Energy transition to zero-carbon economy: estimation of investment costs

Kirill Degtyarev[*], *Sophia* Kiseleva, *Liudmila* Nefedova, *Mikhail* Berezkin,
and *Oleg* Sinyugin

Lomonosov Moscow State University, Faculty of Geography, 119991 Leninskie gory, 1, GSP-1
Moscow, Russian Federation

Abstract. The article contains the estimation of global investment costs required for the global energy transition to zero-carbon economy by 2050. The evaluations are based on the data on global energy supply and its forecast to 2050, assumption that all the global energy needs are to be satisfied only through non-carbon facilities, and data on investment costs per unit for the facilities that use different types of non-carbon energy carriers. The authors conclude that the total costs of the energy transition worldwide are some $120 trillion, and that achieving the goal of totally non-carbon economy by the middle of the century would require a sharp, two-threefold, increase in investments in energy supply comparatively with the modern level, including acceleration in development of hydro and nuclear energy.

1 Introduction

Several evaluations for the costs of the energy transition to zero-carbon economy by 2050 have been made by now. For instance, analyses made International Energy Agency (IEA) [1], Bloomberg NEF [2], and IRENA [3] have shown that Net Zero by 2050 can cost up to $100 trillion worldwide or even more. Some other estimations give the value of $150 trillion [4,5], including $30 trillion or $1 trillion a year for the USA [6] and ¥100 trillion ($16 trillion), for China [7]. The base and approaches for some of those calculations have not been disclosed. Anyway, detailed estimations must be very complicated and take into account a plentitude of assumptions and inputs, regarding technologies, economy and markets, regional differences etc. Here we would like to propose a simplified way that gives us preliminary, but rather reliable approximation, basing on the integrated world's needs for energy supply, necessity to satisfy them only through non-carbon energy facilities and their investment costs per unit.

2 Materials and Methods

We use statistical time series of UN, BP, IRENA, IEA, EIA, and other official and corporate sources, for the world population, energy supply by regions and sources,

---

[*] Corresponding author: kir1111@rambler.ru

investment costs for the different types of power plants. The average values of capacity factor for different types of power plants were calculated on the base of the overworld power generation data. We also use our own scenarios of the world's and regional energy consumption. On this base the calculations of the capacities, required to supply the world with non-carbon energy, and the investment costs for their construction were made.

2.1 World population & World energy consumption

By 2022 the world population has reached almost 8 billion. According to the mean UN projection by 2050 the world population will increase by 2 billion up to about 10 billion, including 1 billion in Sub-Saharan Africa, where the population will double and reach 2 billion, and 1 billion in the rest of the world (mainly in Southern and South-East Asia, excluding China and Japan, where the population will grow from 3.4 to 4.2 billion) [8].

In 2019 the world primary energy supply has consisted about 160 000 TWh of energy equivalent (or 14 000 million tons of oil equivalent), including 135 000 TWh, or 84%, at the expense of fossil fuels (coal, oil, and gas). During the last 50 years the world growth of energy consumption has been contributed by Asian countries, China above all. Despite, there is also a huge gap in energy consumption per capita between the world regions, that are presented in table 1. For the calculations of per capita energy supply and its distribution we used the UN population statistics and BP energy statistics [8, 9].

It could be expected , that the key trend to be in the nearest decades is growth of energy consumption in the least consuming countries, first of all Sub-Saharan Africa, India, and other South and South-East Asian countries, for whom economic development is vital. So, cardinal growth of per capita energy consumption is highly probable in the nearest decades, together with going on population growth.

Earlier we made a forecast on the world energy consumption by 2050 and concluded, that its probable level would be 230 000 – 300 000 TWh (1.4-1.9 times more than the present) [10]. Here we use the approach, using assumption, that in Sub-Saharan Africa per capita energy consumption will grow to 10000 TWh together with 2 billion population, and in India and Indonesia – to 15 000 TWh (level of the modern Latin America) with population of 2 billion too, when in the rest of the world energy consumption will remain the same as a gradual decrease in energy consumption in the Western countries will be balanced with a going on gradual growth in Latin America, China, and the other Asian countries.

In this case, total energy consumption in Sub-Saharan Africa amounts 20 000 TWh, in India and Indonesia – 30 000 TWh, and together with 145 000 in the rest of the world it will be about 200 000 TWh, or by 25% more than now. It seems to be a minimal level of the world energy consumption we could expect by 2050. So, estimating the costs of transition to carbon neutrality we should take into account, that this amount of energy supply must be provided exclusively from non-carbon sources

2.2 Structure of the World energy consumption

In 2019 the structure of the world primary energy supply in 2019 is presented in the table 1 is based on the BP and IEA energy statistics data [9, 11]. The total volume of the primary energy supply was about 160 000 TWh. Almost a half of this amount is used for electricity production (with output of 27 000 TWh of electricity) and approximately 25% each directly for transportation and heating; a part of electricity in its turn is used for transportation and heating, so their final shares are really higher.

Table 1. Structure of the world energy supply and consumption, TWh (2019)

Source	Volume, TWh	Share in the total energy supply	Field of energy use
Coal	43789	27%	80% - for electricity production; 20% - for heating; less than 5% - for transport
Oil	53303	33%	mainly for transportation (as a transport fuel)
Gas	39039	24%	40% - for electricity production; 55% - for heating
Fossil fuels total	**136131**	**84%**	electricity production, transport, and heating - about 1/3 for each
Nuclear	6925	4%	mainly for electricity production
Hydro	10469	7%	
Other renewables	8006	5%	
Non-carbon sources total	**25400**	**16%**	
Total	**161531**	**100%**	about 50% for electricity production and 25% each for transport and heating

The calculations made by the authors using the data [9, 11]

2.3 The approach to the calculation of investment costs for non-carbon world economy

As the non-carbon sources are used mainly for electricity production, non-carbon economy means that all the required energy supply must be based on electricity (directly or through hydrogen, that in its turn is to be produced by water electrolysis using electricity from non-carbon sources). The electricity as a source is to replace fossil fuels everywhere including direct use for transportation and heating. The same amount of energy – at least 200 000 TWh yearly by 2050, must be delivered as electricity. In its turn, all this amount of electricity is to be produced entirely on non-carbon power plants. It gives us a simplified but reliable way to evaluate the costs of the global energy transition at least as an order of magnitude.

We use further this assumption to calculate the global investment costs. We also assume that this amount electricity will be produced at non-carbon power plants of the four main types: nuclear, hydro, wind, and solar photovoltaic, 25%, or 50 000 TWh for each. We calculate the required capacities of plants of each type according to their average capacity factors (CF). The average values of capacity factors for different types of power plants (PP) were calculated on the base of electricity generation data as the unitless ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period. We use the mean capacity factors for the 10 year period (2011-2020) for each type of power plant, that we calculated comparing based on BP Statistical time data series for electricity production and on IRENA and IEA statistical time data series for power plants capacities [9, 11, 12]. The results of our calculations, the global average values of CF for power plants, are presented in Table 2.

Table 2. The estimated mean values of capacity factor for the different types of non-carbon power plants

Type of PPs	Nuclear	Hydro	Wind	Solar
Mean 10 –years CF	80%	44%	27%	14%

Basing on the average values of CP the gross capacitiy of every type of power plants (PP) that is required to produce 50 000 MWh a year was calculated. The difference between the total required capacity and the total installed capacity of operating PP made it possible to determine gross additional capacities that are required to build. For simplicity, we do not take into account the fact that by 2050 some of the existing non-carbon capacities will have already been decommissioned and will have to be replaced too, although this underestimates the real costs.

The information on the average investment costs per unit ($/kW) for the each type of power plant was used for our estimations: for nuclear plants we used data of World Nuclear Association [13, 14], for renewable plants – IRENA data [15].

3 RESULTS AND DISCUSSION

3.1 Calculations of the total investment costs in non-carbon energy supply

The required investment costs results of our calculations are presented in table 3. Our result finally was some $120 trillion (or some $4 trillion a year by 2050, that is about 4.5% of the world's GDP as it was in 2019) what is in the range that has been outlined [4, 5, 16].

Table 3. Calculations of the total investment costs to provide entirely non-carbon energy supply

Type of PPs	Requir. Produc-tion, TWh	Mean CP , %	Requir. Capa-city, Gw	Gross installed capacity, TW (2020)	Required additional capacities, Gw	Investm ent costs, $ billion/T W	Total costs, $ billion
Nuclear	50000	80%	7135	399	6736	6000	40414
Hydro	50000	44%	12972	1154	11818	1870	22099
Wind	50000	27%	16912	698	16214	1355	21970
Solar	50000	14%	40770	710	40060	883	35373
Total	**200000**	**40%**	**77789**	**2961**	**74827**	**1620**	**119856**

It must be noticed, that it's better to designate not an exact value of total costs but the range of $100-150 trillion approximately because of the obvious great uncertainty that depends on a multitude of assumptions that can be divided into 3 principal groups:

- Energy needs and consumption in a long term;
- Energy efficiency of technologies that will be used for energy production;
- Economic drivers determining the changes of prices and investment costs.

The calculated in tabl. 3 total cost of $100 or $150 trillion should be seen as a kind of symbolic expression that underlines complicity and scale of the problem. The primary question here is the real resources to get, and the real problems to solve, for the energy transition, including:

- space for locations of all non-carbon facilities,
- materials (iron, nickel, cobalt, rare earth elements, etc.),
- labor force and jobs,
- environmental problems (non-carbon industries at the early stages of their life cycles are not environmentally friendly) and problems of utilization),

- instability of energy production through RE systems that are highly dependent on daily, seasonal, yearly, long term and a number of unpredictable fluctuations of weather and other natural conditions.

Every point of the abovementioned requires additional detailed analysis, that finally can significantly correct the estimations of the energy transition costs.

3.2 Carbon-free economic and current developments trends in the of world energy.

Our shows that the current trends of world energy will not lead us to carbon neutrality by 2050 or may be even to 2100.

Although non-carbon capacities has rapidly increased over the last decades, it has not changed significantly the structure of the world energy consumption (Figure 1). The share of other renewables (predominantly wind and solar) in 2010-2020 grew since 1.4% to 5.7%, the share of hydro energy grew only by 0.4% - since 6.5% to 6.9%, and the share of nuclear energy even fell since 5.2% to 4.3% [11]. For carbon neutrality by 2050 we need to replace more than 80% of the fossil-fuel share for non-carbon sources that mean the rate of this replacement at some 2.9% a year – it must be 3 times faster, than now.

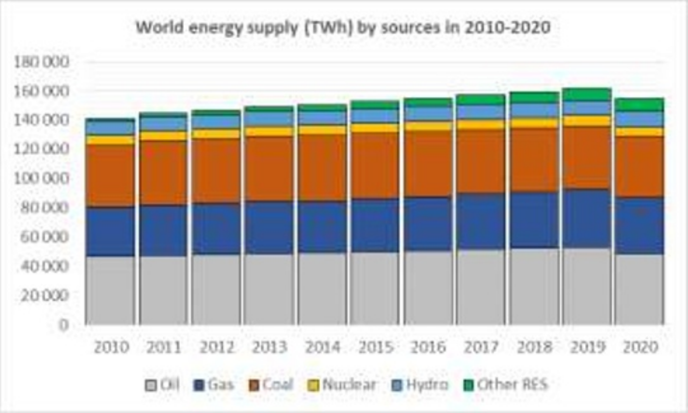

Fig. 1. World energy supply (TWh) by sources in 2010-2020

Besides that, the growth rates of wind and solar energy show the signs of exit to plateau (Figure .2). Maintaining high growth rates for solar PP capacities (34% per year) could compensate stagnating nuclear and hydro energy (table 4). But, the first, this looks unlikely, as the current growth rates are still associated with the low base effect; At the same time, there is already a trend towards a decrease in growth rates. The second, domination of only one non-carbon source, solar energy, would probably create high instability of the energy supply system and high inequality in energy supply between the different world's regions.

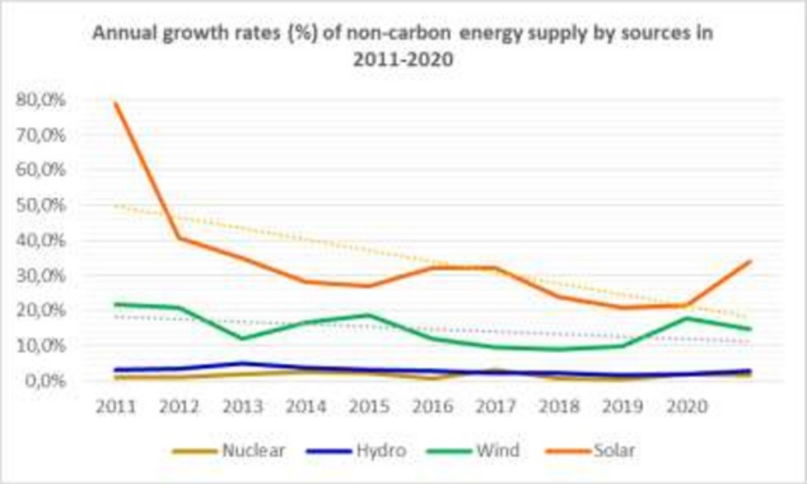

Fig. 2. Annual growth rates (%) of non-carbon energy supply by sources in 2011-2020.

Table 4. Comparison of required and real growth rates for non-carbon power plants

Type of PPs	Available capacities, GW (2020)	Required additional capacities, GW	Required additional capacities per year (to 2050)	Required average annual growth	Real average annual growth in 2011-2020	Year to reach the required capacities by maintaining the present growth rates
Nuclear	399	6736	225	9.9%	1.5%	**2210**
Hydro	1154	11818	394	8.0%	2.8%	**2104**
Wind	698	16214	540	11.1%	14.7%	**2043**
Solar	710	40060	1335	14.3%	34.1%	**2034**

The calculations were made by the authors using the data [17,18]

At present average annual global investments in energy supply is less than $2 trln; moreover, since 2016 it is $1500; in 2020 even less [18]. Basing on our evaluation, to reach carbon neutrality by 2050, they must be increased to $4000 billion annually, or almost threefold.

4 Conclusion

An approach to evaluate the cost of the global energy transition to zero-carbon by 2050 is to present the required global energy supply in electricity equivalent and then to evaluate:

1) the total capacity of non-carbon power plants required to produce this amount of electricity, basing on their capacity factors;
2) the total investment costs for them, basing on the data of their investment costs per unit.

Assuming that the total energy (electricity) supply must be 200 000 TWh a year, the total costs would amount some $120 trillion over the world, or some $4 trillion a year up to 2050.

It would require two- or threefold increase of the global investments in energy supply comparatively with the present level and rapid acceleration of the growth of nuclear and hydro facilities from the present 1.5%-2.8% a year to 8%-10% a year.

Analyzing investment costs and capacity factors for renewable and fossil fuel PPs in comparison, we can conclude, that the latter are still considerably less expensive – with comparable capital costs per unit they have at the same time 2-3 times more productivity per a kW of capacity. So, cardinal increase of investments in energy supply for the sake of energy transition to zero-carbon looks inevitable.

The work was carried out within the State task «Geographical Bases of Sustainable Development of Energy Systems using Renewable Energy Sources» (state budget I.22, number 121051400082-4).

References

1. *Net Zero by 2050. A Roadmap for the Global Energy Sector. IEA report*. (October 2021)

2. *Energy Transition Investment Trends 2022. Tracking global investment in the low-carbon energy transition. BloombergNEF* (January 2022).

3. *World Energy Transitions Outlook* (IRENA, 2022)

4. S.R. Golroudbary, I. Makarava, A. Kraslawski, E. Repo, Science of the Total Environment, **832**, 155022 (2022).

5. M.Z.Chishti, A. Sinha, U.Zaman, U.Shahzad, Energy Economics, **119**, 106570 (2023).

6. J. Bistline & G. Blanford Value of technology in the U.S. Energy Economics, **86**, 104694 (2020).

7. C.Lin, Y.Li & at al., Frontiers in Energy Research **9**, 630847 (2021)

8. United Nations. Department of Economic and Social Affairs. Population. URL: https://www.un.org/en/development/desa/population/publications/database/index.asp
reference date: 28.02.2023

9. BP Statistical Review of World Energy (2022). URL: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html, reference date: 28.02.2023.

10. K. Degtyarev, Energy policy, **5**, 54–63 (2021)

11. IEA. Data and Statistics. URL: https://www.iea.org/data-and-statistics, reference date: 28.02.2023.

12. IRENA Statistics Time Series. URL: https://www.irena.org/Data/View-data-by-topic/Benefits/Employment-Time-Series, reference date: 28.02.2023.

13. *Economics of Nuclear Power.* World Nuclear Association.(2022)

14. World Nuclear Generation and Capacity. IAEA (2022).

15. Renewable Power Generation Costs in 2020. IRENA (2021).

16. World GDP. 1960-2022. Macrotrends. https://www.macrotrends.net/countries/WLD/world/gdp-per-capita reference date: 28.02.2022.

17. *Nuclear Power and Secure Energy Transitions. From today's challenges to tomorrow's clean energy systems.* (IEA, Revised version, 2022)

18. *World energy investment 2020. Global Investment in Energy Supply 2010-2020*. (IEA, 2020)