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**ANALYSIS OF RENEWABLE ENERGY SOURCES
AND THEIR ROLE IN ELECTRICITY GENERATION**Scientific supervisor: **A.X. Sulliyev,**Master's student **N. Yesnazarov**

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Abstract. *The paper analyzes the technical and economic characteristics of renewable energy sources (RES) — solar, wind, hydropower, biomass, and geothermal energy. The main relationships determining electricity generation capacity are presented, and illustrative calculations are performed. The effect of solar module temperature on generated power and the power characteristic of a wind turbine are quantitatively evaluated. The results help determine the role of RES in the energy balance and the main constraints on their integration into the power system.*

Keywords: *renewable energy, solar power plant, wind turbine, capacity factor, LCOE.*

Introduction

The need for decarbonization and energy security in the global energy sector is driving rapid growth in the share of renewable energy sources. According to IRENA, 473 GW of new RES capacity was commissioned worldwide in 2023, bringing total installed capacity to 3,870 GW [1]. According to Ember analyses, RES accounted for approximately 30% of global electricity generation in the same year [3]. The International Energy Agency states that solar and wind power will remain the leaders in capacity additions over the next decade [2].

This direction is particularly important for Uzbekistan: solar irradiation is high across the country, and some regions also have sufficient wind potential. Therefore, the Strategy for the Transition of the Republic of Uzbekistan to a “Green” Economy for 2019–2030 sets the objective of increasing the share of RES [11]. Accordingly, evaluating the physical principles, actual generation indicators, and limitations of

each source is a relevant task. The purpose of this paper is to analyze the role of RES in electricity generation and to demonstrate, through illustrative calculations, the main relationships used to determine their power output.

Research Methods and Mathematical Model

The electricity generation chain based on RES is shown in Figure 1: primary energy (solar radiation, wind, water flow, heat) is converted into electrical energy by the corresponding device and transmitted to the grid through an inverter or synchronous generator and a transformer.

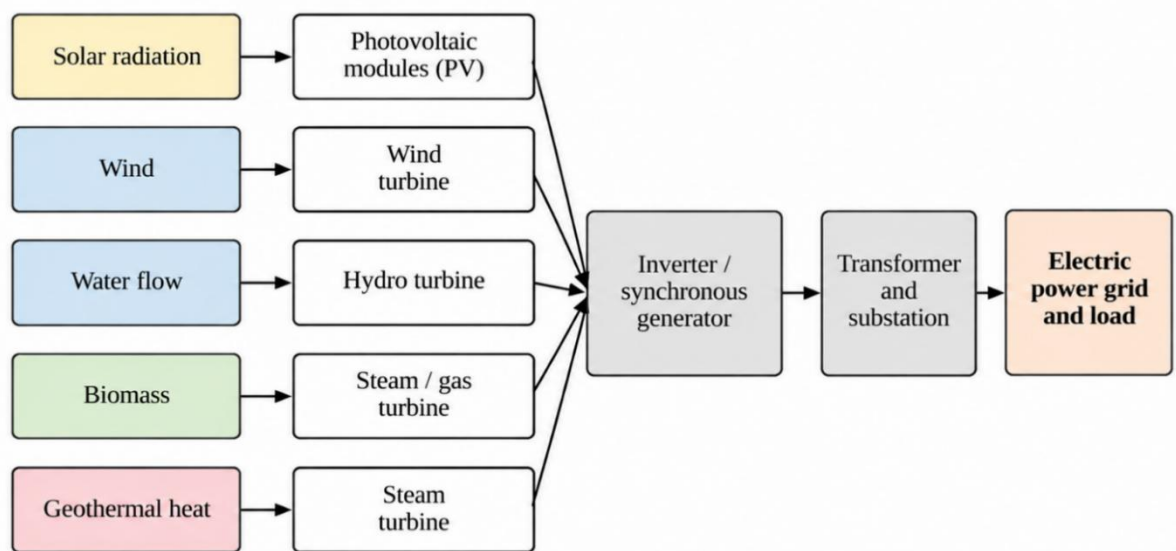


Figure 1. Electricity generation scheme based on RES

The power on the shaft of a wind turbine is determined from the kinetic energy of the air flow [5, 12]:

$$P_w = \frac{1}{2} \rho A v^3 C_p \quad (1)$$

where ρ is air density (1.225 kg/m^3), A is the rotor swept area, v is wind speed, and C_p is the power coefficient. According to Betz's law, the value of C_p theoretically cannot exceed the following limit [5]:

$$C_{p,max} = \frac{16}{27} \approx 0,593 \quad (2)$$

The statistical distribution of wind speed is described by the Weibull law:

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp \left[-\left(\frac{v}{c}\right)^k\right] \quad (3)$$

where k is the shape parameter and c is the scale parameter (m/s). The actual power of a photovoltaic (PV) module depends on irradiance and cell temperature [6]:

$$P_{pv} = P_{stc} \frac{G}{1000} [1 + \gamma(T_c - 25)] \quad (4)$$

$$T_c = T_a + \frac{NOCT - 20}{800} G \quad (5)$$

where G is irradiance (W/m^2), T_a is ambient temperature, γ is the temperature coefficient of power (approximately $-0.35\%/^{\circ}\text{C}$ for crystalline silicon), and NOCT is the nominal operating cell temperature. The power of a hydroelectric power plant and the annual efficiency of RES are determined as follows [7]:

$$P_h = \eta \rho g Q H \quad (6)$$

$$CF = \frac{E}{P_{nom} \cdot 8760} \quad (7)$$

where Q is water flow rate, H is head, E is annual generated energy (kWh), and P_{nom} is nominal power. The levelized cost of energy (LCOE) is used to compare the economic efficiency of the sources [4]:

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (8)$$

where I_t , M_t , and F_t are the investment, operation and maintenance, and fuel costs in year t ; E_t is the generated energy; r is the discount rate; and n is the service life.

Results and Discussion

Table 1 presents generalized comparative indicators for the main types of RES based on the literature [4, 7, 10, 12]. The LCOE values are global weighted averages for 2022 [4], while the capacity factor (CF) ranges are typical values that depend on local climatic conditions.

Table 1. Comparative indicators of renewable energy sources

Source	CF, %	LCOE, USD/kWh	Advantage	Main limitation
Solar (PV)	15–25	0,049	Modular, rapid construction	Daily variability
Wind (onshore)	25–45	0,033	Lowest cost	Dependence on wind speed
Wind (offshore)	35–50	0,081	High CF	Expensive infrastructure
Hydropower	30–60	0,061	Dispatchable	Water resources, ecology
Biomass	50–85	0,061	Stable generation	Feedstock logistics
Geothermal	70–90	0,056	Baseload	Geographical limitations

As shown in the table, onshore wind and photovoltaic power plants can compete with conventional sources in terms of cost; however, their CF values are lower and their generation is variable. In contrast, biomass, geothermal, and hydropower can operate as baseload or dispatchable capacity with high CF values.

Calculation example (wind). For a turbine with a rotor diameter of 90 m, $A = \pi \cdot 45^2 \approx 6362 \text{ m}^2$. According to equation (1), at $v = 10 \text{ m/s}$ and $C_p = 0.45$, $P_w = 0.5 \cdot 1.225 \cdot 6362 \cdot 10^3 \cdot 0.45 \approx 1.75 \text{ MW}$. Since power is proportional to the cube of wind speed, when the speed decreases by 20% (to 8 m/s), the power falls to $0.8^3 \approx 0.51$ of its initial value, i.e., almost by half. Figure 2a shows the calculated power characteristic of a 2 MW turbine.

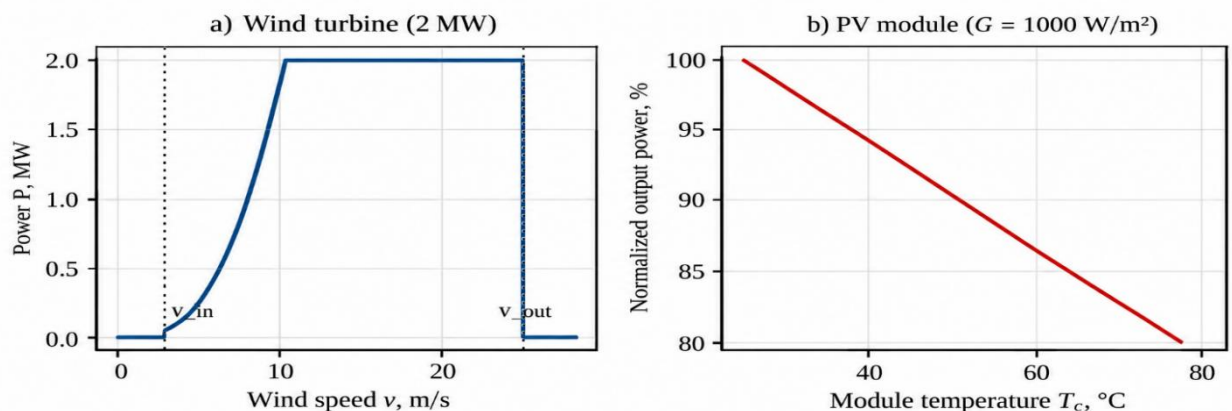


Figure 2. Wind turbine power characteristic (a) and dependence of PV module power on temperature (b)

Calculation example 2 (solar). Let $T_a = 40\text{ }^{\circ}\text{C}$, $G = 1000\text{ W/m}^2$, and $\text{NOCT} = 45\text{ }^{\circ}\text{C}$ on a summer day. According to equation (5), $T_c = 40 + (45 - 20)/800 \cdot 1000 \approx 71\text{ }^{\circ}\text{C}$. From equation (4), the power fraction is $1 + (-0.0035)(71 - 25) \approx 0.84$, meaning that the module loses approximately 16% of its nominal power (Figure 2b). Therefore, in hot-climate regions, it is advisable to account for temperature-related losses in plant design, provide module ventilation, or select modules with better high-temperature performance.

Calculation example 3 (annual generation). For a 100 MW solar power plant with $\text{CF} = 22\%$, equation (7) gives $E = 100 \cdot 8760 \cdot 0.22 \approx 192.7\text{ GWh/year}$. To generate the same amount of energy, a wind farm with $\text{CF} = 40\%$ would require a capacity of approximately 55 MW. This shows that planning these sources requires consideration not only of nominal capacity but also of CF.

The role of RES in the system is not limited to the amount of energy generated. Because solar and wind power plants are connected through inverters, they reduce system inertia and short-circuit power, which affects frequency and voltage stability [8, 9]. Therefore, as the share of RES increases, coordinated planning is required with dispatchable sources such as hydropower and biomass, energy storage systems, and expansion of the electrical grid [8, 13].

Conclusion

The analysis shows that: 1) RES are leading global capacity additions and provide a significant share of electricity generation; 2) onshore wind and solar power plants have the lowest LCOE, but because of their lower CF, greater installed capacity is required to produce the same annual energy; 3) wind power depends on the cube of wind speed, while PV module power decreases by approximately 0.35% for each $1\text{ }^{\circ}\text{C}$ increase in temperature — these losses must be considered in design;

4) reliable integration of a high share of RES into the power system requires an integrated approach combining dispatchable sources and energy storage facilities.

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