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Energy as a driving factor of economic growth and development: History of energy transformations

This article presents energy as a factor with a huge impact on economic growth and development, which is one of the factors of production, examines energy transformations throughout history, and shows the role of energy in growth and development processes and highlights its key role in breakthrough moments of the world's economic development and transformation. Statistical public data analysis, historical data analysis, document analysis, logical reasoning, and drawing conclusions were employed. Data are presented in tables and figures. The article demonstrates that energy plays a significant role in economic and social growth and development; it is a factor of production. Historical analysis of human energy use, statistical data and case studies show that breakthrough moments that marked milestones in the world's economic development were based on successive energy transformations, while technical and technological development based on new forms of energy use and new energy carriers has driven the economic and social transformation of the world.

Keywords: energy, transformation, growth and development, energy transition

JEL classification: O1, O3, Q0, Q4

Introduction

The emergence and popularisation of the use of ever newer sources of energy and power drives is the basis of economic, social and environmental change. Human activity is inextricably linked with energy. It enables all kinds of work to be performed and is essential for the formation and implementation of various natural and anthropogenic processes. Energy development significantly affects the direction of global economic development. The current direction of global development, a turn towards the so-called "green economy", requires the replacement of fossil fuels with more environmentally friendly energy carriers such as renewable energy sources and nuclear power.

The aim of the article is to present energy as a factor with a huge impact on economic growth and development as one of the factors of production. The article examines energy transformations throughout history, shows the role of energy in growth and development processes and highlights its key role in breakthrough moments of the world's economic development and transformation.

1. Energy – basic information

The use of energy allows for the existence of humans and animals on Earth. It ensures economic and social growth and development. Energy accompanies all human activities and is an indispensable part of daily life. It is a factor of economic transformation, facilitating the growth of prosperity.

The term "energy" comes from Greek (gr. *energeia*), from the word *ergon* ("work") and means action, mobility or activity. In physical terms, energy is a measure of the movement of matter [Niedziółka, 2010], and characterises a body, matter, or physical system capable of doing work. Energy comes in different forms due to the different motion of matter, such as electrical, thermal, chemical, electromagnetic (radiation), mechanical and nuclear energy. Energy transformations occur in animate and inanimate nature [Gradziuk, 2019] and are the focus of interest in many fields of science, including physics, astronomy, biology, chemistry, medicine, geology, environmental protection, and economics. Energy carriers include coal, wood, oil natural gas, and electricity. Energy can be divided into primary and secondary (which is a primary energy that underwent a transformation process). Non-renewable and renewable energy resources make up the primary energy sources. Energy in the form of organic and nuclear fuels are non-renewable resources. Renewable resources include those derived from mechanical energy (flowing water, energy of the Earth's interior, gravity, wind, sun, biomass). Secondary energy is represented by electricity, heat and secondary fuels. Table 1 includes sources of renewable primary energy, as well as the possible energy transformations that produce different types of secondary energy.

In 2022, the world's total energy supply (by sources) was as follows [IEA, 2024]:

- oil: 187902349 TJ,
- biomass: 54482802 TJ,
- wind, solar, etc.: 19018259 TJ,
- hydro energy: 15660642 TJ,
- nuclear energy: 29320058 TJ,
- natural gas: 143897186 TJ,
- coal: 171902932 TJ.

Table 1. Renewable energy sources and technical capabilities of energy conversion

Primary energy sources		Natural energy conversion processes	Technical energy conversion processes	Form of energy obtained
Sun	water	evaporation, melting of ice and snow, precipitation	hydroelectric power plants	electricity
	wind	movement of the atmosphere	wind power plants	electric and thermal energy
		wave energy	wave power plants	electricity
	solar radiation	ocean currents	power plants using ocean currents	electricity
		heating of the earth's surface and atmosphere	ocean heat power plants	electricity
			heat pumps	thermal energy
		sun rays	collectors and thermal solar power plants	thermal energy
			photovoltaic cells and solar power plants	electricity
			photolysis	fuels
	biomass	biomass production	heating and thermal power plants	electric and thermal energy
			processing devices	fuels
Earth	isotope decay	geothermal springs	geothermal heating and power plants	electric and thermal energy
Moon	gravitation	the tides of water	tidal power plants	electricity

Source: [Ligus, 2019, p. 17], translation by the author.

Hydrogen and ammonia are energy sources that are the focus of interest for scientists, politicians and businesspeople around the world. They can play a significant role in the ongoing global energy transformation.

Hydrogen is the most common chemical element known to humans, found in the universe. It is referred to as the "fuel of the future". Hydrogen combined with oxygen forms water, and with carbon it creates methane, coal, or oil (petroleum). It is present in all forms of biomass. It can be used where the use of electricity becomes problematic. Hydrogen in the form of H_2 gas does not exist freely on Earth; it must be produced. Hydrogen is obtained through a separation reaction from water, biomass, or natural gas resources. The main advantage of hydrogen energy production is its commonness, as hydrogen is found everywhere on Earth and can be extracted from a variety of raw materials. It is mainly used in refining, metal processing, and the food industry. However, construction of hydrogen power plants based on current technologies is not (yet) cost-effective. Hydrogen enrichment of natural gas and oil (also to increase its efficiency) can lead to a reduction in environmental pollution. Storage and transportation of hydrogen is problematic due

to its flammability when mixed with air. Production of hydrogen is expensive and energy-intensive [IEI, 2019].

Ammonia is a substance that is easier to transport and store than hydrogen due to its higher energy density. It is also safer because of its low explosiveness, although it has lower energy efficiency [Szlęk et al., 2023]. Ammonia is produced by converting hydrogen and nitrogen under low pressure into a liquid. It is easy and safe to store as it is hardly flammable and becomes explosive only under strictly defined conditions, though it is very toxic because nitrogen oxides are released during the ammonia oxidation reaction. Ammonia has been used as a fuel since the 1820s. Its main use remains in agriculture as a fertilizer, but it can be used as a fuel for heating (as boiler fuel or to power heat engines) [Szlęk et al., 2023]. The use of ammonia as an energy carrier in a commercial coal-fired power plant began in Japan in May 2021. Ammonia produced from natural gas using carbon capture technology is imported by Japan from countries including Saudi Arabia [Sikora, Sikora, 2022, pp. 76–79].

2. History of energy transition

The process of energy transition has affected many aspects of modern societies. Humans have utilised the energy resources stored in nature for a very long time. In the beginning, energy obtained from the environment was used to meet basic needs and improve living conditions of man. Later, humans began harnessing energy to produce light and subsequently to power devices and machines. The history of humankind, and consequently of economic development, is closely linked to the use and transformation of energy. Successive energy transformations provided stronger and more flexible driving forces of global development and enabled more efficient and effective ways of energy conversion. The milestones of human development became shorter, and the pace of great energy transformations increased [Smil, 2004, p. 549]. Over the past two centuries, the way we produce and consume energy has changed significantly. This change has been both caused by and contributed to further technological progress and economic development.

These changes occurred at different paces depending on the location and were related to structural changes in the world. There are differences not only in the speed of these transformations but also in national and regional timings of the discovery and spread of new fuels and methods of processing them [Smil, 2022, pp. 301–302].

The earliest, prehistoric transformations took place slowly. They were driven by increasingly sophisticated tools, mastery of fire, more efficient hunting methods, and they lasted for thousands of years. Primar energy transformations ensured

the survival and continuity of the human species. For many centuries, human existence – and therefore the economy – was based on farming of the land.

At a later stage, changes accompanied intensified civilisational development. As settled agriculture expanded, population grew rapidly and the processes of social stratification, occupational specialisation, and urbanisation began. With the increasing use of fossil fuels, high-energy societies emerged. They personified change and the constant need for innovation [Smil, 2022, p. 316]. In the 19th and 20th centuries, the development of industry accelerated rapidly thanks to technical and technological discoveries and innovations such as the steam engine, the kerosene lamp, the internal combustion engine, and electrification. The transition from an agriculture-based to an industrial economy required the use of more efficient energy sources. In the 21st century, the main goal of the energy transition appears to be the mitigation of adverse climate change, reduction of greenhouse gas emissions, as well as limitation of environmental pollution.

2.1. Primary energy transformations

The first stage of human development covers the period from the "birth" of the human species (about 5–10 million years ago) to modern times (up to approximately the 16th century). The existence of primitive humans was inextricably linked to the Sun, the first and primary source of energy. The Sun provided light and heat. The activities of primitive humans focused on obtaining food and accessing the energy contained in it, which met the minimum biological needs of existence. By mastering fire, the meal could be more plentiful and nutritious for the body, and heat was also provided during cold weather [Szpilewicz, 1974, p. 5]. Later, early humans began to cultivate the land in a primitive way. The use of animals for labour was a turning point in the first era of human development, while the use of wind power and water movement enabled easier work and faster transportation. Fire was used to produce metals and other durable materials [Smil, 2004, p. 551]. Further changes in the use of energy were brought about by the replacement of muscle work with the work of water wheels and windmills. This increased both the power produced and the energy efficiency.

2.2. Energy transformations in modern times

The second stage of energy change was characterised by the replacement of low-efficiency energy sources with fossil fuels, which became the main means of obtaining high-efficiency energy [Malanima, 2014, p. 5]. This stage began in the 17th century and was marked by the replacement of animals with engines and biomass with fossil fuels. The rate and volume of energy consumption increased

rapidly. Thanks to inventions and technical innovations, coal, oil, natural gas, and biofuels were widely used [Allen, 2013, p. 11].

The first country to make an energy transformation from burning wood to coal was Great Britain in the 16th and 17th centuries [Allen, 2013, pp. 12–13]. The replacement of wood with peat and the massive use of wind power to transport goods by sailing ships via inland canals as well as building windmills took place in the Dutch Republic in the 17th century.

The industrial revolution was fuelled by hard coal, which had higher efficiency than wood. It resulted in a more productive economy, leading to economic progress and urbanisation [Yeager, n.d., p. 390]. The appearance of the steam engine became a milestone in the world's energy transition. The first mechanical drive using coal was a low-power steam engine which pumped water out of coal mines. Invented by Thomas Newcomen, this mechanism became the first steam engine put into operation in 1712, in a mine in Staffordshire [O'Connor, 2010, p. 3].

The steam engine was patented by James Watt in 1769. He transformed and improved the steam engine's condenser, turning it into a machine with a very wide range of applications. In the first half of the 19th century, water turbines were developed and used to build hydroelectric power plants [Smil, 2004, p. 555].

Industry using the steam engine, a hallmark of the Industrial Revolution, required coal. Households used coal for heating and cooking. Over a period of 100 years, comparing the early 19th and 20th centuries, the share of coal production and consumption in the global structure increased from 1.7% to 47%. A comparison of biomass and coal use for energy purposes between 1800 and 1940 is shown in Table 2.

Table 2. The use of biomass and coal in the structure of energy production and consumption in the 19th and 20th centuries

Year	Biomass (% of global share)	Coal (% of global share)
1800	98.3	1.7
1820	97.6	2.4
1840	95.1	4.9
1860	86.8	13.3
1880	73.0	26.7
1900	50.4	47.2
1920	38.4	54.4
1940	31.6	50.7

Source: [Bhutada, 2022].

Within 100 years, coal had become a major energy carrier. As an energy-dense and efficient resource with abundant deposits, it was widely used in industry. The invention of the steam engine reduced the importance of windmills in power

generation (which produced 1TW of energy in the mid-19th century). They were most popular in Denmark and the Netherlands (around 30000 windmills operated in each of those countries).

Discoveries and inventions initiated the process of electrification and the use of hydrocarbons. George Westinghouse patented the transformer [*Westinghouse George*, n.d.], Charles Parsons invented and patented the first steam turbine in 1884 [*Parsons Charles Algernon*, n.d.], while Nikola Tesla developed the first induction motor and electric motors in 1888 [Wielowińska-Pawlak, 2022]. Electricity not only revolutionised industrial production but also helped to reduce the burden of housework (mainly for women).

Fossil fuels and electricity were the driving force behind economic change, the development of mechanisation, industrial production and the service sector, and the decline of the agricultural population. The first coal-fired power plants were put into operation in 1882 in London and New York, and a hydroelectric plant in Appleton, Wisconsin [Igliński et al., 2017, p. 38]. Around 1930, steam and coal-fired power plants were developed. In 2020, fossil fuels accounted for 78% of the world's total energy consumption [WEF, 2022].

The boom in oil use came with the development of electricity. The 1890s were marked by automotive inventions, such as: Gottlieb Deimler's petrol engine, Karl Benz's electric ignition, Wilhelm Maybach's float carburetor, and Rudolf Diesel's new internal combustion engine [Smil, 2004, p. 556]. In the mid-20th century, oil was one of the main energy carriers. After 1960, demand for oil further increased with the spread of gasoline-powered vehicles.

The invention of the gas burner in the mid-19th century by Robert Bunsen popularised the use of natural gas for heating purposes. Table 3 shows the percentage of coal, oil, and natural gas consumption worldwide in the second half of the 20th century.

Table 3. The use of coal, oil, and natural gas in the structure of energy production and consumption in the 20th century

Year	Coal (% of global share)	Crude oil (% of global share)	Natural gas (% of global share)
1950	44.2	19.1	7.3
1960	37	26.6	10.7
1970	25.8	40.2	14.5
1980	23.8	40.6	16.3
1990	24.4	35.5	18.4
2000	22.5	35.1	19.7

Source: [Bhutada, 2022].

Oil was most widely used in the 1970s and 1980s. The popularity of natural gas grew steadily, reaching a peak in 2020.

The popularity of coal for heating purposes has declined in favour of gas and electricity. Oil has displaced coal in transportation. Hard coal continues to play an important role as a fuel for electricity generation, accounting for over 30% of global production.

Nuclear power was developed in the mid-20th century. Atomic energy as a nuclear weapon was used for the first time during World War II. Nuclear power is primarily used to produce electricity. In 1951, the first nuclear research reactor was built in Idaho, USA [U.S. Department of Energy Office of Nuclear Energy, n.d., p. 8], and in 1954, the first nuclear power plant was put into operation in Obninsk, USSR [Chater, 2005, p. 30].

The development of nuclear power has been hampered by the high risk of nuclear reactor accidents, the problem of radioactive waste disposal and resistance from the public [Niedziółka, 2010, p. 17]. In the history of nuclear power, there have been environmental disasters caused by nuclear reactor explosions (such as the 1988 Chernobyl explosion and the 2011 Fukushima reactor accident caused by a tsunami) [Miljanić, Pratt, 2022, p. 7]. Nevertheless, nuclear energy is considered environmentally friendly. Nuclear energy production does not generate carbon dioxide emissions, greenhouse gases, or other pollutants, but leaves radioactive waste that must be properly removed, secured and stored. Construction of nuclear power plants raises objections from residents of the areas where they are to be located due to the possible environmental contamination from malfunctioning reactors or improper storage of waste [Hueting, 1980, p. 47].

The time after World War II marked a period of intense global growth and accelerated economic development. There was a surge in industrial production and an increase in agricultural productivity.

Due to the growing level of economic development and population, the world's energy needs continue to grow. Figure 1 shows world population size from the very beginning to the present, with predictions for 2050.

World population increased over the last 200 years from 1,000 million people in 1800 to 8,160 million in 2024 (in 1850, the population totalled 1,200 million; in 1900 – 1,600 million; in 1950 – 2,580 million; and in 2000 – 6,170 million) [Worldometer, n.d.]. The largest population growth took place in the second half of the 20th century. The world population density (persons per km^2) in 2024 was 55; in 2000 it was 41; in 1970 – 25; and in 1952 it was 17 persons per square kilometre [Worldometer, n.d.]. The top 5 countries whose populations are projected to grow the most by 2050 are: India, Nigeria, Pakistan, the Democratic Republic of Congo, and Ethiopia [WPR, n.d.].

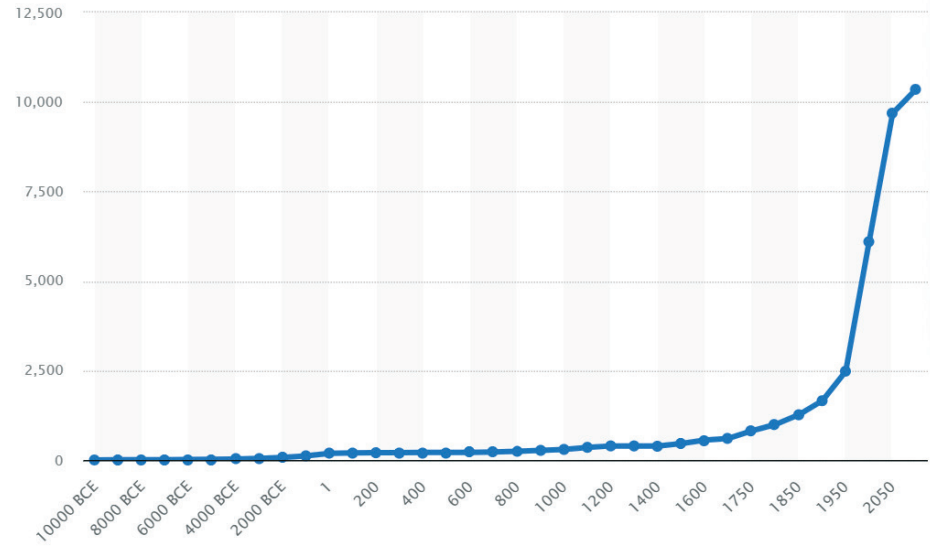

Figure 1. World population in millions
Source: [statista.com 2024].

The most noticeable progress in energy use and the diversity of energy carriers has taken place over the past 220 years (see Figure 2). The biggest increase in energy consumption occurred in the second half of the 20th century. With the growing importance of renewable energy sources in the 21st century, coal, oil, and gas continue to be the world's main energy sources.

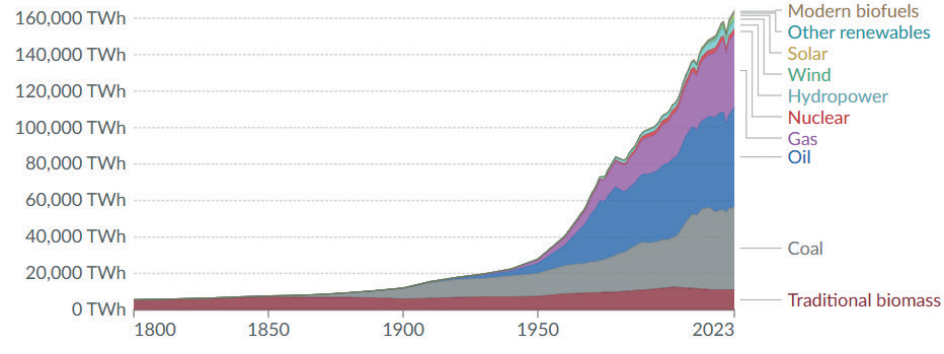

Figure 2. Global direct primary energy consumption during the period 1800–2023
Source: [Our World in Data n.d.].

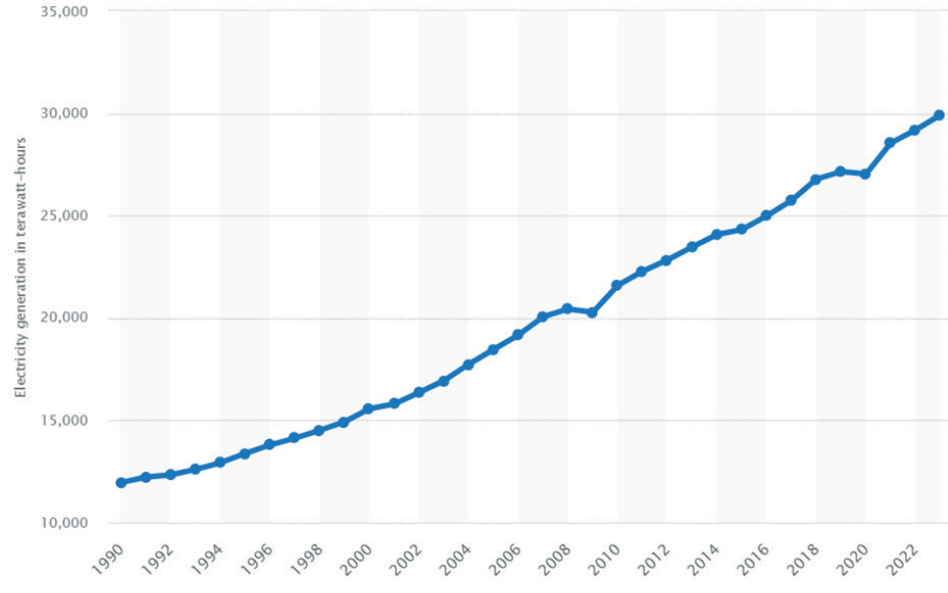

Figure 3. Electricity generation worldwide in terawatt-hours (1990–2023)
Source: [statista.com 2024].

Since 1900, global electricity production has followed an upward trend and has increased from about 12,000 TWh in 1900 to 30,000 TWh today. As shown in Figure 3, there were only two declines in production over that period: the first during the global financial crisis in 2009 and the second during the COVID-19 pandemic in 2020.

The global power generation rose by 2.6% in 2023, in line with its trend of an average annual growth of 2.5%. The world's electricity supply per capita increased from 3,306 kWh in 2015 to 3,620 kWh in 2022 [GUS, 2023, Table 10.11].

2.3. Modern energy – renewable sources of energy

Under the influence of rapid economic development, industrial production, service activities, and a growing population, fossil fuel resources have been rapidly decreasing. Their use has generated environmental pollution and produced large amounts of carbon dioxide. As a result, stakeholders began to seek alternative energy sources with lower exhaustibility and a higher degree of environmental friendliness.

There has been a growing global interest in harnessing the energy of the sun, wind, water, the Earth's interior, and biomass [Hodana et al., 2012, p. 4] as well as in hydrogen; and the interest in nuclear energy has risen again. Table 4 shows the change in the global structure of energy production and consumption in the 21st century.

Table 4. The use of biomass, renewable sources, fossil resources, and nuclear energy in the structure of energy production and consumption in the 21st century

Year	Biomass (% of global share)	Renewable energy sources (% of global share)	Fossil fuels (% of global share)	Nuclear energy (% of global share)
2000	10.2	6.6	77.3	5.9
2005	8.7	6.5	79.4	5.4
2010	7.7	7.7	79.9	4.7
2015	6.9	9.2	79.9	4.0
2020	6.7	11.2	78	4.0

Source: [Bhutada, 2022].

In the 21st century, the share of renewable energy sources in the global energy consumption has increased, doubling over 20 years. The share of biomass has declined. Fossil fuels remained the main energy carrier. The share of nuclear energy has decreased by about 30%.

The World Energy Council estimates that the remaining global coal reserves amount to 665 billion tons, with the annual consumption reaching 7.5 billion tons [Starzycka et al., 2020]. Energy production from coal generates large amounts of carbon dioxide, which are difficult to absorb naturally, and post-production waste. Furthermore, transportation of coal releases dust that is harmful to health and life [Hueting, 1980, p. 51].

3. Energy as an essential element of economic growth and development

Classical economists have already recognised the importance of energy in the economies of states. In classical economics, the basic factors of production such as labour, land, and capital were distinguished; each of these factors is inextricably linked to energy. Natural resources such as coal and oil remain the most popular energy sources in the world. Labor contributes to energy transformation, while energy reserves and the ability to to generate energy.

Reflections on the causes of economic growth and development in the 20th century led to the creation of many theories, including those of Solow, Schumpeter, and Nordhaus. They recognised the power of technological progress and the finiteness and exhaustibility of natural resources, which must be replenished in some way.

Economic growth is the process of expanding the real GDP of an economy over a certain period. It represents the quantitative, sustained growth in output and per capita income, accompanied by the growths in consumption, labour, capital,

and trade. It is measured by the growth rate of real output or real national income. Capital, labour, land, and renewable and non-renewable raw materials are the growth factors [Begg et al., 2014, pp. 414–418].

Economic development is a broader concept as it also includes qualitative changes. The goal of economic development is to improve the livelihood of a country's citizens. It depends on human resources, social attitudes, historical and political conditions, as well as structural changes and technical and technological progress (particularly in: Solow, Schumpeter, and later Romer models). Due to high levels of poverty, economic inequality or unemployment, a country may experience economic growth without achieving development [Sharma, Singh, 2020, p. 8].

Energy plays a fundamental role in economic growth and development. This growth is "a process in which the creators of new trends, economic pathways, energy policy makers and planners, government officials, leaders, entrepreneurs and other stakeholders work to increase energy efficiency and diversify energy sources in a way that promotes job creation and the expansion of regional wealth" [Carley et al., 2011, p. 287].

There is also the so-called "loop" between energy and economic development. As the rate of economic growth has been intensifying, the energy consumption grew, and the rise in the production of increasingly cheaper energy led to an acceleration of the economic growth [Danielewski, 1980, p. 12]. Ensuring continuous economic growth requires the use of more and more energy or increasing its efficiency. Energy integrates production factors, contributes to the creation of added value through labour, and its availability significantly affects the rate of economic change. The key role of energy in economic growth and its flows, and the relationship between the amount of national income and the quality of the environment is shown in the Kuznets curve [Ansari, 2023].

A positive relationship between production growth and energy consumption was observed and described in the second half of the 20th century. It was noted that approximately 1% increase in production led to an increase in energy consumption of 1 to 1.8%. The differences resulted from the specificity of consumer habits and structural differences in the production of specific economies. This indicator can be improved by increasing the efficiency of energy use and engaging in more energy-efficient consumption and production [Hueting, 1980, p. 49]. Negative energy shocks in the economy (such as energy price increases, adoption of energy conservation policies) can adversely affect national income, especially in countries whose energy resources do not meet their needs [Sharma, 2010, p. 3567].

Electricity is referred to as the fifth factor of production, alongside land, labour, capital, and organisation [Sharma, Singh, 2020, p. 9]. It has influenced the development of all areas of the economy and is essential to ensuring a satisfactory and comfortable standard of living. It contributes to improving living conditions and

meeting basic needs – starting with enabling education and learning, providing more time for reading, work, production, and transport, through reducing operating costs and promoting more efficient use of resources, to end with offering more engaging leisure and entertainment opportunities [Anderson, 2000, p. 397–398].

The automation of production processes, the use of office equipment, and access to the Internet would not be possible without electricity. A high level of electrification is an economic necessity. Electricity has been a key factor in improving agricultural productivity through mechanisation [Singh, 2009, pp. 25, 31] and has been essential for many rural industrial activities [Goldemberg, 2000, p. 374].

In his simple empirical analysis conducted in the second decade of the 21st century, D.I. Stern demonstrated a strong positive correlation between GDP and per capita electricity consumption. He confirmed both the impact of economic growth on the level of electricity consumption and the strong positive effect of constant access to electricity on GDP per capita [Stern, 2017, p. 4].

4. Energy and economic growth and development. Norway, China and South Korea case studies

The growth and economic development of some countries were driven by energy and its increasing production. Case studies of selected economies are presented below.

4.1. Norway

Norway's economic development is based on energy. The country is rich in natural resources, especially hydropower and fossil fuels. The unique mountainous landscape and numerous rivers enable a great amount of energy production. Hydropower plants account for almost 90% of Norway's energy mix. Norway reached a record net electricity export in 2020 (20.5 TWh), making Norway one of the largest electricity exporters in Europe. The country is well integrated into the Nordic and European electricity markets [IEA, 2022].

At the beginning of 2023, the total installed production capacity in Norway was 39,703 MW. Regularly, Norwegian power plants produce about 156 TWh. In 2021, Norway set a new production record, reaching a total electricity production of 157.1 TWh. In 2022, due to a low level of water inflow to reservoirs, total electricity production was 146.1 TWh. The energy system constantly balances between production and consumption. A unique feature of the Norwegian hydropower system is its high storage capacity, which accounts for 50% of the overall storage capacity of European

reservoirs. Norway's energy production capacity is flexible, at over 75%. The flexibility of the system is supplemented by wind and solar [Energifaktanorge, n.d.].

Norway's economic development is based on energy, large reserves of crude oil and gas, and its stable energy supply. There has been a significant increase in energy production and GDP per capita in Norway. Table 5 presents the gross national income per capita in comparison with energy production (1971–2021).

Table 5. Energy production and GDP per capita in Norway, 1971–2021

Indicator	1971	1980	1990	2000	2010	2021
Energy production (PJ)	252	2307	5002	9547	8725	8955
GDP per capita (current USD)	3736	15 772	28 243	38 178	88 163	93 073

Source: own study based on [IEA, n.d.; The World Bank, n.d.].

4.2. People's Republic of China

Rich coal resources are the driving force of the Chinese economy and one of the main factors contributing to its rapid economic growth and development. China is the largest investor in renewable sources in the world, but at the same time continues its spending on coal and nuclear energy. China invests in the production and export of electric cars and lithium-ion batteries, as well as in the development of solar energy products. Today, every second passenger car sold in China has an electric or hybrid engine. The electrification process is rapid and helps to strengthen its energy security (almost all electricity is generated from domestic sources) [Kalwasiński, 2024]. Table 6 shows the amount of energy production and GDP per capita, both of which have seen significant growth over the last 30 years.

Table 6. Energy production and GDP per capita in China, 1990–2021

Indicator	1990	2000	2010	2021
Energy production (PJ)	36 880	47 045	93 593	12 4173
GDP per capita (current USD)	318	959	4550	12 617

Source: [IEA, n.d.; The World Bank, n.d.].

4.3. The Republic of Korea

The Republic of Korea is among the top ten largest consumers of energy in the world. This is due to the high level of production of electrical and electronic devices and components [Ghezelbash et al., 2023].

Korea has experienced remarkable economic growth for several decades despite its difficult geography and lack of natural resources. Korea's economy is strongly export-oriented, with exports accounting for 44% of GDP in 2018. Korea is the world's largest producer of semiconductors. To maintain its strong industrial and export base, it is heavily dependent on imports of raw materials, including energy [IEA, 2020]. Table 7 below shows total energy production and consumption in comparison to GDP per capita.

Table 7. Energy production and GDP per capita in South Korea, 1971–2021

Indicator	1971	1980	1990	2000	2010	2021
Energy production (PJ)	267	388	922	1360	1878	2194
Energy consumption (PJ)	570	1310	2733	5301	6738	7763
GDP per capita (current USD)	301	1715	6610	12 257	23 079	32 395

Source: [IEA, n.d.; The World Bank, n.d.].

The country has experienced a significant growth of energy consumption over the last 50 years. Being one of the Asian tigers, Korea reached a high level of GDP per capita in 2021.

The economic growth and development of three different economies presented above are related to energy, its production, and consumption. These countries leverage their individual geographic and political conditions and strengths in international trade.

5. Conclusions

Energy is an essential factor in economic growth and social development. It creates an energy system that underpins all branches of the economy. It is involved in most of the processes that take place. The amount of energy possessed, and its efficiency impacts the momentum of economic change. The use of energy leads to various economic and social benefits and costs. Power engineering (i.e., the process of energy conversion) allows a more efficient use of resources and improves economic and social processes. The main negative externality is environmental pollution. This phenomenon intensified with the advent of the industrial revolution and the massive exploitation of energy resources, which disrupted the Earth's natural physical processes. Due to the varying pace of economic development, natural wealth of different countries, climatic conditions, and political environments, there has been a noticeable polarisation of civilisation development in different parts of the world.

The world has undergone a great energy transformation. Looking back at the historical transformation of energy, three major ones can be identified: the taming

of fire and domestication of draft animals; the use of wheels and windmills; and the construction of the steam engine and use of fossil fuels. The last of these milestones in energy transformation can be further described by three waves of transformation. The first wave was associated with a massive mining of coal. Then, after the invention of the steam engine, these engines became widely used, railroads have been developed, and internal combustion engines appeared. The third wave was marked by the appearance and spread of electricity, the growing importance of electricity in industrial processes, the emergence of jet engines, as well as the use of nuclear energy.

In the history of energy transformations, there have been many instances of shortages and limitations in the access to energy. Cyclical, insufficient energy supplies caused lower production and brought about economic slowdowns [Sharma, Singh, 2020, p. 8]. As a result, innovative energy generation solutions have been developed. By converting different energy sources, more energy could be obtained in a more efficient way [O'Connor, 2010].

In the 21st century, renewable energy sources will most likely play the most important role in the energy sector. They are perceived to be a salvation for the planet and its natural resources that have been overexploited. Hydrogen and ammonia are substances that can play a significant role in the energy sector of economies striving to achieve climate neutrality within several decades.

Some countries (such as Norway, China, or South Korea) took advantage of the specific conditions in which they operated and – among other factors – thanks to energy have achieved high and stable economic growth, fostering economic and social development.

Energy transformation requires an increase in production capacity and substantial investments and financial outlays in the transmission network infrastructure, the construction of energy storage facilities, as well as changes in the behaviours and habits of energy consumers [WEF, 2022]. The types of energy carriers and their source, as well as the size of the demand for energy and its supply have a bearing on economic growth and development. The cost and availability of energy impacts technological development [Pack, 1993, p. 321].

References

Allen R.C., 2013, *Energy transitions in history: The shift to coal* [in:]: *Energy transitions in history: global cases of continuity and change*, eds. R.W. Unger, R. Carson, Center Perspectives, no. 2013/2, https://www.environmentandsociety.org/perspectives/2013/2/energy-transitions-history-global-cases-continuity-and-change [access: 15.12.2024].

Anderson D., 2000, *Energy and economic prosperity*, [in:] *World Energy Assessment, Energy and the challenge of sustainability*, United Nations Development Programme, New York, https://www.undp.org/sites/g/files/zskgke326/files/publications/World%20Energy%20Assessment-2000.pdf [access: 10.12.2024].

Ansari S., 2023, *The Kuznets Curve*, Economics Online, https://www.economicsonline.co.uk/definitions/the-kuznets-curve.html/ [access: 5.12.2024].

Begg D., Vernasca G., Fischer S., Dornbusch R., 2014, *Makroekonomia*, PWE, Warszawa.

Bhutada G., 2022, *Visualizing the history of energy transition*, Visualcapitalist, https://www.visualcapitalist.com/visualizing-the-history-of-energy-transitions/ [access: 2.12.2024].

Carley S., Lawrence S., Brown A., Nourafshan A., Benami E., 2011, *Energy-based economic development*, Renewable and Sustainable Energy Reviews, no. 15, https://www.sciencedirect.com/science/article/pii/S1364032110002583 [access: 28.11.2024].

Chater J., 2005, *A history of nuclear power*, Focus on Nuclear Power Generation, https://courses.grainger.illinois.edu/npre470/sp2018/web/readings/James_Chater_History_nuclear.pdf [access: 12.12.2024].

Ciechanowicz W., 1995, *Energia, środowisko i ekonomia*, Instytut Badań Systemowych PAN, Warszawa.

Danielewski J., 1980, *Paliwa w handlu międzynarodowym*, PWE, Warszawa.

Energifaktanorge, n.d., https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/ [access: 9.05.2025].

Ghezelbash A., Seyedzadeh M., Khaligh V., Liu J., 2023, *Impacts of green energy expansion and gas import reduction on South Korea's economic growth: a system dynamics approach*, Sustainability, no. 15, https://doi.org/10.3390/su15129281.

Goldemberg J., 2000, *Rural Energy in Developing Countries* [in:] *World Energy Assessment, Energy and the challenge of sustainability*, United Nations Development Programme, New York, https://www.undp.org/sites/g/files/zskgke326/files/publications/World%20Energy%20Assessment-2000.pdf [access: 10.12.2024].

Gradziuk P., 2019, *Rola energii w procesach gospodarowania*, PAN, https://www.researchgate.net/publication/331177588_Rola_energii_w_procesach_gospodarowania [access: 24.11.2024].

GUS, 2023, *Roczniki Statystyki Międzynarodowej*, https://stat.gov.pl/obszary-tematyczne/roczniki-statystyczne/roczniki-statystyczne/rocznik-statystyki-miedzynarodowej-2023,10,11.html [access: 7.11.2024].

Hodana M., Holtzer G., Kalandyk K., Szymańska A., Szymański B., Żymankowska-Kumon S., 2012, *Odnawialne źródła energii. Poradnik*, Stowarzyszenie Helios.org, Kraków.

Hueting R., 1980, *New scarcity and economic growth. More welfare through less production?* North Holland Publishing Company, Amsterdam.

Igliński B., Buczkowski R., Cichosz M., Iwański P., Rzymyszkiewicz P., 2017, *Technologie hydroenergetyczne*, Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika, Toruń.

IEA, n.d., *Total energy supply (TES) by source, World, 1990–2023*, International Energy Agency, https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource [access: 27.11.2024].

IEA, 2020, *Korea 2020, Energy Policy Review*, International Energy Agency, https://iea.blob.core.windows.net/assets/90602336–71d1–4ea9–8d4f-efeeb24471f6/Korea_2020_Energy_Policy_Review.pdf [access: 9.05.2025].

IEA, 2022, *Norway 2022, Energy Policy Review*, International Energy Agency, https://iea.blob.core.windows.net/assets/de28c6a6–8240–41d9–9082-a5dd65d9f3eb/NORWAY2022.pdf [access: 9.05.2025].

IEI, 2019, *Intermediate Energy Infobook*, The Need Project, Manassas, https://www.need.org/wp-content/uploads/2019/10/Intermediate-Energy-Infobook.pdf [access: 20.12.2024].

Kalwasiński M., 2024, *Chiny na drodze do „zielonego" bezpieczeństwa energetycznego*, Ośrodek Studiów Wschodnich, no. 605, https://www.osw.waw.pl/sites/default/files/komentarze_605_0.pdf [access: 9.05.2025].

Ligus L. (ed.), 2019, *Zarządzanie wartością inwestycji*, Wydawnictwo Uniwersytetu Ekonomicznego we Wrocławiu, Wrocław.

Malanima P., 2014, *Energy in history* [in:] *The basic environmental history*, eds. M. Agnoletti, S. Neri Serneri, Springer International Publishing, Cham, https://pdfarchived.net/list/the-basic-environmental-history-mauro-agnoletti-4910671 [access: 17.12.2024].

Miljanić O.Š., Pratt J.A., 2022, *Brief history of our relationship with energy* [in:] O.Š. Miljanić, J.A. Pratt, *Introduction to energy and sustainability*, WILEY-VCH GmbH, Weinheim, https://application.wiley-vch.de/books/sample/352734540X_c01.pdf [access: 12.12.2024].

Niedziółka D., 2010, *Rynek energii w Polsce*, Difin SA, Warszawa.

O'Connor P.A., 2010, *Energy transitions*, The Pardee Papers, Boston University, no. 12, https://www.bu.edu/pardee/pardee-paper-012-energy/ [access: 21.12.2024].

Our World in Data, n.d., *Global direct primary energy consumption*, https://ourworldindata.org/grapher/global-primary-energy [access: 4.12.2024].

Pack H., 1993, *Technology gaps between industrial and developing countries: are there dividends for latecomers?* [in:] *Proceedings of the World Bank annual conference on development economics 1992*, Supplement to the World Bank Economic Review and the World Bank Research Observer, eds. L.H. Summers, S. Shah, Floor Discussion of Bell-Pavitt and Pack Papers, World Bank Group, Washington, D.C., https://documents1.worldbank.org/curated/en/353181468739245145/pdf/Proceedings-of-the-World-Bank-annual-conference--on-development-economics-1992.pdf [access: 21.11.2024].

Parsons Charles Algernon, n.d., Encyklopedia PWN, https://encyklopedia.pwn.pl/haslo/Parsons-Charles-Algernon;3954533.html [access: 30.11.2024].

Ritchie H., 2022, *Primary, secondary, final, and useful energy: Why are there different ways of measuring energy?*, Our World in Data, https://ourworldindata.org/energy-definitions [access: 4.12.2024].

Sharma M., Singh K., 2020, *The role of energy economics in economic development: An overview*, Pramana Research Journal, no. 10, https://www.pramanaresearch.org/gallery/prjp%20-%201627.pdf [access: 18.12.2024].

Sharma S.S., 2010, *The relationship between energy and economic growth: Empirical evidence from 66 countries*, Applied Energy, no. 87, https://www.sciencedirect.com/science/article/abs/pii/S0306261910002291 [access: 23.11.2024].

Sikora A.P., Sikora M., 2022, *Amoniak surowcem energetycznym?* Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN, no. 110, https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-0f3660e3–50b1–4d5a-a2f2–753bb187e68a [access: 27.02.2024].

Singh K., 2009, *Rural development principles, policies and management*, SAGE Publications India Pvt Ltd., New Delhi, https://www.cabidigitallibrary.org/doi/full/10.5555/20093064484 [access: 2.12.2024].

Smil V., 2004, *World history and energy*, https://vaclavsmil.com/wp-content/uploads/docs/smil-article-2004world-history-energy.pdf [access: 20.12.2024].

Smil V., 2022, *Energia i cywilizacja. Tak tworzy się historia*, Helion SA, Gliwice.
Starzycka A., Młynarczyk M., Zdanowski A., 2020, *Węgiel kamienny, Hard Coal*, Państwowy Instytut Geologiczny, Warszawa, https://www.pgi.gov.pl/images/muzeum/kopalnia_wiedzy/surowce/foldery/wegiel_kamienny.pdf [access: 9.11.2024].
Statista.com, 2022, *Estimated global population from 10,000BCE to 2100*, https://www.statista.com/statistics/1006502/global-population-ten-thousand-bc-to-2050/ [access: 4.12.2024].
Statista.com, 2024, *Electricity generation worldwide from 1990 to 2024*, https://www.statista.com/statistics/270281/electricity-generation-worldwide/ [access: 4.12.2024].
Stern D.I., 2017, *Energy and economic growth applied research programme thematic note: the linkages between electricity supply and economic growth, applied research programme on energy and economic growth*, https://assets.publishing.service.gov.uk/media/5a267ab8e5274a75088c42b0/Line_23_-_Thematic_note_1.EEG.26.05.2017.v1__1_.pdf [access: 14.12.2024].
Szlęk A., Bijańska J., Wodarski K., 2023, *Amoniak jako nośnik energii*, Nowa Energia, no. 2, https://www.cire.pl/filemanager/Materia%C5%82y%20Problemowe%20(Wies%C5%82aw%20Drozdowski)%20/202848a1a3070cbb27b9faf05d342c4485c17b7280c72995c3b7322f577c206b.pdf [access: 17.12.2024].
Szpilewicz A., 1974, *Surowce dla przyszłości. Paliwa i energia*, Książka i Wiedza, Warszawa.
U.S. Department of Energy Office of Nuclear Energy, n.d., *The history of nuclear energy*, Science and Technology Washington, D.C., https://www.energy.gov/sites/prod/files/The%20History%20of%20Nuclear%20Energy_0.pdf [access: 21.12.2024].
WEF, 2022, *The 200-year history of mankind's energy transitions*, World Economic Forum, https://www.weforum.org/agenda/2022/04/visualizing-the-history-of-energy-transitions/[access: 10.11.2024].
Westinghouse George, n.d., Encyklopedia PWN, https://encyklopedia.pwn.pl/haslo/Westinghouse-George;3995008.html [access: 30.11.2024].
Wielowińska-Pawlak B., 2022, *Nikola Tesla i jego wizjonerska spuścizna*, Nauka na UMCS, https://www.umcs.pl/pl/wszystkie-aktualnosci,23641,nikola-tesla-i-jego-wizjonerska-spuscizna,119447.chtm [access: 30.11.2024].
The World Bank, n.d., https://data.worldbank.org/indicator?tab=all [access: 9.05.2025].
World Energy Balances database, n.d., IEA, https://www.iea.org/data-and-statistics/data-product/world-energy-balances#indicators [access: 9.05.2025].
Worldometer, n.d., *World Population by Year*, https://www.worldometers.info/world-population/world-population-by-year/ [access: 4.12.2024].
WPR, n.d., World Population Review, https://worldpopulationreview.com/ [access: 4.12.2024].
Yeager K., ed., n.d., *Energy and economy*, https://previous.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter6_economy_hires.pdf [access: 27.11.2024].

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