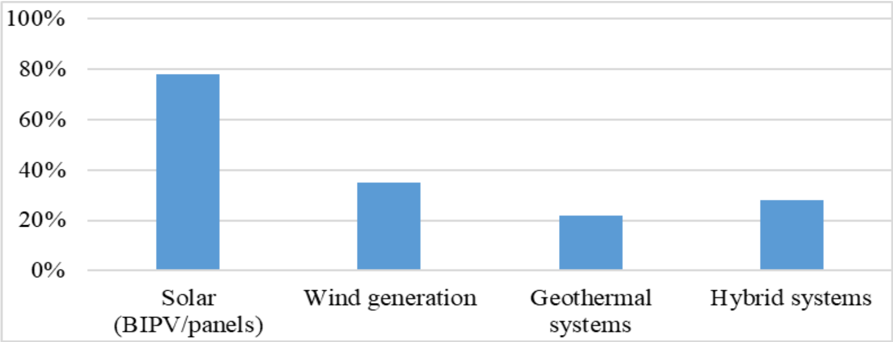

Fig. 2. Prevalence of various RES technologies.

Geographically, the largest number of implemented projects is in Europe (40%), due to strict environmental regulations. China shows rapid growth (25% of the total), especially in infrastructure projects (bridges, stations, airports). North America accounts for 15%, and the rest of the world – 20% (Fig. 3).

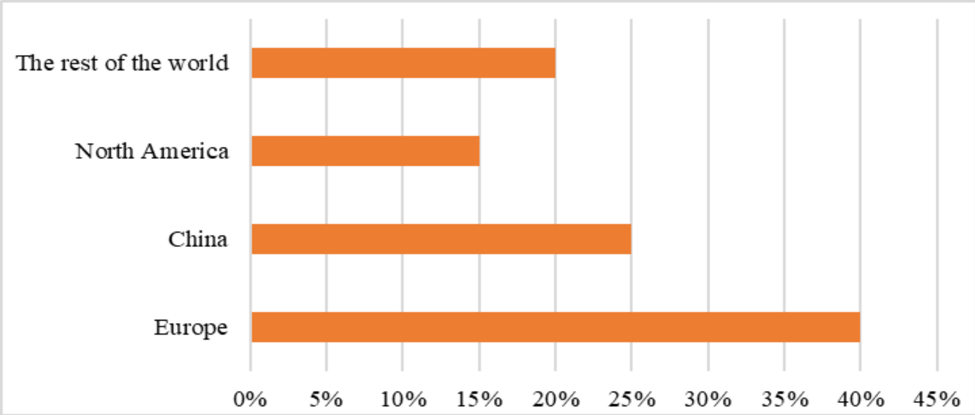

Fig. 3. Geographical distribution of projects with RES integration.

Over time, there is a steady increase in the number of projects with RES integration, especially after 2010. The peak occurs in 2015-2020, which is associated with cheaper technologies and stricter environmental standards (Fig. 4).

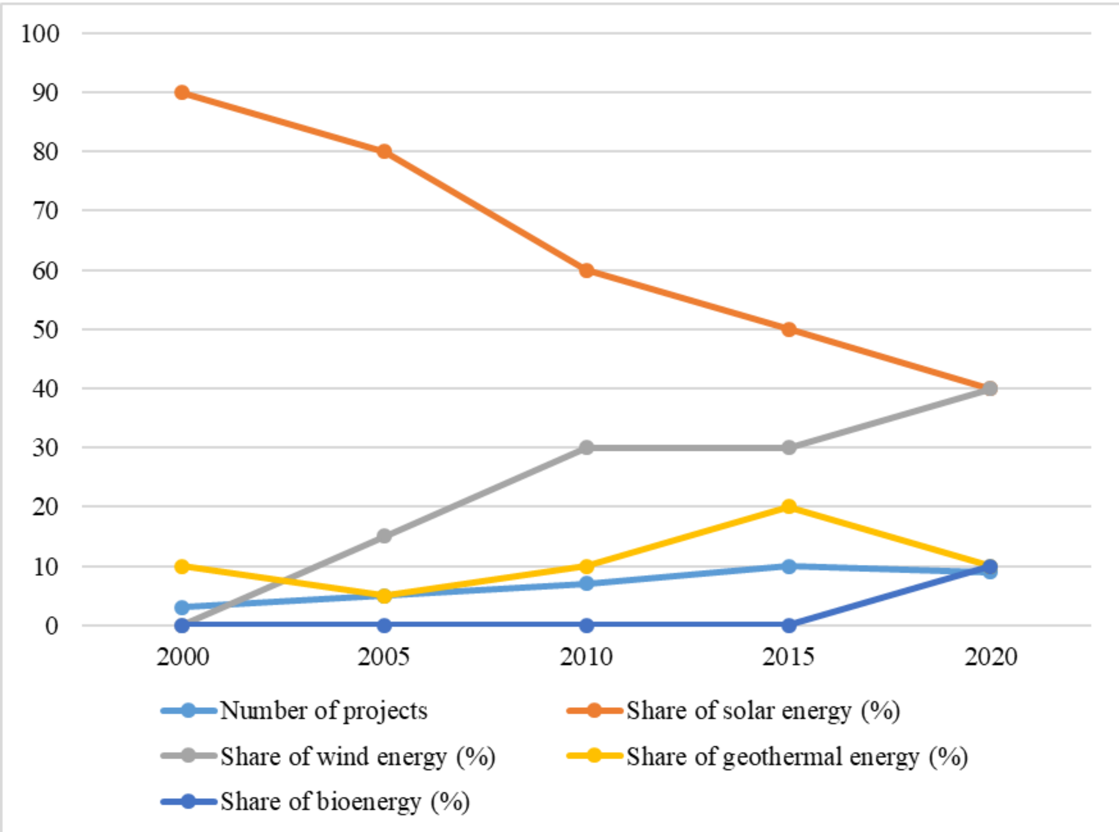

Fig. 4. Dynamics of commissioning of buildings with RES integration.

Three stages of evolution of RES integration into buildings and structures have been identified.

Stage 1 (additive) – RES are installed on an already built building, without affecting its structure or form. Characteristic of projects from 1990-2005. Low efficiency, aesthetic conflicts are observed.

Stage 2 (integrative) – RES become part of the building envelope (BIPV facades, solar roofs), but remain static. The building structure is adapted to them (frame reinforcement, development of fastening units, maintenance methods). Examples: Copenhagen International School (2017), Pearl River Tower (2011).

Stage 3 (adaptive) – RES acquire the ability to move, reconfigure, and be mobile. Examples: adaptive facades of Al Bahr Towers (2012, with BIPV potential), concepts of robotic facade platforms, aerostatic generators.

Table 1. Comparative characteristics of RES integration stages.

Parameter	Stage 1	Stage 2	Stage 3
Time period	1930-2005	2005-2015	2015-present
Example	Solar panels on roof, balcony railings on typical buildings	Copenhagen International School, Pearl River Tower	Al Bahr Towers, HiLo, Dynamic Tower concept
Role of RES in architecture	Addition, attached equipment	Element of building envelope	System-forming factor, kinematics
Structural frame	Does not change	Adapted considering RES equipment	Rethought (designed in relationship with equipment)
Reconfiguration capability	No	Partial module replacement	Full. Includes unit replacement, seasonal mobility
Generation efficiency	Low (5-10% of consumed power)	Medium (10-20% of consumed power)	High (over 25% of consumed power)

A promising contemporary direction is the integration of dynamic adaptive elements, which requires rethinking the principles of architectural design, tectonics, and artistic expression of the structure's operation. Architecture ceases to be «frozen music in stone,» turning into a «living organism.» Dynamic RES have the ability to change their position in space for maximum energy generation and to perform other functions, such as regulating illumination or protecting against overheating [20].

A dynamic adaptive RES is defined as an energy system possessing the following key features:

- Ability to move or reconfigure without major construction or complex construction and installation work;
- Autonomy or ease of integration into existing engineering networks;
- Targeting to cover base, peak, or emergency load;
- Adaptability to changing conditions (time of day, weather, season).

Based on the analysis of global experience, a three-vector architectural classification of such systems is proposed, presented in Table 2.

Table 2. Comparative characteristics of RES integration stages.

Sign	Type	Characteristics / implementation example	Example
By type of mobility	Physically movable systems	Installations on trailers, platforms, and mobile structures / Masdar City: container solar farms, wind tower	
	Reconfigurable systems	Modular panels on rails, unfolding/folding structures / Kinetic facades of Al Bahr Towers	

Continuation of Table 2

	Temporary/seasonal systems	Mobile complexes deployed during peak load / Temporary solar canopies at stadiums during competitions	
For the intended purpose	Operational	To permanently cover part of the energy consumption / BIPV facades of Copenhagen International School	
	Emergency and backup	To ensure the energy security of the facility / Mobile generators in healthcare facilities and data centers	
	Integration (BIPV-lite)	Integration without violating architectural integrity / Lightweight photovoltaic membranes	
By type of energy resource	Solar energy	The most technologically advanced area / BIPV facades	
	Wind energy	New forms for urban environments / VAWT Vertical Turbines	
	Hybrid systems	Combination of multiple sources / Solar-wind bridges, hybrid facades (projects)	

The transition from statics to dynamics requires fundamentally new architectural and structural solutions and an automated control system to ensure durability and safety. Let us consider architectural solutions for mass and unique development.

For mass development, the key solution is ready-made **mobile photovoltaic complexes**, including foldable arrays of PV panels, inverters, storage systems (lithium-ion batteries), and intelligent control. Their placement on surrounding territory or flat garage roofs allows bypassing the shortage of roof space and legal restrictions related to the status of roofs in multi-apartment buildings.

The architectural task is reduced to designing landscaped receiver sites with provided connection points and visual integration of equipment into the landscape. For unique facilities (stadiums, exhibition centers), such complexes become a tool for flexible power supply to temporary infrastructure, reducing peak network load during events.

Reconfigurable and dynamic BIPV facades transform the facade from a static shell into an adaptive, multifunctional system. Modular cells with photovoltaic elements are mounted on a standardized frame system attached to the facade. Individual modules can be replaced, added, or changed in orientation without reconstructing the main structures.

The architectural and structural feature is the creation of a double frame: the main one, ensuring the overall stability of the building, and a secondary one – a lightweight but rigid spatial lattice for attaching kinetic modules. This lattice must compensate for dynamic loads from panel movement, ensure positioning accuracy, and include cable routes. The integration of small-format dual-axis trackers allows modules to track the sun, increasing generation while simultaneously regulating insolation and shading of premises.

The use of wind in an urban environment is associated with challenges of turbulence, vibration, and noise. The solution comes in the form of **mobile wind power installations** with low vibration and noise levels, installed on mobile masts or roof parapets. Such installations are effective in wind «corridors» between high-rise buildings.

Architecturally, such installations can be interpreted as dynamic art objects or technological accents. The structural task is to calculate mast attachment points taking into account gyroscopic moments and fatigue loads. Promising systems are those based on the Magnus effect (rotating cylinders creating lift) or kinetic generators that convert energy from water flowing down the facade.

High-rise buildings represent both a challenge and a unique opportunity due to extreme conditions (strong winds, lack of shading, large facade area). An analysis of international experience allows us to identify three promising directions.

Autonomous service robotic platforms with RES involve the creation of robotic platforms (similar to «smart» window washers) that, moving along the facade, perform its maintenance and simultaneously generate energy using built-in flexible PV panels and solid-state batteries. Moving along the facade, such a platform charges from the sun, and excess energy is transferred to the building’s network via wireless charging or contact stations on floors. The platform can also perform local monitoring of the condition of structures and BIPV coating.

The architectural feature is the design of integrated path structures – rails, consoles, or cable systems that are part of the facade frame. The facade becomes an active transport-energy network, turning maintenance costs into a generating asset.

Guy wires, cables, and vibration damping nets of high-rise structures (towers, bridges) can be functionalized and become **energy harvesting systems on high-rise cable structures**. The technology involves integrating flexible PV tapes, organic photovoltaic (OPV) elements, or piezoelectric/electromagnetic generators into the attachment points of high-rise masts or antennas, converting mechanical vibrations from wind into electricity.

The architectural and structural task is to ensure the durability of electrical components under significant mechanical deformation and cyclic loading. For a TV tower or cable-stayed bridge, such a system can provide energy autonomy for lighting systems and monitoring sensors.

A promising, though not yet realized, direction is the use of **mobile aerostats or UAV systems with photovoltaic panels**, hovering at an altitude of 100-200 meters above the roof, allowing avoidance of shading and use of more stable wind flows and increased insolation. An airship or tethered drone-aerostat generates energy that is transmitted via a power cable to the building. In stormy weather, the system automatically descends to the roof into a protected hangar.

Architecturally, this platform can be designed as a special technology pavilion or relay tower.

The introduction of mobile and transformable RES requires rethinking the architectural and structural solutions of the building. The analysis of implemented projects has allowed formulating key requirements.

Let us highlight the key architectural principles for designing dynamic facades:

1. Functional priority of dynamics.

Dynamic elements must solve specific tasks: adaptation to solar radiation, optimization of natural lighting, regulation of heat gains, energy generation. Every movement must have a functional justification, not be purely decorative.

2. Integration with engineering systems.

The facade functions as a component of a single building ecosystem, interacting with heating, ventilation, air conditioning, and lighting systems. Data from environmental sensors should be transformed into algorithms for controlling facade elements.

3. Modularity and scalability.

The dynamic facade is designed from repeating modules, allowing solutions to be replicated to different parts of the building. This simplifies production, installation, and maintenance.

4. Anthropocentric control.

The system must take into account user needs – provide visual comfort, individual lighting scenarios, and manual control while maintaining overall energy efficiency.

5. Structural reliability and safety.

The structural system should be designed not as a final shape, but as a universal load-bearing platform with excess capacity and safety margin. Regular megaframe systems and core-outrigger schemes are ideally suited to this, providing rigidity and large, internal-support-free zones for placing mobile modules [21].

The frame must be designed for a complex set of loads (Table 3).

Table 3. Types of loads from mobile and dynamic RES on the load-bearing frame.

Load type	Source	Structural consequences
Static	Weight of modules, equipment	BIPV panels, batteries: floor reinforcement, local node strengthening
Dynamic (vibrational)	Operation of wind turbines, robot movement	VAWT turbines, facade robots: damping units, fatigue strength calculation
Impact	Drone landing, module docking	Aerostatic systems: local reinforced platforms, shock absorbers
Cyclic	Repeated movements, position changes	Kinetic facades: fatigue calculation, wear resistant materials
Aerodynamic	Wind loads at different positions	Rotating panels: calculation for all intermediate positions

6. Material and kinematic integrity.

The choice of materials (metal alloys, composites, tempered glass) and types of movement (rotation, sliding, folding) must correspond to the architectural concept and ensure the durability of the mechanisms [22-23].

The implementation of these solutions is impossible without the use of new-generation materials (Table 4):

Table 4. Materials for structures with integrated RES.

Material	Application area	Advantages	Examples of use
Light high strength composites (carbon, glass fiber)	Moving elements (panels, blades, louvers)	Weight reduction, high fatigue strength	Turbine blades, kinetic facade elements
Flexible and organic photovoltaics (OPV)	Curved and deformable surfaces	Integration into complex shapes, lightness	Membrane roofs, cable systems, guy wires
Shape memory «smart» materials	Kinetic nodes, actuators	Simplicity, reliability, no complex mechanics	Experimental developments
Corrosion resistant alloys and coatings	Friction nodes, mechanical drives	Durability in aggressive environments	All external mechanisms
Self supporting membrane structures	Temporary and seasonal systems	Lightness, fast deployment	Temporary canopies, aerostat shells

7. Aesthetic organization of dynamics.

The movement of facade elements should create a harmonious visual image – form rhythmic sequences, geometric patterns, smooth transformations where mechanics become part of the architectural expression.

8. Energy balance.

The energy consumption of the drive systems must be compensated by energy savings from the facade's operation and generation from integrated RES, striving for energy self-sufficiency [12].

The highlighted principles demonstrate the evolution of the facade from a static shell to an active, intelligent system, turning the building into an adaptive organism that responds to external conditions and internal needs. In this regard, we propose the integration of dynamic modules directly into the architectural system (facades, roof, canopies) to create a constantly changing, energy-efficient, and aesthetically expressive building. If dynamic RES represent an evolutionary development of technologies, then the concept of a Dynamic Adaptive Energy System (DAES) is revolutionary, marking a transition to a new type of architecture – symbiotic.

The design of the envelope is based on the study of natural prototypes:

- *Phototropism (plants).* Envelope elements orient towards the light source, like sunflowers, maximizing energy capture.

- *Thermoregulation (warm-blooded animals).* The envelope regulates heat loss - «contracts» to retain heat in winter and «opens» to cool in summer (similar to dilation of skin vessels or ruffling of feathers).

- *Photonasty (flowers).* Reaction to light level – petal-photovoltaic elements open towards the sun and close in cloudy weather or at night to retain heat or for camouflage.

Let us highlight the key architectural principles of DAES:

Principle 1: Multilayering and functional synthesis.

The building facade is considered not as a single wall but as a system of layers (by analogy with the skin of living organisms).

- *Outer layer (Epidermis)* – dynamic RES modules (solar panels, micro-wind turbines). Protects from weather, captures energy.

- *Buffer layer (Dermis)* – technical floor or space with control systems, converters, batteries, ventilation, and rainwater harvesting.

- *Inner layer (Hypodermis)* – load-bearing structure and enclosing elements of the building, heating or cooling systems.

The result is separation of functions, ease of maintenance, and increased overall energy efficiency of the building or structure.

Principle 2: Kinematics and adaptability.

Modules are not static. They move, adapting to external conditions.

- *To the sun:* Rotating photovoltaic «scale» or «petal» panels. Change the tilt angle during the day, tracking the sun (like a sunflower).

- *To the wind:* Vertical anemo-shaped wind turbines integrated into building corners or spaces between them. In strong winds, they can «open» to increase capture area, and during a hurricane, fold to reduce windage [14].

- *To the weather:* In rain, modules can change angle to facilitate water runoff into the collection system and also self-clean.

Principle 3: Control and monitoring (creation of a digital nervous system)

Sensors for light, wind, temperature, building energy consumption, weather forecast. An AI algorithm in real time calculates the optimal configuration of all modules to maximize energy generation, minimize the load on air conditioning systems, and create comfortable indoor illumination [24].

For an objective comparison of the efficiency of a static BIPV facade and the proposed adaptive system, energy modeling was performed on a typical 30-storey office building under the climatic conditions of Moscow, Rostov-on-Don, and Kemerovo. The calculation period is a calendar year.

Table 5. Initial climatic parameters for modeling.

Parameter	Kemerovo	Moscow	Rostov-on-Don
Latitude	54°53' N	55°45' N	47°14' N
Number of sunny days per year	~230	~172	~230
Average annual temperature, °C	+1.5	+5.8	+10.5
Annual total horizontal insolation, kWh/m²·year	950–1 050	1 160-1 200	1 371.1
Annual total vertical insolation, kWh/m²·year	820–900	900-950	1 112.2
Insolation at optimal tilt, kWh/m²·year	1 030–1 150	~1 350	~1 593.6

Modeling was carried out for a building with the characteristics presented in Table 6.

Table 6. Initial climatic parameters for modeling.

Parameter	Value
Number of storeys	30
Building height	120 m
Plan dimensions	30×30 m
Total area of south facade	3600 m²
Orientation	South facade, tilt angle 90°
Specific energy consumption	100 kWh/m² per year

The baseline is a static BIPV facade based on thin-film photovoltaic modules, ensuring architectural integration while preserving the facade aesthetics. The alternative system includes rotating BIPV elements on dual-axis trackers, allowing tracking of the sun's position throughout the day and seasons, as well as an additional thermal energy storage layer (PCM) to smooth peak heat gains.

For a conceptual comparison of systems, a simplified method for calculating annual electricity generation using the formula is adopted:

$$E = A \cdot I \cdot \eta \cdot k \tag{1}$$

where:

- E – annual electricity generation, kWh/year;
- A – panel area, m²;
- I – annual insolation (vertical surface), kWh/m²;
- η – panel efficiency (static – 15% for BIPV facade, adaptive envelope – 18%, modeled using efficiency data from open sources);
- k – efficiency coefficient for the adaptive system, assumed to increase generation by 24-40%.

The economic assessment is based on international data for ventilated BIPV facades. The calculation is performed in 2024 prices without taking into account operating costs, which are 10-15% higher for the adaptive system.

Table 7. Comparison of energy performance for three Russian regions.

Parameter	Kemerovo	Moscow	Rostov-on-Don
Annual generation (static), thousand kWh	145.2	197.1	223.1
Annual generation (adaptive), thousand kWh	253.4-259.2	326.9	400.7-410.9
Generation increase from adaptive envelope	+74-79%	+66%	+80-84%
Payback period (static), years	10.9	7.9	6.9

Continuation of Table 7

Payback period (adaptive), years	6.2-7.0	4.5	3.2-3.8
Reduction in payback period	36-43%	43%	45-54%
PCM saving potential	Low	Medium	High (hot summer)
Effect of low temperatures on efficiency	Favorable	Moderate	Insignificant

The presented results are estimated. Detailed modeling in PVsyst taking into account hourly insolation, shading, and temperature coefficients may refine the results, but the overall ratio between the systems will remain.

Kemerovo occupies an intermediate position between Moscow and Rostov-on-Don in absolute generation figures, but shows the highest relative increase from the adaptive envelope (74-79%) compared to Moscow (66%). This makes adaptive RES envelopes economically feasible even in Siberian conditions, especially when using bifacial panels. The obtained quantitative estimates confirm the technical and economic feasibility of the adaptive envelope and serve as a basis for further in-depth modeling.

Based on the analysis, seven practical recommendations for working in the new dynamic paradigm are formulated:

1. At the concept stage, include energy modeling (insolation, wind regimes) among the primary parameters determining the shape and orientation of the building. Use digital twins to test configurations of kinetic elements.
2. Select structural schemes with excess rigidity – regular megaframe or core-outrigger systems. They allow creating free zones for placing mobile RES and better absorb dynamic loads.
3. Design unified fastening units for kinetic elements, including damping gaskets, sealed cable entries, and backup locks. The calculation must be based on fatigue strength (at least 10^6 cycles).
4. Use light high-strength composites (carbon fiber, fiberglass) for moving parts, and corrosion-resistant alloys for external units.
5. Provide reinforced areas on technical floors for temporary storage and maintenance of mobile modules (aerostats, robots), as well as automatic docking and recharging systems.
6. Involve robotics and control algorithm specialists to develop adaptive strategies (panel orientation, gap ventilation, thermal flow management) [25].
7. For unique high-rise buildings, consider a double structural shell: an outer kinetic shell and an inner static one. This allows installation and maintenance without interrupting operation.

4. CONCLUSIONS

The analysis of 52 objects worldwide confirms the evolutionary transition towards dynamic systems, with the succession of three stages: additive; integrative; adaptive. International experience demonstrates the successful scaling of RES technologies to the level of large-scale infrastructure projects (bridges, railway stations, airports), providing unique data for analysing the long-term operation of such systems. A new architectural paradigm is emerging, in which the building is designed as a dynamic ecosystem or a «symbiotic organism». Here, the requirements for energy harvesting (optimal orientation, shading, wind corridors) become as important input data as room insolation or wind loads on the structural frame. In accordance with this, practical recommendations for design within the new dynamic adaptive paradigm have been formulated.

The proposed three-vector classification - by type of mobility, by intended purpose, and by type of energy resource – allows designers to systematically approach solution selection depending on functional tasks and external conditions, and also serves as a foundation for further development of the regulatory framework. Materials science is becoming a critical factor in development. Lightweight composites, flexible photovoltaics, «smart» materials, and corrosion-resistant alloys make it possible to implement solutions that are unattainable with traditional materials.

Numerical modelling for three regions of Russia (Kemerovo, Moscow, Rostov-on-Don) showed that the adaptive system with dual-axis trackers and PCM (phase-change material) thermal storage provides an increase in energy output of 66-84% compared to a static BIPV facade. The payback period is reduced by 36-54% and amounts to 4.5 years in Moscow, which falls within typical investment horizons for commercial real estate. The share of building energy consumption coverage increases from 2.2% to 5.6-7.6%, which, for a vertical surface, is a significant result, especially when using bifacial modules. Even under harsh Siberian climatic conditions, the adaptive envelope is economically viable, confirming its universality.

Mobile RES will not replace stationary systems, but will become their critically important complement, shaping a sustainable, distributed, fault-tolerant, and intelligent energy landscape for the cities of the future. On the path towards this, promising directions include aerostatic and UAV-based systems, robotic facade platforms, as well as integration with urban energy networks according to the principle of «active buildings». Further research should be directed towards creating a regulatory framework for dynamic systems, developing long-term monitoring methods, and adapting standard mass-construction designs to new technologies.

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