Innovation, Sustainable Growth, and Energy: Is Leap Forward for Civilization Possible?

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Abstract

The article explores the relationship between economic development, technology, and energy consumption. It would be hard to imagine technological and social progress without the energy supply that fuels the growth of people's well-being. Thanks to the "energy revolution" of the last century, a technological explosion became possible, including the development of an information society. The free supply of energy is the most important factor determining long-term trends in the development of the world economic system. At the same time, the author shows that at a certain stage of economic development, reserves of free energy resources begin to run low. The emergence of energy shortages is becoming probable, which can restrain further progress. The modern concepts of sustainable development are rightly singled out as one of the most important tasks for limiting the use of traditional, non-renewable energy resources. This is important not only in the ecological sense, but also economically. At the same time, the given concept pays special attention to renewable energy sources, the efficiency and volume of which can not yet be compared with the indicators for hydrocarbon use. The author believes that the very concept of sustainable development runs counter to the aims of humanity to maintain progress. Often, technologies that are designed to reduce the wasteful consumption of fossil fuels lead to additional costs. The author suggests that one objectively analyze the risks of implementing the concept of sustainable development and also warns against unfounded illusions and delusions that can plunge society into a prolonged state of stagnation and regression.

Keywords: sustainable development; energy efficiency; energy innovations; breakthrough innovations; exponential growth

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Achieving sustainable development is the leitmotif of today's long-term forecasts and assessments of the society's progress. This concept was elaborated upon in the 17 goals approved by the UN General Assembly in 2015 and set for implementation by 2030 [UN, 2015]. The sustainable development idea is the embodiment of humanity's perfectly legitimate hope to create a new prosperous society offering relatively equal universal access to the benefits of civilization, while dangerous diseases, key factors of environment pollution, racial and other forms of discrimination – everything that makes the present-day world less-than-perfect, unfair, wasteful, and even dangerous — should be eradicated. The UN documents present the sustainable long-term transformation of society as a new quality of life for future generations. And fundamentally new, non-carbon power industry is supposed to become the most important resource for implementing the sustainable development model. The present generation is expected to lay the foundation for achieving the above goals in the process ensuring their validity, compliance with long-term development trends, and appropriateness of the effort.

Social development is an innovative, frequently chaotic process with a high degree of uncertainty and risk [*Milovidov*, 2015a]. The prominent American anthropologist David Graeber [*Graeber*, 2015] raises a question about where all the inventions every child dreamed of in the middle of the 20th century are now. These include things such as teleportation, protective force fields, tractor beams, Martian colonies, tricorders for remote diagnostics, flying cars, and so on. People make mistakes trying to predict the future all the time, while achievements and ideas that look important and significant at one stage of technological development do not always remain so during subsequent stages – not by far. History knows many examples of one fashion being replaced by another without turning into, as Jared Diamond put it, "the mother of necessity" [*Diamond*, 1997]. Even nuclear energy, seemingly cheap and potentially capable of drastically changing human life, no longer stirs the imagination. However, the fate of the aviation and automotive industries, the internal combustion engine or petrol technologies – disruptive innovations that revolutionized the lives and activities of billions of people – turned out to be completely different. Today humanity is facing the challenge of moving to a new development stage without choosing wrong technological drivers and correctly estimating the resources we still have at our disposal.

The paper analyzes the links between economic development, technology, and humanity's energy potential. It also assesses the risks associated with implementing the sustainable development concept, which in our opinion is fraught with lasting stagnation and even regress.

Civilization's Leap Forward and Energy Resources

Vaclav Smil, a prominent Canadian researcher of energy innovation, wrote: "Modern civilization is the product of the incessant large-scale combustion of coals, oils, and natural gases and of the steadily expanding generation of electricity from fossil fuels, as well as from the kinetic energy of water and the fissioning of uranium nuclei" [*Smil,* 2010].

Given the current desire of a number of developed countries to abandon nuclear energy, the last statement looks a bit like a stretch, but on the whole this statement obviously seems to be valid. The structure of energy consumption is not just linked to the nature and formats of social development, but largely determines them.

The above correlation became the subject of a number of recent studies. Smil was one of the first to try to describe and measure it [*Smil*, 1991]. Subsequently this work was continued by an international group of scientists comprising Timothy Lenton, Peter-Paul Pichler, and Helga Weisz [*Lenton et al*., 2016]. The British economist Angus Maddison compiled data on global GDP growth over a period of more than 2,000 years [*Maddison*, 2001]. Today experts at the University of Groningen maintain a regularly updated database of global GDP growth using Maddison's methodology[1]. The aggregated results of these studies are published on websites devoted to economic history and those in the scope of a special program to promote historical knowledge, "Our World in Data," implemented by the University of Oxford [University of Oxford, n.d.]. Such resources allow one to compare the level of energy consumption with economic growth rate at various stages of human history. A look at global GDP's long-term growth trend (Figure 1) immediately reveals its exponential nature starting from the industrial revolution of the mid-18th century. If in 1700 global GDP was estimated at $643.3 billion, 120 years later it has almost doubled to $1.2 trillion. By 1900 it tripled to $3.42 trillion, and by the end of the 20th century global GDP reached $63.1 trillion, that is, it grew by 18.5 times, or 100 times in 300 years. In a historical perspective, this looks very much like a civilisational explosion.

The prominent US futurist Ray Kurzweil is given credit for the term *the second half of the chessboard*, which he used to describe exponential processes [*Kurzweil,* 2004]. It was not something Kurzweil invented; he simply introduced the well-known parable of a chessboard into academic discourse: if the number of grains placed on its cells doubles in each subsequent cell, it begins to grow rapidly from the fifth rank. The data presented in Figure 1 allows one to view the industrial revolution as an exponentially scalable event (ESE) leading to radical changes in society [*Milovidov*, 2015b]. So which

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[1] Maddison Project database 2018: https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2018, accessed 07.07.2018.

factors led to such a powerful increase in the scale and effectiveness of human activities?

Apart from technological inventions such as the steam engine, energy resources have had a special place among the factors of the global economy's exponential growth since the industrial revolution, above all coal, whose production became a powerful development driver [*Allen*, 2009]. If in 1800 the consumption of energy generated by burning coal amounted to 96.2 TWh (or 1.8% of the total) and energy produced by burning wood and other biofuels 5,555.56 TWh (98.3%), by 1850 the share of coal in the total energy balance had increased to 7.3% (569.44 TWh), and by 1900 to 47.3% [University of Oxford, n.d.]. The industrial revolution was in effect a coal revolution, leading to a skyrocketing rise in fossil fuel consumption compared with the customary, biological fuel types used for thousands of years. As a result, it contributed to a sharp increase in overall energy consumption.

Timothy Lenton et al. tried to estimate energy consumption over tens of thousands of years [*Lenton et al.*, 2016]. Their data confirms that the exponential growth of energy consumption declined during the industrial revolution and clearly follows the GDP growth rate (Table 1). It is also noteworthy that the amount of energy required to produce $1 billion of GDP has dropped from 5.2 TWh (according to Lenton et al., 13.86 TWh) in 1820 to 1.4 TWh in 2015. This figure is expected to further drop to 1.2–0.6 TWh by 2050. An obvious interpretation of these dynamics is the growing energy efficiency of human activities due to the increase in power plants' productivity in the modern economy. If so, how do we explain the extremely low energy consumption for the production of material goods at the beginning of the new era, at 0.3 TWh? Does it mean our ancestors were able to achieve better results at the level of energy consumption we will only be getting close to by the middle of the 21st century?

Low energy intensity can be explained by various reasons that are related to the particular characteristics of the energy being used and the nature of the work. The alleged energy efficiency of economic activities in ancient times was due to the lack of a wide choice of energy resources available for production purposes and relevant technologies. Fire was the main source of energy, while work remained predominantly manual or was based on making use of the propelling force of domestic animals. People were gradually harnessing the energy of water and wind, however, despite these technological discoveries, the notional "energy balance" remained extremely primitive and deficient.

The 18th century industrial revolution radically changed the situation, bringing in not only radically new steam engine technology, but also new energy resources. It was the mass proliferation of coal as an energy resource that led to the significant increase of energy inputs for the production of GDP. It should be noted that energy saving suggestions were first made during the industrial revolution era.

Table 1. **GDP Growth and Energy Consumption**

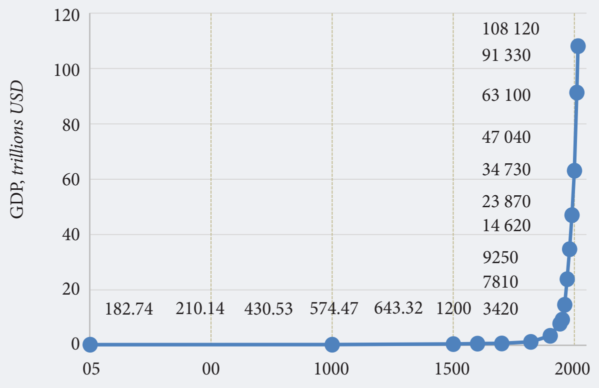
Year	**GDP (*$ billion, in 2011 prices*)**	**Energy consumption** (*TWh*)	**Energy consumption per $1 billion of GDP** (*TWh*)
1	183	55.6	0.3
1820	1202	6263.9	5.2
2000	63 101	112 810	1.8
2015	108120	150 307.8	1.4
2050	230 000–330 000	180 000–280 000	1.2–0.6

Source: author's calculations [*Lenton et al.*, 2016]; Our World in Data [University of Oxford, n.d.].

The prominent English economist William Jevons was one of the first to note the energy consumption effect. He formulated the paradox subsequently named after himself, the Jevons paradox: finding ways to use a resource more efficiently leads to the increased consumption of said resource [*Jevons*, 1865]. As subsequent research demonstrated, this effect was not limited just to the period of the industrial revolution alone [*Rubin*, 2004; *Herring*, 2006; *Polimeni*, 2008]. Smil referred to the same research when he refuted the myth about energy efficiency leading to reduced energy usage [*Smil*, 2010]. In the context of the above studies, reducing energy inputs for the production of $1 billion of GDP can be interpreted not as increased energy efficiency but as the reduced energy basis for extended reproduction.

Thus, from the very beginning of the industrial revolution, humanity has been moving towards an inevitable shortage of energy resources, which in the long term is fraught with reduced economic growth. The current level of energy consumption is a necessary condition of social development. Resources like oil and gas have significantly accelerated the progress of civilization in

Figure 1. **Global GDP Growth between 1-2015 (*trillions USD, in 2011 prices*)**



Source: [University of Oxford, n.d.].

the 20th century. In 1900, oil was the source of 180.56 TWh of consumed energy (1.5% of total consumption), while in 2000 this figure grew to 41,747.31 TWh (36%). The 21st century opens promising prospects for generating energy from natural gas, whose share in the energy balance has been steadily growing since World War II. In 1950, 2,091.67 TWh of consumed energy was generated by burning natural gas (7.5%) and in 2015, the relevant figure reached 36,596.66 TWh (24.3%) [University of Oxford, n.d.].

The application of new technologies combined with new energy resources supported the civilizational leap humanity made over the last 150 years. In the 20th century, the production of material resources grew eightfold while global GDP grew 23 times (or 18 times in 2011 prices) [*Hilty, Aebischer,* 2015]. There is an obvious gap between these two development indicators. What would narrowing this gap lead to? The answer largely depends upon the correct classification of risks. The currently very popular sustainable development logic and the ubiquitous supranational bureaucracy dictate the need to save resources, limit consumption, overcome material inequality, and fairly distribute material wealth. However, these objectives must be accomplished in an integrated and balanced way. Identifying them in the flow of more significant facts, designing optimal algorithms for managing innovation development, and comprehensively assessing initiatives using a broad range of the relevant indicators and risks are critically important for predicting the energy future [*Milovidov,* 2015c].

A Quest for Disruptive Innovations

In the mid-1990s, Clayton Christensen proposed the disruptive innovations concept, that is, technologies and inventions that fundamentally change the accustomed way of life [*Christensen,* 1997]. Typically, the proliferation of such innovations happens exponentially: they are adopted by a large number of users and become instrumental to human activities until the next wave of innovation comes. A specific feature of disruptive innovations is that at the early stage only a small group of people tend to be aware of them while the general public does not pay much attention and sees them as something exotic, irrelevant, or just curious. That is why such innovations are very hard to identify or predict, their disruptive nature only becomes evident at a stage when preventing their proliferation is no longer possible [*Milovidov,* 2018].

Many large companies fell victim to disruptive innovations. The energy industry's history abounds with such examples, in energy resource production, transformation into energy, and energy consumption by industry and households alike. Frequently such innovations appeared due to the explosive development of technologies in other areas such as the automobile industry, communications, new production processes or materials, and so on. There was a time when simply using electricity at home was a disruptive innovation that replaced many other ways to supply energy to households. For example, in 1908 only 10% of US households were electrified, but already by 1928 their share grew to 64%, and by 1958 to 99% [University of Oxford, n.d.].

More impressive technological developments in the "information" century (21st century) are one way or another related to storing and analyzing large volumes of information, so-called "big data" [*Milovidov,* 2017]. These technologies create additional demand for energy resources. In 2007, Laetitia Souchon et al. analyzed the phenomenon of the "energy iceberg" which amounts to the fact that energy consumption by ICT infrastructure (internet servers, mobile networks' base stations, data centers, uninterrupted power sources, etc.) is significantly higher than energy consumption by end user devices (PCs and mobile phones) [*Souchon et al.,* 2007]. On the whole, infrastructures' share may be as high as two-thirds of the total energy consumption. According to the estimates by a Swedish research team headed by Jens Malmodin, global ICT-related energy consumption (including infrastructure and end user devices) in 2007 amounted to 1,286 TWh [*Malmodin et al.,* 2010]. Estimates and forecasts by other authors allow one to conclude that energy consumption will keep growing due to the increasing informatization of the society [*Hilty, Aebischer,* 2015].

The proliferation of technologies such as social networks and cryptocurrencies further increases the pressure on expected energy consumption growth. Between 2011-2016 energy demand by Facebook grew from 532 GWh to 1,830 GWh (or 0.5-1.8 TWh), or more than threefold[2]. If the current energy consumption growth rate remains in place, in 2050 this social network may use more than 10 TWh. Bitcoin miners demonstrate an even more impressive rate of energy consumption growth. According to Digiconomist portal, in just over a year, between February 2017 and July 2018, energy inputs for the emission (mining) and circulation of this cryptocurrency grew from 9.6 TWh to 71 TWh, coming close to the total national energy consumption in countries like Chile. This is 1.7% of the total energy consumption in the US, 7.5% in Russia, 12.4% in Germany, or 29.9% in Australia[3].

Only research and development of profoundly new energy supply technologies can provide an answer to the radical emergence of information society and its growing energy consumption. However, the amount of funding allocated for such R&D illogically follows very obvious cycles determined by the changing situation on energy markets (Figure 2), which clearly shows

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[2] https://www.statista.com/statistics/580087/energy-use-of-facebook/, accessed07.07.2018.

[3] https://digiconomist.net/bitcoin-energy-consumption, accessed 07.07.2018.

that most countries completely lack any strategic long-term research policies for this area. At the same time, if we look at the structure of overall public R&D expenditures, we will see that, for example, in the US in 2006-2016, the share of energy-related R&D funding grew from 6.67% to 9.33%. This is comparable with the growth of expenditures on aerospace-related R&D (from 4.79 to 8.64% [NSF, 2018]), whose share in total public R&D expenditures is much (several times) lower than investments in military-related intellectual activities.

The cyclic nature of energy-related R&D funding is accompanied by structural shifts in the scope and focus of such research. According to the International Energy Agency, in 1974-2017 the share of expenditures on nuclear energy-related R&D dropped from 75% to 19% and remained unchanged (at 8-9%) in the fossil fuel segment. The share of expenditures on energy efficiency-related R&D grew from 4% to 23%, and on R&D in the renewable energy and energy storage fields – from 3% to 19% and from 2% to 9%, respectively. Note that expenditures on interdisciplinary R&D grew from 8% to 20% [IEA, n.d.], while the funding for the development of seemingly disruptive energy innovations such as fuel cells or hydrogen energy remained quite modest, at less than 3% of the total.

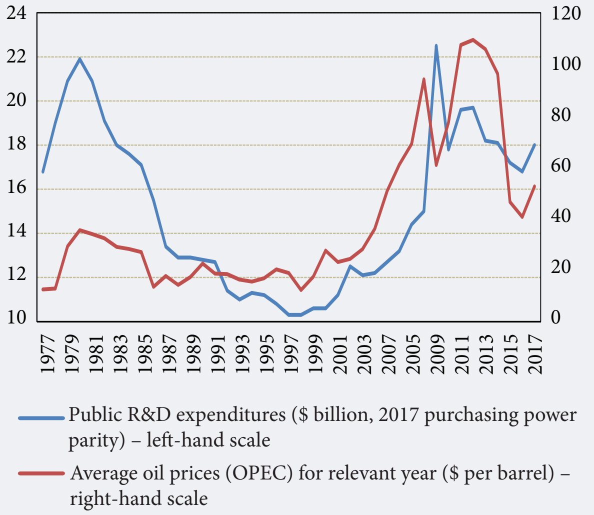
Google Trends[4] allows one to identify topics that are most popular among internet users. Very specialized queries are commonly made along with the most general ones, such as "new energy" or "energy efficiency". If the former was at the top of the list (60 points out of 100) in New Zealand, Colombia, Italy, Indonesia, Pakistan, and Poland, the latter (41 points) turned out to be more interesting to users in Sri Lanka, Saudi Arabia, Hong Kong, Portugal, Finland, and South Africa. Meanwhile for the whole interval observed since 2004 this query's popularity has dropped from 64 to 24 points. The popularity of "fuel cells" queries rapidly decreased from 86 points in 2004 to 9 points in June 2018. However, in Denmark, Japan, Mexico, Taiwan, Egypt, and Iran interest in this topic remained high. The popularity of a query on another potentially disruptive technology, "energy storage", grew from 14 to 20 points, mainly in South Korea, the Czech Republic, Iran, Thailand, Egypt, and Portugal. Finally, attention to technologies for harvesting kinetic energy during the operation of various mechanisms or people's movements is not yet very high (at just 3 points) and was mainly noted in South Korea, Taiwan, Iran, Malaysia, and Japan. In other words, an analysis of search queries does not reveal any fundamentally new trends.

Back to the Future

The very first cars were based on steam engine and electric drive technologies. In 1896, an electric vehicle won the first car race in the US and in 1897, the mass production of such vehicles was launched [*Smil,* 2010]. A few years later, however, internal combustion engine cars took the lead, not only because of their speed and power but primarily due to better opportunities for scaling production, supply chains for components and parts, and ultimately assembly belt production which allowed for cutting costs and significantly increasing profits. Now the world is turning back to the electric vehicle concept, armed with advanced technologies, and pursuing much more ambitious goals. Several countries intend to completely the stop the production of internal combustion vehicles in 2040. Let us take a look at the factors that could seriously undermine faith in electric cars in the medium term.

The production of cars in general and electric vehicles in particular is an extremely energy-intensive process. In 2010, scientists at the US Argonne National Laboratory estimated the total energy inputs of the full automobile production cycle over the past 30 years [*Sullivan et al.,* 2010]. In 1972-2010, this figure varied between 13.5 and 52.8 GJ (3.75×10^{-6} – 14.7×10^{-6} TWh). The authors' own assessment falls in the same range, at 33.92 GJ (9.42×10^{-6} TWh). According to their calculations, the amount of energy needed to make an electric vehicle is 50.73 GJ (14.09×10^{-6} TWh), that is, the production cycle of internal combustion cars is more energy efficient. The above calculations can be supplemented with data on energy consumption during the vehicles' operation for 10 years' time, as an example. In the case of internal combustion cars, total energy consumption can reach 247 GJ (68.6×10^{-6} TWh) and for electric vehicles – 187 GJ (51.94×10^{-6} TWh), that

Figure 2. **Public Expenditures on Energy-related R&D and Average Oil Prices (OPEC) in 1977-2017**



Source: calculated by the author based on [IEA, n.d.; Statista, 2018].

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[4] https://trends.google.com/trends/, accessed 27.07.2018.

is, for the ten-year long term. The difference is slightly more than 30%[5], while for a two-year period there is no difference at all. This is without taking into account a multitude of additional circumstances that over several years can tip the scales in one direction or another. Thus, according to the estimates by Oxford experts, the energy required to charge the battery of a Tesla Semi heavy electric lorry is equivalent to the total energy consumption of 4,000 average private households [WEF, 2017].

Taken together with annual car sales forecasts, the above estimates allow one to expect the arrival of the new automobile production era in 2040, when according to the author's calculations, energy inputs will reach 1,130 TWh for internal combustion cars and 704 TWh for electric vehicles. When the production of the first type is discontinued, the second one will have to take over the relevant market share. As a result, annual energy consumption can reach 1,600-2,800 TWh (approximately 240 million tons of oil equivalent), which is 2.3-3.8 times more than current total consumption by all production (and related) facilities in the automobile industry. The significant growth of energy consumption due to the mass adoption of all kinds and models of electric vehicles will probably create additional demand for conventional energy sources.

Switching to electric cars will create a challenge for the mining industry and battery manufacturers. Making one electric car battery requires between 5 and 15 kg of cobalt and no adequate alternatives for it have yet been found (though relevant research is underway) [*Felter*, 2018]. Global explored reserves of cobalt are estimated at 25 million tons and taking into account the ocean floor, 120 million tons. However, manufacturers tend to refer to the U.S. Geological Survey data according to which in 2017, the officially confirmed industrially developed reserves amounted to 7.1 million tons. The current annual production of 110,000-120,000 tons by 2026 may grow to 190,000 tons [USGS, 2018]. Therefore, with average annual output of 150,000 tons global cobalt reserves will be depleted by 2064 or 24 years after the world is supposed to switch to electric vehicles.

The competition for cobalt deposits has already begun and is reflected in the growing prices for this metal. Today 60% of cobalt is produced by the Democratic Republic of Congo (DRC) in cooperation with China, which supports the full cycle of cobalt production including processing. This gives some experts grounds to speak about the dominance of the Chinese "supply chain", which prompts a number of countries, Germany in particular, to look for alternative suppliers. Russia is not among the major cobalt producers, its domestic reserves are relatively small. However, according to the EU list of critical raw materials approved by the European Commission in 2017, Russia is listed as the main supplier of this metal in the EU with a 91% share. A possible competitor is Finland where increased market prices made it possible to start mining cobalt in 2017, bringing the EU's self-sufficiency to 32% [European Commission, 2017].

Given the aforementioned conditions, the road to complete vehicle electrification will be complex and controversial, raising questions not only about the energy efficiency of production but also about socio-political aspects, such as the exploitation of labor at Congolese mines or atmospheric pollution by metallurgical companies. The redistribution of commodity markets and other systemic risks, including environmental ones, also cannot be ruled out. The low efficiency of renewable energy remains a serious challenge. The efficiency factor in power generation reaches its highest values (up to 90%) in hydropower engineering, while when electricity is generated by burning fossil fuels (coal, oil and gas) energy losses exceed 60%[6]. However, alternative energy sources do not offer fundamental solutions. The efficiency of wind generation still remains under 37%, solar energy has less than 20%, and that of biomass processing has efficiency of just over 35%. Fuel cells demonstrate the best values among alternative energy sources. Depending on the type of media (e.g. molten carbonate), their efficiency can reach 57%, which is slightly higher than gas-based generation (55%). Fuel cells are more efficient than coal (40-45%) and oil products (37%)[7], though not to a radical degree. The amount of investments required for the development of this technology, the projects' internal rate of return, and equipment installation costs can negate any possible benefits from it.

However, biased as this conclusion may appear, no adequate (in cost and efficiency terms) alternatives to fossil fuels have yet been discovered. Global oil, gas, and coal reserves are finite but sufficient to support yet another technology leap. Further prospects look vague and require efforts in areas such as prospecting, the development of mining technologies, and more efficient use of resources (not resource saving, but more efficient generation). Even the development of existing reserves can promote technological transformations. At the same time, the application of these resources can potentially transform the entire technological chain. For example, completely replacing internal combustion cars by electric vehicles while continuing to use coal as the main energy source would look nothing but hypocritical to future generations.

The sustainable development concept insists on abandoning conventional resources in favor of more expensive and less efficient alternatives. Perhaps David Graber is right calling to put an end to the dominance of bureaucracy, which not only consumes a significant portion of the added value created by productive labor,

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[5] https://www.quora.com/How-much-energy-is-required-to-build-an-electric-car, accessed 23.05.2018.

[6] https://flowcharts.llnl.gov, accessed 22.07.2018.

[7] http://bxhorn.com/power-generation-efficiency/, accessed 11.08.2018.

but also imposes its own image of the future, which at some point can diverge from the interests of the rest of humanity [*Graeber,* 2018].

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The issue of supporting humanity's long-term development by providing an adequate supply of necessary energy resources is critical at present. No solution that is even remotely unambiguous and generally accepted exists today for the conflict between environmental considerations and increased energy consumption, which lays fertile ground for speculations about the end of the fossil fuel era. Environment protection should not get in the way of the development of human civilization, which shows no inclination towards downshifting. It would not be right to hail the consumerist side of human nature, but it is exactly what encourages people to make discoveries, explore new lands, and even advance to outer space. The laws of social and economic development occasionally do put humans in their place, curbing their limitless aspirations, but deluding ourselves with the prospects of an ecological utopia while trying to harness them could be much more dangerous.

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