



# Gibrid atom elektr stansiyalari: qayta tiklanadigan energiya manbalari bilan integratsiya

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**Dolzarbli:** zamonaviy ekologik holat va issiqxona gazlari chiqindilarini kamaytirish zarurati sharoitida asosiy muammolardan biri qayta tiklanuvchi energiya manbalarini (QTM) integratsiya qilishda energetik tizimlarning ishonchligini ta'minlash hisoblanadi. An'anaviy energiya manbalari, jumladan ko'mir va gaz elektr stansiyalari, atrof-muhitga sezilarli ta'sir ko'rsatadi, shu bilan birga, energetik tizimlarning to'liq dekarbonizatsiyasi ishlab chiqarishning kombinatsiyalangan sxemalariga o'tishni talab qiladi. Qayta tiklanuvchi energiya manbalarining, ayniqsa shamol elektr stansiyalarining (ShES) rivojlanishi uglerod izini sezilarli darajada kamaytirish imkonini beradi. Biroq, ishlab chiqarishning o'zgaruvchan tabiati quvvat tebranishlariga olib keladi, bu esa energetik tizimni muvozanatlashtirishni murakkablashtiradi. Zamonaviy energiya saqlash tizimlariga asoslangan yechimlar esa saqlash davomiyligi va yuqori narx bilan cheklangan bo'lib, yangi texnologik yondashuvlarni izlash zaruriyatini keltirib chiqaradi. Yadro-qayta tiklanuvchi gibrid tizimlar konsepsiyasini o'rganish barqaror, xavfsiz va iqtisodiy samarali global kelajak energetik tizimini ishlab chiqishga yo'naltirilgan dolzarb ilmiy-texnik vazifadir.

**Maqsad:** gibrid atom elektr stansiyalari (AES) konsepsiyasini tahlil qilish, ularning qayta tiklanuvchi energiya manbalari (QTM) bilan integratsiya sxemalarini ko'rib chiqish, afzalliklari va cheklovlarini aniqlash, shuningdek, kichik modul reaktorlari (KMR) va energiya saqlash tizimlari kabi istiqbolli texnologiyalarni muhokama qilish.

**Usullari:** mazkur maqolada atom elektr stansiyalarini (AES) qayta tiklanuvchi energiya manbalari (QTM) bilan integratsiya qilish bo'yicha mavjud va istiqbolli texnologiyalar analitik tahlil qilindi. Gibrid energetik tizimlarning turli sxemalarining qiyosiy tahlili, kichik modul reaktorlari (KMR) ning texnik xususiyatlari va iqtisodiy samaradorligini o'rganish, shuningdek, zamonaviy energiya saqlash tizimlari (EST) ko'rib chiqildi. Ma'lumotlar manbai sifatida ilmiy nashrlar, xalqaro energetika agentliklari ma'lumotlari va gibrid energetik tizimlar bo'yicha innovatsion loyihalar hisobotlari ishlatildi.

**Natijalar:** tahlil shuni ko'rsatdiki, gibrid AES an'anaviy energetik tizimlarga nisbatan bir qator afzalliklarga ega, jumladan energiya ta'minotining barqarorligini oshirish, uglerod izini kamaytirish va generatsiya moslashuvchanligini oshirish. Kichik modul reaktorlari (KMR) yuqori boshqaruvchanlik va modullilik xususiyatlari tufayli qayta tiklanuvchi energiya bilan eng yaxshi moslashish potensialiga ega ekanligi aniqlandi. Bundan tashqari, akkumulyator batareyalari, gidroakkumulyatsiya stansiyalari va vodorod texnologiyalari kabi energiya saqlash tizimlaridan foydalanish energiya oqimlarini samarali boshqarishga yordam beradi. Biroq, gibrid AESlarni joriy etish qator muammolar bilan bog'liq, jumladan elektr tarmoqlari infratuzilmasini modernizatsiya qilish zaruriyati, yuqori kapital xarajatlar va tartibga solish murakkabligi.

Shunga qaramay, texnologik rivojlanish va davlat tomonidan qo'llab-quvvatlash yaqin o'n yilliklarda gibrid energetik tizimlarni jadal rivojlantirishni ta'minlashi mumkin.

**Kalit so'zlari:** gibrid atom elektr stansiyalari, qayta tiklanuvchi energiya manbalari (QTM), kichik modul reaktorlari (KMR), AES va QTM integratsiyasi, shamol elektr stansiyalari (ShES), quyosh elektr stansiyalari (QES), energiya saqlash tizimlari (EST), energiya tizimining moslashuvchanligi.

## Гибридные атомные электростанции: интеграция с возобновляемыми источниками электроэнергии

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**Актуальность:** в условиях современной экологической ситуации и необходимости снижения выбросов парниковых газов ключевыми вызовами остаются обеспечение надежности энергосистем при интеграции возобновляемых источников энергии (ВИЭ). Традиционные источники энергии, включая угольные и газовые электростанции, оказывают значительное воздействие на окружающую среду, в то время как полная декарбонизация энергосистем требует перехода на комбинированные схемы генерации. Развитие ВИЭ, в частности ветровых электростанций (ВЭС), позволяет значительно снизить углеродный след, однако переменный характер выработки приводит к колебаниям мощности, что усложняет балансировку энергосистемы. Современные решения, основанные на аккумуляторных системах хранения

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энергии, имеют ограничения по длительности хранения и высокой стоимости, что требует поиска новых технологических подходов. Исследование концепции ядерно-возобновляемых гибридных систем является актуальной научно-технической задачей, направленной на разработку устойчивых, безопасных и экономически эффективных решений для будущей глобальной энергетической системы.

**Цель:** проанализировать концепцию гибридных атомных электростанций (АЭС), рассмотреть возможные схемы их интеграции с возобновляемыми источниками энергии (ВИЭ), выявить их преимущества и ограничения, а также обсудить перспективные технологии, такие как малые модульные реакторы (ММР) и системы накопления энергии.

**Методы:** в данной статье проведён аналитический обзор существующих и перспективных технологий интеграции атомных электростанций (АЭС) с возобновляемыми источниками энергии (ВИЭ). Используются сравнительный анализ различных схем реализации гибридных энергосистем, исследование технических характеристик и экономической целесообразности малых модульных реакторов (ММР), а также рассмотрение современных систем накопления энергии (СНЭ). В качестве источников информации использованы научные публикации, данные международных энергетических агентств и отчёты об инновационных проектах в области гибридных энергосистем.

**Результаты:** анализ показал, что гибридные АЭС обладают рядом преимуществ перед традиционными энергосистемами, включая повышение устойчивости энергоснабжения, снижение углеродного следа и увеличение гибкости генерации. Малые модульные реакторы (ММР) продемонстрировали наибольший потенциал в сочетании с ВИЭ за счёт их высокой регулируемости и модульности.

**Ключевые слова:** гибридные атомные электростанции, возобновляемые источники энергии (ВИЭ), малые модульные реакторы (ММР), интеграция АЭС и ВИЭ, ветровые электростанции (ВЭС), солнечные электростанции (СЭС), системы накопления энергии (СНЭ), гибкость энергосистем.

## Hybrid Nuclear Power Plants: Integration with Renewable Energy Sources

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**Relevance:** in the context of the current environmental situation and the need to reduce greenhouse gas emissions, one of the key challenges remains ensuring the reliability of energy systems while integrating renewable energy sources (RES). Traditional energy sources, including coal and gas power plants, have a significant impact on the environment, whereas complete decarbonization of energy systems requires transitioning to hybrid generation schemes. The development of RES, particularly wind power plants (WPPs), significantly reduces the carbon footprint. However, their variable nature leads to power fluctuations, complicating energy system balancing. Modern solutions based on battery energy storage systems have limitations in terms of storage duration and high costs, necessitating the search for new technological approaches. The study of nuclear-renewable hybrid systems is a relevant scientific and technical challenge aimed at developing sustainable, safe, and economically efficient solutions for the future global energy system. Implementing such systems will help achieve a balance between stable baseload generation and the environmental benefits of RES, which is particularly crucial amid growing energy demand and the transition to a carbon-neutral economy.

**Aim:** to analyze the concept of hybrid nuclear power plants (NPPs), examine possible schemes for their integration with renewable energy sources (RES), identify their advantages and limitations, and discuss promising technologies such as small modular reactors (SMRs) and energy storage systems (ESS).

**Methods:** this article presents an analytical review of existing and emerging technologies for integrating nuclear power plants (NPPs) with renewable energy sources (RES). The study includes a comparative analysis of different hybrid energy system implementation schemes, an examination of the technical characteristics and economic feasibility of small modular reactors (SMRs), and an assessment of modern energy storage systems (ESS). The research is based on scientific publications, reports from international energy agencies, and data on innovative projects in the field of hybrid energy systems.

**Results:** The analysis demonstrated that hybrid NPPs offer several advantages over traditional energy systems, including increased energy supply resilience, reduced carbon footprint, and enhanced generation flexibility. Small modular reactors (SMRs) have shown the highest potential in combination with RES due to their high controllability and modularity. Moreover, the use of energy storage systems, such as battery storage, pumped hydro storage, and hydrogen technologies, contributes to efficient energy flow management.

**Key words:** hybrid nuclear power plants, renewable energy sources (RES), small modular reactors (SMRs), NPP and RES integration, wind power plants (WPPs), solar power plants (SPPs), energy storage systems (ESS), energy system flexibility.

### 1. Introduction

The global energy landscape is undergoing a significant transformation driven by the imperative to enhance reliability, sustainability, and environmental responsibility in power generation. As nations strive to meet ambitious decarbonization targets, the integration of diverse energy sources has become



paramount. Nuclear power plants (NPPs) have long been a cornerstone of stable and low-carbon electricity production. Simultaneously, renewable energy sources (RES) such as wind and solar power have experienced rapid growth due to technological advancements and policy support. However, the intermittent nature of RES presents challenges in maintaining a consistent and reliable energy supply. Hybrid energy systems that combine NPPs with RES offer a promising solution to this challenge. By leveraging the continuous output of nuclear energy and the variable contributions of renewables, these systems can provide a balanced and resilient power supply. The International Atomic Energy Agency (IAEA) emphasizes that such integrated approaches can support various applications beyond electricity production, including desalination, hydrogen production, and district heating (IAEA) [1].

The integration of energy storage technologies further enhances the flexibility and responsiveness of hybrid systems. Innovations in battery storage, pumped hydro storage, and hydrogen production allow for the effective management of energy supply and demand, ensuring grid stability even with the fluctuating input from RES. The National Renewable Energy Laboratory (NREL) has demonstrated through its "Super Lab" project that combining nuclear and renewable assets can effectively meet grid demands while supporting industrial decarbonization efforts (NREL) [2].

## 2. Methods and materials

Over the past two decades, global energy consumption has experienced a notable increase, driven by factors such as industrialization, population growth, and economic development. Between 2000 and 2023, primary energy consumption rose from approximately 420 exajoules to around 620 exajoules, marking an increase of roughly 47%. This surge is particularly pronounced in emerging economies; for instance, the BRICS nations (Brazil, Russia, India, China, and South Africa) collectively accounted for 42% of global energy consumption in 2023, with China's energy use increasing by 6.6% that year [3].

In response to escalating energy demands and environmental concerns, there has been a global shift towards decarbonization, emphasizing the integration of renewable energy sources (RES) such as wind and solar power. Renewable energy consumption as a percentage of total final energy consumption has been on the rise, reflecting efforts to reduce greenhouse gas emissions and combat climate change. However, the inherent intermittency of RES poses significant challenges to maintaining a continuous and stable electricity supply. Variability in RES output can lead to grid instability, necessitating the development of strategies to ensure reliability [4].

To address these challenges, many governments and industry experts advocate for the expansion of nuclear energy, particularly through hybrid energy systems that integrate nuclear power plants (NPPs) with RES. Hybrid energy systems leverage the consistent baseload generation of nuclear power to complement the variable output of renewables, thereby enhancing grid stability and reducing greenhouse gas emissions [5].

This study employs a comprehensive methodology to evaluate the feasibility and effectiveness of hybrid NPP-RES systems. The approach includes a thorough literature review of hybrid energy models, data analysis from reputable energy agencies, and projections based on current industry trends. Case studies from various countries are examined to provide empirical evidence of the operational performance, economic viability, and environmental impact of such integrated systems. By analyzing diverse implementations, the study aims to identify best practices and potential challenges in the deployment of hybrid energy systems.

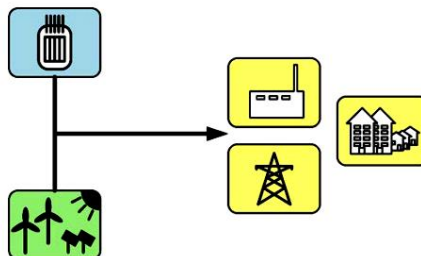
The literature review encompasses a wide range of sources, including peer-reviewed journals, reports from international energy organizations, and governmental publications. Data analysis involves the examination of energy consumption statistics, generation capacity, and grid reliability metrics from agencies such as the International Energy Agency (IEA) and the World Bank. Through this multifaceted methodology, the study seeks to provide a robust assessment of hybrid NPP-RES systems as a viable solution for sustainable and reliable energy production.

## 3. Results and discussion

A hybrid nuclear power plant is an energy system in which nuclear generation is combined with renewable energy sources (RES), such as wind (WPPs) and solar (SPPs) power plants. Unlike traditional NPPs, which operate in a baseload mode and rarely change output levels, a hybrid system allows nuclear generation to be adapted depending on the availability of RES and current energy demand.

The integration of nuclear power plants (NPPs) with renewable energy sources (RES) offers a synergistic approach to energy generation, effectively addressing the limitations inherent in each type of power production. Nuclear energy provides a stable and continuous power supply, ensuring grid reliability and energy security. In contrast, RES such as wind and solar power are intermittent, with outputs fluctuating based on weather conditions and time of day. By combining these sources, hybrid

systems can balance energy supply, with nuclear power compensating during periods of low renewable output, and surplus renewable energy being utilized for applications like hydrogen production or stored for future use [6]. This approach enhances grid flexibility, optimizes resource utilization, and contributes to significant reductions in greenhouse gas emissions. Studies have demonstrated that such hybrid systems can dynamically adjust to changing energy demands and resource availability, thereby enhancing the resilience of the power grid. Additionally, economic analyses indicate that these systems can be cost-competitive, but should be studied yet [7]. Implementing hybrid nuclear-renewable energy systems thus emerges as a viable solution for decarbonizing electricity generation while ensuring stability, affordability, and sustainability.



**Fig. 1.** General representation of Nuclear-Renewable system [1]

Hybrid NPPs are characterized by:

1. **Flexible Load Following Capabilities:** Unlike conventional large reactors that operate primarily in baseload mode, hybrid NPPs are designed with flexible load-following capabilities. This flexibility allows them to adjust their power output dynamically in response to the variability of RES generation and fluctuations in energy demand. Grid-responsive control systems are integral to this adaptability, enabling the optimization of energy dispatch and the maintenance of grid stability by modulating power output as needed. The International Atomic Energy Agency (IAEA) has highlighted the importance of such flexible operations, noting that advanced reactor designs are being developed to support load-following and frequency control modes, thereby enhancing the integration of nuclear power with renewable energy sources [8].

2. **Advanced Reactor Technologies:** The successful implementation of N-R HES relies on advanced reactor technologies that inherently support operational flexibility. Small Modular Reactors (SMRs) and High-Temperature Gas-Cooled Reactors (HTGRs) are particularly well-suited for hybrid systems due to their enhanced load-following capabilities and modular designs. SMRs, typically defined as reactors with an electrical output of up to 300 MW, offer advantages such as modular construction and the ability to be deployed incrementally, aligning capacity with demand. These reactors are being developed across various technologies, including water-cooled, gas-cooled, liquid metal-cooled, and molten salt designs. HTGRs, utilizing helium as a coolant and operating at high temperatures, provide not only electricity but also high-quality process heats suitable for industrial applications. Additionally, some hybrid NPP projects are exploring the use of Molten Salt Reactors (MSRs) and Liquid Metal-Cooled Fast Reactors, which offer enhanced flexibility and thermal efficiency, further contributing to the robustness of hybrid energy systems [9].

3. **Energy Storage Integration:** Integrating energy storage solutions is a critical component of N-R HES, as it addresses the intermittency of RES and enhances the overall reliability of the energy supply. By incorporating storage systems such as batteries, pumped hydro storage, and hydrogen storage technologies, surplus energy generated during periods of high renewable output can be stored and utilized during times of low production or peak demand. This approach not only ensures a consistent energy supply but also maximizes the utilization of generated energy, reducing waste and improving economic efficiency. For instance, thermal energy storage using molten salt or high-temperature steam accumulators can store excess heat produced during peak generation periods, which can later be converted back into electricity or used directly for heating purposes.

Case studies from various countries illustrate the potential of hybrid nuclear power plants (NPPs), showcasing diverse approaches to integrating nuclear and renewable energy sources to enhance grid stability, energy security, and sustainability.

1. **France:** With nuclear power contributing approximately 67% of its electricity generation in 2024, France is actively investing in smart grid technologies to better integrate renewable energy sources (RES) with its existing nuclear infrastructure. These advancements aim to enhance energy efficiency and reduce grid imbalances. Additionally, France is exploring hybrid nuclear-hydrogen production facilities to utilize excess nuclear power for hydrogen fuel generation, further improving energy efficiency and supporting decarbonization efforts [10].

2. **United States:** The U.S. Department of Energy has been supporting hybrid energy system demonstrations utilizing advanced Small Modular Reactors (SMRs). Projects at the Idaho National Laborato-



ry (INL) have tested the integration of nuclear and renewable energy sources, including the potential for nuclear power plants to provide process heat for industrial applications. INL, in collaboration with Oak Ridge National Laboratory and Argonne National Laboratory, has developed dynamic, physics-based modelling capabilities for Nuclear-Renewable Hybrid Energy Systems (N-R HES) using the Modelica programming language. These efforts aim to assess the technical and economic viability of such integrated systems [11].

The economic feasibility of hybrid nuclear-renewable power plants (N-R HES) depends on multiple factors, including capital costs, operational efficiency, and government subsidies. While nuclear energy typically requires a higher initial investment compared to renewable energy sources (RES), its long-term stability and high-capacity factors can make it financially viable in hybrid configurations. For instance, tightly coupled N-R HES can generate dispatchable electricity and provide hydrogen, potentially leading to beneficial economic impacts such as higher capacity factors and domestic energy production.

Hybrid nuclear-renewable systems have the potential to improve financial efficiency through multiple revenue streams. The integration of hydrogen production, industrial heating applications, and ancillary grid services can enhance economic returns. Studies indicate that hybrid N-R HES with hydrogen production through electrolysis can be profitable, especially in scenarios with higher electricity and natural gas prices, low hydrogen prices, and increased electricity price volatility [12].

Furthermore, hybrid N-R HES can mitigate negative electricity pricing events caused by overproduction from renewables. Flexible nuclear operation, combined with advanced energy storage solutions, reduces economic losses due to curtailment. These systems can operate as dynamic cogeneration plants, adjusting output to meet grid needs and maintain economic operation of the overall plant.

Several optimal schemes have been proposed for the implementation of hybrid NPPs, considering energy efficiency, operational flexibility, and integration with renewable sources. The following are key implementation models, along with relevant examples.

#### **NPP + RES in a Unified Energy System:**

Integrating Nuclear Power Plants (NPPs) and Renewable Energy Sources (RES) within a unified energy system offers a strategic approach to achieving a resilient, low-carbon energy infrastructure. In this configuration, NPPs provide a stable baseload power supply, while RES such as wind and solar contribute variable outputs based on environmental conditions. This synergy leverages the reliability of nuclear energy and the sustainability of renewables, aiming to enhance grid stability, optimize resource utilization, and reduce greenhouse gas emissions. The combined operation of NPPs and RES within a unified system necessitates advanced grid management to address the inherent variability of renewable energy. Key operational considerations include:

1. **Load Balancing:** Fluctuations in RES output require flexible response strategies to maintain grid stability. While traditional large-scale reactors have limited load-following capabilities, modern advancements in reactor design and grid technology are improving this flexibility. For instance, the integration of energy storage systems and demand-side management can help balance supply and demand effectively.

2. **Grid Infrastructure:** The transmission and distribution networks must be capable of handling diverse energy inputs. Investments in smart grid technologies, including real-time monitoring and automated control systems, are essential to manage the dynamic interplay between NPPs and RES. For instance, France exemplifies the implementation of a unified energy system combining NPPs and RES. As of 2024, nuclear energy accounts for approximately 67% of the country's electricity production, with nuclear output reaching a six-year high of 361.7 terawatt-hours (TWh) in 2024. This robust nuclear foundation is complemented by a growing share of renewables, including hydroelectric, wind, and solar power [3].

**Hydroelectric Power:** In 2024, hydroelectric generation increased by 30.5%, contributing 50.6 TWh to the national grid.

**Wind and Solar Power:** The combined output from wind and solar installations reached 31 TWh in 2023, marking an 11% increase from the previous year.

To manage the variability of RES and ensure grid stability, France is investing in smart grid technologies and energy storage solutions. The French transmission system operator, RTE, has developed new-generation smart substations capable of accommodating up to 30% more electricity from renewable sources. These substations are equipped with optical fibers and sensors to monitor real-time power flows, facilitating dynamic control of the power system.

Integrating NPPs and RES within a unified energy system presents several challenges:

**Variability of RES:** The intermittent nature of renewable energy sources necessitates flexible grid management and backup generation solutions.

**Limited Flexibility of Traditional NPPs:** Conventional nuclear reactors are designed for continuous operation and may lack the agility to adjust output rapidly in response to RES fluctuations.



To address these challenges, hybrid nuclear-hydrogen production facilities should be explored. These facilities aim to utilize excess nuclear power during periods of low electricity demand to produce hydrogen fuel. This approach will not only help in balancing the grid but also contributes to the development of a hydrogen economy, providing a clean energy carrier for various sectors.

In summary, the integration of Nuclear Power Plants and Renewable Energy Sources within a unified energy system could be strengthened by adding storage systems.

#### **NPP + RES + Energy Storage Systems:**

Integrating Nuclear Power Plants (NPPs) with Renewable Energy Sources (RES) and Energy Storage Systems (ESS) is better for creating a resilient and sustainable energy infrastructure. The most common types of ESS:

1. Battery storage (Li-ion, Na-ion, lead-acid) – suitable for short-term storage (from a few hours to a day).
2. Pumped hydro storage (PHS) – used for long-term storage of large amounts of energy.
3. Hydrogen technologies – allow converting electricity into hydrogen, which can then be used for electricity generation or industrial purposes.

This configuration leverages the consistent baseload power from NPPs, the variable yet clean energy from RES, and the balancing capabilities of ESS to address the intermittency of renewables and enhance overall grid stability. Energy Storage Systems are pivotal in this triad, serving multiple functions:

**Balancing Supply and Demand:** ESS can store excess energy generated during periods of high RES output and release it during low production or peak demand times, ensuring a continuous energy supply.

**Enhancing Grid Stability:** By mitigating the fluctuations inherent in RES, ESS contribute to maintaining consistent voltage and frequency levels within the grid.

**Optimizing Resource Utilization:** ESS enable NPPs to operate at optimal, steady-state conditions by absorbing surplus energy, which can then be dispatched as needed, improving overall system efficiency.

For instance, the Idaho National Laboratory (INL) is at the forefront of researching and developing integrated energy systems that combine nuclear power, renewable energy, and advanced storage solutions. INL's efforts include:

1. **Integrated Energy Systems:** INL is developing hybrid energy systems that incorporate both heat and power for grid services and industrial processes. These systems efficiently produce clean hydrogen and, when combined with biogenic carbon, can generate a wide range of chemical commodities and low-emission fuels [13].
2. **Energy Storage Technology:** INL's Energy Storage Technology Group is involved in multiple federally sponsored programs aimed at enhancing the energy and power capabilities of next-generation batteries. Their work focuses on improving diagnostics, prognostics, and predictive capabilities of energy storage systems [13].
3. **Net-Zero Microgrid Program:** INL has launched a Net-Zero Microgrid program to research carbon-free solutions that offer enhanced resilience to critical infrastructure. This initiative supports global efforts, including underserved communities, in achieving sustainable energy goals.[14]

#### **Small Modular Reactors (SMRs) + RES:**

Small Modular Reactors (SMRs) are emerging as a pivotal technology in the evolution of nuclear energy, particularly when integrated with Renewable Energy Sources (RES) to form resilient and flexible hybrid energy systems. This integration addresses the intermittency challenges associated with RES and enhances overall energy system reliability.

##### **Key Features of SMRs:**

1. **Flexibility:** SMRs are designed to adjust their power output to complement the variable nature of RES such as wind and solar. This adaptability ensures a stable energy supply, effectively balancing fluctuations in renewable generation.
2. **Compactness and Modularity:** The modular design of SMRs allows for factory fabrication and ease of transportation, facilitating deployment in diverse locations, including remote areas. Their compact size enables integration into existing energy infrastructures with minimal spatial requirements.
3. **Enhanced Safety:** Modern SMR designs incorporate advanced safety features, including passive cooling systems and inherent safety mechanisms, which reduce the risk of accidents and enhance public confidence in nuclear energy.

##### **Global Implementations and Initiatives:**

Canada is actively exploring the deployment of SMRs to provide reliable power to remote communities and support industrial applications. This initiative aims to leverage SMRs' flexibility to integrate seamlessly with renewable energy sources, ensuring a consistent and clean energy supply.



The U.S. is investigating the integration of SMRs with renewable energy systems to enhance grid stability and reduce carbon emissions. Studies have demonstrated the feasibility of combining SMRs with renewable energy sources and battery storage systems to create efficient and sustainable energy solutions [15].

In a strategic move to meet its growing energy demands and reduce reliance on fossil fuels, Uzbekistan has entered into an agreement with Russia's state nuclear corporation, Rosatom, to construct a nuclear power plant in the Jizzakh region. This facility will feature six RITM-200N SMRs, each with an electrical output of 55 MW. Construction is slated to commence in the summer of 2024, with the plant expected to reach criticality by 2029 [16].

The energy landscape of Uzbekistan is currently dominated by natural gas, with renewables playing a relatively minor role. The following graph illustrates the total energy supply in Uzbekistan by source from 2000 to 2022. This visualization highlights the country's heavy dependence on fossil fuels and the necessity of incorporating nuclear power to diversify the energy mix and enhance grid stability [17].

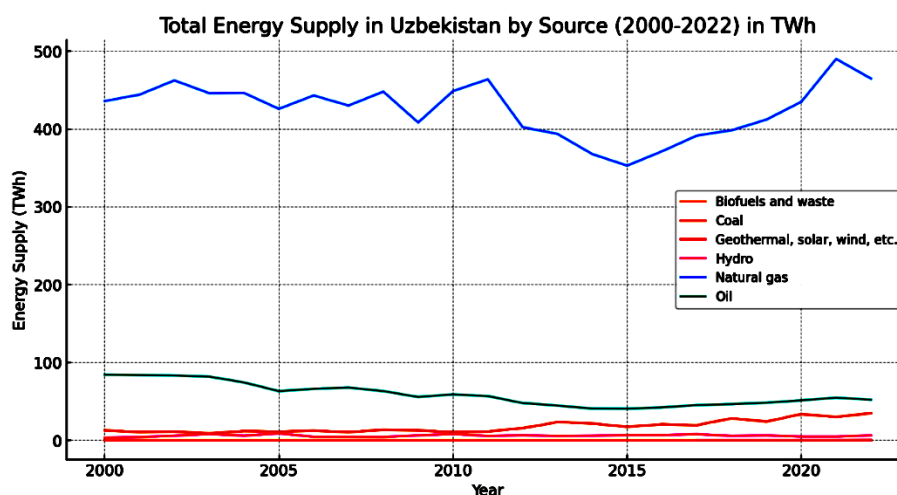


Fig.2. Total Energy Supply in Uzbekistan by Source (2000-2022) in TWh

The data underscores the potential for hybrid NPPs to serve as a crucial component of Uzbekistan's energy transition. The integration of nuclear energy with renewables can help mitigate reliance on natural gas, reduce carbon emissions, and support energy security. Additionally, nuclear power could complement intermittent renewable sources, ensuring consistent power generation and grid stability.

#### Utilization of Excess Nuclear Energy:

Utilization of Excess Nuclear Energy in hybrid Nuclear Power Plants (NPPs) offers a strategic approach to enhance energy efficiency and support various industrial applications. By redirecting surplus energy generated during periods of low electricity demand, NPPs can contribute to several key processes:

1. **Hydrogen Production:** excess electrical or thermal energy from NPPs can be utilized for hydrogen production through electrolysis. This approach not only provides a method for storing energy but also supplies hydrogen for industrial uses, transportation, and as a feedstock for chemical processes [18].

2. **Water Desalination:** Nuclear energy can be harnessed for seawater desalination, addressing freshwater scarcity issues. The thermal energy produced by NPPs is used to convert seawater into potable water, providing a reliable and sustainable freshwater source. Small- and medium-sized nuclear reactors can support desalination activities, often while supporting electricity cogeneration using low-pressure steam from the turbine and hot seawater fed from the final cooling system.

3. **Industrial Process Heat:** Surplus energy from NPPs can supply process heat for various industrial applications, such as oil refining, chemical production, and district heating systems. This integration reduces reliance on fossil fuels and lowers greenhouse gas emissions. Nuclear energy is an excellent source of process heat for various industrial applications, including desalination, synthetic and unconventional oil production, oil refining, biomass-based ethanol production, and, in the future, hydrogen production.

Challenges and Limitations of Hybrid NPPs:



Despite the obvious advantages of hybrid nuclear power plants, their implementation faces a number of technical, economic, and regulatory challenges. These challenges are related both to the operational characteristics of NPPs and to the limitations of RES and energy storage systems.

Technical challenges include the complexity of load balancing, the need for grid modernization, and the limited flexibility of traditional reactors.

Hybrid energy systems require efficient generation management, especially when RES output fluctuates. Traditional large nuclear reactors are not designed for frequent power changes, as this affects their economic efficiency and may accelerate equipment degradation. Moreover, the integration of NPPs with RES requires modernization of the power grid infrastructure. In conventional energy systems, nuclear power plants operate in a baseload mode, and the grid is not designed for frequent power fluctuations. The introduction of hybrid NPPs will require the development of digital energy management systems (SCADA, AI algorithms), an increase in the transmission capacity of power lines, and the creation of new dispatching and forecasting standards. It is important to consider that modern large reactors are not designed to operate in variable mode, as their efficiency is maximized under stable load conditions. Some new projects, such as PWR (Pressurized Water Reactor) with enhanced control, allow for power adjustment, but their large-scale implementation requires significant changes in the nuclear industry.

The construction of nuclear power plants is a long-term and capital-intensive process. The integration of NPPs with RES and energy storage requires additional costs for development, grid modernization, and the installation of ESS. Despite their low operating costs, NPPs have a long payback period (15–30 years) [17]. For hybrid NPPs, this period may increase, especially if additional investments in energy storage and grid infrastructure are required. The development of hybrid NPPs requires significant investment amid high competition from RES. Financial risks include:

Regulatory uncertainty – changes in policies supporting RES may affect the economic viability of projects.

Electricity price fluctuations – if RES become cheaper, investments in nuclear energy may be less attractive.

In addition, nuclear energy is regulated by strict standards, including licensing, operational requirements, and control over nuclear fuel and waste management. The introduction of hybrid NPPs will require a revision of the regulatory framework, particularly regarding reactor flexibility.

Despite the environmental benefits of NPPs, public concerns about nuclear risks persist. The main perception issues include: concerns about radiation and safety, the impact of past accidents (Chernobyl, Fukushima) on public attitudes toward nuclear energy, lack of understanding of the principles of modern safe reactors.

The development of hybrid systems requires public outreach, demonstrating the advantages of nuclear-renewable systems and implementing new safety technologies (passive cooling systems, automatic reactor control, etc.).

The development of nuclear energy largely depends on government policies. Some countries have abandoned nuclear energy in favour of RES (Germany), while others are actively developing nuclear generation (France, Russia, China).

Factors influencing hybrid NPP policy development: government support programs for nuclear and renewable energy, international agreements on decarbonization, sanctions and trade restrictions on technology.

#### Prospects and Future of Hybrid NPPs:

Hybrid nuclear power plants represent one of the most promising directions for energy development in the 21st century. Their combination with renewable energy sources (RES) enables the creation of a sustainable, environmentally friendly, and flexible energy system. In the future, the development of such systems will depend on technological innovations, economic factors, and government energy policies.

One of the key areas in the development of hybrid NPPs is the implementation of small modular reactors (SMRs). These units have high manoeuvrability, making them optimal for operation in combination with RES.

#### Current SMR projects:

1. NuScale Power (USA) – modular reactors with a capacity of 77 MW, capable of adjusting power based on energy system demand.
2. Rolls-Royce SMR (UK) – compact reactors designed for integration with RES.
3. RITM-200 (Russia, currently is considered for Uzbekistan pilot Nuclear project) – reactors used in icebreakers but also considered for land-based energy systems.

The advantages of SMRs include high flexibility in power adjustments, shorter construction times and capital investments, and an increased level of safety due to passive cooling systems.

Due to these characteristics, SMRs can become a key element of hybrid energy systems, replacing traditional large reactors that are poorly adapted to variable loads.



As mentioned earlier, for the efficient operation of hybrid NPPs, modern energy storage systems are required, allowing for the storage of excess RES generation and its use during low production periods. Promising directions include next-generation battery storage, pumped hydro storage (PHS), and hydrogen technologies.

Global trends in the development of hybrid nuclear power plants (NPPs) reflect the goal of creating sustainable and environmentally clean energy systems that combine nuclear energy with renewable energy sources (RES). The main directions include the development of small modular reactors (SMRs), the integration of NPPs with RES, and energy storage systems.

As of 2024, more than 80 SMR projects are being developed in 19 countries [19]. The first operational prototypes are already in use in Russia and China. For example, the floating NPP "Akademik Lomonosov" in Pevek, Russia, became the world's first operational prototype, and in China, in 2021, the first unit of the high-temperature gas-cooled reactor HTR-PM with a capacity of 210 MW was connected to the grid.

The implementation of hybrid systems combining NPPs, RES, and energy storage is still at the research stage. To successfully implement these projects, further research and economic calculations are necessary, considering costs, competitiveness, and greenhouse gas emissions.

#### 4. Conclusion

The global energy transition is reshaping the power generation landscape, with an increasing focus on reliability, sustainability, and decarbonization. Hybrid energy systems that integrate nuclear power plants (NPPs) with renewable energy sources (RES) present a viable solution to address the challenges of intermittent renewable generation while enhancing grid stability and reducing greenhouse gas emissions. By leveraging the continuous and stable output of nuclear power alongside the variability of wind and solar energy, hybrid systems create a balanced, resilient, and efficient energy supply framework.

A critical advantage of hybrid NPP-RES systems lies in their flexible load-following capabilities. Traditional large reactors operate in a baseload mode, but advancements in nuclear technology, including Small Modular Reactors (SMRs) and High-Temperature Gas-Cooled Reactors (HTGRs), provide greater adaptability to fluctuating energy demand and renewable output. These next-generation reactors are designed to adjust power levels dynamically, ensuring better synchronization with RES and contributing to overall energy system flexibility.

The integration of energy storage technologies further strengthens hybrid systems by mitigating the inherent intermittency of renewables. Advanced battery storage, pumped hydro storage (PHS), and hydrogen production technologies allow for surplus renewable energy to be stored and dispatched when required, optimizing resource utilization and ensuring consistent electricity supply. Several international research initiatives, including those by the International Atomic Energy Agency (IAEA) and the U.S. Department of Energy's Idaho National Laboratory (INL), highlight the growing feasibility of hybrid nuclear-renewable systems as a sustainable energy solution.

Economic feasibility remains a key consideration for the deployment of hybrid NPP-RES systems. While nuclear power requires high initial capital investments, its long-term stability, high-capacity factors, and the potential for revenue diversification through hydrogen production and industrial heating applications contribute to its financial viability. Countries such as France and the United States are investing in hybrid energy projects to optimize energy efficiency, reduce curtailment losses from renewables, and enhance economic returns.

Case studies from various nations underscore the practical benefits of hybrid nuclear power plants. In France, where nuclear energy comprises approximately 67% of electricity production, investments in smart grid technologies and nuclear-hydrogen integration exemplify efforts to strengthen grid resilience. In the United States, research at national laboratories has demonstrated that coupling SMRs with renewable energy sources can provide dispatchable power while supporting decarbonization strategies. Uzbekistan's recent agreement to deploy RITM-200N SMRs further highlights the potential for hybrid systems to enhance energy security in fossil fuel-dependent regions.

Despite their numerous advantages, hybrid NPP-RES systems face several challenges, including technological complexity, regulatory uncertainties, and economic competitiveness. The transition from conventional baseload nuclear reactors to flexible hybrid configurations necessitates advancements in grid modernization, digital energy management systems, and energy storage infrastructure. Furthermore, the development of clear regulatory frameworks is essential to address licensing, operational flexibility, and nuclear fuel management for hybrid systems.

Public perception also plays a crucial role in the adoption of hybrid nuclear technologies. Concerns about nuclear safety, historical accidents, and waste disposal must be addressed through transparent communication, enhanced safety measures, and educational initiatives to build public confidence in nuclear-renewable integration.

Looking ahead, hybrid nuclear power plants represent a cornerstone of the future energy land-



scape. The development of SMRs, improved energy storage solutions, and hybrid nuclear-hydrogen facilities will further enhance the feasibility and competitiveness of these systems. As nations strive to achieve their decarbonization goals, investments in hybrid energy systems will play a pivotal role in shaping a sustainable, secure, and economically viable energy future. Continued research, policy support, and technological advancements will be essential to realizing the full potential of hybrid NPP-RES systems in achieving global energy transformation.

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