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The Impact of Energy Consumption on the Three Pillars of Sustainable Development

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Abstract: The paper analyzes the impact of energy consumption on the three pillars of sustainable development in 74 countries. The main methodological challenge in this research is the choice of a single integral indicator for assessing the social component of sustainable development. Disability-adjusted life year (DALY), ecological footprint, and GDP (Gross domestic product) are used to characterize the social, ecological, and economical pillars. The concept of physics, namely the concept of density (specific gravity), is used. It characterizes the ratio of the mass of a substance to its volume, i.e., reflects the saturation of a certain volume with this substance. Thus, to assess the relationship between energy consumption and the three foundations of sustainable development, it is proposed to determine the energy density of the indicators DALY, the ecological footprint, and GDP. The reaction to changes in energy consumption is described by the elasticity of energy density functions, calculated for each of the abovementioned indicators. The state of the social pillar is mostly dependent on energy consumption. As for the changes in the ecological pillar, a 1% reduction in energy consumption per capita gives only a 0.6% ecological footprint reduction, which indicates a low efficiency of reducing energy consumption policy and its danger for the social pillar. The innovative aspect of the research is to apply a cross-disciplinary approach and a calculative technique to identify the impact that each of the pillars of sustainable development imposes on energy policy design. The policy of renewable energy expansion is preferable for all sustainable development pillars.

Keywords: ecological; economic; social pillars; energy density; energy policy; ecological footprint; regression

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1. Introduction

The beginning of active scientific discussions and political debates, which resulted in the concept of sustainable development, was laid down by the well-known commission report by Gro Harlem Bruntland, titled *Our Common Future* [1]. This report formulated the definition of sustainable development as one that enables future generations to meet their own needs. In September 2015, within the framework of the 70th session of the UN General Assembly in New York, the UN Summit on Sustainable Development was held, which resulted in the adoption of the post-2015 development agenda and new development guidelines. The final document of the summit, "Transforming Our World: An Agenda for Sustainable Development until 2030", concretized the content of this concept in the form of the approved 17 Sustainable Development Goals and 169 tasks [2]. The report "Multiple

Benefits of Energy Efficiency" [1,2] prepared by the IEA is valuable because it touches upon the topic of the impact of energy consumption on all three components of health (sociology), ecology, and business (economics). At the same time, the essence of nit can be clearly illustrated by the following theses: (1) The World Health Organization estimates that globally air pollution causes about 3 million premature deaths a year making air pollution a significant environmental risk; (2) energy efficiency measures targeting indoor and outdoor air quality can have major impacts for global health [2]. A deductive result of this kind does not give an idea of the dependencies inherent in the multidimensional phenomenon of sustainable development.

For more than 30 years, the concept of sustainable development has evolved and is now widely presented in the literature, but at the same time, it has been repeatedly criticized, mainly due to the inconsistency of combining economic growth and the preservation of the natural system in one concept [3]. It was also noted that "there is no agreement on a comprehensive sustainable development theory, there are different contested theoretical approaches and definitions" [4] (p. 468).

Nevertheless, there is a certain consensus in the scientific community that sustainable development is determined by a dynamic balance between the three pillars of the development of civilization: economic, social, and environmental [5]. Recently, scientific discussions and political debates have increasingly emphasized the acuteness of the problem of the impact of economic activity and the everyday life of humankind on the environment, in particular, on the planet's climate change [6,7]. However, the current pattern of economic growth not only poses environmental threats to human existence but also exacerbates social and economic troubles, which are largely associated with the very phenomenon of climate change (droughts, devastating hurricanes, floods, etc.), and with those measures of a structural restructuring of economies, which is due to a significant reduction in the anthropogenic impact of production activities. As emphasized in many publications, change is needed in the current paradigm of global economic development, driven by materialistic selfishness, systems of decision-making and strategic planning on all levels of governing, as well as in the habitual behavior of consumers and stakeholders [8–13]. According to the report "Common!" which was prepared by Ernst von Weizsäcker and Anders Wijkman in collaboration with 34 other Club members for the 50th Anniversary of the Club of Rome, "Current trends are in no way sustainable. Continued conventional growth leads to massive collisions with natural planetary boundaries. The economy under the dictates of the financial system with its seduction to speculation tends to lead to widening gaps in terms of wealth and income" [9] (p. vii).

Obviously, a fundamental approach for resolution of an environmental block of these problems depends largely on strategic decisions and practical actions aimed at the transition to fewer carbon-emission technologies, introducing effective organizational patterns and business models for the production and delivery of energy to the consumer, as well as improvements related to reduced growth rates and energy consumption [14–17]. The realization of these decisions through the efforts of international organizations, national and regional authorities, as well as influential nongovernmental organizations will help achieve the tasks set for the implementation of SDG 7, which is to "ensure access to affordable, reliable, sustainable and modern energy for all" [2]. At the same time, such decisions and actions can have an ambiguous and multidirectional impact on each pillar of sustainable development, and can cause certain socioeconomic tensions and political resistance on a national, regional, or local level [18–21].

It is becoming increasingly evident that the desire to implement a specific conceptual model of energy policy in a community of countries as well as in each specific country or region requires an integrated approach to decision-making at the level of the supranational institutions, national, regional, and local authorities, taking into account the economic, social, and environmental consequences of policy decisions as well as issues of energy security (see [14,20,22–26]). This requires simultaneous consideration of the interaction of the energy factor with all three pillars that form sustainable development in the long term.

The issues of assessing the influence of the energy factor on various aspects of sustainable development of civilization are not new. One of the first attempts to interpret this connection is described in a book published in 1955 (a revised edition was published in 2009 after the death of the author) [27]. In the book, Fred Cottrell traced the co-evolution of man's methods of extracting energy, its sources, and civilization itself. In addition, the pioneer in ecological economics, Howard T. Odum, made a significant contribution to understanding the causal relationships between the generation and consumption of energy, on the one hand, and the environment, economic development, and culture, on the other (see, for example, [28]). Samuel Z. Klausner examined the relationship between energy consumption and social development in the broader context of the relationship between humans and nature and noted that the development of effective social policies requires an energy dimension [29]. Some authors approached this problem from the other side by finding out how different characteristics reflecting the state of sustainable development in countries with different levels of socioeconomic development influence the intensity of energy consumption (see, for example, [30]).

The conclusions of theoretical studies required confirmation by the results of empirical studies, and this led to the appearance of works in which attempts were made to establish the quantitative values of these relationships. Thus, Charles Hall and Jessica Lambert tried to assess the availability of energy for modern society and its relationship with indicators of quality of life. For this, a composite Lambert Energy Index (LEI) has been proposed [22]. LEI is calculated as the geometric mean of three normalized indicators:

- the average energy consumption per capita for a given economy;
- the energy efficiency of the economic process (i.e., the ratio between all the energy generated in the economy and the energy used in this economy to obtain it);
- the Gini coefficient, which characterizes the level of equality in the incomes of the population and, as the authors suggested, is an indirect indicator of the equality of energy distribution in the economy.

The calculations performed by the authors in the papers [22,31] showed a high degree of correlation between LEI and some commonly used quality of life indicators, such as the UN Human Development Index (HDI), the percentage of children underweight, the average health expenditure per capita, female literacy rate, gender inequality index, and the availability of clean water in rural areas. Therefore, it was concluded that the proposed LEI can be used to predict the welfare impact of energy consumption population. However, it should be noted that such calculations and the conclusions based on them are contingent, since the index itself integrates multidirectional values, without taking into account their weight, and it also does not reflect the relationship of energy consumption with the environmental consequences.

The calculations of Lyeonov et al. show that a 1% increase in green investment can cause a 6.4% increase in GDP per capita, a 3.1% decrease in greenhouse gas emissions, and an increase in the share of renewable energy sources in total energy consumption by 5.6% [32] (p. 6). It should be noted that an even deeper understanding of the relationship between green investments and sustainable development of national economies would be obtained if social indicators were included in the range of assessed indicators, for example, life expectancy, the level of morbidity due to air pollution, etc.

Bowen Liu and Jun Matsushima conducted a regression analysis of statistical data for 25 years for 29 OECD countries and 37 non-OECD countries, and in the analysis they determined the relationship between three indicators, i.e., the energy return on energy investments for its production in the public dimension (EROIsoc), the GDP per capita, and the energy consumption per capita (EC per capita), and a set of indices characterizing the quality of life. Their calculations showed that the ratios between EROIsoc, GDP per capita, EC per capita, and the eight quality of life indices are highly variable over time and differ between OECD and non-OECD countries, especially during energy price increasing [33] (p. 1363).

Andrew Jorgenson along with Juliet Schor et al. examined the relationship between energy intensity, CO_2 emissions, working hours, income inequality, and the level of democratization of society in the context of the energy sources transformation [34–36]. As a result, the study of the relationship between energy consumption and the economic, environmental, and social directions of sustainable development is complicated by the introduction of a political component into this process.

The political as well as legal aspects of energy consumption are also presented in the paper of Raphael J. Heffron et al. [37], where they described the results of a study of the energy trilemma in the relationship between energy consumption and social development. The energy trilemma was represented by them in the form of a triangle, in the center of which is law and politics, and the vertices of the triangle indicate three problems: economic (ensuring financial and price stability, efficiency, competition in the markets), political (ensuring energy security), and environmental (mitigating the consequences of changes climate, reducing CO_2 emissions, ensuring a healthy environment). All three of these issues affect energy legislation and policy, each in a different direction. Ideally, effective and efficient energy legislation and policies should balance the three directions to deliver the best results for society. However, in practice, economics, politics, and the environment are competing goals of the energy trilemma and, according to the authors, often only one of these issues dominates in an energy agenda. They argued that energy justice should be seen as the driving force behind energy legislation and policy, and the metric for this is proposed in the paper. The main purpose of this metric is to provide societies with a tool to make more informed decisions about which energy infrastructure projects should be built and that these projects meet the criteria for distributing full costs and fairly and equitably benefits for current and future generations.

Some publications contain quantitative assessments of the relationship between indicators characterizing the country's energy sector from the standpoint of national security and indicators reflecting various aspects of sustainable development. The paper [25] analyzes energy security in some European countries and the relationship between the main macroeconomic parameters and the new energy security index (NESI) proposed by the authors. The estimates made by the authors using regressions showed that NESI is positively correlated with the dynamics of GDP but negatively with the dynamics of the consumer price index.

Yuri Kharazishvili [38] considered energy security as the most significant characteristic of sustainable development, the level of which he determined by comparing integral indices based on a set of indicators, each of which has threshold values. For research in dynamics at the level of a specific country or region, his proposed approach can be considered universal, but the expediency of its application for cross-country comparisons is questionable. These doubts are caused by the fact that different countries, which are located in different climatic zones, have different access to energy sources, as well as different structural and institutional conditions, including those associated with energy consumption. This requires taking into account these specifics in the threshold values of the indicators, which makes it difficult to compare between countries and does not allow us to identify general patterns of the impact of energy consumption on global transformation processes.

The authors of [39] investigated the impact of an increased use of renewable energy sources on sustainable development. To this end, various technological solutions were considered from the point of view of their ability to ensure energy security and energy availability, contribute to an increase in the level of socioeconomic development, mitigate the effects of climate change, and reduce the impact on the environment and public health.

Of course, the quality of political decisions and legislative acts in the field of energy policy and energy security significantly affects how relationships are built between energy production and consumption, on the one hand, and the evolution of all three pillars of sustainable development of society, on the other. However, these factors are to a certain extent secondary for assessing the relationship between energy consumption and the level of sustainable development. At the same time, establishing quantitative relationships between energy consumption and each pillar of sustainable development ensures more informed policy decisions and the necessary laws.

The purpose of the paper is to study the concept of sustainable development from a systemic point of view in relation to the level of energy consumption based on the establishment of the quantitative values of these relationships. This allows us to identify the constraints that each of the pillars of sustainable development imposes on the energy policy design.

The paper is structured as follows. Section 2 explains the choice of indicators for assessing the relationship between energy consumption and the three pillars of sustainable development, and it also describes the method that is proposed for calculations. Section 3 presents the results of calculations performed and some preliminary conclusions. Section 4 presents general conclusions and recommendations arising from these conclusions regarding energy policy, as well as some discussion points and directions for further research on the proposed topic.

2. Materials and Methods

A flow chart to define the different steps of the research is as follows in Figure 1:

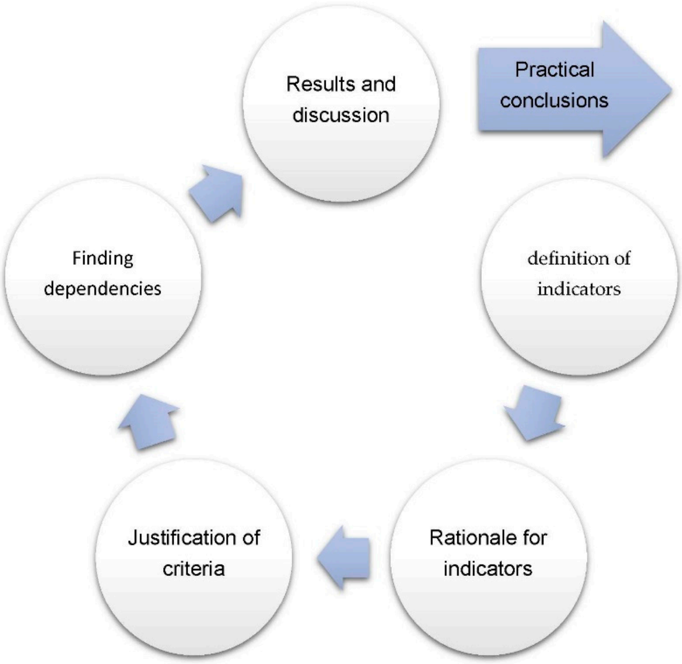

Figure 1. The research scheme.

The most difficult methodological issue was the choice of a single integral indicator for assessing the social component of sustainable development, which is necessary for this study. It is quite obvious that social development within the national framework determines the quality of life of the population of a given country. Therefore, the assessment of the social pillar of sustainable development must certainly reflect this aspect. Attempts to develop indicators that give an objective notion of the quality of life of the population are at the epicenter of many studies, and the results of a number of them eventually find application in political decision-making. Although several sets of different indicators have been proposed, existing developments do not give a clear and unambiguous answer on whether any of them can adequately reflect the wide range of conditions and characteristics that determine the quality of life. In addition, it is methodologically and technically difficult to combine various parameters of the quality of life into one integrated indicator [40], when taking into account also the fact that there are significant contradictions between many indicators reflecting the achievement of the sustainable development goals, as well as between these goals themselves [4].

Doris Fuchs et al. put forward the organizational principle of the quality of life, which integrates the main aspects discussed in the literature regarding the characteristics of well-being and sustainable development. In doing so, they rely on "the economic, social and political aspects of well-being, on the one hand, as well as the quality of the environment and equality between generations and intergenerational boundaries, on the other" [40] (p. 13). The authors analyzed nine sets of indicators used by various international organizations that assess the well-being or sustainable development of nations. They opted for a set of indicators used to determine the composite SSI (the Sustainable Society Index), which the Sustainable Society Foundation calculates for 154 countries every two years since 2006.

In a number of works, the UNDP's Human Development Index (HDI) is used to characterize social development (see, for example, [31,32,41–43]). According to the UNDP (United Nations Development Programme), the HDI "is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. The HDI is the geometric mean of normalized indices for each of the three dimensions" [44].

The HDI, to one degree or another, has shortcomings and raises doubts about its ability to capture the complexity of the interrelated aspects of the life of society [40,45]. Even the UNDP, the organization that "holds" the index, noted the following on its website: "The HDI simplifies and captures only part of what human development entails. It does not reflect on inequalities, poverty, human security, empowerment, etc." [44]. Moreover, the indicators that make up the index have the same weight, which is not objective enough. In addition, as noted in [46], "[the] HDI embodies a contradiction whereby the process of maintaining high levels of development in high-income nations constrains development—and even drives de-development—in poorer nations. For a development indicator that purports to be universal, such a contradiction is indefensible" (p. 4). As for this article, this index has an additional drawback since it includes the income index as an economic indicator, while the study assumes this separately, taking into account the influence of the energy factor on the social, environmental and economic pillars of sustainable development. Of course, to a large extent, the state of the social sphere depends on the level of economic development of a particular country, but this should be reflected in the indicator used to assess this state only indirectly in order to avoid double counting.

When choosing an indicator to determine the relationship between social development and energy consumption, we proceed from the logic that is described by the English proverb: "Those who live well, live long." In recent years, in studies assessing the quality of life for populations of different countries and regions, the disability-adjusted life year (DALY) indicator has become widespread. It reflects the number of years of healthy life lost as a result of illness or premature death, per 100 thousand population [47]. The DALY, which measures the total burden of disease, was developed by Harvard University for the World Bank in the 1990s. It is now widely used by WHO to assess the health status of nations and the quality of a national health system [48]. The indicator is a linear sum of potential life years lost due to premature death and illness (suffering, temporary or permanent disability, inability to normal/habitual life). Using the DALY indicator as an integral characteristic of the social pillar of sustainable development, we proceed from the fact that, directly or indirectly, all factors that determine the social aspects of the development of society manifest themselves in the quality of life of the population of a given state, and ultimately, in the duration of the painless life of the members of this society [49].

To assess the country's impact on the environment, we used the ecological footprint, which is measured in global hectares (gha) by the not-for-profit organization Global Footprint Network in conjunction with the World Wildlife Fund (WWF) [50]. The ecological footprint is not characterized as the harm caused by human activities to the environment but as the ability of the natural environment to compensate for it through assimilation. The assimilation potential of the natural environment (which is regarded as an ecosystem) is understood as its margin of safety ("resistance"), which allows it to neutralize negative consequences, that is, neutralize or process harmful substances without changing its basic properties [50]. The largest components of the ecological footprint are (a) land used for growing food and trees as well as for producing biofuels and for eliminating or absorbing waste, in particular, carbon dioxide emissions; (b) fossil fuels; and (c) marine and oceanic areas used for fishing. The ecological footprint measures how much land is needed to support a given population at current levels of consumption, technological development, and resource efficiency. Footprint sizes for different countries range from more than 10 to less than 1 gha/person.

The gross domestic product per unit of energy use (at purchasing power parity per kg of oil equivalent) was chosen as an indicator for studying the impact of the use of energy resources on the economic pillar of sustainable development [51]. Despite the widespread criticism of the GDP indicator in the scientific audience and the repeated attempts to construct a more suitable indicator for assessing economic development, this indicator remains the most accessible and most often used for relevant analytical studies [31,32,52,53].

In physics, there is the concept of density (specific gravity), which characterizes the ratio of the mass of a substance to its volume, i.e., reflects the saturation of a certain volume with this substance. To assess the relationship between energy consumption and the three foundations of sustainable development, it is proposed to determine the energy density of the indicators DALY ($\rho(DALY)_k$), the ecological footprint ($\rho(FP)_k$), and the GDP ($\rho(GDP)_k$) by Equations (1)–(3):

$$\rho(DALY)_k = \frac{DALY_k}{E_k}, \tag{1}$$

$$\rho(FP)_k = \frac{FP_k}{E_k}, \tag{2}$$

$$\rho(GDP)_k = \frac{GDP_k}{E_k}, \tag{3}$$

where $DALY_k$ is the disability-adjusted life year indicator of the k-th national economy (expressed in million years); FP_k is the size of the ecological footprint of the k-th national economy (in million gha); GDP_k is the value of the GDP of the k-th national economy (in billion USD); and E_k is the energy used in the k-th national economy (in million tons of oil equivalent).

For the study, data were taken from 2016 for 74 countries (see Appendix A) that are located on different continents, in different climatic zones, and have different levels of economic development. In addition to those noted above, the calculations also used data from World Bank statistics on population, the GDP measured in purchasing power parity (PPP), and the GDP (measured in PPP) per capita, as well as data from the BP Statistical Review of World Energy (June 2017) on total energy consumption calculated in oil equivalent for the countries included in the sample for the study [54–58].

The quality of the received regression results is assessed by R^2 (the coefficient of determination), i.e., the square of the linear Pearson's correlation coefficient. The preferable value of this indicator is [0.7, 1].

3. Results

3.1. Impact of Energy Consumption on the Social Pillar of Sustainable Development of National Economies

A sample of data from 2016 for 74 countries suggests that with a probability of 0.95, this year's DALY will be within a confidence interval from 22,139 to 36,685 years per 100 thousand people with a mathematical expectation of 29,412 years, with a minimum of 15,000 years (Qatar) and a maximum of 49,240 years (South Africa). Consumption of primary energy resources (FER (fossil energy ratio)) per capita within the same sample of countries is in the confidence interval from 3224 to 4056 kg of oil equivalent (kgoe) per person (mathematical expectation at 3640; minimum of 194 in Bangladesh; maximum of 18,510 in Qatar). In Ukraine, in 2016, the DALY indicator was equal to 46,000 healthy life years lost per 100,000 population, and the specific consumption of primary energy resources was 2000 kgoe per capita. In the Russian Federation, these figures were 45,000 and 5000 kgoe per capita, respectively, and in Poland, it was 34,000 and 2500 kgoe per capita.

It is noteworthy that all the countries of the Arabian Peninsula, as well as Israel and the Maldives, have DALYs very close to the minimum level: Maldives at 15,800 years, Bahrain at 16,900; UAE at 17,000; Kuwait at 19,000; Israel at 19,600; Oman at 19,900; Brunei at 20,700; and Saudi Arabia at 21,500 years. The exception to the rule is Yemen, with a DALY of 44,900 years (as of 2016), which is not surprising since Yemen is one of the poorest countries in the world and has many mountain villages with a population living from hand to mouth. In contrast to Yemen, which in 2016 had a GDP per capita at purchasing power parity of USD 2400, other countries of the Arabian Peninsula have the corresponding indicators from USD 46.6 thousand per capita (Oman) to USD 79.5 thousand per capita (Brunei).

The relationship between a healthy longevity and the amount of consumed energy resources is demonstrated not only by the countries of the hot Arabian Peninsula but also by the countries of the frosty North, for example, in Norway, whose DALY indicator was 26,600 years per 100 thousand people, and the average per capita energy consumption was 9000 kgoe; for Iceland, this was 27,500 years/100 thousand people and 16,000 kgoe/person, respectively.

There is reason to believe that a high quality of life is a product of not only economic but also energy abundance. One UAE resident accounts for 12,000 kgoe (8000 kgoe in Saudi Arabia). The significant influence of the level of energy consumption on the quality of life is also confirmed by the indicators of Canada: Its DALY is 24,500 years/100 thousand population with an energy consumption per person of 9000 kgoe. The data for Singapore, however, is even more eloquent: Its DALY is 17,400 years per 100 thousand of population, and its consumption of primary energy resources per person is about 15,000 kg of oil equivalent. Situated on the island, the city-state of Singapore with a population of 5.6 million has one of the most highly developed economies in the world. It is a financial, trade, and transport center with a powerful seaport. Singapore ranks third in the world in oil refining and fourth in semiconductor production; its GDP measured in PPP per capita in 2019 amounted to USD 101.7 thousand (for comparison in the United States, this figure for 2019 was USD 65.3 thousand) [56].

Figure 2 presents data from 2016 for the sample countries. This figure reflects the dependence of the energy density of DALY (i.e., healthy life years lost by the population of these countries per 1 kg of consumed energy in oil equivalent) relative to the per capita energy consumption in these countries.

As the figure shows, each unit of small volumes of energy consumed by underdeveloped economies is literally “saturated” with lost years of a healthy life, that is, ill-health and poverty. The data that are presented empirically confirm the conclusion: The greater the specific consumption of energy by the inhabitants of a given country, the higher the level and quality of their life and the lower the energy density of DALYs. The characteristic of the process has the following form of dependence:

$$\rho(DALY)_k = 740.21 f_k^{-1.121}, \quad (4)$$

where f_k is the specific consumption of primary energy resources by a person of the k-th national economy, measured in kgoe/person.

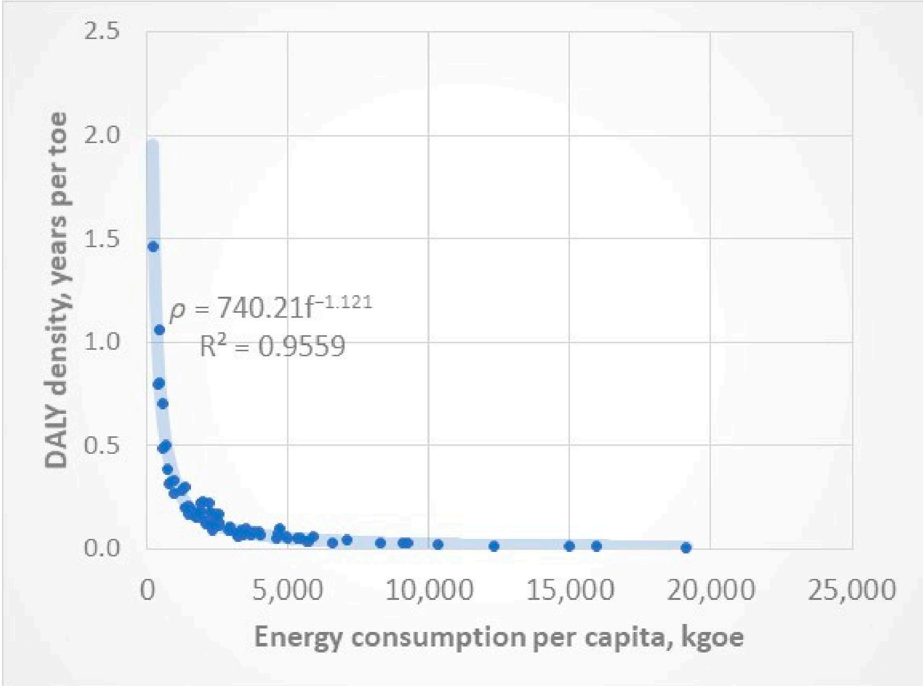

Figure 2. The energy density of disability-adjusted life year (DALY) and energy consumption per capita (2016). Source: Calculated by the authors based on [49,56,58].

A certain hint regarding the phenomenon of active longevity of the population of mentioned above peninsular and northern countries is given by the specificity of their energy. For example, Qatar is a major producer and global exporter of natural gas. Norway, while being a major supplier of oil and gas to the European market, ranks first in the world in terms of electricity production per capita. At the same time, despite the presence of large reserves of hydrocarbons, 99% of electricity is produced at hydroelectric power plants. Singapore is a state that is a major producer of petroleum products. Iceland is a country that previously had an economy with an almost monospecialization—fishing and fish processing—but in recent years its economy has been experiencing intense diversification based on cheap renewable energy (mainly geothermal sources that form the country's hydropower). In other words, all these economies use a large amount of relatively clean fuel and not coal. The Arabian monarchies demonstrate an example of "catch-up modernization" of an astonishing depth and scope, in particular in the financial sector. Since the 1980s, the countries of the "Arabian Six" have made considerable efforts to reduce dependence on hydrocarbon energy exports as the main source of economic growth, development, and prosperity. The policy of these countries is focused on diversifying the economy, developing manufacturing and service sectors, in particular financial services, investing petrodollars not in Western banks and government securities but in the creation of new industries and the implementation of various economic projects that contribute to the diversification of their economies.

3.2. Impact of Energy Consumption on the Ecological Pillar of Sustainable Development

The flip side of the energy phenomenon in countries with the highest levels of public health is their largest ecological footprint, measured in global hectares (gha). According to the World Wildlife Fund (WWF) and the Global Footprint Network [50], Qatar has the worst ecological footprint per capita in the world (14.7 gha per capita), followed by the United Arab Emirates (8.9). The fourth position in this rank is taken by Bahrain (8.7) and the ninth by Kuwait (8.0, like the USA). Oman is ranked 12th (7.3), Saudi Arabia is 23rd (5.8), Singapore is 25th (5.9). The rank of the Russian Federation is 33rd (5.5), while Ukraine is ranked at 91st (2.7), almost the best. Energy consumption per capita in Yemen equals

329 kgoe, but the country leaves almost no ecological footprint (0.6 gha per capita), being ranked at 187 out of 188.

The diagram shown in Figure 3 characterizes the energy density of the ecological footprint of countries in relation to the per capita energy consumption in these national economies.

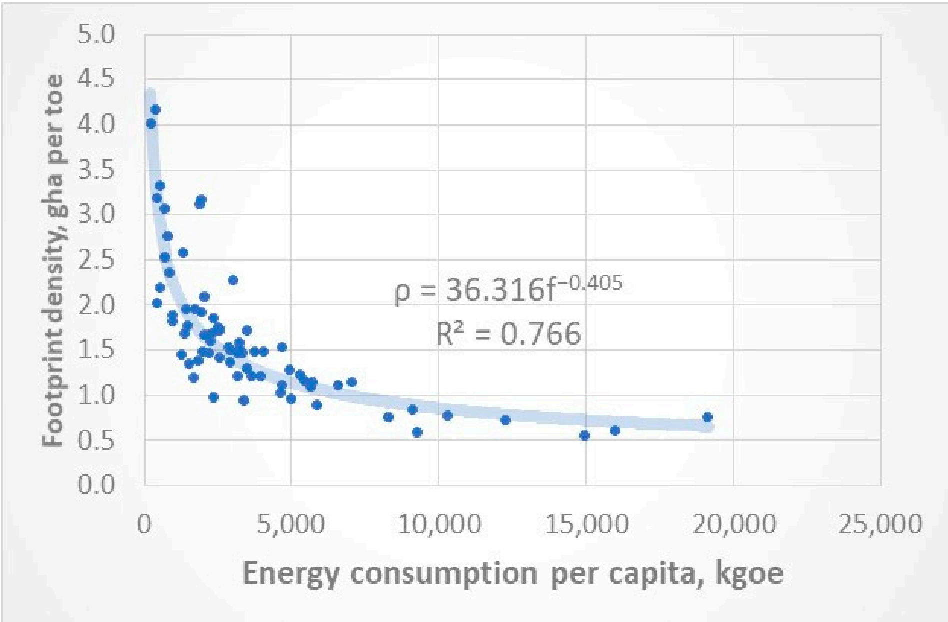

Figure 3. The energy density of ecological footprint and the energy consumption per capita (2016). Source: calculated by the authors based on [49,56,58].

The decrease in the energy density of the ecological footprint due to the increase in per capita energy consumption occurs exponentially:

$$\rho(FP)_k = 36.316 {f_k}^{-0.405}, \quad (5)$$

where f_k is the specific consumption of primary energy resources by a person of the k-th national economy, measured in kgoe/person.

The environmental problem of intensive energy consumption lies not so much in the fact certain countries (e.g., Canada, Norway, Singapore, Qatar or its neighbors) are consuming a bulk of energy resources. Nor does it lie in the fact that, for example, Qatar and other countries of the Arabian Peninsula have a biocapacity deficit (i.e., the percentage that the ecological footprint exceeds the biological potential of the country's ecosystem restoration), while Canada and Norway have a biocapacity reserve in the amount of 95% and 32%, respectively. The biocapacity deficit of Qatar reached 1340%, with Kuwait at 1350%, Saudi Arabia at 1390%, UAE at 1480%, and Israel at 1840%. The same deficit in Singapore reached 9950%. Unlike Canada, the US demand for biosphere exceeded the available biological capacity of the country by 122%. The biocapacity deficit in Germany reached 199%, with Italy by 371%, the Netherlands by 487%, and Belgium by 696%. Ukraine exceeds the biological capabilities of its territory by 2% [50].

At first glance, it appears that economies with a bio-reserve are "lending" to biodeficient economies, but this is not the case: Already in 2001, humanity has a great need for the biosphere, i.e., its global ecological footprint was 13.7 billion gha or 2.2 gha per capita, but the Earth's biocapacity was about 11.2 billion gha or 1.8 gha per capita, and the gap is growing. The planet's biocapacity is being depleted faster than it can be restored.

Challenges caused by climate change and the intention to achieve an increase in global temperatures to 1.5–2 °C above pre-industrial levels have prompted initiatives to implement strategies to accelerate the transition in societies and economies by using low-carbon technologies, improving the energy efficiency of business and utilities, as well as redirecting financial flows from the economic sectors with high CO_2 emissions, especially those using fossil fuels, to ones with the production and use of low-carbon energy [10,15,19,23,59–62]. Moreover, several investigations have proven that higher renewable energy consumption corresponds to higher economic benefits and a resolution of socioeconomic issues in disadvantaged areas, whether rural or peripheral [32,38,63–66].

3.3. Impact of Energy Consumption on the Economic Pillar of Sustainable Development

Unlike the indicators of the energy density DALY and the ecological footprint discussed above and calculated by us, the energy density of the GDP is a standard indicator (GDP per unit of energy use), which is regularly published in World Bank Data, albeit with a great delay. At the time of the preparation of this paper, the source [51] provides data only up to 2015 and not for all countries included in the sample. In this regard, the work used data recalculated in terms of GDP (PPP) and energy consumption for 2016 for selected countries, taken from sources in [55,58].

Within the sample of 74 countries in 2016, the minimum value of GDP per capita in terms of purchasing power parity was USD 3993 (Bangladesh), with a maximum of USD 89,152 (Singapore).

Figure 4 shows the cumulative GDP energy density curve for 74 countries in the sample, tied to total energy consumption.

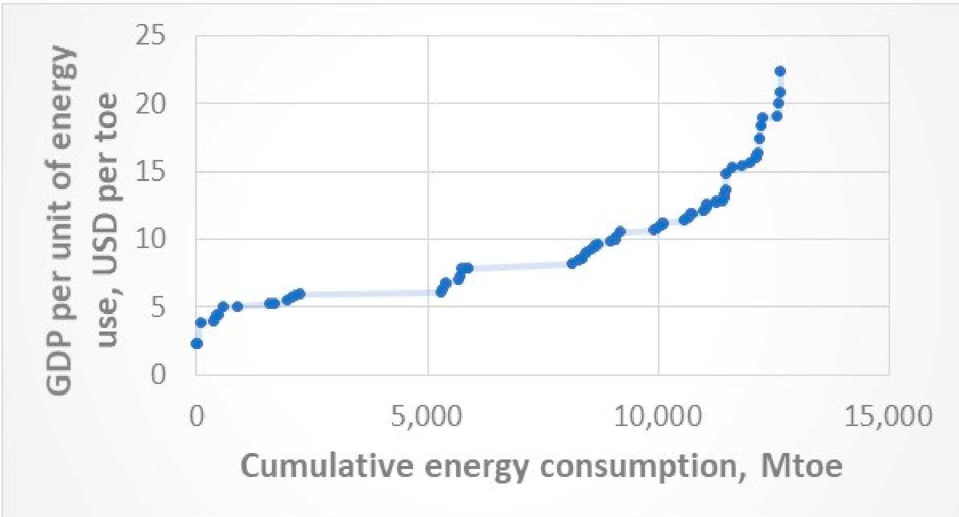

Figure 4. Cumulative curve of the energy density of GDP and energy consumption in 74 national economies (2016). Source: calculated by the authors based on [58].

Approximately one-third of the total energy consumption gives an economic return (GDP) at a rate of 3 to 7 USD/kgoe, while two-thirds give 8–15 USD/kgoe, and only the final part of the cumulative curve is formed by economies with a high return on the use of primary energy resources.

The minimum value, i.e., the worst value of the energy density of GDP (the point closest to the origin of coordinates), is obtained by Turkmenistan (2.4 USD/kgoe), while the maximum values among the countries considered include Ireland (with a value of 25.3 USD/kgoe), Switzerland (22.4 USD/kgoe), and Germany (19.1 USD/kgoe). Kuwait, Oman, and Qatar have low ranks in terms of economic efficiency in the use of energy resources, i.e., ranked at fourth (4.2 USD/kgoe), fifth (4.5 USD/kgoe), and sixth (4.5 USD/kgoe), respectively, followed by Ukraine, Canada, and the Russian Federation (5.0–5.3 USD/kgoe). Singapore has the 14th rank (6.0 USD/kgoe), while Japan is at 44th (11.4 USD/kgoe), France at 51st (12.1 USD/kgoe), Great Britain at 61st (15.4 USD/kgoe), and Italy at 63rd (16.0 USD/kgoe). The two largest economies in terms of size—China and the United

States—have the energy density of GDP of 6.1 USD/kgoe (15th rank) and 8.2 USD/kgoe (24th rank), respectively.

Energy consumption and economic performance vary significantly across countries for many reasons, including climatic differences. In this regard, 3 clusters were identified, while taking into account the following characteristics: the cost of primary energy resources per capita; the GDP per capita, and the average January temperature (Table 1).

Table 1. Economic and energy indicators by clusters of countries (2016).

Clusters	Countries	Cost of Primary Energy Resources Per Capita (kgoe/Person)	GDP Per Capita (USD Thousand)	Average January Temperature (°C)
I	Austria, Belgium, Great Britain, Germany, Ireland, Korea, Netherlands, Norway, Singapore, US, Finland, Japan	4584	46.0	0.9
II	Argentina, Hong Kong, Israel, India, Spain, Italy, Cuba, Mexico, Panama, Portugal	1741	24.1	15.0
III	Armenia, Azerbaijan, Bulgaria, Belarus, Hungary, China, Latvia, Lithuania, Kazakhstan, Kyrgyzstan, Macedonia, Mongolia, Poland, Russia, Romania, Serbia, Slovakia, Slovenia, Turkey, Ukraine, Czech Republic, Estonia	2543	17.9	−6.2

Source: [67].

The first cluster is formed by 12 countries that are leaders of the world economy with an average annual fuel consumption of 4584 kgoe/person and an average GDP per capita of USD 46 thousand. The second cluster (10 countries) consisted of national economies with a warm climate and a relatively low energy consumption (on average 1741 kgoe/person) with an average GDP per capita of USD 24 thousand. The third cluster (22 countries) consisted of 22 industrial economies, in particular Ukraine, Russia, Poland and Turkey, as well as China (average GDP per capita—approximately USD 18 thousand). Despite the relatively harsh climate, energy consumption in these countries is on average 2 times lower than in developed economies (2543 kgoe/person), but much higher than in the countries of the second cluster.

The data of the table confirm the impact of climate on energy consumption, but it is clear that countries with developed economies, i.e., post-industrial and close to them, are consuming much more primary energy resources per capita than industrial economies.

The diagram in Figure 5 demonstrates the interdependence of the economic productivity of countries (GDP per capita) and the specific consumption of primary energy resources by their citizens.

The formula for the function that approximates the presented dependence looks as follows:

$$q = 123.91 f_k^{0.674}, \tag{6}$$

where q is GDP per capita in PPP USD/person; f_k is the specific consumption of primary energy resources by a person of the k-th national economy in kgoe/person.

The dependence graph, under the approximation by the Equation (6), is shown in Figure 6.

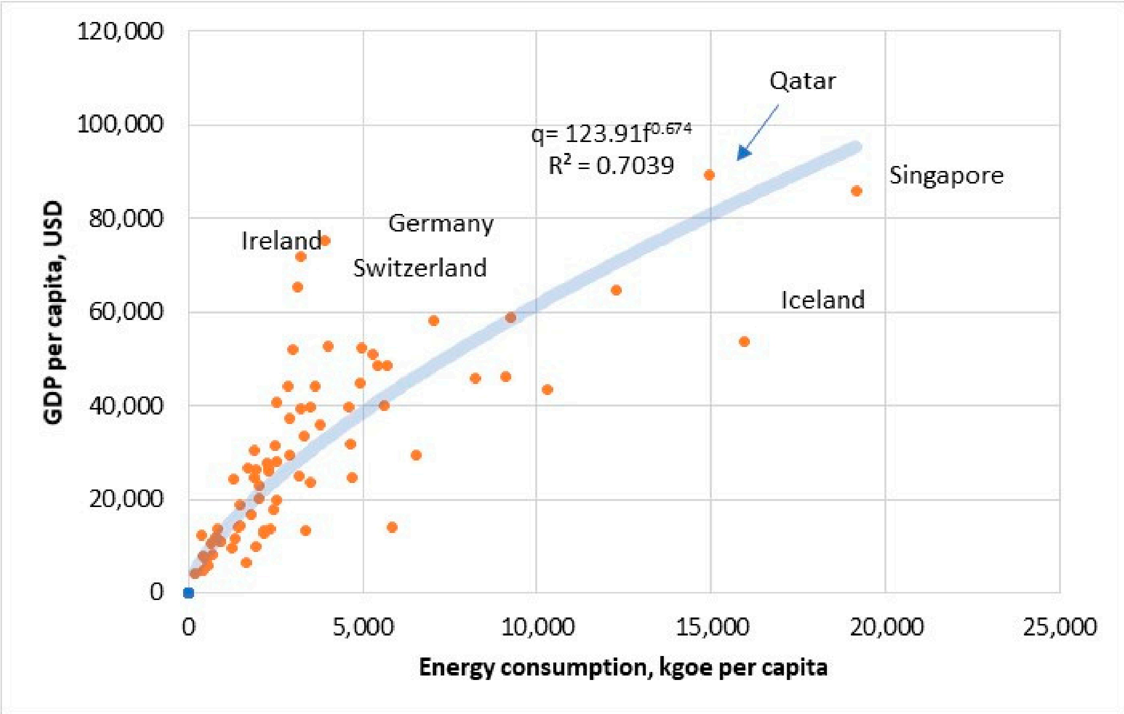

Figure 5. The relationship between economic productivity and per capita consumption of energy resources in national economies (2016). Source: calculated by the authors based on [51,54–57].

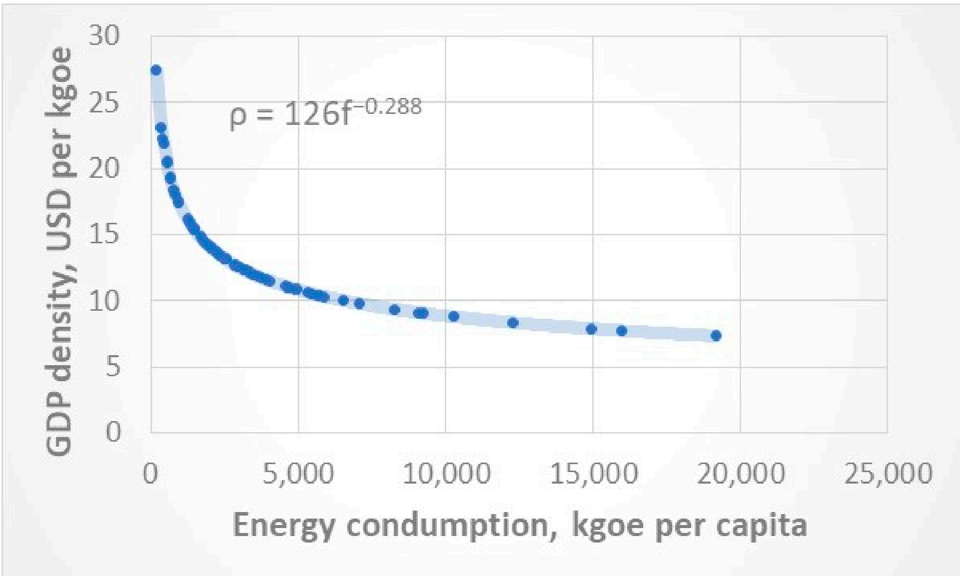

Figure 6. The relationship between the energy density of GDP and the average per capita consumption of energy resources in 74 national economies (2016). Source: calculated by the authors on the basis [51,55,56,58].

The formula for the calculated energy density of GDP has the following form:

$$\rho(GDP)_k = 126{f_k}^{-0.288}. \quad (7)$$

where f_k is the specific consumption of primary energy resources by a person of the k-th national economy in kgoe/person.

4. Discussion

The struggle for energy resources on world markets is intensifying, as prices are rising or as giant mining companies are dumping and lowering prices for certain types of energy; moreover, international conflicts are arising, and risks to energy supply stability and critical pollution in energy production and use are increasing. Therefore, energy security has recently become the subject of increased attention of the world community, individual countries, and their associations. Sustainable development is impossible without the motor fuel for it, with that fuel being energy resources. The energy component is sufficient in:

- the protection of citizens, society, the economy from threats of unsatisfactory energy supply;
- the protection of interests (national, state, public) in the energy sector;
- the sustainability of energy supply systems (in particular, fuel and energy) under different conditions.

The study of the influence of energy consumption on the indicators of the state of the social sphere, the environment, and the economy has made it possible to establish the energy densities of the DALY, the ecological footprint, and GDP values. However, the study of indicators that reflect relative changes often makes it possible to identify patterns better than absolute ones, which makes it advisable to use the category of elasticity in this case. As it is known, the elasticity of a function is the limit of the ratio of the relative increment of a function to the relative increment of the argument. The elasticity of a function roughly expresses the percentage change in a function when the argument changes by 1%.

The elasticities of the energy densities of the considered indicators are summarized in Table 2.

Table 2. The elasticity of energy density indicators characterizing the pillars of sustainable development.

Function	Exponent Value	Elasticity
ρ(DALY)	−1.121	−1.1
$\rho(FP)$	−0.405	−0.4
$\rho(GDP)$	−0.288	−0.3

As one can see from the above table, the most sensitive to changes in energy consumption is the development of the social sphere, represented in this study by the state of health of nations. The corresponding function is elastic; its value is greater than 1, in contrast to the functions of the energy density of the environment and economic development pillars, the values of elasticity of which are significantly less than 1.

The negative sign of the elasticity values of all three functions means that a decrease in the argument, i.e., the energy consumption per capita, causes an increase in the energy density of characteristics, and vice versa. For the social development pillar, a decrease in energy consumption means an increase in the healthy years of the life of its citizens lost by society, i.e., the deterioration of the state of the social sphere, and more intense than the decline in energy consumption. For the economy, the effect is positive because social welfare per unit of energy resource spent is growing, but to a much lesser extent than there is a decrease in the consumption of energy resources per citizen of the country. The same trend can be seen for the environment pillar. At the same time, it should be borne in mind that the dependences obtained correspond to the existing structures of national economies, the degree of their participation in global value chains, as well as the level of technological development of the leading sectors of these economies, among others those addressing well-being indicators [67,68]. A change in the noted factors will inevitably cause quantitative changes in these dependencies, the clarification of which will require deeper research, in particular, the involvement of the mathematical apparatus for studying system dynamics. Adaptable software applications [69,70] can be used to keep track of these changes, simplifying sustainability performance assessment.

Generally, there are different approaches to understanding the phenomenon of sustainable development and, especially, to the ways of implementing sustainable development. There are, for example, the concepts of protective, modernization, structuralist types, differing both in the degree of radicalism and in the body of stakeholders. It should be noted, however, that the presented article is from the category of an objectivist one, as it is devoted to identifying the dependence of the influence of energy consumption on each of the components of sustainable development and is therefore "out of politics". The aim of the study was not to "put things in order" in the conceptual and categorical apparatus of the theory of sustainable development, but, relying on the recognized allocation of the three pillars and the available opportunities to quantify them, the goal here is to explore the relationship between the directions of sustainable development and energy consumption.

The milestones of the presented research are in the shortage of all facets of the sustainable development, their correlation and causality with Industry 4.0, digitalization, and most importantly, the calculation of COVID-19 impacts. However, the presented approach pushes the idea of further gravity analyses and force assessment that involve the duty of binding socioeconomic analyses with the basis of physics, while accounting for the multidisciplinary spillovers.

5. Conclusions

To characterize the relationship between energy consumption and sustainable development, the paper considers the concept of the energy density of indicators characterizing the state of each of the three pillars of sustainable development, i.e., social, environmental and economic. Disability-adjusted life year (DALY), ecological footprint, and GDP were used as these indicators, and the energy density of these indicators for 74 national economies was calculated by dividing them by the volumes of primary energy resources consumed in these economies. The performed studies give grounds to conclude that the state of the social component is most dependent on the consumption of energy resources. Its inherent elasticity of the dependence of the DALY energy density on energy consumption per capita is -1.1, i.e., more than 1 in absolute value. The effect of changes in per capita energy consumption on the state of the environment pillar is much weaker (the elasticity of the footprint dependence is -0.4), and the effect on the economic pillar is even weaker, with the elasticity of the GDP dependence being -0.3.

The low elasticity inherent in the change in the ecological component of sustainable development gives rise to a certain pessimism regarding the effectiveness of sustainable development policy, which is based on limiting growth or even reducing energy consumption since each percentage reduction in per capita consumption of primary energy resources will give only 0.6% reduction in ecological footprint area.

Another result will ensure the transition to environmentally friendly energy technologies, which will reduce greenhouse gas emissions while not holding back the energy factor of economic growth and, especially, social development. Moreover, there is evidence that a higher share of renewable energy sources in total energy consumption corresponds to higher economic benefits and solutions to socioeconomic problems in socially disadvantaged areas.

In addition, public policy measures aimed at restructuring national economies and improving energy efficiency will contribute to increase the economic productivity of the energy used in the economy, while reducing the energy density of the DALY and the ecological footprint. This is especially important for countries with developing market economies, for example, post-Soviet countries, in which the economy is still dominated by an industry of the third technological order (mining and metallurgical, large-scale chemical branches) that is harmful to the environment and human health. This will require the design and practical implementation of such a mix of energy policy instruments (including tax measures, financial and investment preferences, appropriate training of new and retraining of existing personnel, etc.) that will make energy consumption in all sectors of the economy more productive and environmentally friendly, and, if the effect of such a policy appears in the form of a reduction in energy consumption, to reorient the resulting energy savings towards solving social problems.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Basic statistics for analysis.

Country	Population (mln Persons)	DALY (mln Years)	DALY (Years Per 100 Thousand Population)	Energy Use (mln Toe)	GDP (PPP; bln USD)	Footprint (mln Gha)	Footprint Per Person (Gha Per Capita)
Algeria	40.6	10.8	26,678	55	471	93.4	2.3
Argentina	43.8	12.0	27,415	89	885	149.1	3.4
Australia	24.1	5.6	23,132	138	1174	159.2	6.6
Austria	8.7	2.4	27,578	35	460	52.3	6.0
Azerbaijan	9.7	2.9	29,747	15	140	19.5	2.0
Bangladesh	163.0	47.5	29,157	32	651	130.4	0.8
Belarus	9.5	3.9	40,851	23	168	39.8	4.2
Belgium	11.4	3.2	28,506	62	551	71.6	6.3
Brazil	207.7	61.5	29,633	298	2939	581.4	2.8
Bulgaria	7.1	3.1	43,046	18	143	25.7	3.6
Canada	36.3	8.9	24,513	330	1678	279.4	7.7
Chile	17.9	4.4	24,840	37	413	77.0	4.3
China	1411.4	376.4	26,666	3053	18,702	5081.1	3.6
Colombia	48.7	13.4	27,583	41	672	97.3	2.0
Croatia	4.2	1.5	35,211	8	104	15.6	3.7
Cyprus	1.2	0.2	20,808	3	30	4.6	3.9
Czechia	10.6	3.4	32,290	40	381	59.4	5.6

Table A1. *Cont.*

Country	Population (mln Persons)	DALY (mln Years)	DALY (Years Per 100 Thousand Population)	Energy Use (mln Toe)	GDP (PPP; bln USD)	Footprint (mln Gha)	Footprint Per Person (Gha Per Capita)
Denmark	5.7	1.6	27,544	17	298	38.8	6.8
Ecuador	16.4	4.2	25,490	15	182	27.9	1.7
Egypt	95.7	30.4	31,744	91	1057	172.2	1.8
Estonia	1.3	0.5	36,023	6	42	9.3	7.1
Finland	5.5	1.6	28,954	27	247	34.7	6.3
France	64.7	16.8	25,931	236	2864	284.8	4.4
Germany	81.9	25.8	31,485	323	6174	393.2	4.8
Greece	11.2	3.3	29,265	26	300	48.1	4.3
Hungary	9.8	3.8	39,398	22	272	35.1	3.6
Iceland	0.3	0.1	22,051	5	18	2.1	6.2
India	1324.2	509.0	38,440	724	7735	1589.0	1.2
Indonesia	261.1	87.6	33,539	175	2745	443.9	1.7
Iran	80.3	19.5	24,239	271	1079	256.9	3.2
Iraq	37.2	13.3	35,737	46	362	67.0	1.8
Ireland	4.7	1.1	22,649	15	340	24.1	5.1
Israel	8.2	1.6	19,570	26	323	40.1	4.9
Italy	59.4	17.1	28,817	151	2420	261.5	4.4
Japan	127.7	35.6	27,882	445	5076	574.9	4.5
Kazakhstan	18.0	6.0	33,493	63	424	107.9	6.0
Kuwait	4.1	0.8	19,029	42	177	32.4	8.0
Latvia	2.0	0.8	42,365	4	52	12.0	6.1
Lithuania	2.9	1.2	42,074	6	89	17.2	5.9
Malaysia	31.2	7.3	23,323	100	784	121.6	3.9
Mexico	127.5	31.2	24,463	187	2383	331.6	2.6
Morocco	35.3	9.3	26,449	19	254	63.5	1.8
Netherlands	17.0	4.6	26,846	85	890	81.5	4.8
New Zealand	4.7	1.1	23,304	21	185	21.9	4.7
Norway	5.3	1.3	23,792	49	308	28.9	5.5
Oman	4.4	0.9	19,887	29	130	32.3	7.3
Pakistan	193.2	88.0	45,573	83	898	168.8	0.9
Peru	31.8	8.1	25,444	25	376	69.9	2.2
Philippines	103.3	33.9	32,816	42	799	134.3	1.3
Poland	38.2	12.9	33,774	97	1074	168.2	4.4
Portugal	10.4	3.1	29,673	26	326	45.6	4.4
Qatar	2.6	0.4	15,000	49	221	37.0	14.4
Korea	50.8	11.3	22,273	286	2027	314.9	6.2
Romania	19.8	7.8	39,346	26	479	67.2	3.4
RussianFederation	144.0	64.9	45,062	674	3539	748.6	5.2
Saudi Arabia	32.3	6.9	21,471	267	1476	200.1	6.2
Singapore	5.6	1.0	17,352	84	501	33.2	5.9
Slovakia	5.4	1.7	31,957	16	161	24.0	4.4
Slovenia	2.1	0.6	30,455	7	70	10.2	4.9
South Africa	56.0	27.6	49,240	122	708	179.2	3.2
Spain	46.3	11.9	25,730	135	1733	185.4	4.0

Table A1. *Cont.*

Country	Population (mln Persons)	DALY (mln Years)	DALY (Years Per 100 Thousand Population)	Energy Use (mln Toe)	GDP (PPP; bln USD)	Footprint (mln Gha)	Footprint Per Person (Gha Per Capita)
Sri Lanka	20.8	6.0	28,843	8	259	31.2	1.5
Sweden	9.8	2.6	26,619	52	500	63.9	6.5
Switzerland	8.4	2.1	24,707	26	550	38.6	4.6
Thailand	68.9	22.1	32,147	124	1146	172.2	2.5
Turkey	79.5	21.1	26,552	138	2116	270.3	3.4
Turkmenistan	5.7	2.1	37,481	33	79	29.4	5.2
Ukraine	44.4	20.3	45,581	87	435	128.9	2.9
United Arab Emirates	9.3	1.6	17,009	114	599	82.5	8.9
United Kingdom	65.8	17.9	27,246	188	2898	289.5	4.4
United States of America	322.2	100.4	31,158	2273	18,745	2609.7	8.1
Uzbekistan	31.4	8.6	27,282	53	206	62.9	2.0
Venezuela	31.6	9.0	28,616	75	437	72.6	2.3
Viet Nam	94.6	25.2	26,640	65	771	198.6	2.1

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