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Integral assessment of low-carbon energy sources effectiveness based on multi-criteria analysis

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Abstract. The study applies the multi-criteria analysis of various low-carbon energy sources to assess their ecological and economical effectiveness. The work is specific by researching renewable energy sources as well as traditional ones which take hydrocarbon fuel by using innovative technologies of carbon dioxide capturing and its storage. The analysis applies three parameters: LCOE (Levelised Cost of Energy)/LEC (Levelized Energy Cost), specific value of carbon dioxide emission in electrical power generation and total MI (Material Input) - numbers. The study results in educing low-carbon energy sources which not only lead to the most reduction of carbon dioxide emission with least costs but also help reduce the general negative impact on the environment due to decreasing violence of biosphere material energy flows. The research states that wind power plants are the most effective, followed by solar and geothermal energy sources. Gas and coal-fired power stations, using technologies of carbon dioxide capturing, are less effective than renewable energy sources. Nevertheless, despite significant divergence in two out of three parameters, they have an identical summative assessment of efficiency because gas power stations have higher utilization costs than coal-fired power stations.

1 Introduction

Currently the development of low-carbon energy sources is considered the key factor to influence the processes caused by climate change and to stabilize the environmental situation in general. The transition to low-carbon energy industry should ensure successful environmental and economic development in the long term [1]. This will allow for a transition to sustainable development, the main provisions of which were determined by documents adopted at international conferences on environmental protection and sustainable development and confirmed by the sustainable development goals approved by the UN General Assembly. Many countries have adopted and are implementing their own strategies of transition to low-carbon energy industry, having achieved some success [2]. At international level the issues of carbon emissions are determined by the Paris Agreement, which was ratified by 186 countries and entered into force in 2016. According to the Paris

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Agreement, countries define national goals for reducing greenhouse gas emissions independently and voluntarily. They also independently determine necessary measures to achieve these goals. To implement these measures they require significant investments in the energy sector. The measures having been implemented, greenhouse gas emissions are expected to become minimal, which will lead to the climate system stabilization and the environmental situation improvement [3].

It is possible to achieve this goal by introducing various low-carbon energy sources [4-5], including not only renewable energy sources, but also traditional energy sources (often overlooked by researchers) using fossil fuels with the latest carbon dioxide capture and storage technologies. This situation requires additional analysis for low-carbon energy industry, which would allow comparison of energy technologies of different nature.

There is one more important point often overlooked by researchers when they study low-carbon energy sources. It lies in the fact that negative environmental changes are not only related with the emission of greenhouse gases, but are also caused by the energy capacity decrease of biosphere material flows to suppress the consequences that inevitably arise in the process of economic activity. To some extent the extraction of significant volumes of natural resources from the biosphere, their transfer and processing are a more significant environmental factor than activities resulting in pollutant emission. It is the extraction of natural materials from existing ecosystems that deprives the latter of important functions, and ecosystems become unable to maintain the necessary living conditions.

According to the concept of biotic regulation by V.G. Gorshkov, developed in the 1990s, the main contradiction between human society and nature lies in the fact that economy switches over the material and energy flows in the biosphere to itself [6]. Even with a complete transition to low-carbon energy industry the negative environmental destruction processes will not cease if these flows have greater material intensity.

Thus, an integrated assessment of the environmental and economic benefits of low-carbon energy sources should take into account both the volume of the greenhouse gas emissions reduction and the material flows decrease resulting from their activities. However, the current assessment methods pay more attention to emissions into the environment, including greenhouse gases created by energy activities, while material flows are often ignored. It should be noted that the assessment of material flows allows us to establish a direct relationship between the natural and economic systems, since extracted natural resources have a market price, which, therefore, helps more adequately assess the effectiveness of various low-carbon energy sources [7]. This point makes the assessment and analysis of low-carbon energy sources, involving not only the greenhouse gas emissions reduction but the decrease of biosphere material flows violation as well, one of the most important factors to rate their competitive abilities.

Currently, there is no integrated assessment of various low-carbon energy sources that would take into account together the operating costs, the possibility of reducing greenhouse gas emissions and the decrease of biosphere material flows in the process of activity. There is no substantiated scientific data on the most promising low-carbon energy sources or any theoretically-predicted scenarios for their possible development, which will provide the greatest environmental and economic effect at the lowest cost. To solve this issue, one needs methodological tools involving together the extraction, transfer and processing of natural resources from existing ecosystems.

2 Materials and methods

The methodological tools are based on multi-criteria analysis and the economic and mathematical problem analysis for various low-carbon energy sources. The peculiarity lies in the integrated use of the following parameters to assess the environmental and economic efficiency of low-carbon energy: LCOE (Levelized Cost of Energy)/LEC (Levelized Energy Cost) (dollars/kW), specific value of carbon dioxide emissions (kg/kW), total MI (Material Input) – numbers (kg/kW).

The value of the levelized cost of electrical energy is estimated on the basis of the generally accepted indicator LCOE/LEC, widely used in world practice while comparing economic efficiency of various energy sources [8-9]. It characterizes the average estimated cost of electrical power generation throughout the entire life cycle of a power station (including all possible investments, costs and income). This research modifies it by including the cost of implementation of the latest carbon dioxide capture and storage technologies into the formula. The authors use the data published by the IEA (International Energy Agency) as well as those obtained by other research teams.

$$\text{LCOE/LEC}_{\text{ccus}} = \frac{\sum_{t=1}^{n} \frac{I_t + I_{Ct} + M_t + M_{Ct} + F_t + F_{Ct}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

Where $\text{LCOE/LEC}_{\text{ccus}}$ – Levelised Cost of Energy when using CCUS (Carbon capture, use, and storage); I_t – investment costs per year for electrical power generation; I_{Ct} – investment costs per year for carbon dioxide capture; M_t – operating costs per year for electrical power generation; M_{Ct} – operating costs per year for carbon dioxide capture; F_t – fuel costs per year; F_{Ct} – energy costs for carbon dioxide capture per year; E_t – volumes of electrical power generation; r – discounting rate; n – life cycle of a power station.

To assess carbon efficiency the authors use the data published by the IPCC (Intergovernmental Panel on Climate Change) and their own research carried out for the electrical power sector, including low-carbon energy industry. The IPCC Guidelines for National Greenhouse Gas Inventories are internationally agreed procedures for countries to use when estimating greenhouse gas inventories to report to the UN Framework Convention on Climate Change. Estimates of greenhouse gas emissions and removals are divided into major sectors combining relevant processes, sources and absorbers. Energy industry is one of the sectors. According to the IPCC classification the energy module takes into account the emissions of all greenhouse gases related with the combustion of all types of fuel during economic activities. However, for ease of use they are recalculated into the indicator CO_2- equivalent with kg/kW as unit of measurement.

The common methodological approach lies in combining information on the scales at which human activity occurs with the coefficients which determine the amount of emissions or removals per unit of activity. These numbers are called emission factors. The factors are established using expert estimation. Carbon dioxide emission factors mainly depend on the carbon content of the fuel and the combustion technologies used.

The basic formula of the methodological approach is:

$$\text{V} = \text{T}_\text{e} * K_v \tag{2}$$

Where V – the existing volume of carbon dioxide emissions; T_e – data on technologies used for power generation; K_v – carbon dioxide emission factor for the fuel used.

The values of material intensity for various low-carbon energy sources are determined based on the total MI (Material Input) – numbers based on MIPS (Material input per unit service or utility) – analysis [10]. MI-numbers, proposed by the Wuppertal Institute for Climate, Environment and Energy, make it possible to characterize the material input flow per unit of product or service. As a result, it makes possible to carry out a general assessment of the negative impact of material inputs on the environment arising from the industrial production. Material intensity is calculated for various low-carbon energy sources and expressed in kilogram per kilowatt hour (kg/kWh). When calculating MI-numbers, one typically uses five categories of material inputs: abiotic resources, biotic resources, soil movement, water resources, and atmospheric air. The use of MI-numbers for five categories of material inputs is justified when designing products. However, to analyze entire sectors of economy, such as low-carbon energy industry, it is more logical to use the modified author's indicator of total MI-numbers, without distinguishing separate categories of material inputs. Combining material inputs allows reducing all consumed resources and environmental components to a single value, which makes it possible to correlate the material intensity of low-carbon energy industry with the anthropogenic impact on ecosystems.

In order to conduct the study, the authors have introduced original methodological tools that allows assessing the effectiveness of various low-carbon energy sources with regard to reducing greenhouse gas emissions, reducing material intensity and relatively levelized cost of electrical energy at the same time. The specified tools are based on multi-criteria analysis and the economic and mathematical problem analysis for various low-carbon energy sources, including renewable and traditional sources using carbon dioxide capture and storage technologies. The use of tools allows identifying sources of low-carbon energy with the greatest environmental and economic effect, the priority development of which makes it possible to obtain the greatest environmental effect at the lowest cost.

3 Results

The study discusses the following low-carbon energy sources.

Solar power stations (SPS) are energy systems designed to convert solar energy through photovoltaic cells. SPS have the following average specific indicators of material intensity in MI-numbers, established by the Wuppertal Institute for Climate, Environment and Energy [11], and related with the production of components and equipment operation: atmospheric resources, kg/kWh – 0.0009; abiotic resources, kg/kWh – 0.12; water resources, kg/kWh – 4.93; biotic materials and soil resources are not taken into account. The total MI-number, reflecting the total material intensity, is 5.051 kg/kWh.

Wind power plant (WPP) are one or more wind power stations combined into a single network to generate electrical energy. WPPs have the following specific indicators of material intensity in MI-numbers: atmospheric resources, kg/kWh – 0.008; abiotic resources, kg/kWh – 0.09; water resources, kg/kWh – 0.84. The total MI-number is 0.938 kg/kWh.

Geothermal power stations (GeoPS) are power plants that generate electrical energy based on the use of thermal energy from underground sources. Currently, they have a limited area of application, usually in areas of high geological activity. Geothermal power stations have the following specific indicators of material intensity in MI-numbers: atmospheric resources, kg/kWh – 0.009; abiotic resources, kg/kWh – 0.1; water resources, kg/kWh – 44.5. The total MI-number of electrical energy generated at the GeoPS is 44.609 kg/kWh.

Thermal power stations use natural gas as fuel and modern carbon capture technologies (CCUS - Carbon capture, use, and storage) [12]. The value of material intensity in MI-numbers for these power stations is the following: atmospheric resources, kg/kWh – 0.847; abiotic resources, kg/kWh – 0.32; water resources, kg/kWh – 79.4. The total MI-number of electrical energy generated at thermal power stations with gas generation is 80.657 kg/kWh.

Thermal power stations can also use coal fuel and carbon capture technologies (CCUS) [13]. The MI-numbers are the following: atmospheric resources, kg/kWh – 0.81; abiotic resources, kg/kWh – 0.77; water resources, kg/kWh – 80.3. The total MI-number is 81.88 kg/kWh.

The research leads [14,15] to the following table to conduct a multi-criteria analysis.

Table 1. Parameters characterizing low-carbon energy sources.

Type of low-carbon energy source	LCOE/LCE, USD/ kWh at 2021 values	Total MI-number, kg/ kWh	Specific emission of carbon dioxide, kg/ kWh
Wind power plants	0.036	0.938	0
Solar power stations	0.058	5.051	0
Geothermal power stations	0.084	44.609	0
Gas power stations with CO_2 capture	0.137	80.657	49
Coal-fired power stations with CO_2 capture	0.083	81.88	82

Since the given parameters have different units of measurement, they are initially reduced to a dimensionless form. For this purpose, the parameters are ranked, with the ranking being on a scale from 1 to 5, where 5 is defined as the most preferable value.

The summary indicator for various low-carbon energy sources is determined as the sum of the scores of all indicators using the following formula:

$$S_j = \sum_{t=1}^{n} K_i * L_i \quad (3)$$

Where S_j – the summary indicator for the *j* low-carbon energy source; K_i – the score for the *i* parameter; L_i – the significance level of the *i* parameter; n – the number of parameters.

Whereby the K_i score is determined by the formula:

$$K_i = \frac{N_i}{N_m} \quad (4)$$

Where N_i – the value of the *i* parameter for a specific low-carbon energy source; N_m – the maximum possible value of the *i* parameter.

Table 2. Assessment of efficiency of low-carbon energy sources based on multi-criteria analysis.

Preferred value	Parameter	Wind power plants	Solar power stations	Geothermal power stations	Gas power stations with CO_2 capture	Coal-fired power stations with CO_2 capture
0.036	LCOE, USD/ kWh at 2021 values	5	4	2	1	3
0.938	Total MI-number, kg/ kWh	5	4	3	2	1
0	Specific emission of carbon dioxide, kg/ kWh	5	5	5	4	3
Summary indicator		15	13	10	7	7

The multi-criteria analysis shows that wind power plants have the highest summary indicator for all three parameters (LCOE, USD/ kWh; specific emission of carbon dioxide, kg/ kWh; total MI-number, kg/ kWh), they received the highest possible score in all parameters. Solar power stations are in second place, geothermal power stations come third. Surprisingly gas and coal-fired power stations with carbon capture technologies get equal scores being both in fourth place.

4 Discussion

It should be noted that, when studying the effectiveness of low-carbon energy sources, researchers often overlook that they may include not only renewable energy sources, but also power stations using fossil fuels with carbon dioxide capture technologies. Modern technologies at some thermal power stations using gas and coal fuels can have a specific efficiency that reduces carbon dioxide emissions by up to 90%. In some cases the value may be higher, but this requires a significant increase in energy consumption, which ultimately leads to an increase in the levelized cost of electrical energy LCOE/LEC, making such energy sources less competitive. One more important indicator is that the transition to low-carbon energy industry should lead to a general improvement of the environment, and this is only possible by reducing the biosphere material flows used by the energy sector. Therefore, to assess the environmental and economic efficiency of low-carbon energy sources adequately, one needs to take a mandatory assessment of the three parameters indicated above. In some cases it can produce unexpected results, for instance, gas and coal-fired power stations with carbon dioxide capture technologies have the same level of efficiency. In prospect the authors plan to develop the analysis by researching other sources of low-carbon energy.

5 Conclusions

The multi-criteria analysis reveals that wind power plants have the greatest environmental and economic efficiency; they have the lowest LCOE/LEC value, amounting to only 0.036 USD/kWh (at 2021 values), and the total MI-number is 0.938 kg/kWh, with no carbon dioxide emissions. Solar power stations are slightly lower in terms of LCOE/LEC, while the value of material intensity in total MI-numbers is 5.38 times worse; while solar panels being produced, biosphere material and energy flows are transformed to a greater extent. Geothermal power stations require significant capital investments and consumption of natural geothermal water, resulting in the value LCOE/LEC of 0.084 USD/kWh and the total MI-number of 44.609 kg/kWh, however, with no carbon dioxide emissions. Unexpectedly the study reveals that, despite the initially higher carbon efficiency of gas power stations compared to coal-fired ones (1.81 times) and approximately equal specific material intensity, they have the same environmental and economic efficiency due to the high costs of carbon dioxide utilization.

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