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## WAYS OF APPLYING INNOVATIVE TECHNOLOGIES IN ENERGY SECTOR ENTERPRISES

Khamdamova Gavhar Absamatovna  
Doctor of Economics, Professor,  
Tashkent State University of Economics,  
g.khamdamova@tsue.uz  
ORCID: 0000-0002-0690-6845

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### Abstract

The article discusses the main ways of applying innovative technologies in the energy industry in the context of digital transformation and transition to sustainable development. Special attention is paid to the impact of innovative solutions on improving energy efficiency, reliability of energy supply, reducing operating costs and environmental burden. The results of the research can be used in the development of strategies for the innovative development of energy industry enterprises and the formation of investment programs.

**Keywords:** Energy, innovation, innovative technologies, methodology, energy efficiency, energy, strategy, sustainable development, energy conservation, modernization, industry.

### Introduction

The relevance of studying ways to apply innovative technologies in energy sector enterprises is associated with the need to modernize existing infrastructure, improve energy efficiency and the reliability of energy supply, as well as transition to environmentally oriented models of energy production and consumption. The implementation of innovations requires not only significant investment resources, but also a systematic approach that takes into account change management as well as technical, economic, and organizational factors.



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The purpose of this work is to analyze the main directions and methods of applying innovative technologies in energy sector enterprises, as well as to assess their impact on the operational efficiency of energy companies. Within the framework of the study, it is planned to examine promising technological solutions, the specific features of their implementation, and the key challenges that arise in the process of innovative development of the energy sector.

### **Methodology**

The methodological basis of the research consists of the works of domestic and foreign experts devoted to the implementation of innovative approaches in the field of improving energy efficiency and the competitiveness of enterprises. In the course of the analysis, legislative and regulatory documents, as well as materials from scientific and practical conferences dedicated to these topics, were used. The study is based on a systematic approach, and methods such as logical, comparative, and statistical analysis were applied to achieve the research objectives.

### **Result and discussion**

Most people primarily associate solar energy with photovoltaic panels. However, for a long time, solar thermal installations using selectively absorbing coatings have been widely applied in the energy sector. Such materials are characterized by a high capacity to absorb solar radiation—more than 97% of the incident light—while their own thermal radiation amounts to only 3–4%.

If this element is not air-cooled, its surface can be heated under conventional solar radiation, without the use of concentrating devices, to temperatures of 200 °C and higher. [6]

The parameters of solar energy conversion devices can be used to generate water steam that meets the requirements of the thermodynamic cycles of steam turbines. The efficiency of solar steam turbine systems ranges from 15–20%, which is comparable to the performance of photovoltaic modules.

In such systems, an aerostat filled with water vapor is used as the element that converts solar radiation into thermal energy. Its design consists of two layers: the outer layer is made of a transparent material that allows solar radiation to



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pass freely, while the inner layer is coated with a selective absorbing layer that is heated by solar radiation to temperatures of 150–180 °C. The space between the shells performs a thermal insulation function, reducing heat losses. As a result, the temperature of the water vapor inside the aerostat can reach 130–150 °C at normal atmospheric pressure. Since the boiling point of water at sea level is 100 °C, the steam inside the balloon becomes superheated. [4]

Supplying water into the volume of superheated steam inside the balloon in the form of a fine spray leads to its instant evaporation, providing a simple and efficient method of steam generation. Subsequently, the generated steam is directed to a steam turbine through a flexible pipeline, and after expansion it is condensed in a heat exchanger and returns to a liquid state. The condensate is then fed back into the balloon, where it is resprayed and evaporated again through interaction with the superheated steam.

The reserve of superheated steam accumulated inside the aerostat ensures the continuous operation of the steam turbine, including during nighttime hours. At night, steam losses and a decrease in temperature reduce the balloon's lift by no more than 10–20%, which has almost no effect on its stable position. During the daytime, the volume of superheated steam is restored through solar heating. The operation of the turbogenerator can vary depending on current energy demand. When using a balloon with a shell diameter exceeding 100 m, the lifting force generated by the water vapor inside is sufficient to raise it into the air.

The design features of solar balloon power plants largely depend on their method of installation. Aerostats with a shell diameter of approximately 200–300 m, when ground-anchored, are capable of rising several hundred meters above the surface, while the steam turbine is located on the ground, and steam is supplied from the aerostat to the turbine via a flexible pipeline.

Experimental studies conducted in Taiwan have shown that the highest energy efficiency is achieved by flexible tubular panels with dust-absorbing coatings. Water vapor is pumped through such panels using a fan or a low-pressure compressor and is heated when it comes into contact with surfaces that actively absorb solar radiation. A system of valves installed on the panels regulates the direction of steam flow, ensuring that it passes only through areas exposed to sunlight. The steam inside the aerostat is reliably insulated from the external



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environment by a multilayer thermal insulating film, which simultaneously reduces the mass of the structure and serves as a heat shield, helping to retain heat. Due to air exchange, daily heat losses do not exceed 10%.

The thermal insulating film is mounted on a supporting frame made of nylon ropes or carbon fiber elements, which ensures the stability of the structure even under the influence of strong storm winds with speeds of up to 50 m/s. When using balloons with a shell diameter in the range of 200–300 m, steam turbine installations are capable of generating electricity with a daily output of approximately 1,000–5,000 kW.

In the southern regions of Taiwan, seasonal variations in the duration of solar radiation led to changes of approximately 50% in the average daily electricity generation of the experimental solar balloon power plant between June and December. In regions located at higher latitudes, operational variability may be even more significant. In this regard, ground-based solar balloon power plants demonstrate the highest efficiency in regions with more than 300 sunny days per year, including the Mediterranean, North Africa, the Near and Middle East, Central Asia, the Caspian region, Mongolia, western regions of China, Australia, Southeast Asia, and other areas with similar climatic conditions.

The concept developed by Peking University professor Wang Li предусматривает the placement of aerostat power plants in the upper layers of the atmosphere, above the level of cloud cover, ensuring their operation regardless of weather conditions. Such plants are planned to be installed at an altitude of approximately 5–7 km above land or sea level, without the need for mountainous terrain. The steam turbine unit may be located either on the ground or directly inside the balloon. If the power equipment is placed on the ground, steam is supplied from the aerostat to the turbine via a flexible steam line approximately 7,000 m in length; however, to date, there is no practical experience in the development and operation of steam pipelines of such length. [4]

One of the possible technical solutions proposed is the use of a flexible pipeline made of elastic shells with flexible thermal insulation. The outer layer may be manufactured from reinforced glass fabrics used in large aerodynamic structures and capable of maintaining performance within a temperature range from –70



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to +650 °C. To protect against the effects of water vapor, a polyamide membrane resistant to temperatures of up to +180 °C can be used. The mass of such a flexible pipeline system with a length of 7,000 meters accounts for approximately 15% of the total mass of the aerostat.

Water supply to the balloon can be carried out using a cascade of pumping units. If the steam turbine installation is placed directly in the aerostat gondola, the generated electrical energy is transmitted to the ground via an electrical cable.

In the first half of the 20th century, effective methods for tethering aerostats to the ground were developed and widely used for the air defense of cities during World War II. At present, work is underway in the United States on the creation of aerostat-based communication systems using tethered dirigibles. In particular, Platforms Wireless International is implementing a project involving a tethered dirigible designed to operate at altitudes ranging from 3 to 10.5 km and connected to the ground by a cable approximately 2.5 cm in diameter.

Heliothermal energy is recognized by the international community as one of the promising directions that facilitates the transition from the use of fossil energy resources to environmentally friendly and renewable energy sources. For countries with high solar insolation, such as Spain, Morocco, the United Arab Emirates, and Mexico, commercial energy production based on helioconcentrator technologies is becoming a key vector of development.

Among the most widespread commercial methods of harnessing solar energy are photovoltaic and heliothermal technologies. In heliothermal systems, solar radiation is converted into thermal energy, which is then used to generate electricity through various thermodynamic cycles, such as the Rankine, Brayton, and Stirling cycles, while also enabling thermal energy storage with delayed electricity generation.

Modern solar energy devices are classified into several main types based on their structural and technological characteristics:

1. Systems with parabolic mirror solar concentrators.
2. Parabolic concentrator devices equipped with thermal energy storage systems based on inorganic salts.
3. Solar power plants using linear Fresnel reflectors.
4. Tower-type solar devices in which steam is generated directly in the receiver.



5. Tower-type solar systems that store thermal energy in molten salt heat carriers.
6. Solar devices with parabolic dishes operating together with Stirling engines.
7. Hybrid solar power plants combined with gas boilers for fossil fuel use.
8. Hybrid solar energy complexes integrated with solid-fuel boilers for biomass combustion.
9. Parabolic trough hybrid solar devices combined with combined-cycle steam-gas energy systems. [4]

In general, heli concentrators can be divided into two main classes. The first includes devices designed to concentrate solar thermal flux along a linear focus, while the second type of systems collects solar radiation at a single focal point, allowing for significantly higher temperatures. Linear systems include solar thermal power plants that use parabolic troughs and Fresnel reflectors.

The second group of devices operates at high-temperature regimes and tracks the Sun in two coordinates. Such systems employ central-receiver tower schemes or parabolic mirror devices combined with Stirling engines. Modern high-efficiency solutions allow the accumulation of thermal energy for subsequent conversion into electricity on demand. At the same time, hybrid solar thermal power plants combining solar radiation with fossil fuels or biomass are being developed, which significantly enhances the investment attractiveness of such projects. [8]

Parabolic concentrator solar thermal power plants are the most common type of such devices, accounting for 80–90% of the total number worldwide. A modern example is the Csnp Royal Tech Urat 100 MW plant, commissioned in January 2020 and connected to the electrical grid. These facilities are widely used in a number of countries, including Spain and the United States.

The operation of such plants is based on the use of parabolic non-metallic reflectors, which direct solar radiation along a linear axis several hundred meters long and provide stepwise heating of the cooling water. The working fluid, heated to high temperatures, is then used to generate steam and power the steam turbine unit. Currently, special attention is given in the design and operation of parabolic solar plants to environmental safety issues and to reducing the complexity of maintenance. As the cooling water passes through the



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concentrator system, its temperature typically reaches 380–390 °C, which is considered a permissible and safe level.

If the temperature limit exceeds 400 °C, thermal decomposition of the aromatic hydrocarbons used begins, which can negatively affect the operation of the heliocolector system and create potential hazards. Therefore, specialized equipment is required to remove decomposition products from the cooling fluid regardless of operating conditions, which is typically carried out using filtration and distillation technologies.

The area occupied by parabolic cylindrical concentrators, referred to as the solar field, can be considerable, reaching several hectares per installed megawatt of capacity. Thus, constructing a solar thermal power plant with a capacity of 100 MW may require approximately 200 hectares solely for the placement of the concentrators, not including the areas occupied by auxiliary infrastructure.

Collector systems are designed so that their geometry and overall parameters provide the most efficient concentration of solar radiation in the cooling fluid flowing through the pipes. Such devices include reflective surfaces, dust-absorbing tubes, and supporting structures that optimally position the system elements to best retain solar energy.

Collector modules are arranged taking into account a synchronous orientation that ensures solar rays fall perpendicularly on the working surfaces. Individual collectors are connected in series to form typical arrays. Large solar thermal power plants may include hundreds of such autonomous schemes integrated into a single energy system. The steam generation stage plays a crucial role in transferring thermal energy, as it ensures the conversion of heat from the cooling fluid into steam for power production.

Water, pre-compressed to 50–100 bar using a multi-stage centrifugal pump, is converted into steam and heated to approximately 380 °C, while the cooling fluid transfers heat and is prepared for reuse. The cooled working fluid is returned to the solar field in parabolic concentrators for additional heating. The process of heat transfer between the cooling fluid and the water-steam cycle is carried out using shell-and-tube heat exchangers.

Designing steam generators for solar thermal power plants is a technically challenging task, requiring consideration of numerous operational factors,



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potential hazards, and ensuring ease of maintenance. Each element of a solar thermal power plant requires special handling and maintenance, which increases operational costs. In this regard, high-quality design solutions and the reliability of the equipment used are key conditions for the successful implementation of such projects.

The steam turbine is one of the main components of any power plant, providing the conversion of the thermal energy of steam into electrical energy, which fully applies to solar thermal power plants (STES). During operation, high-pressure steam enters the turbine, where its internal energy is converted into the mechanical rotational energy of the shaft. In such systems, the use of gas turbines is limited by relatively low steam temperatures, approximately 380 °C. The efficiency of the energy conversion process is generally in the range of 30–45% and reaches its maximum when operating at nominal load. When designing a solar thermal power plant, selecting the optimal type of steam turbine is especially important, taking into account the specific operating conditions, modes, and other technically significant factors.

After expanding in the turbine, the steam loses a large portion of its mechanical energy and, at temperatures below 50 °C and pressures lower than atmospheric, becomes unsuitable for direct use. At the same time, it is demineralized water, which can be condensed and returned to the technological cycle.

The condensers used in solar thermal power plants perform a number of key functions:

Ensure condensation of exhaust steam for water reuse;

Maintain a vacuum in the condenser, which helps increase the efficiency and output of the turbine unit;

Support an increase in the pressure of the condensate returned to the boiler section, which is an energetically beneficial solution compared to recompressing the steam.

To ensure effective condensation of exhaust steam, a cooling medium—either cold water or air—must provide heat dissipation during the heat transfer process. This factor is critical because the phase transitions of evaporation and condensation involve significant heat fluxes, which in turn require large volumes of cooling water. Consequently, high-capacity steam condensers in solar thermal



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power plants can consume anywhere from hundreds of thousands to several million cubic meters of water annually, significantly limiting the feasibility of locating them far from natural water sources.

In conditions of limited water resources, air-cooling systems are sometimes used in solar thermal plants, where the thermal energy of the exhaust steam is released directly into the atmosphere. This method is characterized by lower efficiency and increased operational costs and is primarily employed as a necessary alternative when water resources are unavailable.

At the final stage of the energy cycle, the mechanical energy obtained from the rotation of the steam turbine shaft is converted into electrical energy by the generator. The generator is a highly reliable and efficient device, after which the generated electricity is transmitted to the power grid via high-voltage transmission lines.

Electricity can be transmitted through overhead or underground (cable) lines, each requiring specialized infrastructure components. Voltage levels are increased at transformer substations, which is necessary because electricity is generated at a voltage optimal for the generator's operation, while transmission is carried out at high voltages to minimize losses.

To ensure the safe and stable operation of generator equipment and the electrical grid, electrical protection systems are employed, including grounding devices designed to prevent the consequences of short circuits and emergency situations. Monitoring and measuring instruments continuously track parameters of the electrical network, such as current and voltage, which helps maintain the reliability and efficiency of the protection systems.

In many countries, numerous projects have been implemented that have created a broad practical base for the development of new commercial initiatives. Equipping solar thermal power plants involves a sequential process of selecting, procuring, and installing equipment, including electric generators, transformers, steam turbines, pipeline system components, cooling water treatment devices, and other key structural elements, supported by skilled installation and logistical planning.

One of the major challenges faced by solar thermal power plants is the issue of energy storage, which is a common difficulty for renewable energy, especially



for weather-dependent technologies. The main challenge is the lack of synchronization between electricity generation and consumption: production typically occurs during periods of favorable insolation, which do not always coincide with peak demand. Since electricity storage is associated with high costs, the most practical approach is to meet demand at times of maximum necessity.

In this regard, there is a need to develop energy storage systems designed to mitigate the imbalance between generation and consumption. Considering the complexity and limitations of existing technologies for storing large amounts of electrical energy, alternative storage methods based on changes in physical parameters, such as pressure or temperature, are often employed in practice. For example, in pumped-storage power plants, energy is stored in the form of water, allowing it to be used for electricity generation at times that are most economically and technologically advantageous.

#### **Some technologies for thermal energy storage [6]**

<b>Technology</b>	<b>Brief description</b>
Hot Thermal Fluid (HTF) Storage	This technology was successfully tested at the SEGS power plant in the United States, where a large tank was used to store HTF from the solar field. After a severe fire that nearly destroyed the facility, it became clear that storing a flammable substance at high temperatures is impractical. In addition, the cost of the cooling fluid is significantly higher compared to inorganic salts.
<b>Thermal energy storage in hot solidified concrete</b>	Hot liquid can heat a large mass of solidified concrete through pipes designed for this purpose. If needed, cold fluid—water, steam, or HTF—can be supplied through the same channels, allowing the thermal energy stored in the concrete to be transferred back to the fluid.
<b>Storage using the latent heat of solidification of inorganic salts</b>	An important advantage of this technology is that the salts do not need to be continuously pumped through a pipeline, which reduces operational costs. The amount of salt required for energy storage is relatively small.
<b>Energy storage in the form of molten salts</b>	Some facilities use a single-tank energy storage technology with molten salts, where cold and hot salts separate due to their density difference.



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Various approaches are used to store energy in solar thermal power plants, typically in the form of thermal energy, which is later converted into electricity. Among alternative solutions, one of the most developed and practically implemented technologies is the use of molten inorganic salts, which has already been successfully deployed in several operating solar thermal power plants.

Currently, engineers are actively developing new materials and technological solutions aimed at reducing heat losses and increasing the efficiency of energy transfer at all stages of the electricity generation process.

The integration of heliothermal systems with fossil fuel-based systems is also associated with the complexity of forecasting meteorological conditions and ensuring stable electricity generation at solar thermal power plants. During the initial development of the SEGS series plants in California, the concept of supplementing solar input with a fossil-fuel boiler was considered to improve the reliability and stability of electricity supply.

Storing large amounts of electrical energy remains a complex technical challenge, as it requires precise synchronization between generation and consumption processes. A disruption of this balance can lead to instability in the energy system and cause emergency outages.

According to a number of experts, despite the high cost of implementation, solar thermal power plants should be equipped with thermal storage systems that allow regulation of energy production regardless of the level of solar radiation. In Spain and several other countries, regulatory requirements encourage the integration of auxiliary boilers powered by natural gas or biomass into solar thermal power plants. Such measures are aimed at increasing the stability of the plants under variable weather conditions. Additionally, these boilers ensure the required thermal regime and prevent the crystallization of cooling water at temperatures as low as +12 °C.

## **Conclusion**

One of the main advantages of hybrid solutions using biomass is the ability to operate solar thermal power plants without incorporating thermal storage systems or installing auxiliary natural gas boilers. This approach allows the STES to operate for 2,000–3,000 hours per year, which corresponds to



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approximately 60–75% of the total operating time of the plant. This, in turn, facilitates more efficient use of already invested capital and expands the opportunities for stable electricity generation through alternative sources. Additionally, energy facilities located in regions with a developed agricultural sector can use biomass as fuel to produce electricity.

Integrating biomass boilers into solar thermal power plants is of significant interest to investors not only in Southern European countries but also in other regions of the world. An advantage of hybrid solutions based on a combined cycle is that most of these plants operate on the Rankine thermal cycle, which simplifies the delivery of superheated steam from solar radiation and steam generated from other sources to a single turbine. A practical example of this concept is Integrated Solar Combined Cycle (ISCC) power plants, where the steam from the solar field can be combined with the steam produced in a conventional waste heat boiler.

Although the use of fossil fuels comes with certain limitations, ISCC plants offer two significant advantages: they provide relatively low-cost electricity generation and allow flexible adjustment of power output according to current demand.

A promising innovative direction is the placement of solar steam turbine units on aerostat platforms, which opens new opportunities for integrating renewable energy sources into the power system and allows achieving an efficiency of 15–20%, comparable to that of photovoltaic solar plants.

Innovative technologies have become a key factor in the development of energy industry enterprises, ensuring the efficiency, reliability, and stability of power systems. Their application includes digitalization of management, implementation of automation and robotics, development of renewable energy sources, and the use of energy-saving and environmentally friendly solutions.

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