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Efficiency of applying various types of basic renewable energy sources in modern buildings and structures

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Abstract. The article presents a comprehensive analysis of the applicability and efficiency of basic renewable energy sources (RES) in modern buildings, including high-rise and unique structures. A comparative analysis of key technologies—solar (PV and thermal), wind, geothermal (heat pumps), and bioenergy—was conducted, highlighting their specific advantages as determined by efficiency indicators, COP, capacity factor (CUF), and temperature potential. The selection methodology is implemented as a sequence of iterative steps based on international statistical data (IRENA, IEA), modeling tools, and multi-criteria analysis principles. Key engineering requirements for the external and internal units of solar (photovoltaic and thermal), wind, geothermal systems, and bioenergy are identified. It is established that the selection and design of RES systems are determined by a triad of imperatives: achieving architectural harmony, maximizing energy efficiency, and ensuring safety and durability. A universal solution does not exist, and the efficiency of integration is determined by a combination of factors: climatic conditions, architectural and structural features of the building, and its energy profile. A typology of solutions for different building classes – from mass multi-story construction to skyscrapers – is proposed, with a detailed examination of wind and vibration loads, thermal deformations, and installation logistics. It is proven that for complex facilities, a hybrid approach is optimal, combining, in particular, geothermal heat pumps, building-integrated photovoltaics (BIPV), and adapted small wind turbines. The article emphasizes the necessity of interdisciplinary design at the intersection of architecture, energy engineering, and mechanics to create efficient energy-active buildings. The transition from assessing RES potential in general to designing adaptive solutions for specific buildings is a necessary condition for creating energy-efficient and carbon-neutral buildings. The practical value of the work lies in providing designers and developers with a structured decision-making tool, which contributes to the creation of energy-efficient, carbon-neutral buildings and a sustainable urban environment.

Keywords: building-integrated photovoltaics (BIPV), wind turbines, geothermal systems, energy-efficient buildings, smart facades, renewable energy sources, building integration of RES, high-rise construction, symbiote building

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1. INTRODUCTION

Modern global architecture and urban planning are at a turning point, defined by the challenges of global climate change, the need for energy security, and the decarbonization of the urban environment. In this context, buildings-which, according to the International Energy Agency (IEA), account for up to 40% of global energy consumption and about 30% of greenhouse gas emissions—are ceasing to be perceived as passive infrastructure objects and are transforming into active, intelligent energy hubs capable of not only minimizing consumption but also producing energy on-site. This trend is reflected in strategic documents of many countries, including the Climate Doctrine of the Russian Federation (2009), Presidential Decree No. 666 of 11/04/2020 «On the Reduction of Greenhouse Gas Emissions,» the Energy Strategy 2035 of 06/09/2020, and the Strategy for Socio-Economic Development of Russia with Low Greenhouse Gas Emissions until 2050. Thus, the transition from the «building-consumer» paradigm to the «building-symbiote» paradigm is becoming not only a technological but also a political necessity.

The issues of integrating renewable energy sources (RES) into building architecture are being actively developed both in Russia and abroad. In the works of Sheina S.G. [1], the need to manage the lifecycle of capital construction projects under a changing climate is emphasized, which is directly linked to the choice of energy-efficient solutions. The authors of [2] were the first to systematize the main types of RES applicable to high-rise buildings, highlighting architectural and structural constraints such as wind loads and limited roof areas. Karamysheva A.A. [3], using international experience as an example, showed that unique high-rise structures can serve as a testing ground for validating hybrid energy systems that include building-integrated photovoltaic facades (BIPV) and small-scale wind turbines. Semikin P.P. and Batsunova T.P. [4] investigated the volumetric-spatial solutions of high-rise buildings with RES, pointing out the crucial role of aerodynamic shape in the efficiency of wind generation. In the modern scientific school of high-rise building architecture, the works of Generalova E.V. [5] and Generalov V.P. stand out. Their research is dedicated to the typology of high-rise housing and office skyscrapers, as well as the architectural and planning solutions of unique structures, creating a morphological matrix without which analyzing the evolution of RES structures is impossible [6].

Foreign studies focus on improving the efficiency of individual technologies. For instance, Roose Bart [7] analyzes the prospects of perovskite solar cells capable of reaching record efficiencies of up to 47% under laboratory conditions. The work of Alsailani and co-authors [8] is dedicated to optimizing the aerodynamic characteristics of wind-catching towers (badgirs), which is significant for passive methods of wind utilization in buildings. Kim and colleagues [9] presented a model of a hybrid solar-geothermal heat pump system, confirming high generation stability with a COP of 3.5-5.0. Khudyakov A.Y. and Voronina A.A. [10] considered the problems of placing wind energy installations in civil architecture, specifically noting the impact of urban turbulence on the CF (capacity factor of installed capacity).

An important aspect is structural safety when integrating RES. Shumeiko V.I. and Karamysheva A.A. [11] investigated the prevention of progressive collapse of high-rise buildings under dynamic loads generated by wind turbines. Mailyan and co-authors [12] performed calculations on the stress-strain state of the «tower - foundation - soil» system for high-rise structures, which is necessary when deploying heavy geothermal equipment. A review by Biyik et al. [13] covers key aspects of BIPV systems—from modularity to aesthetic integration. Abualigah and colleagues [14] applied machine learning methods to optimize the operation of hybrid wind-solar systems with storage, opening the way for intelligent energy flow management [15]. Questions of fire resistance and residual load-bearing capacity of reinforced concrete elements, which are relevant when placing wind turbines on roofs, are addressed in [16].

Despite a significant number of publications, comprehensive methodologies for selecting the optimal mix of RES for a specific building that simultaneously account for climatic, structural, economic, and architectural factors remain insufficiently developed. Most works focus either on a single technology or on specific aspects of integration. This problem is particularly acute for high-rise and unique buildings, where extreme loads and a shortage of useful area require an individual approach. Furthermore, existing research rarely applies multi-criteria analysis to quantitatively compare different energy supply scenarios.

Integrating RES into a building is a complex architectural and engineering task that goes far beyond simply mounting equipment on a roof. The design, placement, and interconnection of external and internal RES system units directly affect not only their energy efficiency (efficiency, CF, COP) but also the reliability and durability of the entire structure, operational safety, and, crucially, the architectural appearance [17].

The purpose of this work is to analyze the structural solutions of basic RES systems applied to the architecture of modern buildings, evaluate their applicability under various conditions, and formulate principles that ensure a synergy of energy efficiency, structural reliability, and architectural value in buildings and structures. To achieve this goal, the following tasks were set:

- conduct a comparative analysis of the architectural and structural features of external and internal units of the main RES technologies (solar PV and thermal, small-scale wind turbines, geothermal heat pumps, bioenergy);
- systematize the key factors, limitations, and requirements arising during the integration of these systems into the architecture of buildings of various typologies (mass multi-story developments, public buildings, skyscrapers);
- evaluate the impact of specific high-rise construction conditions (wind and vibration loads, thermal deformations, installation logistics) on structural solutions.

The scientific novelty of this work lies in the developed step-by-step algorithm for choosing base RES technologies based on their efficiency, as well as in forming design principles for hybrid energy systems using a systematic approach that combines architectural, structural, and technological evaluations of RES. Unlike known works, the proposed methodology includes a multi-criteria comparison of scenarios using weighted indicators (economics, autonomy, ecology, safety, architectural harmony) and can be adapted to any type of building.

2. METHODS AND MATERIALS

The study is based on an analysis of modern architectural and technical solutions, data from international reports (IRENA, IEA) for the period 2020-2025, and a synthesis of design practices in the field of sustainable construction, including completed objects (the «Morskaya Milya» residential complex in Saint Petersburg, The Crystal in London, Pearl River Tower in Guangzhou) and experimental developments.

The methodology includes several interconnected approaches and stages, ensuring systemic rigor and the validity of the results.

1. Systematization and Comparative Analysis. A detailed breakdown of the designs of each type of RES system was conducted—solar photovoltaic (silicon and thin-film panels, BIPV facades), solar thermal (flat-plate and evacuated tube collectors), small-scale wind turbines (horizontal-axis and vertical-axis turbines), geothermal heat pumps (with vertical probes and horizontal collectors), and bioenergy plants (biomass boilers, biogas reactors). For each type, common and unique elements, material requirements, mountings, placement, and limitations related to operation in an urban environment were identified. Key performance metrics (efficiency, COP, CF) are summarized in Table 1, allowing for a clear comparison of the technologies.

2. Factor Analysis of Applicability. Based on the literature review and the author's own research, three groups of factors determining the feasibility and effectiveness of integrating RES into a specific object were identified and classified:

- *Resource and climatic factors:* insolation (according to NASA SSE, PVGIS data), wind potential (taking into account the aerodynamic shadow of buildings, modeled in ANSYS Fluent), geological conditions (soil thermal conductivity, groundwater level), temperature regime (heating degree days).
- *Architectural and structural factors:* building morphology (area and tilt angle of the roof, facade glazing area), load-bearing capacity of structures (calculation of static and dynamic loads according to established methodologies), availability of technical zones, aesthetic and regulatory requirements (especially for historical developments).
- *Economic and regulatory factors:* energy profile of the building (daily and seasonal load profiles), tariffs (cost of grid energy, green tariffs), regulatory framework (height restrictions, noise limits, grid connection rules).

3. Typological Approach. Buildings are grouped into three architectural classes: mass multi-story developments, unique public and administrative objects, and high-rise buildings (above 100 m). Characteristic RES integration scenarios were developed for each class based on its specifics. For example, for skyscrapers, priority is given to hybrid systems combining BIPV, geothermal heat pumps, and adapted small-scale wind turbines, whereas for mass housing, the focus is placed on non-invasive «BIPV-light» solutions (balcony railings, awnings).

4. Step-by-Step Selection Algorithm. A structured methodology implemented as a sequence of six iterative steps was developed. The first three steps (energy audit, resource potential assessment, architectural and structural analysis) are performed using modeling tools: PVsyst or Solarius for solar radiation considering local shading, ANSYS Fluent for wind flows around the building, and thermal response tests of the soil for geothermal systems. The fourth and fifth steps involve forming alternative energy supply scenarios and performing their techno-economic modeling (calculation of CAPEX, OPEX, NPV, IRR, simple and discounted payback periods). The sixth step is a multi-criteria analysis based on weighted criteria (economics – 40%, technical reliability – 30%, environmental effect – 20%, architectural harmony – 10%).

To quantitatively assess performance, methods described in [18] (evaluation of elasticity moduli of multi-layer structures, hysteresis analysis, dissipation of strain energy) were used, allowing for the correct accounting of dynamic loads from wind turbines on the building's structural elements. Forecasting energy consumption and generation was carried out using neural network models similar to [19], which increases the accuracy of short-term and long-term planning.

Thus, the proposed methodology ensures a transition from a qualitative description of RES potential to a quantitative multi-criteria comparison of alternatives, which is an essential condition for making informed design decisions. All calculations and modeling were performed using publicly available data and verified software packages, ensuring the reproducibility of the results.

3. RESULTS AND DISCUSSION

A comparative analysis was adopted as the basis for selecting RES technologies. The selection begins with understanding the technological capabilities and limitations. The analysis was carried out according to parameters critical for buildings: ability to cover heating and electrical loads, space requirements, generation stability, and structural compatibility. The data are summarized in Table 1.

Table 1. Comparative characteristics of main RES technologies for building integration.

Techno-logy	Energy efficiency (Efficiency/ COP)	Thermal potential	Key advantage for buildings	Main limitation for integration
Solar PV	Efficiency: 15-22% (silicon), up to 47% (multilayer lab)	Low (module heating – side effect)	Modularity, scalability, operation over a wide insolation range, low OPEX	Dependence on time of day and season, requirement for large free area, efficiency degradation due to overheating
Solar thermal	Efficiency: 60-80% (flat plate), 60-70% (vacuum tube)	High (heat carrier up to 150°C)	High efficiency of direct conversion to heat for DHW and heating, fast payback with high heat tariffs	Seasonality in temperate climates, need for complex hydraulic circuit and buffer tank, risk of summer overheating
Wind energy (small)	Aerodynamic efficiency up to 45% (Betz limit), actual CUF in city: 5-15%	Low (can be used for direct heating via hydraulic systems)	Complementarity with solar generation (winter/ night), use of building height potential	Strong dependence on local turbulence, vibration and acoustic load on structure, need for complex safety systems (brake, orientation)
Geothermal HP	COP: 3.5-5.0 (ground-water), 2.0-4.5 (air-water)	Medium (heat carrier 35-65°C)	High stability and efficiency for base heating and cooling, lowest LCOE among heating solutions	High capital costs for borehole field, need for land / wells, long payback period without subsidies
Bioenergy	Boiler efficiency: 85-92%	High (direct combustion, steam/hot water)	Dispatchability, utilization of local waste, creation of local energy cycles	Low volumetric energy density, complex logistics and storage, emissions of particulate matter in urban environment

Analyzing the data in the table, one can conclude that each technology occupies its own niche. Solar PV is the most universal for electricity generation, geothermal heat pumps are optimal for covering the base heating load, and solar collectors are effective for DHW. Successful integration, especially under resource constraints (area, wind), lies in the hybridization of these technologies.

Table 2 presents data illustrating the placement potential of RES for various climatic zones of the Russian Federation.

Table 2. Recommended types of RES for various climatic zones of the Russian Federation.

Climatic Zone (Example: by degree days)	Characteristic Cities	Preferred RES	Non-Recommended RES	Explanation
I – Arctic (HDD > 10000)	Norilsk, Vorkuta	Geothermal HP (vertical), wind turbines (in winter)	Solar PV (low insolation in winter)	Low insolation, strong winds, high heat consumption
II – Moderate-cold (HDD 6000-10000)	Moscow, St. Petersburg, Ekaterinburg	Hybrid: HP + solar collectors for DHW + BIPV (southern facades)	Bioenergy (resource limitation in the city)	Seasonal imbalance, storage required
III 2 Moderate-warm (HDD 3000-6000)	Krasnodar, Rostov-on-Don	Solar PV and thermal, wind turbines (with aerodynamic optimization)	Geothermal HP (high drilling cost with low heat consumption)	High insolation, episodic heating

Continuation of Table 2

IV – Southern (HDD < 3000)	Sochi, Makhachkala	Solar PV wit cooling, win turbines	Geothermal HP fo heating (not cost effective)	Priority – cooling and power supply

To assess the effectiveness of RES implementation for a specific object, applicability factors were identified and divided into three interrelated groups.

The first group – resource and climatic factors:

- Insolation – annual value (kWh/m²), seasonal distribution, probability of prolonged cloudiness [7].

- Wind potential – average annual wind speed at installation height, wind rose, turbulence level created by the buildings themselves. Urban environments are characterized by zones of aerodynamic pressure (windward side) and aerodynamic shadow (leeward side) [8].

- Geological conditions – soil thermal conductivity, groundwater level, chemical composition (for corrosion of heat exchangers).

- Temperature regime – number of degree-days of the heating period, summer peak temperatures.

The second group – structural-architectural and planning factors:

- Building morphology – area, orientation, and slope angle of the roof; area, orientation, and glazing type of facades; presence of balconies, terraces, technical floors.

- Load-bearing capacity – ability of roof and facade structures to withstand additional static (weight of panels, boiler) and dynamic (vibrations from wind turbines) loads [20].

- Availability of technical zones – rooms for internal HP units, inverters, battery banks, buffer tanks, taking into account ventilation, temperature, and safety requirements.

- Aesthetic and heritage requirements – particularly relevant for historical buildings or objects in historical districts.

The third group – energy, economic, and regulatory factors:

- Energy profile – daily and seasonal load curves for electricity, heating, DHW, and cooling.

- Tariffs – cost of grid electricity and heat, availability of «green» tariffs, night tariffs, possibility of bi-directional grid settlements.

- Regulatory framework – restrictions on height, noise, setbacks from property lines; grid connection rules; requirements for energy accounting and distribution in multi-apartment buildings.

Based on a combination of these factors, typological solutions for the main building classes are formulated.

<u>For mass multi-storey development</u> priority technologies: roof-mounted solar PV system, apartment-by-apartment air-source heat pumps, centralized solar thermal installations for hot water supply.

Challenges: lack of roof area, legal uncertainty in the distribution of common building-generated electricity among owners, difficulty in organizing communal supply systems.

Innovative solution – «BIPV-lite»: a non-invasive architectural addition in the form of stylized panels on balcony railings, loggias, canopies over entrances. Such systems, which do not replace the building envelope but complement it, generate energy for lighting common areas, intercoms, elevators, reducing the burden on common building expenses. Example: residential complex «Morskaya Mila» (St. Petersburg, Russia) (Fig. 1), where photovoltaic panels are integrated into balcony glazing.

Fig. 1. Residential complex «Morskaya Mila».

For unique public and administrative buildings priority technologies: full-scale building-integrated photovoltaic facade and roof systems; centralized geothermal heat pumps; combined systems. The architecture of such objects often dictates the solutions themselves. The possibility to use large investment budgets at the construction stage to create an energy-efficient core. An example is The Crystal building (London, England) (Fig. 2). Here, BIPV facades are combined with a geothermal heat pump system (120 wells 150 m deep), heat recovery from grey water and ventilation, allowing the building to achieve zero energy balance.

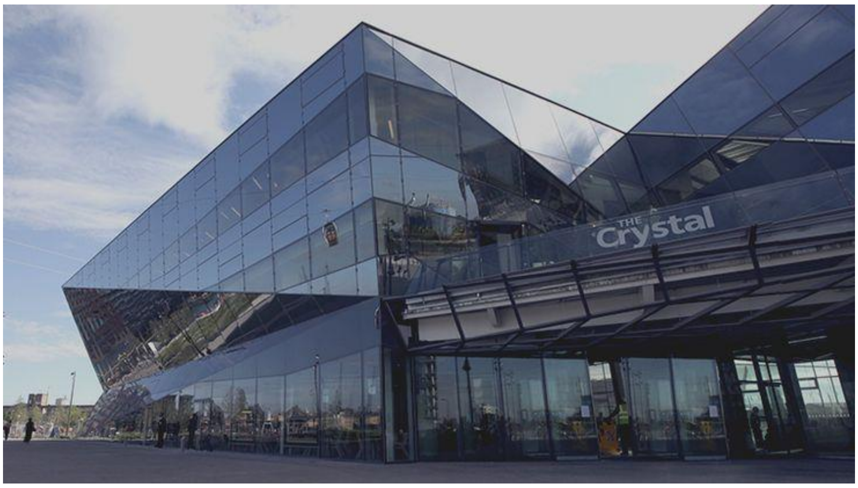

Fig. 2. The Crystal building, London City Hall.

For high-rise buildings, the integration of RES represents the most challenging but also high-potential direction.

Priority technologies – integration of a hybrid system combining geothermal, solar, and wind energy. For example, the Pearl River Tower (Guangzhou, China), 309 m high, uses photovoltaic panels and wind turbines (Fig. 3).

Challenges – extreme wind and vibration loads, installation and maintenance logistics, significant variation in insolation across facades.

Fig. 3. Skyscraper in Guangzhou business center – Pearl River Tower.

Let us review the architectural and structural features of the external and internal units of basic RES systems.

Table 3. Summary analysis of the architectural structures of basic RES systems for buildings.

RES System	External units	Internal units	Integration challenges
Solar PV	Roof systems: Cladding or ballasted on flat roofs. BIPV facades: Modules as part of curtain wall systems.	Inverters (centralized / microinverters), batteries	Waterproofing of roof penetrations, wind load, organization of cable routes in the facade, heat dissipation, weight of equipment.
Solar thermal	Collectors (flat plate / vacuum tube) on roof or frames. Insulated pipelines.	Buffer tank (boiler), pump unit, heat exchanger	Compensation for thermal expansion of pipes, load from filled buffer tank, risk of overheating.
Small wind turbine	Turbine on a mast or vertical axis structure.	Controller, inverter, braking system	Dynamic wind and vibration loads, overturning moment, noise - critical for the structure. For building safety, a braking system and danger of icing of the installation are important.
Geothermal HP	Ground heat exchanger: vertical borehole heat exchangers or horizontal collector.	Heat pump unit (monoblock / split), hydraulic module	Need for land / depth for wells, thermal influence of wells on each other, balancing of the hydraulic circuit.

Additionally, parameters for vibration and wind loads for integrated wind turbines on high-rise buildings are presented depending on installation height and turbine type.

Table 4. Main parameters of vibration and wind loads for integrated wind turbines on high-rise buildings.

Installation Height (m)	Turbine Type	Avg Wind Speed (m/s)	CUF (city)	Add. Dynamic Load (kN)	Building Freq. (Hz)	Resonance Risk
50-100	Horizontal-axis (3 kW)	4.5-6.0	0.08-0.12	1.5-2.5	0.8-1.2	Low (with dampers)
100-200	Vertical-axis (5 kW)	6.0-8.0	0.10-0.15	3.0-5.0	0.5-0.8	Medium – active damping required
>200	Vertical-axis (10 kW)	8.0-11.0	0.12-0.20	8.0-12.0	0.2-0.4	High – mandatory FEM analysis

The data in Tables 3 and 4 confirm that integration specifics are dictated by a triple imperative: architectural harmony, maximum efficiency, and safety and durability. Successful execution of such projects is possible only at the intersection of the specialties of the architect, structural engineer, energy specialist, and building systems engineer.

Table 5 reviews various configurations of BIPV systems applied to high-rise buildings, showing that monocrystalline silicon systems possess maximum thermal resistance and efficiency.

Table 5. Comparison of structural solutions for BIPV systems on high-rise building facades.

BIPV System Type	Material	Efficiency, %	Trans parency	Thermal Resistance (m²·K/W)	Installation Features	Building Example
Semi-transparent thin-film (CdTe) on glass	Glass + CdTe	10-14%	20-40%	0.3-0.5	Curtain wall Ventilated facade	The Crysta (London)
Monocrystalline silicon (opaque)	Silicon + composite	18-22%	0%	0.8-1.2	Clamp/rivet systems, rivets	Pearl Rive Tower (wester facade)
Organic photovoltaics (OPV)	Polymer film	8-12%	30-60%	low	Roll applicatior lightweight	Energy-active atriums

Based on the analysis, a structured selection methodology implemented as a sequence of iterative steps is proposed.

Step 1. Energy audit and load profiling.

Objective - obtain initial data for modeling. Consumption data from meters for previous years are used; if unavailable, calculation using standard methods is performed. To obtain an objective picture, an annual electricity consumption graph, an annual heat consumption graph for heating and DHW are constructed, base (constant) and peak (short-term) load components are identified, and the energy saving potential (up to 30-40%) is assessed, as investments in efficiency are often more profitable than in generation.

Step 2. Assessment of local resource potential.

At this stage, a quantitative analysis of basic sources is performed. Solar resource is assessed using NASA SSE or PVGIS data, corrected for local shading, analyzed in specialized software such as Solarius or PVsyst. Wind resource is assessed by analyzing data from the nearest weather station with extrapolation to the building height using the logarithmic law. For high-rise objects, CFD modeling (ANSYS Fluent) of wind flows around the building is applied. To assess geothermal potential, thermal response tests are carried out on site to determine the exact thermal conductivity of the soil.

Step 3. Architectural-structural analysis.

Collaboration between architect, structural engineer, and energy specialist to identify key constraints. First, generation zones are determined – accurate mapping of suitable roof and facade areas taking into account insolation, shading, and orientation. Load constraints are considered [21].

The permissible additional static and dynamic load is calculated. Additionally for wind turbines – analysis of the structure's resonant frequencies. Integration options and placement of internal equipment are determined. Choice between cladding systems and full BIPV, decisions on module color and texture. Planning of technical rooms considering dimensions, weight, noise, heat generation.

Step 4. Scenario development and modeling.

Development of 3-4 fundamentally different energy supply options (scenarios). For example, three likely scenarios:

- Scenario 1 (minimal): Only solar PV on available areas.
- Scenario 2 (thermal): Solar PV together with geothermal heat pumps (or solar collectors for DHW).
- Scenario 3 (full hybrid): combination of BIPV, geothermal heat pumps, small wind turbines, and an energy storage system.

Fig. 4 and 5 display hourly modeling results for hybrid Scenario C. Chart data clearly verify the impact of the first group of factors (climatic resources) described above. In winter (low insolation), a deep energy deficit occurs in the evening, requiring grid purchases (up to 89 kW). In summer (high insolation), the system generates a surplus during daytime hours (up to -13 kW), confirming the necessity of accounting for seasonal resource distribution when choosing equipment configuration, as stated in the factor group analysis.

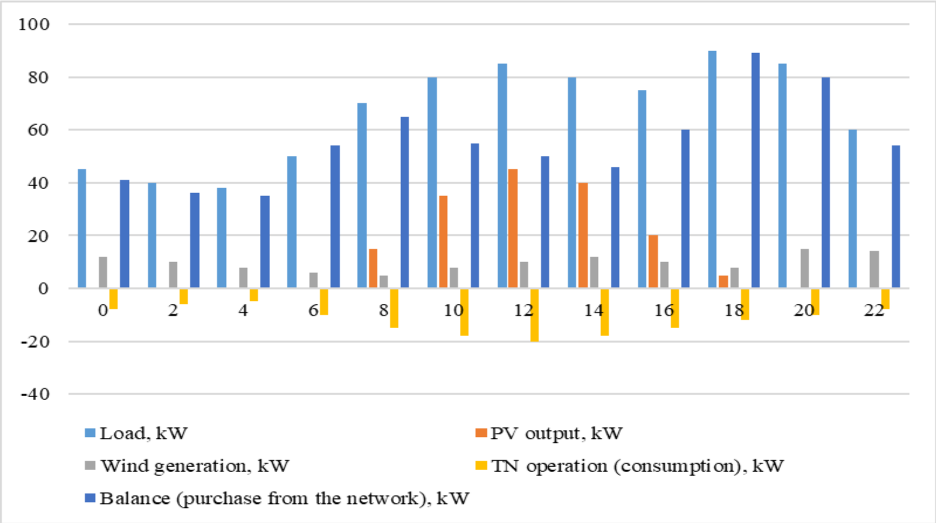

Fig. 4. Hourly Profile of Load and Generation — Winter Day.

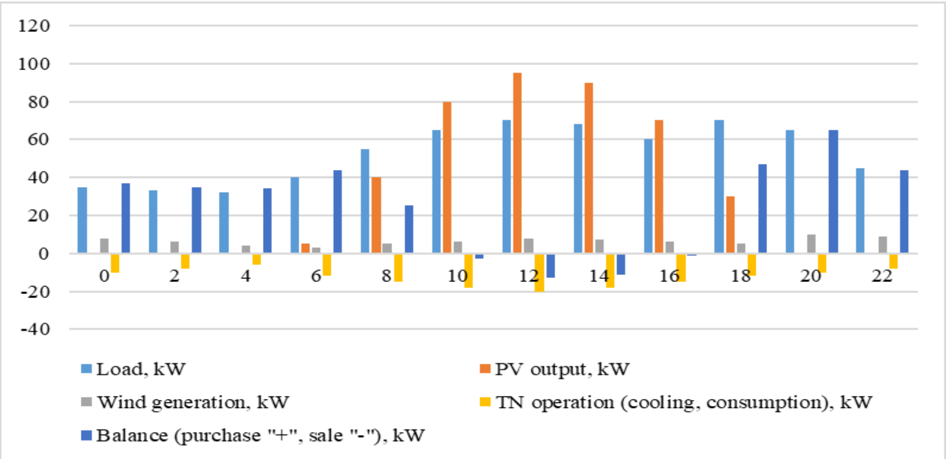

Fig. 5. Hourly Profile of Load and Generation – Summer Day.

Step 5. Techno-economic modeling.

For each modeled scenario, a set of calculations is performed to objectively assess the effectiveness of the decisions:

- CAPEX (capital costs): cost of equipment, design work, installation, commissioning, grid connections.
- OPEX (operational expenses): service maintenance, repair, insurance, grid redundancy fee.
- Performance indicators: simple and discounted payback period (SPP, DPP), net present value (NPV), internal rate of return (IRR).
- Consideration of external factors: forecast of growth in traditional energy tariffs, possibility of obtaining «green» tariffs or carbon credits, impact on the property value itself.

Step 6. Multi-criteria analysis and decision making.

Since the best economic option is not always optimal in terms of reliability or architecture, an evaluation according to weighted criteria is carried out:

- Architectural integration and image effect (weight 10%) – contribution to aesthetics, alignment with the customer's sustainable development concept [22].
- Economics (weight 40%) – net present value and discounted payback period (NPV, DPP).
- Technical reliability and autonomy (weight 30%) – degree of coverage of base load, resilience to grid failures.
- Environmental effect (weight 20%) – CO_2 emission reduction over the entire life cycle.

Thus, a structured multi-criteria assessment methodology is required for informed decision-making, allowing different technological scenarios to be compared on a common, quantitatively measurable basis. Such an approach transforms qualitative reasoning into a tool for quantitative comparison and selection of the optimal solution adapted to the specific conditions of the object.

As an example of the methodology's implementation, a simulation of generation and load coverage throughout the year was performed for each scenario, allowing for an evaluation of the degree of autonomy, as well as grid feed-in and consumption amounts.

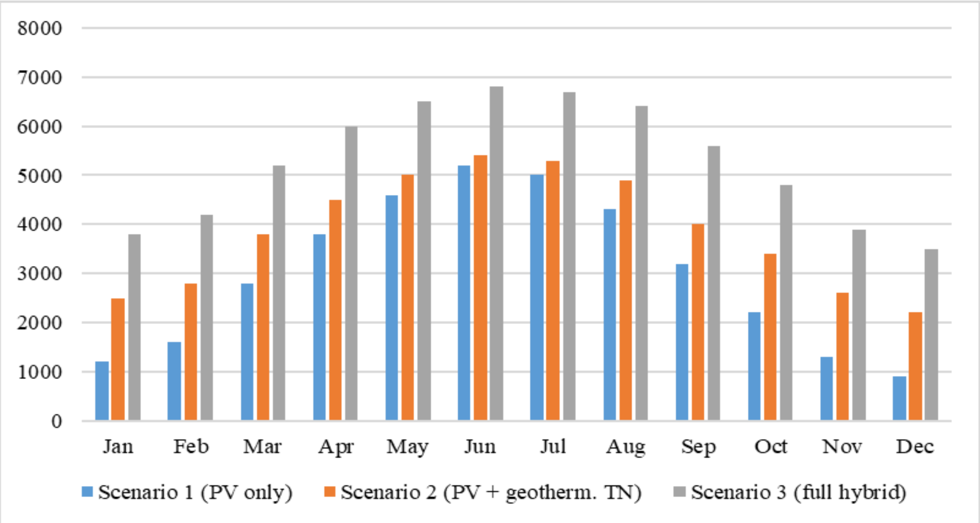

Fig. 6. Annual Electricity Generation by Month – kWh.

Fig. 7 visually demonstrates how payback periods change depending on initial investments under different electricity tariffs. Capital expenditures in the graph represent averaged expert-calculated figures based on an analysis of the Russian market and industry data.

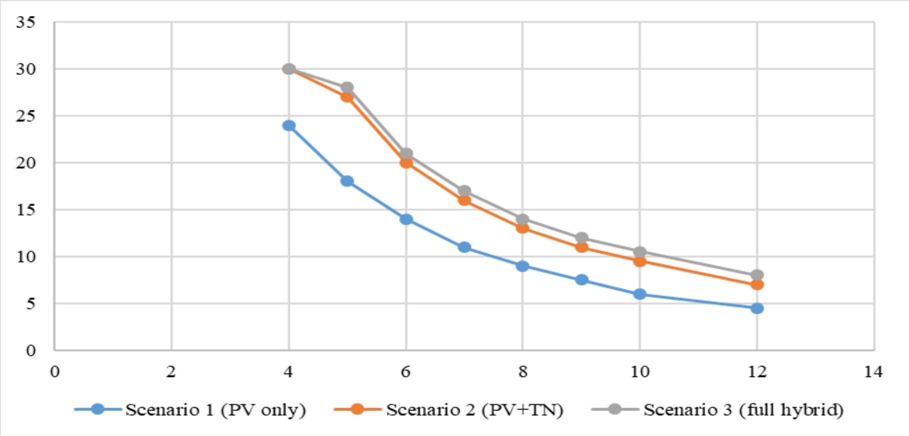

Fig. 7. Discounted Payback Period – Years – depending on electricity tariff.

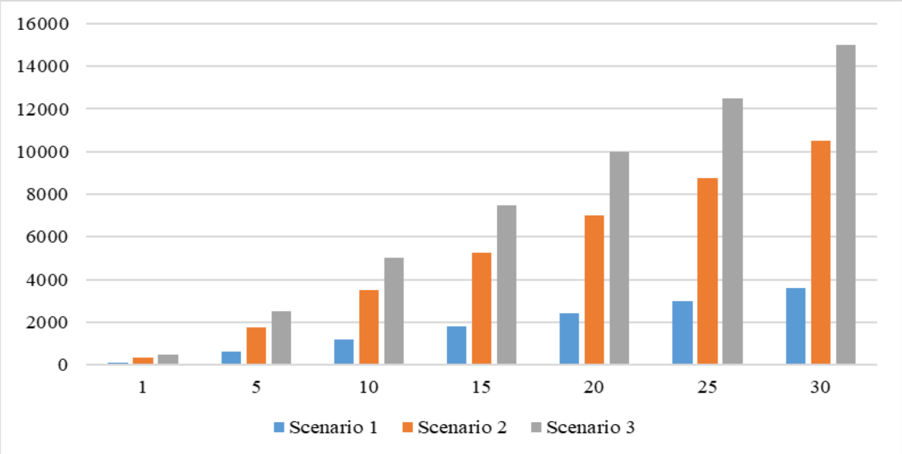

Fig. 8. Cumulative Reduction in CO2 Emissions over 30 Years – Tons.

The baseline data for the graph in Figure 8 assumes a reference building without RES that emits 400 tons of CO_2. Scenario A reduces it by 30%, B by 70%, and C by 90%.

Table 6 is not a report on a specific project but serves as an illustrative example of the proposed six-step methodology. The data in the table (payback period, autonomy, emission reduction) are conditionally calculated, modeled to demonstrate the working principle of the method.

Table 6. Example comparative table for multi-criteria analysis of scenarios.

Criterion / Weight	Scenario A: Only PV	Scenario B: PV + HP	Scenario C: Full hybrid
NPV, million rubles (Weight=0.4)	5.2	7.8	4.1
Payback period, years (Weight=0.3)	8	12	15
Autonomy, % of annual load (Weight=0.2)	25%	60%	85%
Emission reduction, t CO_2/year (Weight=0.1)	150	400	550
Final weighted score	6.34	7.05	5.98

As a consequence of choosing the optimal system, there is a need for its quality operation. Therefore, promising in this area is the introduction of digital twins and demand-side management. This will allow generation forecasting based on weather service data, optimization of load operation, participation in aggregated services for the energy market, selling surpluses or reducing consumption during peak hours.

Having analyzed modern architectural and engineering solutions for integrating RES into buildings, including unique and high-rise ones, we can conditionally divide the application of RES in architecture into two main approaches: passive and active.

The *passive approach* is based on the use of natural resources (solar radiation, wind, ground heat) without the use of mechanical equipment. The following architectural-planning methods are highlighted:

- solar orientation and layout – zoning of premises in accordance with insolation (e.g., placing living rooms to the south and auxiliary rooms to the north in the Northern Hemisphere);
- bioclimatic design – using elements of the building itself to collect, store, and distribute heat (Trombe walls, attached greenhouses, massive materials with high heat capacity);
- natural lighting and ventilation – design of light wells, atriums, wind towers (badgirs), specially shaped facades to capture prevailing winds.

The *active approach* is based on the use of technical devices to convert energy from natural sources. The following architectural-planning methods are defined:

- solar energy – photovoltaic panels (Building Integrated Photovoltaics – BIPV) converting sunlight into electricity; solar collectors converting solar radiation into thermal energy for DHW or heating;
- wind energy – installation of wind turbines integrated into the building structure (Building-Integrated Wind Turbines – BIWT);
- geothermal energy – use of heat pumps to extract low-grade ground heat for heating in winter and cooling in summer;
- biomass energy – use of organic waste or specially grown crops for the production of biogas or biofuel.

Summarizing the results of the analysis of renewable energy technologies and architectural solutions using alternative energy, practical recommendations for architects and designers are proposed.

<u>For the use of solar energy:</u>

- conduct a detailed insolation analysis of the site at the pre-design stage;
- orient the building and roof slopes for maximum solar radiation capture (azimuth and tilt angle);
- regard BIPV not as a cost but as an investment in the long-term economy of the building, considering the dual function of the elements (structure + generator);
- use semi-transparent panels for glazing atriums and skylights to create a comfortable light environment and generate energy.

<u>For the use of wind energy:</u>

- carry out mandatory CFD (Computational Fluid Dynamics) modeling to analyze wind flows around the building and determine optimal turbine locations;
- give preference to bladeless or vertical-axis turbines, which are safest and least sensitive to turbulence;
- consider noise and vibration generation at the design stage and apply appropriate damping technologies;
- consider integrating wind generation as an element of the high-rise building’s brand identity that works for its image.

<u>For the use of geothermal energy and ambient energy:</u>

- conduct geological surveys to determine the feasibility and type of geothermal system;
- allocate the necessary areas for equipment and utilities at the concept development stage;
- integrate the system with other elements, for example, use the heat extracted by the building’s cooling system to heat pool water or pathways.

The most promising is a synergistic approach combining passive (energy demand reduction) and active (energy generation) methods and systems.

The analysis performed points to several trajectories for future development that will elevate RES integration to a new level:

- *multifunctional materials:* developing construction materials [23] with energy-generating properties. Examples include spray-applied photovoltaic roofing membranes, highway noise barriers based on organic photovoltaics, and transparent thermoelectric generators in insulated glass units that utilize temperature differentials [24];
- *energy-active urban linkages:* moving beyond individual buildings toward designing quarters and districts as unified energy systems, which implies creating local microgrids where buildings with surplus generation (office towers during the day) exchange energy with objects at peak consumption (residential buildings in the evening) through continuous energy exchange systems;
- *full-cycle environmental accounting:* future solutions are evaluated not only by their carbon footprint during operation but also by their environmental impact from production to disposal, stimulating the development of easily recyclable BIPV modules and the elimination of rare-earth elements in wind turbine structures;
- *low-voltage systems integration:* a promising direction of development is integrating low-voltage systems directly into the structural mass—in particular, embedding heating cables or flexible conductive elements into the pavement layers [25] of bridge structures allows for creating effective anti-icing systems, preventing the accumulation of snow and ice deposits, increasing winter safety [26], and enabling a transition from preventive to predictive maintenance.

4. CONCLUSIONS

Integrating RES into modern buildings is a complex interdisciplinary problem situated at the intersection of architecture, urban planning, structures, materials science, digital technologies, and economics. Success here will be determined by the ability of architects, system designers, structural engineers, and technologists in the community to think systematically and comprehensively, creating a truly sustainable, energy-autonomous, and architecturally expressive environment for the future.

A structured multi-criteria assessment methodology is required for informed decision-making, allowing different technological scenarios to be compared on a common, quantitatively measurable basis. Such an approach transforms qualitative reasoning into a tool for quantitative comparison and selection of the optimal solution adapted to the specific conditions of the object.

The study carried out, based on the systematization of RES technologies, factor analysis, and multi-criteria modeling, allows for the formulation of the following scientifically substantiated conclusions:

- The effectiveness of RES integration is strictly determined by climatic and architectural conditions.
- Hybrid systems demonstrate the best seasonal uniformity and environmental efficiency.
- Structural solutions for high-rise buildings require individual aerodynamic and vibration calculations.
- Architectural integration of BIPV systems must account for tilt angle, material, and degree of transparency.
- Hourly modeling confirms the necessity of storage systems and intelligent management.
- Practical implementation of the proposed methodology makes design decisions more robust.

Thus, the stated goal of the work—creating a structured tool for selecting RES that ensures a synergy of energy efficiency, reliability, and architectural harmony—has been achieved. The scientific novelty lies in the development and validation of a step-by-step algorithm that includes multi-criteria analysis with weighting coefficients (economics – 40%, reliability – 30%, ecology – 20%, architecture – 10%), as well as in the quantitative justification of optimal parameters (tilt angles, installation height, BIPV type) for various climatic and structural conditions. The results obtained can serve as a baseline for creating regulatory design guidelines for energy-active buildings in Russia, taking into account regional specificities.

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