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CHAPTER 4

CHOICE OPTIMIZATION OF THE TYPE OF ENERGY RESOURCE FOR THE REGION

ABSTRACT

The work is devoted to a close analysis of the state and prospects for the development of the energy complex of Ukraine. The aim of the study is to develop a methodology for selecting and substantiating the predominant type of energy resources for energy supply of regions.

The state of use of available energy resources, their share in the total volume of energy production is clarified. The advantages and disadvantages of available resources in connection with their impact on the environment are considered.

It is proved that the predominant amount of energy is produced using traditional fossil and produced resources: coal, oil, gas and nuclear fuel. Energy production traditionally follows the availability of resources in the region and the need for energy, which creates an uneven concentration of industry and its accompanying environmental impact.

The use of a complex indicator for assessing the efficiency of types of energy resources and the impact of their use on the state of the environment is proposed. A methodology for using the proposed complex indicator to substantiate the energy strategies of regions is developed.

KEYWORDS

Energy resource, hydropower, wind power, solar power plants, bioenergy, thermal power, nuclear power, efficiency and pollution index, energy strategies, regions.

In the modern world, energy is the basis for the development of basic industries that determine the progress of social production.

According to British Petroleum in 2022 [1]. 29,165.1 TWh of electricity were produced in the world. Among the main sources of electricity generation by type of resource are: oil – 728.6 TWh (2.5 %); gas – 6,631.4 TWh (22.7 %); coal – 1,031.2 TWh (35.4 %); nuclear – 2,679.0 TWh (9.2 %); hydro – 4,334.2 TWh (14.9 %); renewable – 4,204.3 TWh (14.4 %); other – 270.5 TWh (0.9 %) (**Table 4.1**).

According to Reuters, the Energy Institute's Statistical Review of World Energy in 2023 [2] reports that total global primary energy consumption reached a historic high of 620 exajoules (EJ) (620 1018 J), and emissions exceeded 40 gigatons of CO_2 for the first time. Fossil fuel use in 2023 increased by 1.5 % to 505 EJ, accounting for 81.5 % of total energy consumption, down 0.5 % from 2022. Oil consumption in 2023 exceeded 100 million barrels per day for the first time in history.

Table 4.1 Global electricity production in 2022 by resource type, according to British Petroleum

Place of production		Oil	Gas	Coal	Nuclear	Hydro	Renewable	Other	Total
Worldwide	TWh	728.6	6,631.4	10,317.2	2,679.0	4,334.2	4,204.3	270.5	29,165.1
	%	2.5	22.7	35.4	9.2	14.9	14.4	0.9	–
European Union	TWh	43.9	556.2	461.2	608.6	276.9	801.7	63.5	2,812.0
	%	1.6	19.8	16.4	21.6	9.8	28.5	2.3	–
Ukraine	TWh	0.5	7.2	24.8	62.1	11.1	7.0	–	112.7
	%	0.4	6.4	22.0	55.1	9.8	6.2	–	–

Source: [1]

Total electricity generation in 2023 grew by 2.5 %, slightly higher than the 2.3 % increase in the previous year. Renewable fuel generation (excluding hydropower) increased by 13 % to a new record high of 4,748 terawatt-hours (TWh). The share of renewable energy sources in the total energy balance excluding hydropower was 8 %, compared to 7.5 % in the 2022 report.

Including hydropower, renewable energy sources account for 15 % of the global balance. The record growth in renewable generation was driven by increases in wind and solar capacity: in 2023, the capacity growth in these two categories was 67 % higher than in 2022.

The 2 % increase in emissions (over 40 gigatons of CO_2) in 2023 is due to more intensive consumption of oil and coal, while gas consumption has remained stable.

This figure is expected to increase to 3.3 % in 2024 due to the improvement of the global economic outlook [3].

By 2030, the global demand for electricity may amount to 33,275 TWh [4]. The Ministry of Energy and Coal Industry predicts an increase in electricity consumption in Ukraine by 86 % by 2030 to 280 billion kWh [5].

4.1 STATE AND PROSPECTS FOR THE DEVELOPMENT OF THE ENERGY SECTOR OF UKRAINE

According to the Energy Strategy of Ukraine [6], the share of renewable energy sources in the structure of electricity production by 2030 will be 13 %.

The main directions of development of RES until 2030 (**Table 4.2**) and further prospects are:

– use of wind energy and hydropower for electricity production;

– use of solar and geothermal energy – for electricity and heat production;

– utilization of biomass waste, solid household waste, etc. – by burning or obtaining biogas for heat and electricity production.

Table 4.2 Promising directions and levels of development of renewable energy sources in Ukraine until 2030

Indicators	Production of thermal and electrical energy from renewable sources in 2020–2030			
	2020		2030	
	MTOE	%	MTOE	%
Wind energy	1.00	6.97	2.15	9.95
Photovoltaics	0.01	0.07	0.03	0.14
Small hydropower	0.48	3.36	0.65	3.01
Large hydropower	5.6	39.06	6.53	30.23
Solar thermal collectors	0.7	4.88	1.28	5.93
Bioenergy	6.3	43.93	10.13	46.9
Geothermal energy	0.247	1.73	0.83	3.84
TOTAL	14.34	100	21.6	100

In 2022–2024, the entire Ukrainian energy sector found itself in the epicenter of a full-scale war, therefore, the information component of the performance indicators of electricity production subsectors in the materials provided is based on data from the pre-war period (until 2022).

In 2021, the share of electricity generated from renewable energy reached 8.1 % or 12.8 TWh, of which 56 % was due to solar radiation, 33 % to wind energy, almost 8 % to biomass and biogas combustion, and 3 % to small hydropower [7].

Thus, in 2021, all RES power plants produced 12,804 million kWh [7] of clean electricity, which exceeded last year's figures by 1,941.9 million kWh or 17.8 %:

– Ukrainian wind power plants produced 3,866 million kWh or 614.4 million kWh more compared to 2020, which is 2.9 7 % of total electricity production;

– solar power plants produced 7,670 million kWh or 4.8 %, which is 1,065.4 million kWh more than the amount of electricity produced in the same period of 2020;

– small hydropower plant generation increased by 56.1 million kWh, reaching 276 million kWh or 0.17 % of the total balance;

– Ukrainian bioenergy plants generated 992 million kWh or 0.6 %, which is 206 million kWh more than the previous year's production level.

4.1.1 HYDROPOWER

In 2019, in the Unified Energy System (UES) of Ukraine, with a total capacity of all generating sources of 52.7 million kW and a total production of 154 billion kWh, the capacity of hydroelectric power plants (HPPs) and pumped storage power plants (PSPPs) amounted to 12 % of the total capacity, and the production without small HPPs amounted to 7.87 billion kWh (5.1 % of the total production) [8, 9], including:

1) large HPPs of the Dnipro and Dniester cascades (taking into account the first stage of the reconstruction of the Dnipro cascade HPP), respectively:

– Dnipro cascade HPP (capacity 3.92 million kW, production 9.42 billion kWh);

– Dniester cascade HPP (capacity 0.74 million kW, production 1.01 billion kWh);

2) small hydroelectric power plants (Tereblia-Rikska on the Tereblia River, Oleksandrivska on the Southern Bug River) with a total capacity of 0.041 million kW and a production of 0.23 billion kWh;

3) small hydroelectric power plants (SHPs up to 10 MW) with a total capacity of 0.1 million kWh and a production of about 0.3 billion kWh (according to the existing classification, small hydroelectric power plants (SHPs) include hydroelectric power plants with a capacity of 1 to 10 MW, mini hydroelectric power plants – from 200 to 1000 kW, and micro hydroelectric power plants – no more than 200 kW).

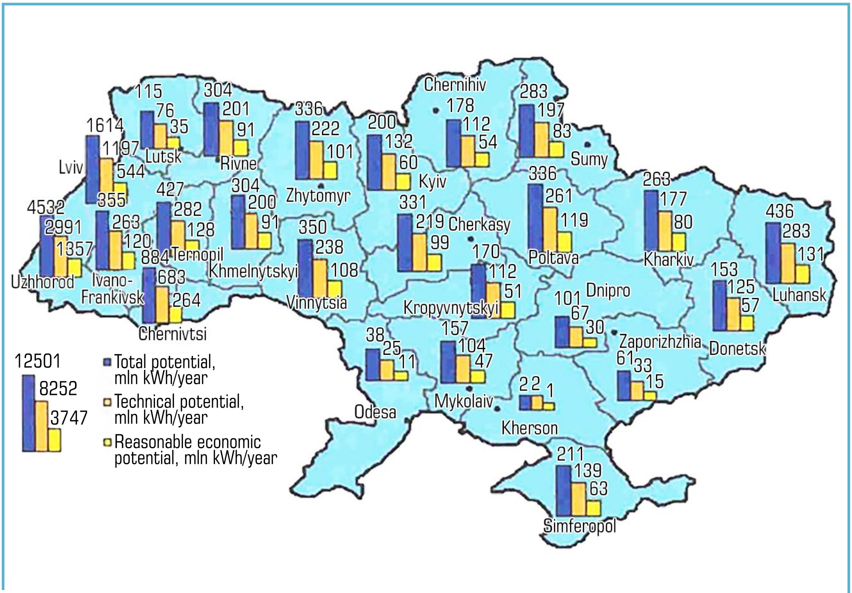


Fig. 4.1 Hydropower potential of small rivers of Ukraine

The total installed capacity of pumped storage power plants (PSPPs) (in turbine mode) is 1.5 million kW, production – 1.5 billion kWh, including:

– Kyiv PSPP (capacity – 0.23 million kW, production –0.226 billion kWh);

– three units of Dniester PSPP (capacity – 0.97 million kW, production –1.02 billion kWh);

– two units of Tashlyk PSPP (capacity – 0.3 million kW, production –0.23 billion kWh).

According to the Institute of Renewable Energy of the National Academy of Sciences of Ukraine, the hydropower potential of small rivers is about 12.5 billion kWh, which is about 28 % of the total hydropower potential of all rivers in Ukraine [10]. The potential by region of Ukraine is shown in **Fig. 4.1** [11].

The main disadvantage of the construction of SHPPs is the threat of disrupting the natural state of the ecological system.

Environmental protection. Potentially, the construction of hydropower facilities changes the landscape and land use conditions, ecological chains in the relevant rivers, water temperature and quality, affects biodiversity, can lead to increased greenhouse gas emissions as a result of intensification of organic compound decomposition processes, etc.

4.1.2 WIND POWER

For Ukraine, wind power plants (WPPs) are a new industry, their contribution to energy supply is currently not significant (6.97 % in the overall structure of electricity production in Ukraine, **Table 4.1**), and while it is in its infancy.

According to the draft of the updated Energy Strategy, Ukraine has significant potential for the development of wind power. The most promising areas for its development are the southern and southeastern regions of the country, where the average wind speed exceeds 5 meters per second (see the areas shaded in brown and red in **Fig. 4.2**).

Most often, to ensure the economic efficiency of WPP construction, the minimum required average annual wind speed should be 2.0–4.5 m/s. To reliably ensure the efficient operation of WPP, the average annual wind speed should be in the range from 5 m/s to 25 m/s [12].

At the end of 2021, the total capacity of the wind energy sector in mainland Ukraine reached 1,672.9 MW [7]. Installed wind energy capacity by regions of mainland Ukraine in the first half of 2021, MW is shown in **Fig. 4.3** [13].

It should also be noted that in the first half of 2021, 73 new wind turbines with a total capacity of 278.4 MW were put into operation in three regions of Ukraine [13]:

– the first stage of the Dniester WPP with a total capacity of 40 MW in the Odessa region;

– the first stage of the Zaporizhzhia WPP with a total capacity of 98 MW in the Zaporizhzhia region;

– the second stage of the Syvash WPP with a total capacity of 140.4 MW in the Kherson region.

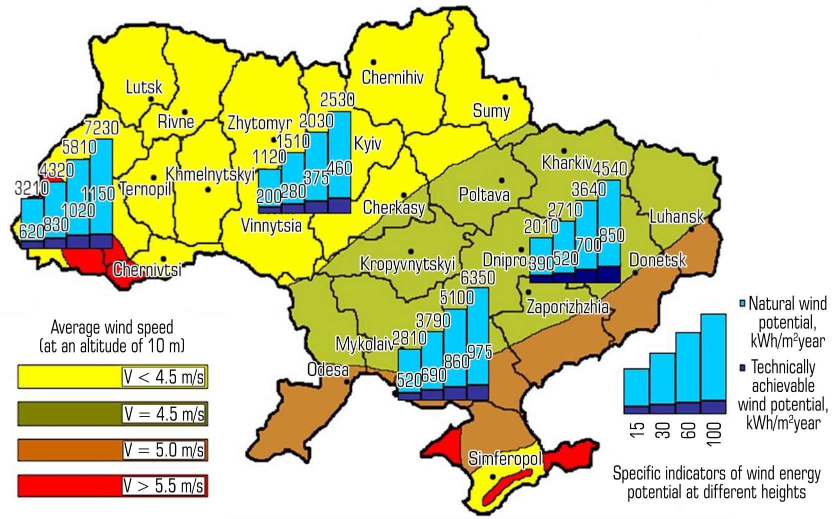


Fig. 4.2 Wind energy potential in Ukraine

Source: [11]

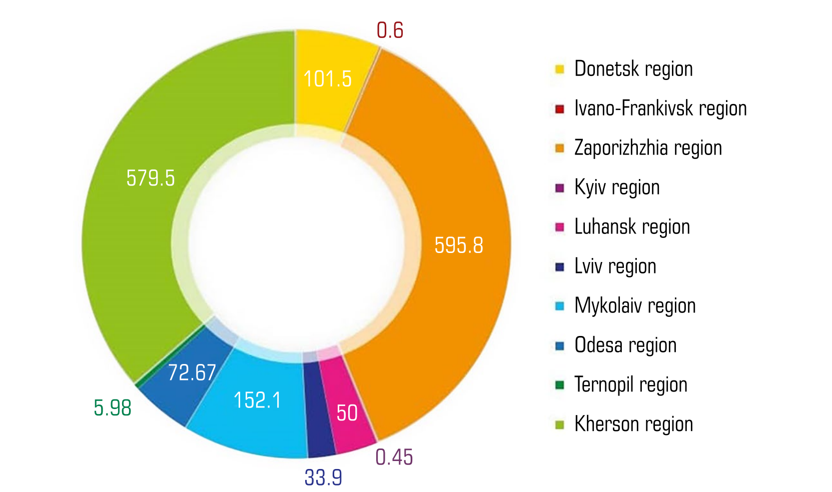


Fig. 4.3 Installed wind power capacity by regions of mainland Ukraine in the first half of 2021, MW

Source: [13]

4.1.2.1 DISADVANTAGES OF MODERN WIND POWER PLANTS

Along with the obvious advantages of wind power plants (autonomy, available energy resource, etc.), one cannot fail to note the characteristic disadvantages [14]:

1. Instability and wind dependence. It is impossible to accurately predict how much electricity will be received in a certain period of time, and in the absence of wind, energy production will completely cease.

2. High construction cost. Installation of a plant capable of producing 1 MW of electricity is more than 1 million USD.

3. Interference with radio communications and telecommunications. The operation of wind power plants causes signal distortion.

4. Change in the natural landscape.

5. Large area required to install an entire generator unit.

6. Danger to living creatures. The blades of turbines that constantly rotate pose a potential threat to certain species of living organisms, in particular, birds. For example, according to statistics, such turbines are the cause of the death of about 5 birds per year.

7. Noise pollution (up to 50 decibels at a distance more than 1 km). The noise created by «windmills» causes concern not only for wildlife, but also for people living near such structures.

8. The emergence of dangerous infrasound with a frequency of 6–7 Hz, which causes vibration.

9. Low energy output. Wind generators are much smaller in rank than other sources of electricity. Wind turbines are inefficient at high loads.

4.1.3 SOLAR ENERGY

Solar energy is one of the new types of energy production based on renewable sources, in particular, solar energy. The main goal is to convert solar radiation into other technological types of energy.

In Ukraine, as of the end of the first half of 2021, the total installed capacity of solar power plants (SPPs) is 7284 MW, including:

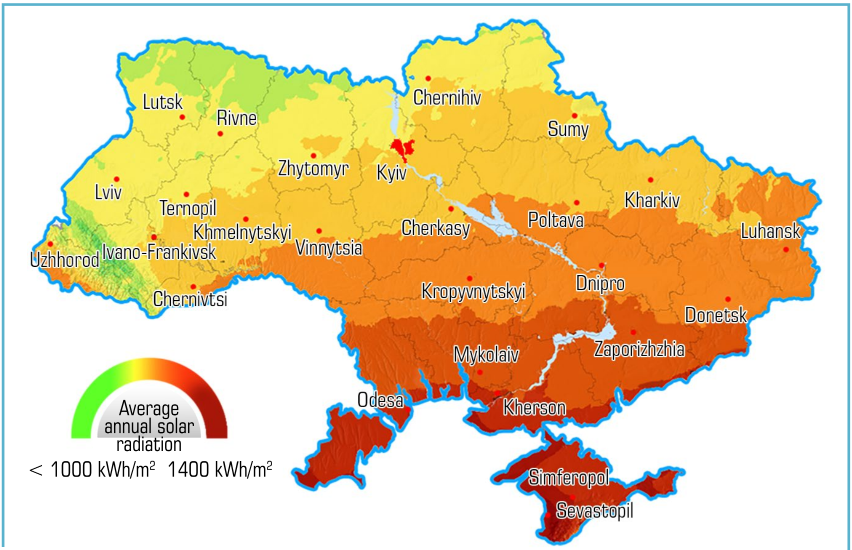
– 6,351 MW – solar power plants;

– 933 MW – household SPPs.

The main determining factors in the use of solar energy are the intensity of solar radiation (**Fig. 4.4**) and the duration of sunshine hours (Fig. 4.5).

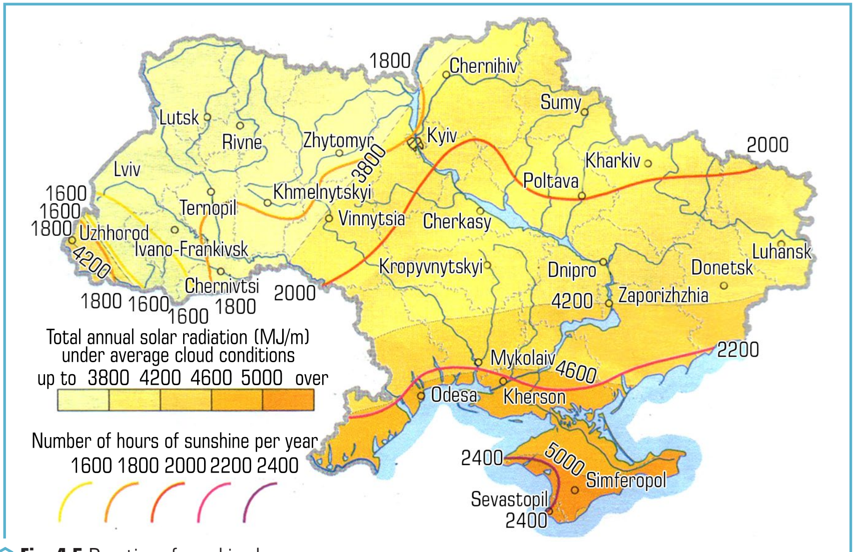
Solar radiation intensity is the power of the Sun's radiation per unit surface area, measured in watts per square meter (W/m^2).

To calculate the amount of solar radiation that is converted into thermal energy, it is also necessary to take into account the duration of radiation (**Fig. 4.5**). The total energy of solar radiation is the power for a selected period of time, measured as watt-hours (W·h). The period can be taken as: day, month, year, etc.



⬡ **Fig. 4.4** Solar energy potential in Ukraine

Source: [15]



⬡ **Fig. 4.5** Duration of sunshine hours

Source: [16]

The maximum daily total solar radiation in Ukraine is about 8 kWh/m^2 in the summer. Sometimes on a sunny winter day, the total solar radiation can reach a value of up to 3 kWh/m^2.

The total average annual solar radiation in the territory of Ukraine, according to long-term observations, varies from 1,000 kWh/(m^2) in the northern and central parts of the country to 1,350 kWh/(m^2) in the Crimean Peninsula and the southern part of the Odesa region. For the convenience of analysis, these calculations were divided into 4 zones.

All southern regions of Ukraine are located in the first and second zones; more than half of the country's territory is located in the third zone, the fourth zone is the least favorable for the use of solar energy.

The highest value of solar radiation in the first zone is 1350 kWh/km^2 per year, and the lowest is in the fourth zone 1000 kWh/km^2 per year. In the second and third zones, these values are, respectively, 1250 kWh/km^2 and 1150 kWh/km^2 per year. In general, the territory of Ukraine belongs to the zone of medium solar intensity. The average monthly level of solar radiation for Ukrainian cities is given in **Table 4.3** [17].

Table 4.3 Average monthly level of solar radiation (solar constant) in Ukrainian cities (kWh/m^2/day). Average over the last 22 years

Regions / Months	January	February	March	April	May	June	July	August	September	October	November	December	Average
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Simferopol	1.27	2.06	3.05	4.30	5.44	5.84	6.20	5.34	4.07	2.67	1.55	1.07	3.58
Vinnytsia	1.07	1.89	2.94	3.92	5.19	5.3	5.16	4.68	3.21	1.97	1.10	0.9	3.11
Lutsk	1.02	1.77	2.83	3.91	5.05	5.08	4.94	4.55	3.01	1.83	1.05	0.79	2.99
Dnipro	1.21	1.99	2.98	4.05	5.55	5.57	5.70	5.08	3.66	2.27	1.20	0.96	3.36
Donetsk	1.21	1.99	2.94	4.04	5.48	5.55	5.66	5.09	3.67	2.24	1.23	0.96	3.34
Zhytomyr	1.01	1.82	2.87	3.88	5.16	5.19	5.04	4.66	3.06	1.87	1.04	0.83	3.04
Uzhhorod	1.13	1.91	3.01	4.03	5.01	5.31	5.25	4.82	3.33	2.02	1.19	0.88	3.16
Zaporizhzhia	1.21	2.00	2.91	4.20	5.62	5.72	5.88	5.18	3.87	2.44	1.25	0.95	3.44
Ivano-Frankivsk	1.19	1.93	2.84	3.68	4.54	4.75	4.76	4.40	3.06	2.00	1.20	0.94	2.94
Kyiv	1.07	1.87	2.95	3.96	5.25	5.22	5.25	4.67	3.12	1.94	1.02	0.86	3.10
Kropyvnytskyi	1.20	1.95	2.96	4.07	5.47	5.49	5.57	4.92	3.57	2.24	1.14	0.96	3.30
Luhansk	1.23	2.06	3.05	4.05	5.46	5.57	5.65	4.99	3.62	2.23	1.26	0.93	3.34
Lviv	1.08	1.83	2.82	3.78	4.67	4.83	4.83	4.45	3.00	1.85	1.06	0.83	2.92
Mykolaiv	1.25	2.10	3.07	4.38	5.65	5.85	6.03	5.34	3.93	2.52	1.36	1.04	3.55
Odesa	1.25	2.11	3.08	4.38	5.65	5.85	6.04	5.33	3.93	2.52	1.36	1.04	3.55

Continuation of Table 4.3

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Poltava	1.18	1.96	3.05	4.00	5.40	5.44	5.51	4.87	3.42	2.11	1.15	0.91	3.25
Rivne	1.01	1.81	2.83	3.87	5.08	5.17	4.98	4.58	3.02	1.87	1.04	0.81	3.01
Sumy	1.13	1.93	3.05	3.98	5.27	5.32	5.38	4.67	3.19	1.98	1.10	0.86	3.16
Ternopil	1.09	1.86	2.85	3.85	4.84	5.00	4.93	4.51	3.08	1.91	1.09	0.85	2.99
Kharkiv	1.19	2.02	3.05	3.92	5.38	5.46	5.56	4.88	3.49	2.10	1.19	0.9	3.26
Kherson	1.30	2.13	3.08	4.36	5.68	5.76	6.00	5.29	4.00	2.57	1.36	1.04	3.55
Khmelnytskyi	1.09	1.86	2.87	3.85	5.08	5.21	5.04	4.58	3.14	1.98	1.10	0.87	3.06
Cherkasy	1.15	1.91	2.94	3.99	5.44	5.46	5.54	4.87	3.40	2.13	1.09	0.91	3.24
Chernihiv	0.99	1.80	2.92	3.96	5.17	5.19	5.12	4.54	3.00	1.86	0.98	0.75	3.03
Chernivtsi	1.19	1.93	2.84	3.68	4.54	4.75	4.76	4.40	3.06	2.00	1.20	0.94	2.94

Note: according to NASA

In most cases, the average annual solar radiation intensity level of 11–12 kWh/m^2 is sufficient for the construction of a solar power plant to be economically feasible.

Based on the intensity of solar radiation, which is the main factor determining the power of a photovoltaic cell, the SPP parameters are calculated. The electrical power (N, W) for a solar power plant with photovoltaic cells is determined by the formula [18]:

$$N=\eta_{PV}\cdot F_{PV}\cdot I, \quad (4.1)$$

where η_{PV} – efficiency of photovoltaic converters (0.12–0.17); F_{PV} – total area, m^2; I – solar radiation intensity, W/m^2.

4.1.3.1 DISADVANTAGES OF SOLAR ENERGY

The existing advantages of solar energy (silence, autonomy, available energy resource, etc.) are reduced by significant disadvantages.

Intermittent cycle. Dependence on weather and time of day. Energy can only be generated during the day in clear weather. In adverse weather conditions (cloudy weather), solar panels simply do not work, which leads to a sharp reduction in the production of electricity by SPPs.

Low power per square meter. One of the most important parameters of electricity is the average power density per square meter (m^2), which is measured in W/m^2 and the amount of energy that can be obtained from a unit of area. For solar energy, this figure is on average 170 W/m^2, this value is greater than for all used renewable energy sources, but compared to traditional energy sources (oil, coal, gas, nuclear energy), this figure is much lower. Which leads to an increase in the area of solar panels for the production of 1 kW of energy.

Impact on the ecosystem. Solar vacuum power plants are equipped with mirrors with precise focus. If a bird falls into the focus of the mirrors, it dies instantly. According to some sources, one bird dies every two minutes above large solar installations.

Environmental pollution. Solar energy as a source is the most environmentally friendly type of energy. But for its production it is necessary to produce solar panels, during the production and utilization of which greenhouse gases are emitted into the atmosphere, and chemical compounds containing: lead, cadmium, gallium, arsenic, etc. [18], which are dangerous for the environment and humans.

4.1.4 BIOENERGY

Bioenergy is a branch of the global energy industry based on the production and use of biofuels based on the use of biomass, including the following technologies: direct combustion and pyrolysis of wood fuel and solid household waste; biogas technologies; production of liquid biofuels for vehicles.

Biomass is biologically renewable substances of organic origin that undergo biological decomposition (wastes from agriculture (crop and livestock farming), forestry and technologically related industries, as well as the organic part of industrial and household waste).

The main sources of biomass for use in energy purposes can be divided into primary and secondary (waste).

Primary sources are biomass of trees, shrubs, some perennial grasses, algae. For these purposes, special "energy plantations" of fast-growing crops in natural conditions such as willow, poplar, reed, corn, oats, sorghum and others are created for their direct use as biofuel in power plants of thermal power plants, in boiler rooms, etc.

Secondary sources include:

– waste from the forestry, woodworking and pulp and paper industries, agricultural waste – residues of primary biomass (straw, husks of grain crops, oilseed cake) and waste from livestock and poultry farming (manure, litter);

– industrial liquid waste from industrial production (food industry, sugar industry, winemaking, etc.);

– municipal waste from urban treatment plants and landfills.

Depending on the sources and properties of organic raw materials, various technologies for its transformation and energy use are possible. The simplest classification divides the initial raw materials into "dry" (for example, wood waste) and "wet" (for example, livestock farm effluents). For the use of dry biomass, thermochemical technologies (direct combustion, gasification, pyrolysis) are most effective. For wet biomass, biochemical processing technologies with the production of biogas (anaerobic decomposition of organic raw materials) or liquid biofuels (alcoholic fermentation processes, etc.) are used.

Solid fuels include: firewood and their new modifications: fuel granules and briquettes, including pellets, which are pressed products from wood waste (sawdust, chips, bark, substandard wood, logging residues), straw, agricultural waste (sunflower husks, nut shells, manure), etc.

As a result of the application of modern thermochemical and biotechnologies, the energy stored in biomass is converted into biofuel, heat and electricity.

The most common types of biomass used as raw materials for obtaining fuel and using it to produce electricity or heat include:

– straw, corn stalks, sunflower; husks and other waste from processing sunflower, grain and other agricultural crops, etc. (in the processing process, granules (pellets), briquettes are obtained);

– annual and perennial plant biomass, energy plants (energy willow, sorghum, miscanthus, millet, etc.);

– wood, its waste and products of its processing (in the processing process, granules, pellets, briquettes are obtained);

– livestock and poultry waste;

– vegetable crop waste and their processing;

– plant waste from the food industry, peat;

– fruit biomass, etc.

For energy production, solid biomass is used, as well as liquid and gaseous fuels obtained from it: biogas, biodiesel, bioethanol [19].

Biomass can also be used for energy purposes by direct combustion (wood, straw, sewage sludge), as well as in the processed form of liquid (rapeseed oil esters, alcohols, liquid pyrolysis products) or gaseous biofuels (biogas from agricultural and crop waste, sewage sludge, solid household waste, gasification products of solid fuels) (**Fig. 4.6**).

Renewable energy production is rapidly developing in most European countries and the USA.

The annual growth of biomass in the world is estimated at 200 billion tons in terms of dry matter, which is energy equivalent to 80 billion tons of oil.

During 2021, 992 million kWh of "green" electricity was produced in Ukraine from biomass and biogas, which is 7.7 % of the total electricity production from renewable sources in 2021 [20]. According to the Ministry of Energy, bioenergy in Ukraine as of 2021 operated with a total capacity of 275.9 MW [20].

The steady trend of increasing biomass energy production observed in Ukraine indicates its desire to comply with global trends in the development of alternative energy. In terms of resources, the presence in the country of powerful agricultural and forestry enterprises, with a favorable climate and large areas of free land suitable for traditional agricultural production creates all the necessary prerequisites for an increase in the share of biofuels produced from biomass. The agrarian orientation of the economy of our state determines the state's special interest in the priority development of the bioenergy complex, the foundation of which will be built in agriculture. Over the past 20 years, the supply of primary energy from biomass and biofuels in the world has increased by a third and is about 11 % of the total primary energy supply (TPES), or almost 70 % of TPES from renewable sources. The supply of primary energy from biofuels and waste reached 4.241 million tons of oil equivalent in 2020, which replaces about 5.2 billion m^3 of natural gas (**Fig. 4.7**) [21].

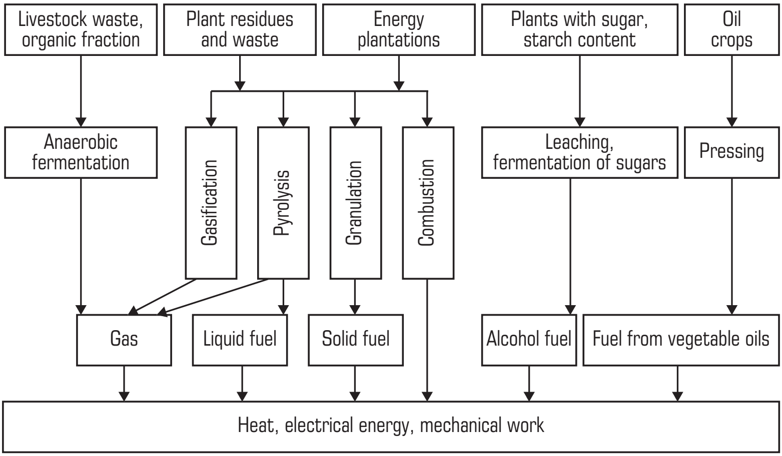


Fig. 4.6 Methods of energy production from biomass
Source: [19]

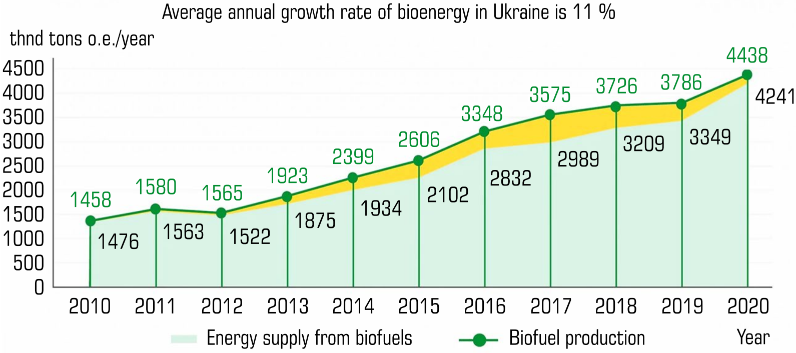


Fig. 4.7 Primary energy supply from biofuels

Ukraine has a large potential of biomass available for energy production, which is a good pre-requisite for the dynamic development of the bioenergy sector. The economically feasible energy potential of biomass in the country is about 20–25 MTOE per year. The main components of the potential are agricultural waste (straw, corn stalks, sunflower stalks, etc.) – more than 11 MTOE per year (according to 2015 data) and energy crops – about 10 MTOE per year. At the same time, agricultural waste is a real part of the biomass potential, and data on energy crops reflect the amount of biomass that can be obtained by growing these crops on free land in Ukraine. It should be noted that this process has been actively developing in the last few years.

Every year in Ukraine, about 2 million tons of biomass of various types are used for energy production. Wood accounts for the highest percentage of use of economically feasible potential – 80 %, while for other types of biomass (except for sunflower husks) this figure is an order of magnitude lower. The least actively (at the level of 1 %) is the energy potential of straw of grain crops and rapeseed (**Table 4.4**) [22].

Table 4.4 Energy potential of biomass in Ukraine

Biomass type	Theoretical potential, million tons	Part available for energy production, %	Economic potential, MTOE
Cereal straw	32.8	30	3.36
Rapeseed straw	4.9	40	0.68
By-products of corn production (stalks, cobs)	46.5	40	3.56
By-products of sunflower production (stalks, baskets)	26.9	40	1.54
Secondary agricultural residues (sunflower husks)	2.4	100	1.00
Wood biomass (fuel wood, logging residues, wood processing waste)	8.8	96	2.06
Wood biomass (deadwood, wood from protective forest belts, waste from pruning and uprooting of perennial agricultural plantations)	8.8	45	1.02
Biodiesel (from rapeseed)	–	–	0.39
Bioethanol (from corn and sugar beets)	–	–	0.82
Biogas from waste and by-products of the agricultural and industrial complex	2.8 billion m^3 CH_4	42	0.99
Biogas from solid waste landfills	0.6 billion m^3 CH_4	29	0.14
Biogas from wastewater (industrial and municipal)	0.4 billion m^3 CH_4	28	0.09
Energy plants:			
– willow, poplar, miscanthus	11.5 billion m^3 CH_4	100	4.88
– corn (for biogas)	3.0 billion m^3 CH_4	100	2.57
Peat	–	–	0.40
Total	–	–	23.10

Source: [22]

The potential for "total primary energy supply from biofuels and waste" by 2050 is given in **Table 4.5** [22].

Table 4.5 Summary indicators of the Roadmap for the development of bioenergy in Ukraine by 2050

Year	Installed capacity		Biofuel consumption*, MTOE	Natural gas displacement, billion m³	Gasoline and diesel displacement, million tons	CO_2 emissions reduction, million tons per year
	MWt	MWel				
2020	8,206	202	3.77	4.34	0.17	8.90
2025	12,276	844	5.83	6.35	0.25	14.31
2030	19,087	1,846	8.57	9.11	0.39	21.35
2035	30,237	2,804	12.01	12.62	0.50	30.37
2040	39,338	3,609	15.13	15.77	0.67	38.66
2045	45,351	4,299	17.64	17.98	0.96	45.79
2050	49,655	5,230	20.28	19.92	1.23	54.40

Source: [22]

4.1.4.1 ADVANTAGES AND DISADVANTAGES OF BIOENERGY

The main advantages of bioenergy [23] are the utilization of organic waste, reducing environmental pollution. Biofuels are made from various raw materials, such as manure, crop waste and plants grown specifically for fuel. These are renewable resources that are unlikely to run out in the near future. Biofuels reduce greenhouse gas emissions. In addition, when growing crops for biofuels, they partially absorb carbon monoxide, which makes the biofuel system even more sustainable.

Biofuels are quite easy to transport, they have stability and a fairly high "energy density", they can be used with minor modifications to existing technologies and infrastructure.

The **disadvantages** of biofuels [23] include:

– limitations in regional suitability (in some areas it is simply impossible to grow biofuel crops, for example in areas with a cold or arid climate);

– water use – the less water used to grow crops, the better, as water is a limited resource;

– food security (too much biofuels can lead to famine). The problem with growing crops for fuel is that they will take up land that could be used to grow food;

– destruction of animal habitats and the risk of environmental change due to the use of fertilizers and pesticides when growing biofuel crops (most often monocultures for ease of cultivation).

4.1.5 THERMAL POWER

The main part of the electricity in the world as of the end of 2021 is produced at thermal power plants (TPPs). This is followed by hydroelectric power plants (HPPs) and nuclear power plants (NPPs) (**Table 4.1**) [1].

Thermal power plants. Coal, black oil, gas, and oil shale are usually used as fuel for thermal power plants. Fossil fuels are non-renewable resources. According to many estimates, coal on the planet will last for 100–300 years, oil for 40–80 years, and natural gas for 50–120 years.

It is known that thermal power plants are decisive in water and oxygen consumption, as well as in thermal pollution. A typical TPP with a capacity of 2 million kW consumes 18,000 tons of coal, 2,500 tons of black oil, and 150,000 m^3 of water daily. 7 million m^3 of water are used daily to cool the exhaust steam at thermal power plants, which leads to thermal pollution of the cooling reservoir. The following are emitted with the products of fuel combustion (of the total amount): ~30 % of solid aerosol particles, ~60 % of sulfur oxides (SO_2) and nitrogen oxides (NO_X), as well as the main share of CO_2 as a determining factor in the greenhouse effect, which leads to climate warming.

The impact of the energy sector on the environment strongly depends on the type of fuel used. The most "clean" fuel is natural gas, which produces the least amount of substances that pollute the atmosphere when burned. This is followed by oil (black oil), hard coal, brown coal, shale, peat.

As mentioned above, many by-products are formed during the combustion of fuel. When burning coal, a significant amount of ash and slag is formed. Most of the ash can be captured, but not all. All exhaust gases are potentially harmful, even water vapor and carbon dioxide CO_2. These gases absorb infrared radiation from the Earth's surface, and some of it is reflected back to the Earth, creating the so-called "greenhouse effect". If the level of CO_2 concentration in the Earth's atmosphere increases, global climate change may occur.

When fuel is burned, heat is generated, some of which is released into the air, leading to thermal pollution of the atmosphere. This, ultimately, entails an increase in the temperature of water and air basins, melting glaciers, etc. This, ultimately, causes an increase in the temperature of water and air basins, melting glaciers, and similar phenomena. In turn, an increase in temperature can cause profound climate changes throughout the Earth.

The effect of a large number of solid particles entering the atmosphere can be equally catastrophic. **Tables 4.6, 4.7** provide quantitative data on various substances formed during the operation of a typical 1000 MW thermal power plant using organic fuel [24].

Table 4.6 Emissions of pollutants during the operation of a 1000 MW thermal power plant

Contaminant	SO_x, t	N_xO_x, t	CO_2, t	CO, t	Solid particles, t	Radioactivity*, Bq	Flue gases, GJ	Heat of condensation, GJ
Per year	1 100	350	72 500	94	300	259	1 350	4 050

*Note: *Radioactivity is mainly caused by the radium isotopes ^{235}Ra and ^{238}Ra. Data are given for coal. For oil, this figure is 50 times lower*

Table 4.7 Comparison of the TPP and NPP operation with a capacity of 1000 MW for one year of operation

Parameters	TPP	NPP
Fuel demand	3.5 million tons of coal	1.5 tons of enriched uranium (or 1 thousand tons of uranium ore)
CO_2 emissions	10 million m^3	Does not release
SO_2 and other acid rain emissions	More than 400 thousand tons	Does not release
Solid waste	100 thousand tons of ash	About 2 tons (radioactive!)

TPPs are characterized by high radiation and toxic pollution of the environment. This is due to the fact that ordinary coal and its ash contain trace impurities of uranium and a number of toxic elements in much higher concentrations than the earth's crust.

The impact of energy on the environment strongly depends on the type of fuel used. The most "clean" fuel is natural gas, which produces the smallest amount of substances that pollute the atmosphere when burned. This is followed by oil (black oil), hard coal, brown coal, shale, peat.

As mentioned above, many by-products are formed during the combustion of fuel. When burning coal, a significant amount of ash and slag is formed. Most of the ash can be captured, but not all. All exhaust gases are potentially harmful, even water vapor and carbon dioxide CO_2. These gases absorb infrared radiation from the Earth's surface and some of it is reflected back to Earth, creating the so-called "greenhouse effect". If the CO_2 concentration in the Earth's atmosphere increases, global climate change may occur.

During coal combustion, most of the uranium, thorium and their decay products are released from the original coal matrix and distributed between the gas and solid fractions. Almost 100 % of the radon present is converted to the gas phase and is released with the flue gases [25].

In addition to flue gases, the main sources of radionuclides entering the environment during coal combustion at power plants include the removal of coal particles from open coal storage sites (coal drift) and ash dumps [26]. During combustion, most of the mineral fraction of coal melts and forms a glassy ash residue, a significant portion of which remains in the form of slag. Heavy particles are trapped in the ash, but the lightest part of the ash, the so-called "fly ash", is carried along with the gas flow into the power plant pipe. The specific efficiency of ash-carryover increases with increasing dispersion.

Highly dispersed ash is practically not captured by equipment for cleaning TPP gases [27], so flue gases are the main source of pollution from power plants.

The total emission of radionuclides at coal-fired power plants, on average, is about $1.33 \cdot 10^{10}$ Bq per 1 GW. **Table 4.8** shows the average annual emissions of radionuclides from US TPPs according to [28] per 1 GWh.

It is seen that the main share is contributed by radon isotopes, which in total give $1.2 \cdot 10^{10}$ Bq per GWh of electricity.

Table 4.8 Average annual emissions of radionuclides from a thermal power plant, Bq/ GWh

Radionuclide	Bq/ GWh	Half-life period
^{220}Rn	$4.07 \cdot 10^9$	55,6 s
^{222}Rn	$8.14 \cdot 10^9$	3.8 days
^{238}U	$5.55 \cdot 10^7$	4.5 billion years
^{234}U	$5.55 \cdot 10^7$	245 thousand years
^{226}Ra	$4.44 \cdot 10^7$	1600 years
^{218}Po	$1.41 \cdot 10^8$	3 minutes
^{214}Pb	$1.41 \cdot 10^8$	27 minutes
^{214}Po	$1.41 \cdot 10^8$	0,00016 s
^{210}Pb	$1.41 \cdot 10^8$	22 years
^{210}Po	$1.41 \cdot 10^8$	138 days
^{216}Po	$8.88 \cdot 10^7$	0.15 s
^{212}Pb	$8.88 \cdot 10^7$	11 years
^{40}K	$1.96 \cdot 10^8$	1.3 billion years

The isotope ^{210}Pb accumulates in ash especially intensively due to thermochemical processes, so that its concentration increases by 5–10 times [29]. It is known that lead and its compounds are toxic. In particular, when entering the body, lead accumulates in bones, causing their destruction. **Table 4.9** presents typical ratios of concentrations of the main radionuclides in coal, slag and fly ash according to [30].

Fly ash emitted into the air poses a great danger due to its ability to spread over considerable distances and penetrate human lungs. Fine fractions of fly ash are enriched with various harmful substances. In addition to radionuclides, they contain heavy metals and trace elements Co, V, Cu, Zn, Cr, Ni, Cd, As, Be [31]. For example, in soils located in the zone of influence of TPPs, concentrations of vanadium up to 110 mg/kg, beryllium – up to 15–50 mg/kg of dry soil were observed [32].

Table 4.9 Specific activity of the main radionuclides in coal, slag and ash in Bq/kg

Isotope	Coal	Slag	Fly ash
^{238}U	9–31	56–185	70–370
^{226}Ra	7–25	20–166	85–281
^{232}Th	9–19	59	81–174
^{40}K	2–130	230–962	233–740

The dispersion of pollution with flue gases occurs over large areas, since TPP emissions into the atmosphere are carried out at an altitude of 100–300 m.

The average emissions of the main radionuclides, the density of contamination of the territory and their retention in the atmosphere in the area of the nominal average TPP location, according to [29], are presented in **Table 4.10**.

Specific emissions of harmful substances with TPP flue gases and exhaust gases of gas turbine plants when using different fuels are given in **Table 4.11**.

Gross emissions and fuel consumption for a 1000 MW TPP are given in **Table 4.12**.

Table 4.10 Average emissions of the main radionuclides, the density of contamination of the territory and the RN concentration in the air per 1 GWh in the area of the nominal TPP location

Indicators	**Radionuclides**					
	^{226}Ra	**^{228}Ra**	**^{210}Pb**	**^{210}Po**	**^{232}Th**	**^{40}K**
Annual emission, 10^{10} Bq	1.96	1.11	8.14	7.40	1.96	19.61
Territory contamination density, 10^{7} Bq/km^{2}	38.85	9.25	114.70	70.30	–	388.5
Air concentration, 10^{-8} Bq/l	6.29	4.07	14.80	14.43	6.29	–

Table 4.11 Specific emissions of atmospheric pollution (g/kWh) from the combustion of organic fuels (according to the International Institute for Applied Systems Analysis, Vienna)

Emissions	**Fuel type**			
	Coal	**Brown coal**	**Black oil**	**Natural gas**
SO_2	6.0	7.7	7.4	0.002
NO_X	2.8	3.4	2.4	1.9
Solid particles	1.4	2.7	0.7	–
Fluorine compounds	0.05	1.11	0.004	–

Source: [33]

Table 4.12 Gross emissions (thousand tons/year) and fuel consumption for a 1000 MW TPP

Emissions	**Type and annual fuel consumption**		
	Natural gas ($1.9 \cdot 10^{9}$ m^{3})	**Black oil ($1.57 \cdot 10^{6}$ t)**	**Coal ($2.3 \cdot 10^{6}$ t)**
SO_2	0.012	52.7 139,0	139.0
NO_X	12.0	22.0	21.0
CO	insignificant	0.08	0.21
solid particles	0.46	0.73	4.49
hydrocarbonates	insignificant	0.67	0.52

Note: Content: in black oil S^{p} = 1.6 %; in coal S^{p} = 3.59 %
Source: [33]

Substances emitted by heat and power enterprises when operating on various types of fossil fuels are given in **Table 4.13**.

Annual emissions from a 1000 MW fossil fuel TPP are presented in **Table 4.14**.

Table 4.13 List of substances emitted by heat and power enterprises when operating on various types of fossil fuels

Fuel type	Gaseous substances	Aerosols	Impurity elements
Coal	NO, NO_2, SO_2, SO_3, CO_2, HCl, HF, Hg (vapors), As(vapors) – The Donetsk deposit is very rich in arsenic., H_2S, NH_3	Fly ash, soot; formaldehyde, benzopyrene; ^{40}K, ^{226}Ra, ^{232}Th(thorium),	As, Cd, Pb, Ti, Cr, Na, Ni, V, Cu, Zn, Mn, Mo, Sb, SiO_2, Al_2O_3, TiO_2, NO_{3-}, SO_4^{2-}
Black oil	NO, NO_2, SO_2, SO_3, CO, CO_2, Hg (vapors), hydrocarbons	Ash (V_2O_5), formaldehyde, benzopyrene, soot (ash contains particles of unburned fuel, soot does not contain these particles)	As, Cd, Pb, Ti, Cr, Na, Ni, V, Cu, Zn, Mn, Mo, Sb – these particles are usually removed from the surface of boilers during cleaning
Gas	NO, NO_2, CO, CO_2, SO_2 traces, hydrocarbons	Hydrocarbons	–

Source: [33]

Table 4.14 Annual emissions from a 1000 MW fossil fuel TPP

Fuel type	Substance, t/year							
	NO_2	CO	SO_2	Solid particles	V_2O_5	Benzapyrene, $C_{20}H_{12}$	Formaldehyde HCOH	Total
Natural gas	13,888	14681	–	2	–	0.0009	–	28,564
Black oil	23,242	27,975	153,786	1,090	2,150	0.018	1,200	209,442
Coal (brown)	45,114	530,405	269,864	134,366	–	0.13	2,850	982,600

Source: [33]

4.1.6 NUCLEAR ENERGY

Nuclear energy is the most important subsector of the global energy industry. The low cost of electricity produced by NPPs represents serious competition to other types of power plants. Nuclear generation is 6 times cheaper than "green" and 3 times cheaper than thermal [34].

A clear advantage of NPPs is the absence of aerosol and greenhouse gas emissions into the atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC) [35–37], greenhouse gas emissions from nuclear power over the entire life cycle are equal to 12 tons of CO_2 equivalent per GWh. For comparison: wind power plants – 11 t CO_2 equivalent per GWh, hydropower plants – 24 t CO_2 equivalent per GWh, solar power plants – 48 t CO_2 equivalent per GWh, gas – 490 t CO_2 equivalent per GWh, coal – 820 t CO_2 equivalent per GWh. If to evaluate the planetary scale, the operation of all nuclear power plants in the world saves greenhouse gas emissions at the level of 2 billion tons of CO_2 equivalent per year, which is proportional to the absorption capacity of the entire forest massif of the planet. A positive factor is also material intensity.

Studies by the Joint Research Center (Jointresearchcenter) at the European Commission [38] show that nuclear power has the lowest specific material intensity compared to other low-carbon types of generation. For example, the metal content for the production of 1 MWh of electricity at NPP is 13 times less than in wind generation. It is also important that NPP requires a relatively small area: for example, 950 hectares of land are required to install a 1 GW WPP, and 28 hectares NPP of the same capacity. At the same time, NPPs provide a stable base load of networks, which does not depend on weather conditions, 24 hours a day, 7 days a week for at least 60 years.

NPPs emit very little CO_2 during their life cycle. The criterion for inclusion in the Taxonomy of electricity generation technology is emissions of less than 100 g/kWh. According to the JRC report [39], NPPs emit an average of 28 g/kWh of CO_2, which is comparable to the emissions of hydro and wind power plants, and even lower than that of solar panels, which have an average emission of about 85 g/kWh. The figures vary from source to source (for example, the ICPP 2014 report [40] gives average emissions for NPPs at 12 g/kWh and for industrial photovoltaics at 48 g/kWh), but the order and ratio are approximately the same. Emissions from gas and coal-fired plants are around 500 and 900 g/kWh, respectively.

According to the IAEA PRIS [41] as of January 1, 2024:

– there are 412 operating reactors in operation worldwide (excluding 25 reactors that have been shut down) with a gross installed capacity of 391,387 MW; 57 reactors are under construction;

– the total NPP number in the world with the status of operating reactors is 170 NPPs; with the status of operating reactors and suspended in operation – 179 NPPs.

Nuclear power can currently be considered as the most promising. This is due to both relatively large reserves of nuclear fuel and a gentle impact on the environment. The advantages also include the possibility of building NPP without being tied to resource deposits, since their transportation does not require significant costs due to small volumes. It is enough to note that 0.5 kg of nuclear fuel allows to get as much energy as burning 1000 tons of coal.

NPPs are safe, reliable and do not emit greenhouse gases, and therefore it is worth considering nuclear power as the most attractive industry for investment. On the other hand, it is impossible not to note the issues of volumes, cost of disposal and safety of radioactive waste produced, which require separate research. In addition, the article [42] discusses the risks of man-made disasters using the examples of events at the Three Mile Island NPP (1979), the Chernobyl NPP (1986), and Fukushima-1 (2011). Among the causes of accidents, errors and shortcomings in the design of the plants and the human factor are primarily highlighted. However, it is noted that after the mentioned events, the designs of nuclear power plants were revised in such a way as to ensure a significant increase in the safety of their operation.

Currently, small modular reactors (SMRs) [43], which produce electricity in the range of 10 to 300 MW [44–48], are considered particularly promising, offering more compact and cost-effective alternatives to conventional nuclear reactors. This makes them particularly attractive for use in smaller or remote locations.

The development of SMRs, which began in the 1970s, has accelerated significantly in recent years due to the increasing demand for clean energy sources and advances in technology. Key design features of SMRs that ensure their increased safety and efficiency compared to classic nuclear reactors include:

– optimized geometric arrangement of the reactor, which minimizes the possibility of accidents;

– application of passive safety systems that operate without external intervention in emergencies;

– simplicity of design to facilitate maintenance and repair.

Thus, SMRs open wide opportunities for the production of electricity, hydrogen and heat. They can be located both on land and in water. The SMR-160, designed as an advanced PWR-type SMR, has a thermal capacity of 525 MW and an electrical capacity of 160 MW [45].

The design includes robust passive safety systems to provide protection against design basis accidents, acts of sabotage or unintentional human actions. According to the Holtec development concept, the SMR-160 is designed for "safe abandonment" in design basis incident situations, allowing for safe dissipation of residual heat without the need for operator action. By combining fully passive safety systems with natural circulation in the primary circuit, the design is significantly simplified compared to classic NPPs, which contributes to the ease of its manufacture, construction and maintenance. The modular design of the SMR-160 involves the manufacture and assembly of key components in advance, which allows for a reduction in the construction time of each NPP – up to 24 months.

4.2 METHODOLOGY FOR SUBSTANTIATING THE CHOICE OF THE TYPE OF ENERGY RESOURCE FOR THE REGION

According to studies [49], any energy source is characterized by two parameters: energy density and speed of its transmission.

The product of these values is the maximum power that can be obtained from a unit of surface using the energy of this type.

For solar energy, this value in the near-Earth space is more than a kilowatt per square meter, and at sea level, taking into account losses in the atmosphere, a flow of 100–200 watts per square meter can actually be used. This flow is sufficient for life on the planet, but as the main source of energy for humanity it is extremely inefficient.

Similar problems limit the use of geothermal energy due to the heat-conducting properties of rocks.

Hydropower of river flows and the use of sea tides is no more than 5 % and is profitable only in mountainous areas, when there is a large potential energy per unit area of the reservoir.

The use of wind, also due to the insufficient density of the energy flow, turns out to be economically insufficiently justified.

Sources with high energy density – fuel cells – are characterized by a low rate of its transmission, so the real energy consumption does not exceed 200 W/m^2.

In addition, it is worth considering such an indicator as the installed capacity utilization factor (abbreviated as ICUF). It indicates the efficiency of the operation of electric power enterprises. It is calculated as the ratio of the arithmetic average capacity to the installed capacity of the electric power plant for a certain time interval [50]. Thus, if there are two power plants – nuclear and solar, with the same nominal capacity (720,000 MWh/month), the solar power plant will produce only 15–30 % of this value, since it directly depends on the sun. This indicator will be its ICUF.

Taking into account the above, there is a need to introduce the "General indicator for the selection and development of energy production taking into account the environmental component" of the Paris Agreement [51].

4.2.1 COMPREHENSIVE ASSESSMENT OF EFFICIENCY INDICATORS OF ENERGY RESOURCES

Analysis of the distribution and use of energy resources convincingly shows that energy production traditionally follows the availability of resources in the region and the need for energy. In this regard, an uneven concentration of industry and its accompanying environmental impact are created. To level the situation, it is necessary to have indicators that allow a comprehensive assessment of the possibilities of regions for the development of the economic sector, taking into account the availability of resources and minimal environmental impact.

In order to justify the choice of the preferred type of energy resource, using the example of the energy supply of the region (Odesa), the "Method of expert assessments of the use of energy resources (system efficiency)" was formed.

The most common energy resources are divided into two main categories: fossil and non-fossil [52] (**Table 4.15**).

Fossil resources are represented by hydrocarbons in various phase states.

Non-fossil resources, in turn, consist of renewable and manufactured resources.

CHAPTER 4

Table 4.15 Main categories of energy resources

Fossil			**Non-fossil**						
			Renewable			**Manufactured**			
Coal, peat	Oil	Gas	Solar	Wind	Hydropower	Biogas	Household waste	Hydrogen	Nuclear

Fossil fuels – coal, natural gas and oil are the main sources of primary energy for thermal energy (thermal power).

In Ukraine, about 30 % of all electricity [53] is provided by thermal power. It works both on its own and on imported raw materials.

The operation of thermal power plants is accompanied by emissions of many greenhouse gases, the main of which are water vapor and carbon dioxide, which are formed during the combustion of all types of hydrocarbon fuels. The products of coal combustion and anthropogenic emissions of carbon dioxide accumulate in the atmosphere, contributing to the development of the greenhouse effect. The annual emission of CO_2 by all TPPs in the world is approaching 10 billion tons of carbon dioxide, accounting for about 30 % of all anthropogenic emissions of greenhouse gases into the atmosphere of the planet [54].

An important element of the study is the establishment of a comprehensive assessment of the efficiency indicators of the choice of the type of energy resource, favorable for electricity and heat supply in the conditions of a specific region.

To conduct such an assessment, the method of expert assessments [55] was used using a random number generator to form an information field about the values of the characteristics of energy resources and statistical processing of data on acceptable energy resources in the conditions of the regions under consideration.

The developed methodology was applied to analyze and form a number of preferences by type of energy resources of the large southern region of Ukraine – Odesa region.

The aim of the presented methodology is to form a comprehensive assessment of the degree of efficiency of electricity generation and pollution of the territories of energy production facilities based on the analysis of the values of the observed environmental indicators.

The methodology proposes two mutually complementary criteria, the resource preference index and the environmental preservation index, which evaluate a number of preferences of energy resources from the standpoint of accessibility and impact on the environment of a particular region.

To achieve the formulated aim, it is necessary to solve the following tasks:

– forming a list of observed indicators;

– forming limit or normalizing values of the observed indicators;

– consistent normalization according to permissible values, amounts of resources under consideration, and observed indicators.

The existing global trend provides for the preferential development of the use of non-fossil resources [56].

Each of the types of energy resources specified in (**Table 4.15**) is characterized by qualities, the totality of which in dimensionless form can be a criterion for making a decision on the preferential acceptability of using a particular resource.

The algorithm for constructing a comprehensive assessment of the efficiency of the system is the sequence of procedures is presented in **Table 4.16** [57].

Table 4.16 Algorithm for constructing a comprehensive assessment of the efficiency of systems

Stage	Procedure
Stage 1	Selection of a set of indicators characterizing the state of systems
Stage 2	Selection of reference systems by indicators
Stage 3	Assessment of intervals of partial indicators of system functioning
Stage 4	Average point estimate of values of temporary indicators of system functioning
Stage 5	Assessment of weighting coefficients for temporary indicators
Stage 6	Integral assessment of system functioning efficiency

Factors reflecting the applicability of the resource formed 6 groups, which include 27 indicators that have a positive (+) or negative (–) trend of change [57] (**Table 4.17**).

Table 4.17 Factors reflecting the applicability of the resource

No.	Group	Indicators		
1	**2**	**3**		
1	TECHNOLOGICAL FACTORS are variables related to the existence, availability and development of technology	1	+	Availability of the resource in the region
		2	–	Need to import resources
		3	+	Availability of delivery transport
		4	+	Availability, readiness
		5	+	Productivity
		6	+	Quality of the resources supplied
		7	+	Final carbon intensity of energy
2	ENVIRONMENTAL FACTORS are variables that are caused by the interaction of resources and the environment	8	–	Volume of waste
		9	–	Level of emissions in general
		10	–	Level of CO_2 emissions per TPES
		11	+	Waste recycling
		12	–	Waste disposal
		13	+	Safety of maintenance
3	RELIABILITY FACTORS are caused by the quality of service, the interaction of the system and the environment (technical, software, operational)	14	+	Reliability, failure
		15	+	Repairability
		16	+	Duration of operation
		17	+	Level of renewal of fixed assets
		18	+	Support of the life cycle of objects

Continuation of Table 4.17

1	2	3		
4	WEIGHT FACTORS are used to assess the need for space for implementation	19	–	Capital investments
		20	–	Dimensions
		21	–	Material intensity
5	TECHNICAL FACTORS include the need for resources for their own needs	22	–	Own energy consumption
		23	–	Consumption of reagents
		24	+	Possibility of utilization
6	INSTITUTIONAL FACTORS are related to management, regulation	25	+	Level of remuneration
		26	+	Quality of management
		27	+	Quality of personnel

4.2.1.1 ANALYSIS OF EXISTING COMPREHENSIVE ASSESSMENTS

The comprehensive approach is based on the formation of groups of indicators that reflect individual aspects of the state of the system. Siemens Corporation, together with the Economist Intelligence Unit, developed an expert methodology for a comprehensive assessment of cities, which includes eight groups of indicators:

1) greenhouse gas emissions;
2) energy consumption;
3) urban management;
4) transport;
5) water use;
6) waste and land use;
7) air quality;
8) environmental management, ensuring the reflection of all aspects of the functioning of the system.

For comparison, all indicators are normalized in a dimensionless form. The overall index is constructed as a quantitative sum of all groups, taking into account the weight assignment [57].

Similar expert assessments by international organizations Mercer Human Resource Consulting and The Blacksmith Institute [58] are also known in urban planning. Other indices for assessing the state of cities are constructed in a similar way.

For example, in the ecological safety of cities, the atmospheric pollution index, the threshold mass index of hazardous substances, the total hazard index of individual components polluting a particular biogeochemical environment (water, air and soil), etc. are used.

Indicators are estimated using the normalization of indicators. If the change intervals are known, the ratio is used for normalization:

$$I_i = \frac{p_i - p_{i,min}}{p_{i,max} - p_{i,min}}, \tag{4.2}$$

where p_i – the value of the i-th indicator for a certain object; $p_{i\,min}$, $p_{i\,max}$ – respectively, the minimum and maximum value of this indicator in the group of objects under study; I_i – the corresponding indicator.

When assessing surface water pollution, the water pollution index is often used:

$$I_{pw} = \frac{1}{6} \cdot \sum_{i=1}^{6} \frac{C_i}{MPC_i}, \tag{4.3}$$

where C_i – the values of the observed indicators; MPC_i – the maximum permissible concentrations of pollutants in water.

Integral indicators for assessment are determined by the relationship [59]:

$$I = \sum_{i=1}^{m} a_i \times I_i, \tag{4.4}$$

where I_i – indicators in the form of values of indicators that are normalized; a_i – weighting factors.

It seems effective to supplement relative indices with multi-stage normalization, which is used in [59]. Based on expert assessments, a reliable complex indicator for comparing the ecological load of the environment was obtained.

4.2.1.2 ENVIRONMENTAL POLLUTION INDICATORS AND THEIR STANDARDIZATION

The methodology presented below differs from that used in [57] by replacing expert assessments with monitoring control data or project documentation. To assess the pollution of territories, 6 groups were used, which contain 33 indicators (**Table 4.18**).

The technological group concentrates indicators that characterize the capabilities and needs of the analyzed systems. The environmental group includes a list of all possible undesirable impurities and their emission levels. The third group combines system reliability indicators. Other groups concentrate indicators of the general characteristics of the systems.

All available limit indicators are used as standardizing parameters: permissible limit values of the indicator (p_{max}; p_{min}), maximum permissible emissions (*MPE*) and maximum permissible concentrations (*MPC*).

The current values of the indicators are taken according to operational monitoring data or project technical documentation of the systems.

Table 4.18 Groupings and types of pollution indicators

No.	Type	No.	Type
1 – Technological		19	^{51}Cr
1	Productivity	20	Thorium
2	Energy consumption	21	Uranium
3	Water consumption as a reagent	22	Tritium into the atmosphere
4	Cooling water consumption	23	Suspensions
2 – Environmental (Emission level)		24	Tritium into the hydrosphere
5	Heat	25	Liquid waste
6	Water vapor	**3 – Reliability**	
7	CO_2 on TPES	26	Duration of operation
8	Carbon monoxide (CO)	27	Level of renewal of fixed assets,
9	NO_x	28	Quality of resources supplied
10	SO_x	29	Security of service
11	Hydrocarbons (5 20 %)	**4 – Technical**	
12	Inert radioactive gases	30	Own energy consumption
13	^{131}I	**5 – Institutional**	
14	^{137}Cs_	31	Level of management
15	^{60}Co	**6 –Dimensions**	
16	^{90}Sr	32	Area occupied by the object
17	^{89}Sr	33	Territory of the region
18	^{54}Mn	–	–

4.2.1.3 COMBINED NORMALIZATION OF RESOURCE EFFICIENCY AND ENVIRONMENTAL POLLUTION INDICATORS

Normalization of current indicator values is performed in several stages.

The primary normalization of current indicator values was performed according to relations (4.2)–(4.4). If data on MPC were available, normalization was performed according to the relation:

$$I_i = \frac{C_i}{MPC_i}, \tag{4.5}$$

where C_i **–** the current values of the *i*-th indicator; MPC_i – the MPC value of the *i*-th indicator.

After the primary normalization, the individual indicator values are normalized by their sums for the systems being compared.

The obtained normalized indicator values are summed for each system and the obtained sums are normalized by their total sum.

4.2.2 RESULTS OF POLLUTING CAPACITY ASSESSMENT

Comparison of the polluting capacity of power plants using fossil resources, carried out according to the presented algorithm, confirmed the distribution of the latter by the degree of saturation of the environment with undesirable impurities (**Fig. 4.8**).

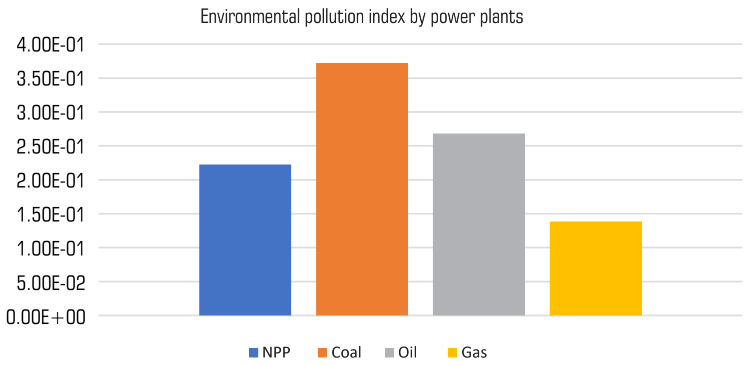


Fig. 4.8 Environmental pollution index by power plants depending on the energy resource

It should be noted that the initial data are of the most general nature without reference to specific objects.

The calculations adopted weighting factors in accordance with the recommendations [58, 60].

The results obtained are characterized by high stability, which indicates the stability of the methodology.

The maximum permissible value of the environmental pollution index by power plants is determined according to the given normalization scheme for its own values and is therefore equal to 1.

4.2.3 USING A COMPLEX INDICATOR FOR RESOURCE SELECTION

The environmental pollution index obtained according to the given methodology is a measure of the share of the maximum permissible relative pollution (**Fig. 4.9**).

The indicators of the environmental group, inherent in the nuclear resource and absent from the carbon group resources, neutralize the advantages of nuclear power plants with their quantity.

The indicators of the technological group and part of the environmental group, which are inherent in all types of resources, have the predominant values.

In the normalization process, the predicted pollution is reduced to unit productivity.

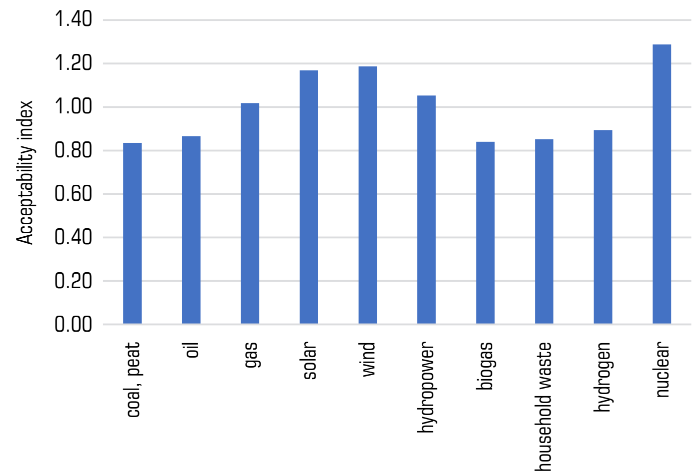


Fig. 4.9 Acceptability index values for energy resources

The lowest acceptability index values in the region under consideration are characteristic of traditional solid and liquid fossil resources, as well as for some resources made from waste and natural raw materials (0.8–0.9).

Fossil gas and hydropower are characterized by an acceptability index slightly higher than 1. Renewable resources (solar and wind energy) are distinguished by a noticeably higher index value (about 1.2). The most promising resource for the region was the nuclear energy resource, which reached an acceptability value of 1.3.

A comparison of the trends in the change in the acceptability index and the environmental protection index (**Fig. 4.10**) allows to note their synchronicity. At the same time, the module of the environmental protection index is slightly higher than the acceptability index for nuclear energy. The comparison made suggests that the acceptability of a particular energy resource for the region under consideration is largely regulated by the environmental characteristics of the resources.

The reliability of the results obtained when using the expert assessment method can be assessed by the degree of consistency of expert positions regarding each indicator using the Kendall concordance coefficient [61]:

$$W = \frac{12 \cdot S}{n^2 \cdot m \cdot \left(m^2 - 1\right)},$$

where S – the sum of the squares of deviations of all estimates of the ranks of each object of expertise from the average value; n – the number of experts; m – the number of objects of expertise.

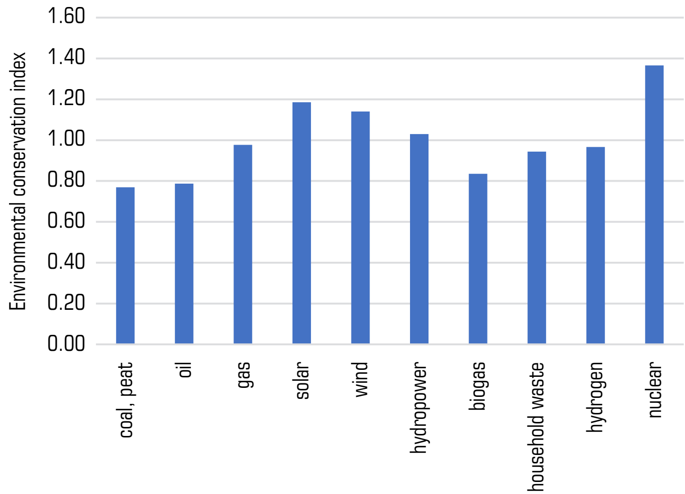


Fig. 4.10 The value of the environmental conservation index

The concordance coefficient (**Fig. 4.11**) varies in the range $0 < W < 1$, with the value $W = 0$ indicating complete disagreement, and $W = 1$ indicating complete unanimity.

For different indicators, the value of the concordance coefficient does not exceed 0.5. There is no specific trend in the change in the coefficient, which confirms the random nature of the data being analyzed.

This allows to extend the obtained patterns proportionally to the distribution of electricity production by type of resources (**Table 4.19**).

Table 4.19 Electricity production and pollution by region and resource (%)

Region	NPP	TPP		
		Coal	**Oil**	**Gas**
World	10.3/3.1	36.7/18.6	2.8/1	23.5/4.4
Ukraine	55/14.5	19.3/8.5	0.5/0.16	9.3/1.5

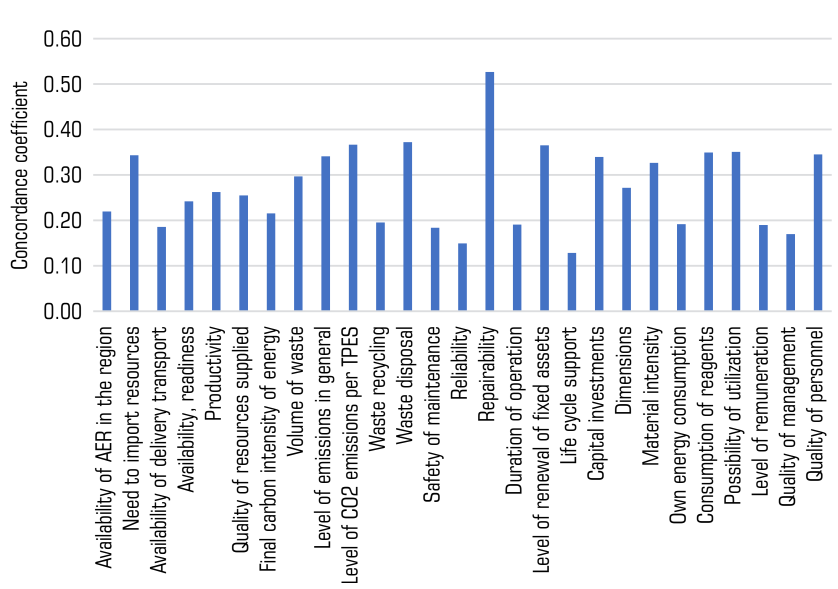


Fig. 4.11 Concordance coefficient

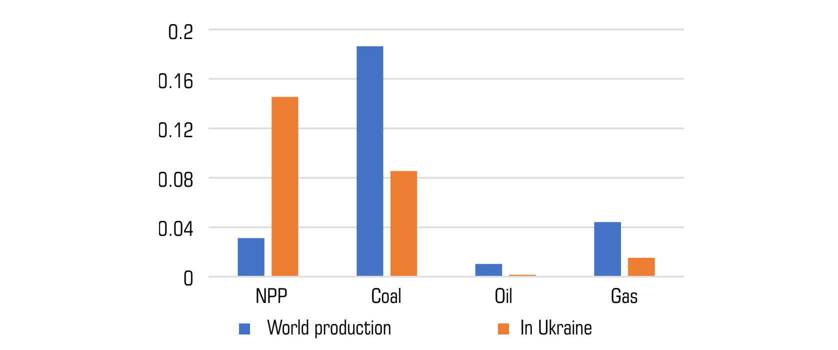


Fig. 4.12 Environmental pollution index by power plants depending on the energy resource for electricity production in the world and Ukraine

The results obtained differ in absolute values of acceptability for different types of resources and different methods. At the same time, the trends of change by resource are preserved.

CONCLUSIONS

Almost all types of energy resources are present in the energy complex of Ukraine. The overwhelming amount of energy is produced using traditional energy resources with a stable trend of using renewable resources.

Hydropower plants and pumped storage power plants produce up to 12 **%** of the total capacity. The use of the potential of small rivers is constrained by threats of disruption of the natural state of the ecological system.

Wind power plants are a new industry in the energy balance of Ukraine, its contribution to energy supply does not significantly exceed 1 **%** in the overall structure of electricity production with a tendency of gradual growth.

The development of the use of wind resources is constrained by characteristic disadvantages: wind dependence, noise pollution, impact on living organisms, change in the natural landscape.

The installed capacity of solar power plants is more than 7.5 GW and continues to grow, mainly in the southern regions, where solar insolation is longer.

The large potential of biomass available for energy production is a good prerequisite for the dynamic development of the bioenergy sector. The economically feasible energy potential of biomass in the country is about 20–25 MTOE per year.

The spread of solar power plants is restrained by: intermittent production mode, the need for storage, indirect impact on the environment, etc.

The spread of biomass potential is restrained by the need for a balance between food and industrial agriculture, the lack of effective waste processing technologies, etc.

The bulk of electricity in the world, and until recently in Ukraine, is produced at thermal power plants using fossil energy resources. Thermal power plants are decisive in the consumption of fossil resources, water and oxygen, as well as environmental pollution. The most “clean” fuel is natural gas, which produces the least amount of substances that pollute the atmosphere when burned. This is followed by oil (fuel oil), coal, brown coal, shale, peat.

Nuclear energy is the most important subsector of the global energy industry. The low cost of electricity produced by nuclear power plants represents serious competition to other types of power plants. Nuclear generation is 6 times cheaper than “green” and 3 times cheaper than thermal. Its clear advantage is the practical absence of aerosol and greenhouse gas emissions into the atmosphere throughout its life cycle.

Energy production traditionally follows the availability of resources in the region and the need for energy, which creates an uneven concentration of industry and its accompanying environmental impact. To level the situation, it is necessary to have indicators that allow for a comprehensive assessment of the opportunities of regions for the development of the economic sector, taking into account the availability of resources and minimal environmental impact.

An integrated approach is based on the formation of groups of indicators that reflect individual aspects of the state of the system.

Existing comprehensive indicators assess the efficiency of the used resource and its impact on the environment differently, as a result of which the detection of the impact of resource use on the environment is lost.

The proposed indicator is built on a monitoring study of 33 indicators, divided into 6 groups, reflecting the capabilities and needs of the analyzed systems.

The summaries of heterogeneous indicators are combined by normalization according to available limit indicators: permissible limit values of indicators, maximum permissible emissions and maximum permissible concentrations.

The proposed efficiency and pollution index consistently reflect the advantage of the resource for the region, taking into account technological, environmental, technical and other indicators.

The proposed efficiency and pollution index allows for independent justification of energy strategies of regions, taking into account their industrial, resource and environmental potentials.

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CHAPTER 4

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