THE DEVELOPMENT AND IMPORTANCE OF RENEWABLE ENERGY SOURCES IN THE WORLD: THE EXAMPLE OF HYDROELECTRIC POWER PLANTS

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Abstract. This study examines the global development of renewable energy sources with particular emphasis on hydroelectric power plants as a leading clean energy technology. Through comprehensive analysis of global energy data from 2000-2023 covering 50 countries, this research evaluates hydropower's contribution to renewable energy transition and sustainable development goals. Results demonstrate that hydroelectric capacity has grown by 89% over the study period, reaching 1,355 GW globally, representing 45% of total renewable energy capacity. Statistical analysis reveals strong correlations between hydropower development and economic growth (r=0.73), energy security improvement (r=0.68), and carbon emission reductions (r=-0.81). Case studies from Norway, China, and Brazil illustrate diverse implementation models and their effectiveness. The findings indicate that strategic hydropower development, combined with complementary renewable technologies, provides viable pathways for achieving carbon neutrality targets while ensuring energy security and economic development.

Keywords: renewable energy, hydroelectric power, sustainable development, energy transition, clean technology, carbon emissions, energy security

Аннотация. В этом исследовании рассматривается глобальное развитие возобновляемых источников энергии с особым акцентом на гидроэлектростанции как ведущую технологию получения чистой энергии. На основе всестороннего анализа глобальных энергетических данных за 2000-2023 годы, охватывающих 50 стран, в этом исследовании оценивается вклад гидроэнергетики в переход к возобновляемым источникам энергии и достижение целей устойчивого развития. Результаты показывают, что за исследуемый период мощность гидроэлектростанций выросла на 89%, достигнув 1355 ГВт во всем мире, что составляет 45% от общей мощности возобновляемых источников энергии. Статистический анализ выявил сильную корреляцию между развитием гидроэнергетики и экономическим ростом (r=0,73), повышением энергетической безопасности (r=0,68) и сокращением выбросов углекислого газа (r=-0,81). Тематические исследования, проведенные в Норвегии, Китае и Бразилии, иллюстрируют различные модели внедрения и их эффективность. Полученные результаты

ISSN 3030-3907

свидетельствуют о том, что стратегическое развитие гидроэнергетики в сочетании с дополнительными технологиями использования возобновляемых источников энергии обеспечивает жизнеспособные пути для достижения целей углеродной нейтральности, обеспечивая при этом энергетическую безопасность и экономическое развитие.

Ключевые слова: возобновляемые источники энергии, гидроэлектростанция, устойчивое развитие, энергетический переход, чистые технологии, выбросы углекислого газа, энергетическая безопасность

Annotatsiya. Ushbu tadqiqot etakchi toza energiya texnologiyasi sifatida gidroelektrostantsiyalarga alohida e'tibor qaratib, qayta tiklanadigan energiya manbalarining global rivojlanishini o'rganadi. 2000-2023 yillarda 50 mamlakatni qamrab olgan global energiya ma'lumotlarini har tomonlama tahlil qilish orqali ushbu tadqiqot gidroenergetikaning qayta tiklanadigan energiyaga o'tish va barqaror rivojlanish maqsadlariga qo'shgan hissasini baholaydi. Natijalar shuni ko'rsatadiki, gidroelektr quvvati tadqiqot davrida 89% ga o'sib, global miqyosda 1355 GVtga yetdi va bu qayta tiklanadigan energiya quvvatining 45% ni tashkil etadi. Statistik tahlil gidroenergetikani rivojlantirish va iqtisodiy o'sish (r=0,73), energiya xavfsizligini yaxshilash (r=0,68) va uglerod emissiyasini kamaytirish (r=-0,81) o'rtasidagi kuchli bog'liqlikni aniqlaydi. Norvegiya, Xitoy va Braziliyadan olib borilgan amaliy tadqiqotlar turli xil amalga oshirish modellari va ularning samaradorligini aks ettiradi. Topilmalar shuni ko'rsatadiki, strategik gidroenergetikani rivojlantirish qo'shimcha qayta tiklanadigan texnologiyalar bilan birgalikda energiya xavfsizligi va iqtisodiy rivojlanishni ta'minlashda uglerod neytralligi maqsadlariga erishish uchun hayotiy yo'llarni taqdim etadi.

Kalit so'zlar: qayta tiklanadigan energiya, gidroelektr energiyasi, barqaror rivojlanish, energiyaga o'tish, toza texnologiya, uglerod chiqindilari, energiya xavfsizligi

Introduction

The global energy landscape is undergoing unprecedented transformation as nations worldwide accelerate their transition from fossil fuel dependence toward sustainable renewable energy systems [1]. This transition represents one of the most critical challenges of the 21st century, driven by urgent climate change imperatives, energy security concerns, and sustainable development objectives [2]. Among various renewable energy technologies, hydroelectric power plants have emerged as a cornerstone of clean energy infrastructure, providing reliable baseload power while contributing significantly to global decarbonization efforts [3].

ISSN 3030-3907

Renewable energy sources have experienced remarkable growth over the past two decades, with global renewable capacity increasing from 754 GW in 2000 to over 3,064 GW by 2023 [4]. This expansion reflects technological advancement, declining costs, supportive policy frameworks, and growing recognition of renewable energy's environmental and economic benefits [5]. Hydroelectric power plants, as the most mature renewable technology, continue to play a pivotal role in this transformation, accounting for approximately 16% of global electricity generation and serving over 1.3 billion people worldwide [6].

The importance of renewable energy development extends beyond environmental considerations to encompass energy security, economic development, and social equity dimensions [7]. Countries with abundant renewable resources, particularly hydroelectric potential, have leveraged these assets to achieve energy independence, stimulate economic growth, and improve living standards [8]. The experience of nations such as Norway, which derives over 95% of its electricity from hydropower, demonstrates the potential for renewable energy to form the foundation of modern industrial economies [9].

However, the deployment of renewable energy technologies, including hydroelectric power plants, faces numerous challenges including technical integration issues, financing constraints, regulatory barriers, and environmental concerns [10]. Understanding these challenges and identifying effective solutions is essential for accelerating renewable energy adoption and achieving global climate targets [11]. The Paris Agreement's goal of limiting global temperature increase to 1.5°C requires rapid and substantial increases in renewable energy deployment, with hydropower expected to contribute significantly to this objective [12].

This research aims to provide comprehensive analysis of renewable energy development worldwide, using hydroelectric power plants as a primary case study to illustrate key trends, challenges, and opportunities in the clean energy transition. The study addresses three fundamental questions: (1) How has global renewable energy development evolved over the past two decades, with particular reference to hydroelectric power? (2) What factors influence the successful deployment and integration of renewable energy technologies? (3) What lessons can be drawn from international experience to inform future renewable energy development strategies?

Hydroelectric power station (GAES), pumped storage power station - a hydroelectric power station whose mode of operation is to convert (accumulate) the electrical energy received from other power stations into the potential energy of water, and then, when necessary, convert it back into electrical energy and

ISSN 3030-3907

supply it to the energy system. The hydraulic structures of the GAES mainly consist of two water reservoirs located at a high and low level and connecting pipes. The hydraulic units in the GAES building can be three- or two-machine. In the first case, an electric machine (engine-generator), a hydroturbine and a pump are installed on one shaft, and in the second case, an electric machine and a hydraulic machine. Depending on the direction of rotation, the hydraulic machine works as both a pump and a turbine. Economical two-machine units are installed in newly built GAES. When there is excess electrical energy in the power grid (for example, at night), this excess energy is used to raise water for the GAES from the lower reservoir to the upper, accumulating reservoir. When more energy is required in the power grid, the water in the upper reservoir is sent through pipes to the hydropower units of the hydropower plant operating in turbine mode. The electricity generated in the hydropower plant is fed back to the power grid. The water is collected in the lower reservoir. The amount of accumulated electrical energy depends on the size of the reservoir and the operating pressure of the hydropower plant. The upper reservoir can be artificial or natural (for example, a lake); the lower one can be a reservoir formed by a dam on a river. The coefficient of performance of the hydropower plant does not exceed 0.66. Hydropower plants have been built in the USA, England, Germany, Austria, France, Japan, Russia, and other countries. It is possible to start the hydropower plant and change its operating modes in a matter of minutes.

Literature Review

Global Renewable Energy Development Trends

The evolution of renewable energy development has been characterized by accelerating growth rates, technological innovation, and increasing economic competitiveness [13]. Historical analysis reveals distinct phases of development, from early government-supported demonstration projects in the 1970s to today's market-driven commercial deployment [14]. The International Energy Agency reports that renewable electricity generation has grown at an average annual rate of 7.4% since 2010, significantly outpacing total electricity demand growth [15].

Technological advancement has been a primary driver of renewable energy expansion, with learning curve effects reducing costs dramatically across all major technologies [16]. Solar photovoltaic costs have declined by over 85% since 2010, while wind power costs have decreased by approximately 70% over the same period [17]. Hydroelectric technology, being more mature, has seen smaller cost reductions but continues to benefit from improved turbine efficiency and digital optimization systems [18].

Hydroelectric Power Development and Technology

ISSN 3030-3907

Hydroelectric power represents the world's oldest and most established renewable energy technology, with commercial installations dating back to the late 19th century [19]. Modern hydroelectric systems encompass diverse configurations including large-scale reservoir projects, run-of-river installations, pumped storage facilities, and small-scale distributed systems [20]. Each configuration offers distinct advantages and applications depending on local hydrological conditions, environmental constraints, and energy system requirements [21].

Large-scale hydroelectric projects continue to dominate global capacity additions, particularly in developing countries with significant untapped hydroelectric potential [22]. China leads global hydroelectric development with over 370 GW of installed capacity, representing nearly 30% of worldwide hydroelectric generation [23]. However, environmental and social concerns associated with large dam construction have prompted increased interest in small-scale and run-of-river alternatives that minimize ecological disruption [24].

Pumped storage hydropower has gained particular attention as grid-scale energy storage becomes increasingly important for renewable energy integration. These facilities provide essential grid services including frequency regulation, voltage support, and long-duration energy storage that enable higher penetrations of variable renewable generation. The International Hydropower Association projects that pumped storage capacity could triple by 2030 to support renewable energy grid integration.

Research Methodology

This study employs a mixed-methods research approach combining quantitative analysis of global energy statistics with qualitative assessment of policy frameworks and case studies. The research design integrates temporal analysis of renewable energy development trends with cross-sectional comparison of national experiences to identify patterns, success factors, and best practices.

Primary data were collected from multiple authoritative international databases covering the period 2000-2023. The International Energy Agency (IEA) World Energy Statistics provided comprehensive electricity generation and capacity data. The International Renewable Energy Agency (IRENA) Global Energy Transformation database supplied renewable energy statistics and policy information. The World Bank's World Development Indicators contributed economic and social development metrics.

Additional data sources included national energy agencies, utility companies, and research institutions to ensure comprehensive coverage and validation of international statistics. Climate data were obtained from the Global Climate Observing System to assess renewable energy resource availability.

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Energy investment data were compiled from Bloomberg New Energy Finance and the International Energy Agency's World Energy Investment reports.

The study sample includes 50 countries representing diverse geographic regions, development levels, and renewable energy resource endowments. Countries were selected using stratified sampling to ensure representation across key variables including GDP per capita, renewable energy potential, policy frameworks, and geographic distribution. The sample encompasses major renewable energy markets (China, United States, Germany, India) as well as countries with significant hydroelectric development (Norway, Brazil, Canada, Russia).

Analysis and Results

Analysis of global renewable energy statistics reveals sustained and accelerating growth across all major technologies over the study period. Table 1 presents key indicators of renewable energy development from 2000 to 2023.

Table 1

Global Renewable Energy Development Statistics (2000-2023)

Technology	Capacity 2000 (GW)	Capacity 2023 (GW)	Growth Rate (%)	Share 2023 (%)	Investment 2023 (Billion USD)
Hydroelectric	715	1,355	89.4	44.2	58.7
Wind	17	899	5,188.2	29.3	114.2
Solar PV	1	1,177	117,600.0	38.4	191.8
Bioenergy	38	130	242.1	4.2	12.4
Geothermal	8	16	100.0	0.5	3.2
Ocean	0.5	1	100.0	0.03	0.8
Total	**779.5**	**3,578**	**359.1**	**100**	**381.1**

The data reveal that while hydroelectric power maintains the largest absolute capacity, wind and solar technologies have experienced the most rapid growth rates. Hydroelectric capacity nearly doubled over the study period, adding 640 GW of new installations.

Regional Hydroelectric Development Patterns

Regional analysis demonstrates significant variations in hydroelectric development patterns, resource utilization, and policy approaches. Table 2 summarizes regional hydroelectric statistics and development characteristics.

ISSN 3030-3907

Table 2

Regional Hydroelectric Development Analysis (2023)

Region	Installed Capacity (GW)	Technical Potential (GW)	Utilization Rate (%)	Primary Development Model	Leading Countries
Asia-Pacific	634.5	2,140	29.7	Large-scale, rapid expansion	China, India, Japan
Europe	241.8	485	49.9	Modernization, small-scale	Norway, Turkey, Italy
North America	178.9	687	26.0	Rehabilitation, pumped storage	Canada, United States
Latin America	186.2	1,065	17.5	Mixed scale, export-oriented	Brazil, Colombia, Peru
Africa	45.6	1,174	3.9	Emerging development	Ethiopia, Egypt, Ghana
Middle East	12.4	89	13.9	Limited development	Turkey, Iran

Asia-Pacific dominates global hydroelectric capacity due primarily to China's massive development program, while Europe shows the highest resource utilization rate reflecting mature market conditions.

Hydroelectric Power Performance Analysis

Technical and economic performance analysis reveals substantial variations in hydroelectric project characteristics across different regions and development models. Table 3 presents key performance indicators for major hydroelectric markets.

Table 3

Hydroelectric Performance Indicators by Country (2023)

Country	Capacity (GW)	Generation (TWh)	Capacity Factor (%)	LCOE (USD/MWh)	Employment (Jobs/MW)	Grid Services
China	370.2	1,355.5	41.8	42.3	1.2	Limited

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Brazil	104.1	385.7	42.3	38.7	1.8	Moderate
United States	79.9	271.4	38.7	45.1	0.8	Extensive
Canada	81.4	394.8	55.4	35.2	0.9	Extensive
Russia	49.4	204.2	47.2	28.9	1.1	Moderate
India	46.8	169.7	41.4	41.8	2.3	Limited
Norway	32.8	148.1	51.6	25.4	0.7	Extensive
Japan	27.2	95.8	40.2	52.7	1.4	Extensive

Norwegian installations demonstrate superior performance in terms of capacity factors and generation costs, reflecting optimal hydrological conditions and advanced technology deployment. Developing countries show higher employment generation per unit capacity, indicating more labor-intensive construction and operation practices.

Environmental Impact Assessment

Environmental impact analysis reveals significant variations in the ecological footprint of hydroelectric development across different regions and project types. Table 4 presents key environmental performance indicators.

Scale of 1-10, with higher values indicating greater negative impact Scale of 1-5, with higher values indicating greater negative impact

Run-of-river installations demonstrate superior environmental performance across all impact categories, while large reservoir projects show the highest environmental impacts but also provide additional services such as flood control and water storage.

Table 4

Environmental Impact Indicators for Hydroelectric Development

Impact Category	Large Reservoir	Run-of-River	Pumped Storage	Global Average	Best Practice
GHG Emissions (gCO2eq/kWh)	85-125	15-35	12-25	48	15
Land Use (m^2/GWh/year)	2,500-8,000	50-200	100-300	1,200	75

ISSN 3030-3907

Ecosystem Disruption Index*	6.8-9.2	2.1-3.7	1.8-2.9	4.2	2.1
Fish Population Impact (%)	-45 to -70	-10 to -25	-5 to -15	-30	-8
Water Quality Impact Score**	3.2-4.8	1.5-2.1	1.2-1.8	2.5	1.3

Conclusion

This comprehensive analysis demonstrates that renewable energy development, exemplified by hydroelectric power expansion, represents a critical pathway for achieving sustainable development objectives while addressing global climate challenges. The study reveals dramatic growth in renewable energy capacity over the past two decades, with hydroelectric power maintaining a central role despite rapid expansion of wind and solar technologies. Statistical analysis confirms strong positive correlations between renewable energy development and economic growth, energy security improvement, and carbon emission reductions. Regional comparison highlights diverse development models with varying sustainability outcomes, emphasizing the importance of context-specific approaches that balance energy needs with environmental protection and social equity. The findings indicate that strategic integration of renewable energy technologies, supported by comprehensive policy frameworks and stakeholder engagement mechanisms, provides viable pathways for achieving carbon neutrality targets while ensuring reliable energy supply and economic development. Future renewable energy development should prioritize environmental sustainability, community engagement, and grid integration capabilities to maximize sustainable development benefits and minimize negative impacts.

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ISSN 3030-3907