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The Importance of Heat Emission Caused by Global Energy Production in Terms of Climate Impact

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Abstract: The global warming phenomenon is commonly associated with the emission of greenhouse gases. However, there may be other factors related to industry and global energy production which cause climate change—for example, heat emission caused by the production of any useful form of energy. This paper discussed the importance of heat emission—the final result of various forms of energy produced by our civilization. Does the emission also influence the climate warming process, i.e., the well-known greenhouse effect? To answer this question, the global heat production was compared to total solar energy, which reaches the Earth. The paper also analyzed the current global energy market. It shows how much energy is produced and consumed, as well as the directions for further development of the energy market. These analyses made it possible to verify the assumed hypothesis.

Keywords: global heat production; energy market; energy conversion; electricity

1. Introduction

Our daily life on Earth requires the production of large amounts of energy. The energy is produced mainly in the forms of electrical energy and mechanical energy as a result of liquid fuels and gases combustion in engines in various types of vehicles. Unfortunately, the various types of useful energy also cause the production of a huge amount of heat. Moreover, these useful energies are eventually converted to heat energy in machines, vehicles, and devices. An important question arises here—whether this release of a large amount of thermal energy is comparable to solar energy and can it significantly affect the global temperature and climate change. In this paper, the thesis was verified whether the heat emission, which is the final result of energy generated by our civilization, has an effect comparable to that of greenhouse warming. The greenhouse effect is well known and is comprehensively presented in many papers—among others [1–4]. However, the effect and greenhouse gas emission have not been discussed in the presented work so far.

Nuclear and fossil fuel power plants are thermal power stations and have a maximum efficiency of around 40%. It means that during the production of electrical energy, around 60% of nuclear or chemical energy in fossil fuel is converted to heat energy and is emitted directly into the atmosphere and water (seas, lakes, rivers). Thus, most of the energy contained in any fuel is lost, but there is currently no technically more efficient way to generate electricity. Unfortunately, that also applies to the combustion of biofuels. Wind and water power plants have much higher energy efficiency, and the production of electricity is accompanied by a low heat emission. Much more information about the energy conversion efficiency in thermal power stations is presented in the papers [5–7].

However, regardless of the way how electricity is produced, almost all electricity is ultimately turned into heat. It may seem surprising, but the following analysis proves this thesis. Electrical energy is distributed to different electricity consumers—factories, buildings, hospitals, railway electrification

systems, etc. For example, any computer consumes electrical power and uses it to perform calculations, which is accompanied by heat production in semiconductor components (microprocessors, transistors, diodes, resistors). In practice, considering the field of physics, all the electric power in any computer is finally converted to heat. In a fridge, an electric motor drives a heat pump, which pumps out heat from inside the fridge to the outside. According to the principle of energy conservation, the heat energy released into the atmosphere (outside) is equal to the sum of heat energy collected from the fridge interior and the consumed electricity. A very similar situation occurs in any device. While an electrical train moves, electric motors cause acceleration driving at a constant velocity and partial energy recovery during braking. When the velocity of the vehicle is constant, all the consumed electrical energy compensates the work of friction forces in mechanical components (in bearings, etc.) and of air resistance forces. The friction in the components causes their heating, and air resistance causes the heating of the train's surface and air. The same situation occurs in cars. In a modern petrol engine, the chemical energy in the fuel is converted to heat (about 60%) and useful mechanical energy (about 40%). All mechanical energy is used to compensate friction forces and air resistance, so always a heat is produced. Thousands of various devices and machines can be considered in which the energy would finally be converted into heat—similar to what it is shown in Figure 1.
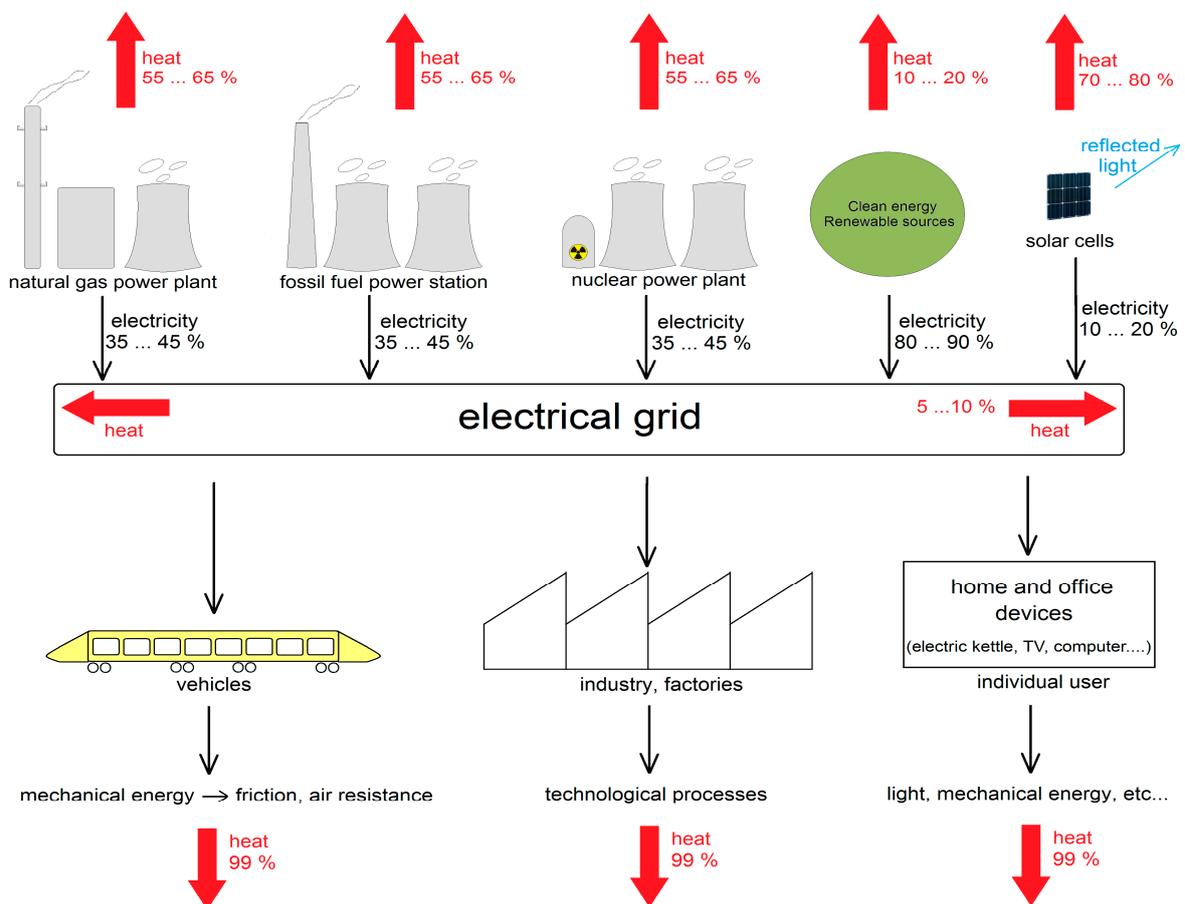

Figure 1. Electrical energy changes into other forms of energy and makes useful work, but almost 100% is finally converted to heat energy (own study).

Consequently, sooner or later, almost 100% of electrical energy or chemical energy in fuels is finally converted to heat energy. To determine the global heat production, it is necessary to calculate the global production of electricity and petrol fuels.

2. Energy Market

The right energy structure and the increase in energy efficiency are the key issues on the way to the transformation in the field of energy, which is to ensure a safe future for all [8–11]. The current way of generating energy is associated with high greenhouse gas emissions because it is based mainly on fossil fuels and the inefficient use of traditional bioenergy, especially in developing countries [12–16]. Besides, the world's demand for energy is growing, which is largely due to the economic growth that drives global energy consumption. Rapid growth occurs in developing countries, such as China and India, while in countries belonging to the OECD (The Organisation for Economic Co-operation and Development), for example, Germany or Italy, energy consumption is beginning to stabilize but is still at a high level. These tendencies are in line with the assumptions of the Singer report [17], and this can also be confirmed by analyzing current trends, both in consumption and in energy production, as shown in Figure 2.
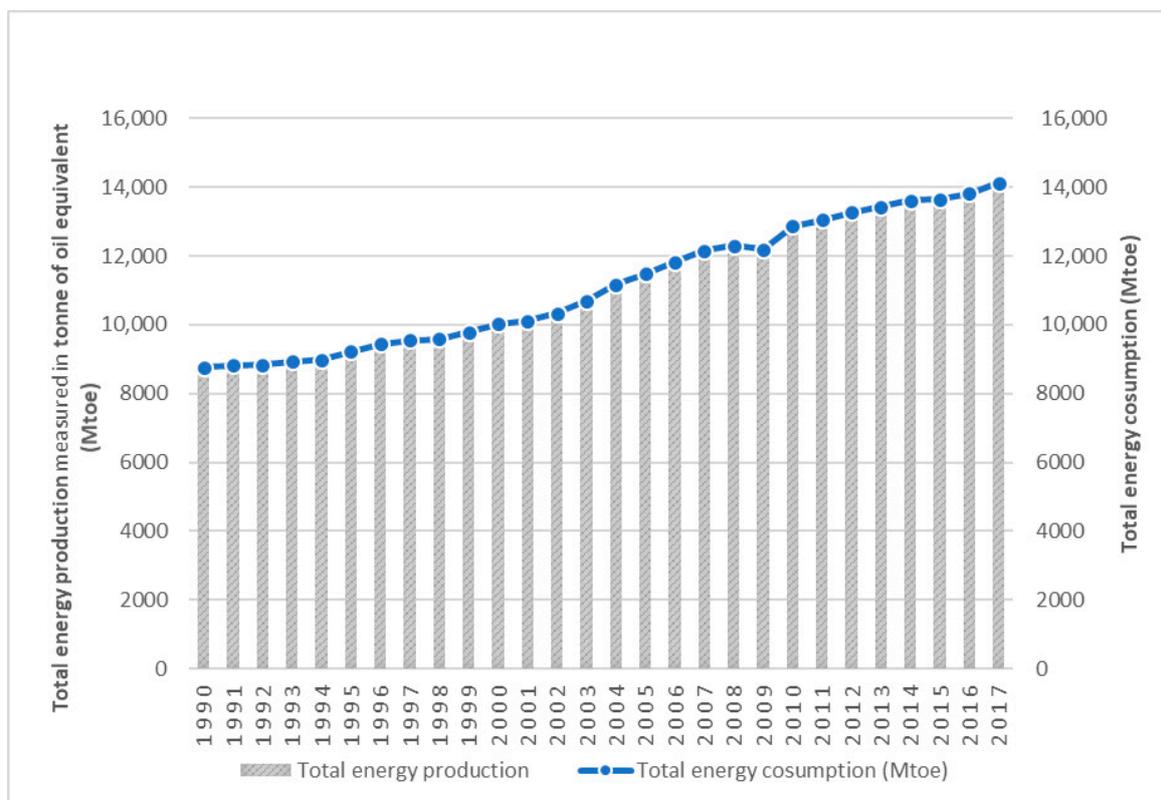

Figure 2. Total energy consumption and production, source: own elaboration based on data [18].

Let us first take a look at how global energy production has changed from a long-term perspective, both in terms of quantity and sources (Figure 3).
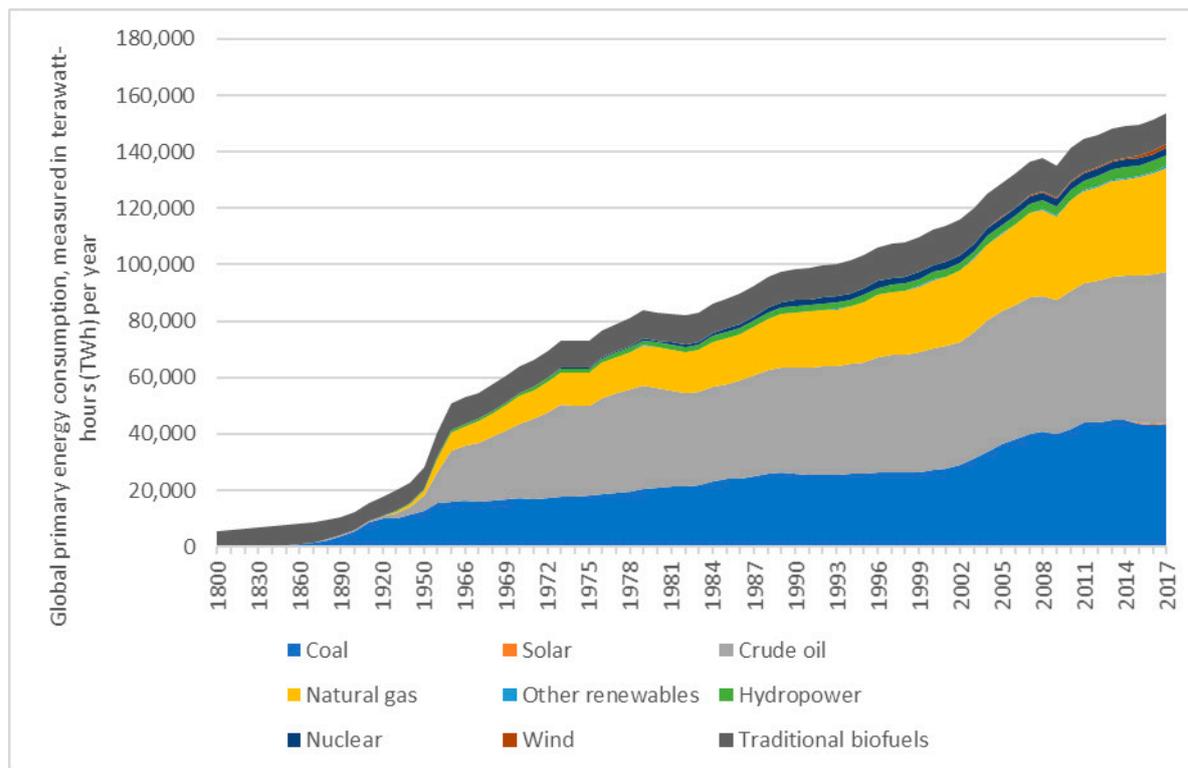
Figure 3. Global primary energy consumption 1800–2017 [19].

In the 1800s, almost all of the world's energy was produced by burning wood and other organic matter [19]. Oil consumption started in the 1870s [19]. Twenty years later, there were natural gas and hydroelectricity in the energy mix. Since 1900, coal consumption has increased significantly, and, now, it constitutes almost half of the world's energy [19]. In the 20th century, the energy mix changed significantly, coal took over traditional biofuels, and oil constituted up to around 20% of the energy market, and since 1960, the world has had nuclear electricity [18]. Today, on the energy market, we have renewable energy sources—RES, not appearing until the 1980–1990s [19].

Besides, apart from analyzing the total consumption of primary energy, we could also compare the contribution of different energy sources. As shown in Figure 4, changes in the energy mix are slow, so, mainly, fossil fuels dominate [19]. Except for the emergence of nuclear electricity, the energy mix was fairly stable for at least fifty years [18].

Changes in the structure of the energy mix began after 1997 [20,21] when the first EU regulations on energy from renewable sources appeared [22–25]. They were stated in the European Commission's White Paper Energy for the Future—Renewable Energy Sources RES (December 1997). In 2001, the European Parliament and the Council adopted Directive 2001/77/EC on the promotion of electricity production from RES on the internal market, which determined the share of RES in total electricity consumption by 2010 (replaced by Directive 28/2009/IN). A breakthrough in the development of RES took place in March 2006, after the publication of the Green Book [26].
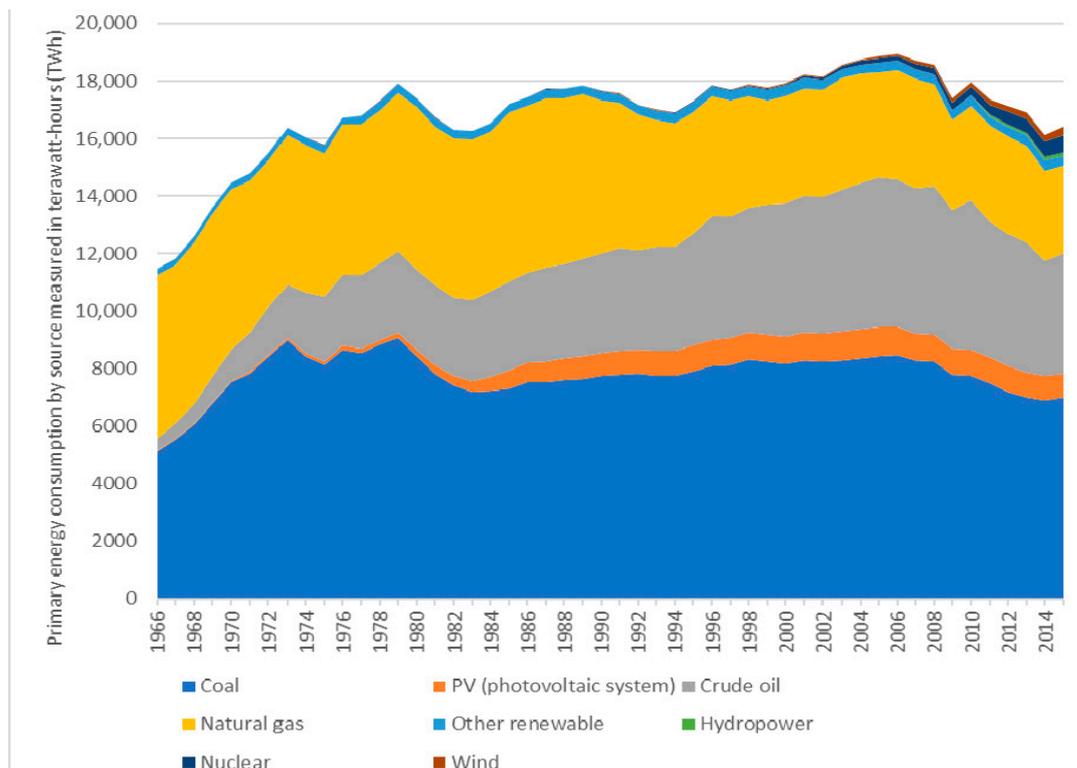
Figure 4. Primary energy consumption by source, European Union [19].

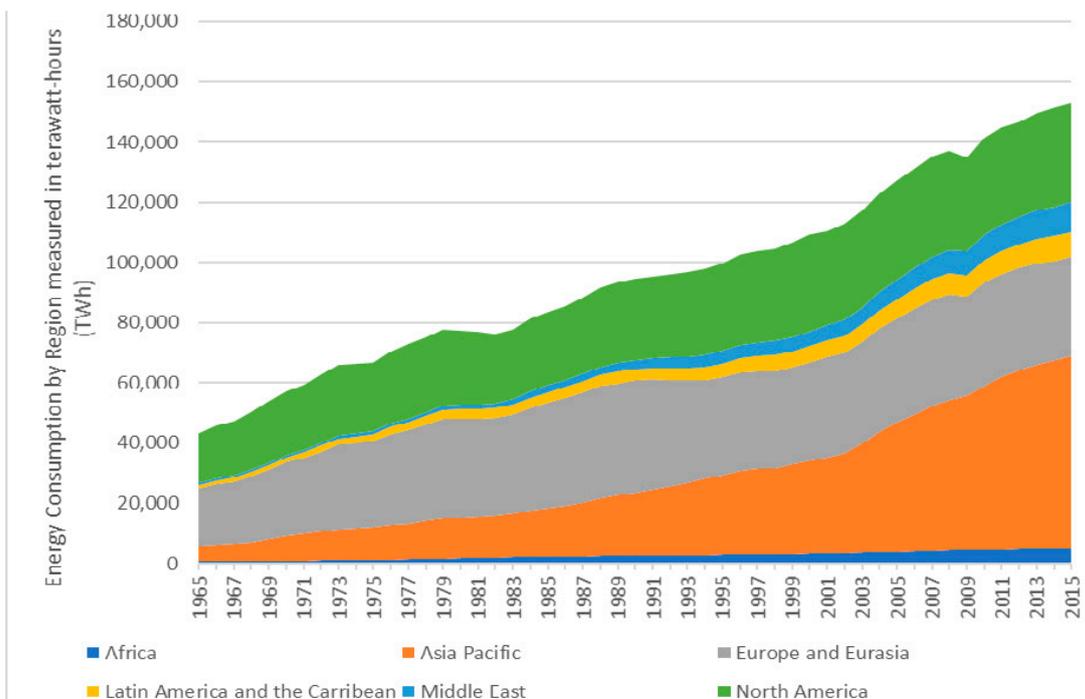Figure 5 shows primary energy consumption from 1965–2017 in continental regions [19].

Figure 5. Global energy consumption by region [19].

In 1965, most of the total energy was consumed in North America, Europe, and Eurasia. In total, they accounted for over 80% of global energy consumption. Consumption in other parts of the world has been increasing, most dramatically in the Asia Pacific. In 2015, Asia Pacific was by far the largest

regional consumer. The total consumption (about 43%) was the same as in North America, Europe, and Eurasia combined [19]. The Middle East used 7%, Latin America 5%, and Africa 3% [18,19].

In 2017, the production of energy from coal increased due to China. Higher energy prices in the world had caused a drop in oil and gas production in the United States. Energy production in the European Union decreased due to moderate growth in energy consumption, lower primary energy production (nuclear and hydro), depletion of oil and gas resources, and climate policy, which ultimately means giving up coal. Large oil and gas exporting countries, such as Russia, Iran after international sanctions, Canada or Nigeria, as well as fast-developing countries (India, Indonesia, Turkey, and Brazil), were the main energy donors. In 2017, total consumption was at 567 EJ (EJ = exajoule = 10^{18} joules), and it is forecast that by 2020, there would be a 10% increase [19].

Prices can have a big impact on the choice of energy sources. While comparing costs between sources, it is important to have relative prices [19]. In the literature, the levelized cost of electricity (LCOE) is used [27]. The concept of LCOE is defined in the following way:

- it measures the cost of living divided by energy production,
- it calculates the current value of the total cost of construction and operation of the plant during the assumed period of use,
- it allows comparison of different technologies (e.g., wind, solar, natural gas) with uneven life span, project size, different capital costs, risk, return, and capacity [27].

Figure 6 shows the levelized cost of electricity (LCOE). The cost range is represented on the column chart for each technology. The white line in each of them represents the global cost of each technology. The average range of fossil fuel costs is shown as a gray column. In this chart, it is shown that, in 2016, most renewable technologies were in a competitive range to fossil fuels. The key exception was the thermal solar radiation, which remained about twice as expensive, but began to decrease [19]. Hydropower is the oldest renewable source. In this technology, the price is low. Analyzing how the average cost of technology changed in the years 2010–2016, we can see that the cost of solar photovoltaic system dropped significantly [19]. This reduction of cost in photovoltaic cells has been deep over the past few decades. The price of solar photovoltaic modules has decreased more than 100 times since 1976 [19].
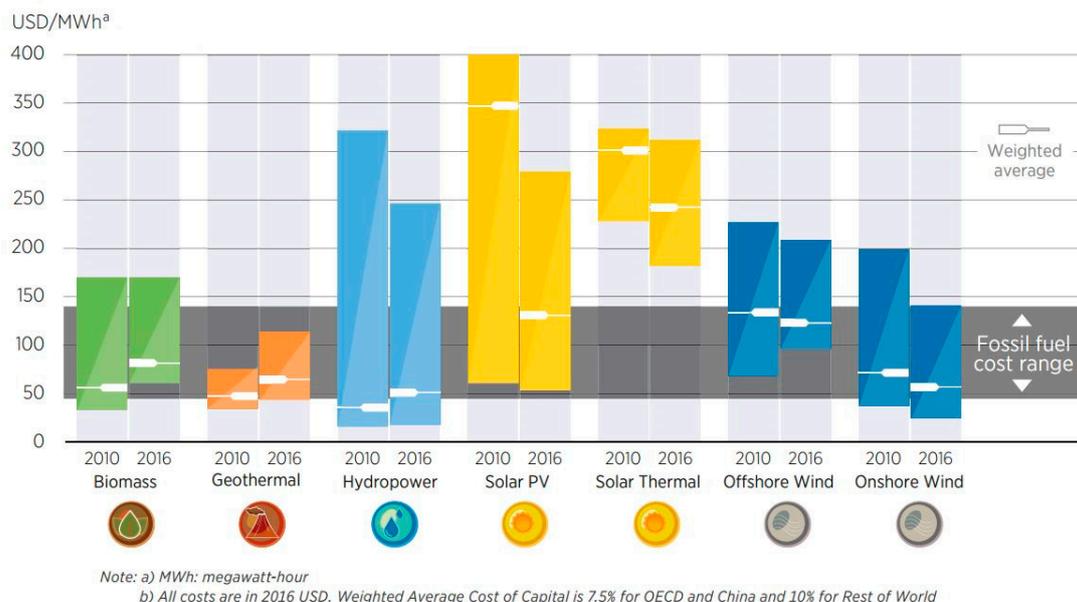

Note: a) MWh: megawatt-hour
b) All costs are in 2016 USD. Weighted Average Cost of Capital is 7.5% for OECD and China and 10% for Rest of World

Figure 6. Levelized cost of electricity (LCOE) in 2010 and 2016 [19].

Measuring the number of people with electricity access is a very important social and economic indicator. We think that the growth of population has caused an increase in energy consumption. Figure 7 shows that the percentage of people with access to electricity has increased at a global level [19].
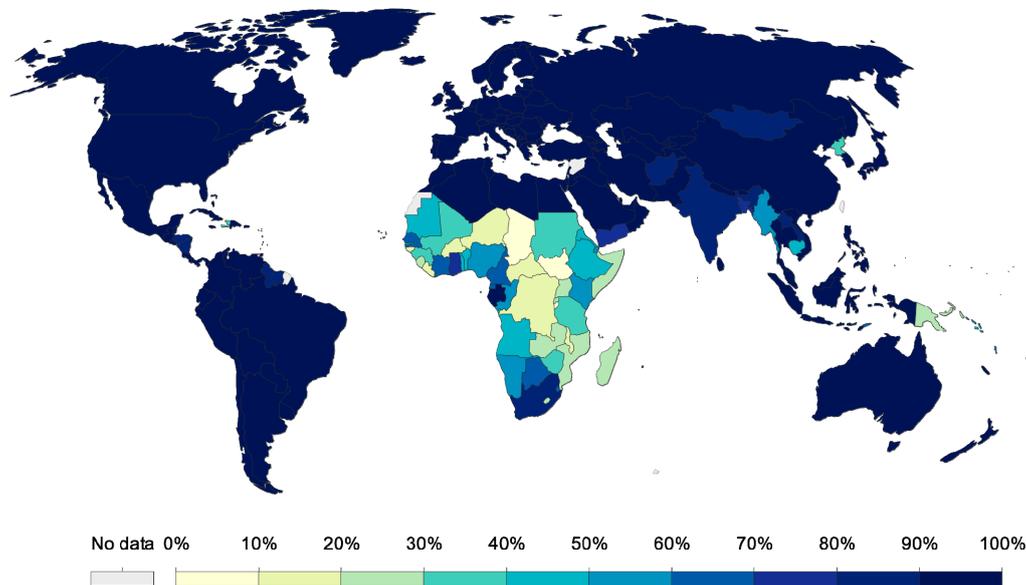

Figure 7. Share of the population with access to electricity [19].

In 1990, about 73% of the population had access to electricity, and this level increased to 85% in 2014 [19]. High-income countries typically have access between 95–100% [19]. The growing global share was, therefore, driven by increased access in low- and middle-income economies. In many countries, this trend has developed, for example, access in India has increased from 45% to 80%, and in Indonesia, it has increased to 97% from 60% in 1990 [19]. While the trend is upward for most countries, there are some countries where this access is very low, for example, only 8.8% of Chad's population has electricity access. Therefore, we can assume that this factor will increase, and thus also energy consumption, in the future.

3. Materials and Methods

The structures of the energy market and total energy production are important to determine the global heat emission. While producing useful energy, as it is shown in the introduction, heat energy is emitted (as an adverse side effect)—Equation (1). Moreover, sooner or later, almost 100% of that useful energy—electrical energy or chemical energy in fuels—is finally converted to heat energy. Because average efficiency of a thermal electric plant is about 40% [5–7], most of the primary energy (chemical energy in coal or natural gas, nuclear energy in nuclear fuel, etc.) is converted directly to heat. Engines in cars, where chemical energy in petrol is converted to mechanical energy, have similar efficiency. The results in Figure 2 show that the values of global energy production and energy consumption are very similar—they are approximately the same. Because the global annual useful energy production is known (Figures 2 and 3), taking the efficiency about 40%, total annual energy produced on the Earth could be written by Equations (1) and (2). Unfortunately, as it is shown in Figure 3, the amount of energy produced by renewable sources is still very low on a global scale. Therefore, it is reasonable to adopt the average efficiency of the energy production process at 40%, as in thermal power plants, because this dominates. The total power produced by our civilization on the Earth is determined by Equation (3).

$$E_{total} = E_{heat} + E_{useful} \tag{1}$$

$$E_{useful} \approx 0.4 \times E_{total} \tag{2}$$

$$P_{total} = \frac{E_{total}}{3600 \times 24 \times 365} \tag{3}$$

where E_{useful}—annual useful energy production (electricity, motion, etc.)—it is given in Figures 2 and 3, E_{total}—total annual energy, which is converted to heat (as an adverse side effect) and useful energy, E_{heat}—annual heat energy production, P_{total}—total power produced on the Earth (in Watts). All energies are in joules per year.

Based on the global energy production of useful energy (E_{useful}), it is possible to estimate the total energy (heat energy and useful energy), which is also finally converted to heat in consumers. At this point, the question arises whether the value of the calculated E_{total} (in global terms) is high, low, significant, or insignificant. To answer this question, the total power produced on the Earth would be compared to the total solar irradiation reaching the Earth's surface. It is presented by factor n in Equation (4).

$$n = \frac{P_{total}}{P_{GND}} \tag{4}$$

where n—the ratio of total power produced on the Earth to the power of solar irradiation hitting the Earth's surface, P_{GND}—solar irradiation power hitting the Earth's surface (the ground).

The heat produced on the Earth combines with the energy supplied from the Sun. Consequently, these two energies together cause the energetical effect as if the Earth was a little closer to the Sun. To illustrate this effect, we imagined the Earth before the industrial revolution (before the 19th century) in orbit with a radius of r_0—Figure 8. Nowadays, additional heat emission causes an effect of the seeming shortening of the Earth's orbit to a radius of r_1.
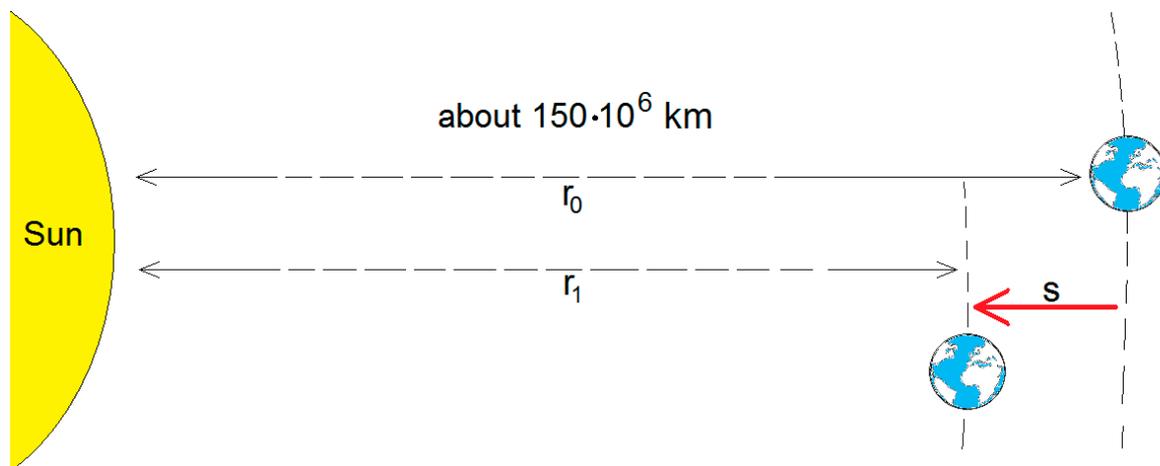

Figure 8. Global heat emission causes the seeming energetical effect as if the Earth was a little closer to the Sun.

The seeming shortening of the Earth's orbit is given by Equation (5).

$$s = r_0 - r_1 \tag{5}$$

Sun radiance, it means the radiant power per unit area emitted over all wavelengths and all directions (watts per square meter) of the Sun's surface area, is given by the Stefan-Boltzmann law [8]—Equation (6). The total power emitted by the Sun is given in Equation (7).

$$R^* = \sigma \times T^4 \tag{6}$$

$$P_{Sun} = R^* \times A_{Sun} \tag{7}$$

where:

R^*—Sun radiance—power emitted by one square meter of the Sun's surface area (W/m^2)
P_{Sun}—total power emitted by the Sun (Watts)
A_{Sun}—Sun's surface area (m^2)
T—the temperature of the Sun's surface
σ—Stefan-Boltzmann constant $5.67 \cdot 10^{-8}$ (W m^{-2}K^{-4})

The sunrays are emitted over all directions from the Sun. As we move away from the Sun (the distance from the Sun increases), the intensity of light decreases. For the distance "r" from the Sun, the solar radiation strikes the surface (sphere) whose area is equal to $4\pi r^2$. The surface power density (called also solar constant, flux density) for the distance "r" is represented by Equations (8)–(11).

$$P_d(r) = \frac{P_{Sun}}{4 \times \pi \times r^2} \tag{8}$$

$$P_d(r) = \frac{A_{Sun} \times \sigma \times T^4}{4 \times \pi \times r^2} \tag{9}$$

introducing the constant "k", we obtain:

$$k = \frac{A_{Sun} \times \sigma \times T^4}{4 \times \pi} \tag{10}$$

$$P_d(r) = k \times \frac{1}{r^2} \tag{11}$$

where P_d—power density, solar constant, power per unit of surface reached to place at a distance of "r" from the Sun in a unit of W/m^2, r—distance from the center of the Sun (in meters)

Finally, the surface power density for the point at a distance of "r" from the Sun is inversely proportional to the square of the distance. Because the mean distance of the Earth from the Sun is about 149.6×10^6 km [9], the surface power density above the atmosphere of the Earth is about 1380 W/m^2, theoretically based on Equation (9), and about 1366 W/m^2 in reality [10].

4. Results and Discussions

Global useful energy produced on the Earth (Figure 2) in 2000 was equal 10,016 Mtoe (419.35×10^{18} J), and in 2017 was equal 14,080 Mtoe (589.50×10^{18} J). Total produced energy (heat + useful energy) is given in Equation (12) (transforming Equation (2)).

$$E_{total} \approx \frac{E_{useful}}{0.4} \tag{12}$$

The Sun always illuminates the surface of the Earth seen as a wheel. Total power of the solar rays reaching the top of the Earth's atmosphere (Equation (13)) can be computed by multiplying the surface power density (Equation (9)) and illuminated Earth's surface—the wheel with a radius of 6378 km [9]. Very rare phenomena, such as the solar eclipse, are omitted.

$$P_{SE} = P_d \times \pi \times R^2_{Earth} \approx 1.7 \times 10^{17}, W \tag{13}$$

where R_{Earth}—radius of the Earth, P_{SE}—the power of the solar irradiation reaching the top of the Earth's atmosphere.

This result is confirmed by the Authors in work [11]. Around 8.1×10^{16} W of solar radiation passes through the atmosphere and arrives at the surface of the Earth, which accounts for 47% of the solar energy that reaches the Earth [11]—Equation (14).

$$P_{GND} \approx 0.47 \times P_{SE} \tag{14}$$

where P_{GND}—solar irradiation power hitting the Earth' surface (the ground).

The "n" ratio (total power produced on the Earth to the power of the solar irradiation ratio) is obtained in Table 1.

Table 1. Calculated values of P_{total} and "n" ratio. $P_{GND} = 8.1 \times 10^{16}$ W.

Year	E_{total}, J/Year	P_{total}, W	$n = \frac{P_{total}}{P_{GND}}$
2000	1048.37×10^{18}	3324×10^{10}	0.414×10^{-3} (0.0414%)
2017	1473.75×10^{18}	4673×10^{10}	0.577×10^{-3} (0.0577%)

Taking Equations (11) and (14), (15) could be written as:

$$P_{GND}(r) = 0.47 \times k \times \pi \times R^2_{Earth} \times \frac{1}{r^2} \tag{15}$$

where $P_{GND}(r)$—solar irradiation power hitting the Earth's surface (the ground) as a function of the distance between the Earth and the Sun.

Next, we introduced the radius r_0 of the actual (real) orbit of the Earth and the hypothetical radius r_1 of the orbit, which is shorter and corresponds to a little higher solar power. It means the heat emission causes the effect of the seeming shortening of the Earth's orbit to a radius of r_1. Because the P_{GND} is inversely proportional to the square of the distance (Equation (16)), it is possible to determine the hypothetical radius r_1 (Equations (17)–(19)). Finally, the seeming shortening of the radius of the Earth's orbit is given by Equation (20).

$$P_{GND} \sim \frac{1}{r^2} \tag{16}$$

$$P_{GND1} = P_{GND0} + P_{total} = P_{GND0} + n \times P_{GND0} \tag{17}$$

$$r_1 = r_0 \times \sqrt{\frac{P_{GND0}}{P_{GND1}}} \tag{18}$$

$$r_1 = r_0 \times \sqrt{\frac{P_{GND0}}{P_{GND0} \times (1+n)}} = \frac{r_0}{\sqrt{n+1}} \tag{19}$$

$$s = r_0 - \frac{r_0}{\sqrt{n+1}} \tag{20}$$

where r_0—radius of the actual (real) orbit of the Earth, r_1—radius of a hypothetical orbit where the little higher solar power is the equivalence of the total energy produced on the Earth, s—seeming shortening of the radius of the Earth's orbit.

In conclusion, the heat emission as a consequence of energy production on the Earth gives the same effect as shortening the radius of the Earth's orbit by about 31,000 km in 2000 and about 43,300 km in 2017 with respect to the time directly before the industrial revolution (before the 19th century).

5. Conclusions

Total energy produced by our civilization on the Earth consists of the useful energy (electricity, mechanical energy, etc.) and heat, as an adverse side effect. Unfortunately, the various types of useful energy are finally converted to heat in machines, vehicles, and devices. The estimated calculations presented in this work prove that the total power produced by us was 0.0414% in 2000 and 0.0577% in 2017 of the global solar power reaching the Earth's surface—it means reaching the lowest layers of the atmosphere, almost the ground. A significant increase in the "n" factor between 2000 and 2017 results from the increase in global energy production.

A few questions arise here—are these values high or low? Are they important? A very good determiner of the importance of these values is the value of cyclic, annual changes of the Earth's orbit. The orbits of planets are not circles; they are ellipses. The eccentricity of planets is a very well-known natural phenomenon in the solar system. As a result of the elliptical trajectory of the Earth around the Sun, the solar light power density varies about 3.3% [11], and that is over 50 times more than the "*n*" factor in Table 1. After inserting data into Equation (20), the total heat produced on the Earth causes an effect like a seeming shortening of the radius of the Earth's orbit around the Sun by about 31,000 km in the year 2000, and about 43,300 km in the year 2017. Consequently, the seeming radius shortening ("*s*" in Equation (5), Figure 8) is about 2.4 (for 2000) and 3.4 (for 2017) times bigger in comparison to the Earth's diameter (12,756 km). These distances are significant compared to the Earth's dimensions, but, in the field of astronomy, they are very small. Taking into account that the average Earth-Sun distance is about 1496×10^5 km, the seeming shortening "*s*" is 3455 times smaller (in 2017). However, the key factor in assessing the importance of the heat emitted during the global energy production in terms of climate impact is the comparison of the parameter "*n*" to the natural changes of the solar light power density reaching the Earth. That power density varies about 3.3% cyclically during every year (the "*n*" is about 50 times smaller), and this is why the total heat energy produced by our civilization has a small impact on the global warming in the time horizon of several dozen years. We can say that there would be a one-year increase of supplied energy by about 3.3% of the average solar energy once every 50 years. It would probably have significance over several hundred years. Therefore, the use of renewable energy sources makes sense regardless of their energy efficiency because the emitted heat during the generation of electric power in such sources does not significantly affect the climate. For example, photovoltaic solar cells have a low energy efficiency—a dozen or so percent [28]. The fact that more than 80% of solar energy is converted into heat in photovoltaic panels should not be a limitation in their widespread use.

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

References

1. Qiao, H.; Zheng, F.; Jiang, H.; Dong, K. The greenhouse effect of the agriculture-economic growth-renewable energy nexus: Evidence from G20 countries. *Sci. Total Environ.* **2019**, *671*, 722–731. [CrossRef] [PubMed]
2. Jones, P.D. Greenhouse Effect and Climate Data. In *Reference Module in Earth Systems and Environmental Sciences*; Elsevier: Cambridge, MA, USA, 2013. [CrossRef]
3. Dunne, J.A.; Jackson, S.C.; Harte, J. Greenhouse Effect. In *Encyclopedia of Biodiversity*, 2nd ed.; Academic Press (Elsevier): Cambridge, MA, USA, 2013; pp. 18–32.
4. Kirk-Davidoff, D. The Greenhouse Effect, Aerosols, and Climate Change. In *Green Chemistry, An Inclusize Approach*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 211–234.
5. Tillman, D.A. *Coal-Fired Electricity and Emissions Control Efficiency and Effectiveness*; Butterworth-Heinemann: Oxford, UK, 2018; pp. 3–299. ISBN 978-0-12-809245-3.
6. Bhatia, S.C. *Advanced Renewable Energy Systems*; Woodhead Publishing: Delhi, India, 2014; pp. 1–31, 490–508. ISBN 978-1-78242-269-3.
7. Fu, C.; Anantharaman, R.; Jordal, K.; Gundersen, T. Thermal efficiency of coal-fired power plants: From theoretical to practical assessments. *Energy Convers. Manag.* **2015**, *105*, 530–544. [CrossRef]
8. Kingston, R.H. Chapter 1—Blackbody Radiation, Image Plane Intensity and Units. In *Optical Sources, Detectors and Systems. Fundamentals and Applications*; Academic Press (Elsevier): Cambridge, MA, USA, 1995; pp. 1–32.
9. Basic Planetary Data. Available online: https://www.britannica.com/place/Earth/Basic-planetary-data (accessed on 1 June 2019).

10. Cohen, S.; Stanhill, G. Widespread Surface Solar Radiation Changes and Their Effects: Dimming and Brightening. In *Climate Change (Second Edition), Observed Impacts on Planet Earth*; Elservier: Amsterdam, The Netherlands, 2016; pp. 491–511.

11. Zheng, H. Chapter 2—Solar Energy Utilization and Its Collection Devices. In *Solar Energy Desalination Technology*; Elservier: Amsterdam, The Netherland, 2017; pp. 47–171.

12. Rybak, A.; Manowska, A. The forecast of coal sales taking the factors influencing the demand for hard coal into account. *Miner. Resour. Manag.* **2019**, *35*, 129–140.

13. Rybak, A.; Manowska, A. The role of hard coal in national energy security with regard to the energy policy in Poland until 2050. *Przegląd Górniczy* **2017**, *73*, 45–51.

14. Manowska, A.; Tobór-Osadnik, K.; Wyganowska, M. Economic and social aspects of restructuring Polish coal mining: Focusing on Poland and the EU. *Resour. Policy* **2017**, *52*, 192–200. [CrossRef]

15. Jonek-Kowalska, I. How do turbulent sectoral conditions sector influence the value of coal mining enterprises? Perspectives from the Central-Eastern Europe coal mining industry. *Resour. Policy* **2017**, *55*, 103–112. [CrossRef]

16. Brodny, J.; Tutak, M. Analysis of the diversity in emissions of selected gaseous and particulate pollutants in the European Union countries. *J. Environ. Manag.* **2019**, *231*, 582–595. [CrossRef] [PubMed]

17. Singer, S. *Demaskowanie Mitów: Obalanie Mitów o Energii Odnawialnej*; WWF Report: Gland, Switzerland, 2014; pp. 1–66.

18. Global Energy Statistical Yearbook. 2019. Available online: https://yearbook.enerdata.net/ (accessed on 1 June 2019).

19. Ritchie, H.; Roser, M. Energy Production & Changing Energy Sources. Available online: https://ourworldindata.org/energy-production-and-changing-energy-sources (accessed on 1 June 2019).

20. Kijewska, A.; Bluszcz, A. Research of varying levels of greenhouse gas emissions in European countries using the k-means method. *Atmos. Pollut. Res.* **2016**, *7*, 935–944. [CrossRef]

21. Bluszcz, A. Classification of the European Union member states according to the relative level of sustainable development. *Qual. Quant.* **2016**, *50*, 2591–2605. [CrossRef]

22. Bluszcz, A. European economies in terms of energy dependence. *Qual. Quant.* **2017**, *51*, 1531–1548. [CrossRef] [PubMed]

23. Kowal, B. Key performance indicators in a multi-dimensional performance card in the energy sector. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *214*, 012093. [CrossRef]

24. Rybak, A.; Rybak, A. Analysis of the Strategy for the Energy Policy of Poland until 2030 implementation effects in the aspect of environmental protection taking into account the energy security of Poland. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *261*, 012044. [CrossRef]

25. Rybak, A.; Rybak, A. Possible strategies for hard coal mining in Poland as a result of production function analysis. *Resour. Policy* **2016**, *50*, 27–33. [CrossRef]

26. Manowska, A. Renewable energy sources in the Polish energy structure. In *Bezpieczeństwo energetyczne—Filary i perspektywa rozwoju. Księga abstraktów IV konferencji naukowej, Rzeszów, 1-2 kwietnia 2019 r. Red*; Borkowski, P., Węgrzyn, P., Guźla, E., Siwiec, D., Czerwińska, K., Eds.; Instytut Polityki Energetycznej im. I. Łukasiewicza: Rzeszów, Poland, 2019; p. 27.

27. US Department of Energy. *Levelized Cost of Energy (LCOE)*; Annual Energy Outlook 2019; U.S. Energy Information Administration: Washington, DC, USA, 2019; pp. 1–9.

28. Luque, A.; Hegedus, S. *Handbook of Photovoltaic Science and Engineering*; Wiley & Sons: Hoboken, NJ, USA, 2010; p. 235.