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Research Article

Energy, demand for computing power and the Green World

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Abstract

The review looks at the main trends in global energy production and consumption over the last half century, based on P.L. Kapitza's 1975 analysis using a unified approach based on the Umov–Poynting vector. Such aspects of the problem as the impact of energy consumption on gross national product per capita, reasons for different approaches of countries to the transition to renewable energy sources, existing sources of energy, global distribution of its production and consumption, features and prospects of different energy technologies, as well as technologies to reduce energy consumption are touched upon. Thus, since 1975, the price of one kilowatt-hour of "solar" electricity has fallen by orders of magnitude and this technology has moved to the forefront, while fusion still remains the "energy of the future" and coal continues to hold its position in the market. Somewhat unexpectedly, electronics and telecommunications have become a major consumer of energy, urging a shift from von Neumann architecture to neuromorphic technology in computers and the development of femto and attowatt optoelectronics. And a totally unforeseen energy consumer has been cryptocurrency mining. On the other hand, the harvesting of dissipated energy in a variety of ways is seen as an environmentally friendly alternative to the use of batteries in low and ultra-low-power devices.

Keywords

energy production, energy consumption, energy harvesting

1. Introduction

Back in 1975, the eminent Soviet physicist P.L. Kapitza, formerly a disciple of E. Rutherford and then Nobel Laureate in 1978, delivered a presentation later published in [1], which began with the words "It is widely recognized that the main factor determining the development of the material culture of nations is the creation and use of energy sources". He gave a graph showing a clear correlation between energy consumption and gross national product (GNP) per capita in different countries. He then analyzed the status and prospects of different ways of generating energy. It is extremely interesting to see what has changed in this respect over the past almost half a century and whether the great scientist's predictions have come true. Note, however, that Kapitza did not consider the issue of energy consumption by different branches of the national economy. Since then, electronics and telecommunications have become a new global energy consumer, and a new aspect of the problem of energy generation and distribution – global warming – appeared. Let us try to address the energy problem based on Kapitza's analysis and using modern data.

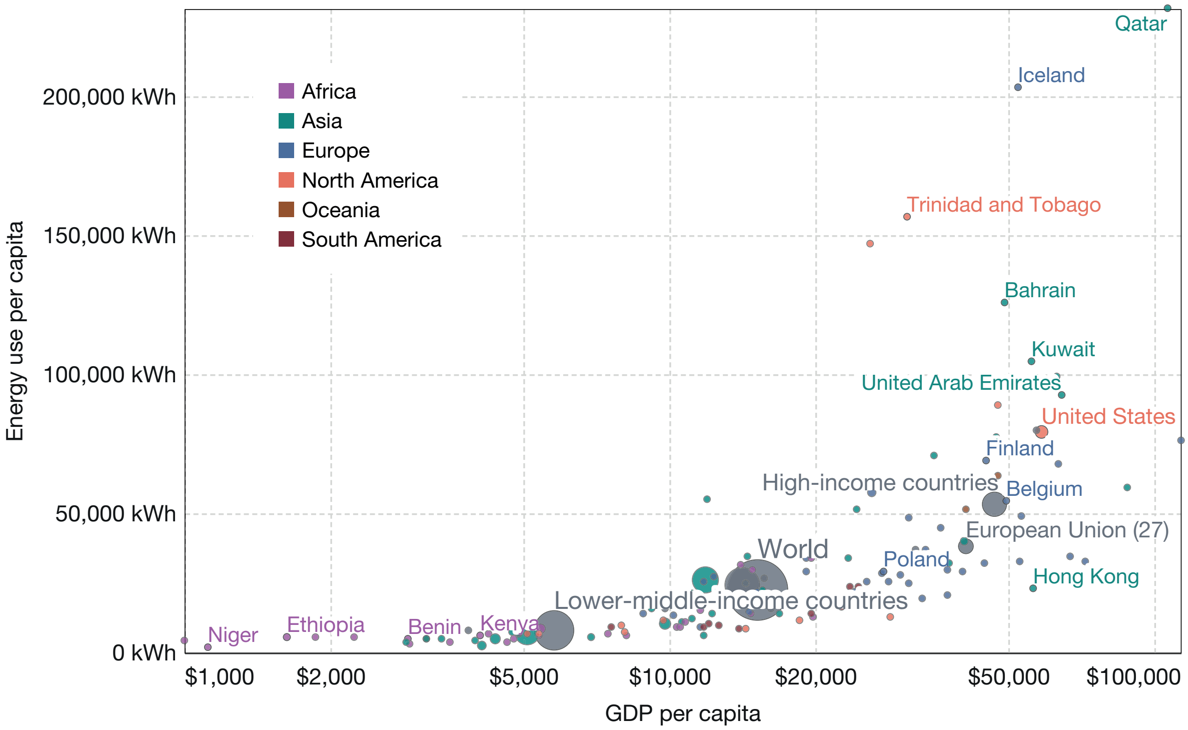

Figure 1. GNP per capita versus energy consumption in 2015. *Source:* Our World in Data. https://ourworldindata.org/grapher/energy-use-per-capita-vs-gdp-per-capita (accessed on 10.04.2024).

2. Existing major energy sources

Let us first look at the relationship between energy consumption and GNP per capita today. Figure 1 shows that nothing has changed in this respect since 1975. Except for some scattering of points (quite natural, though), the correlation is quite unambiguous.

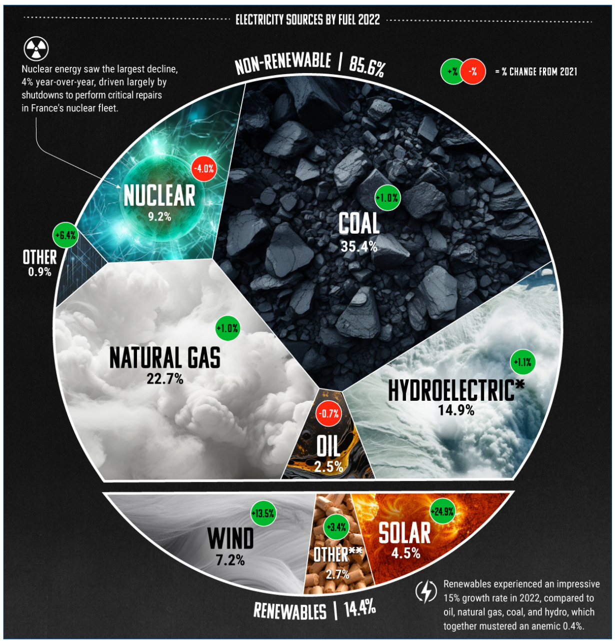

Figure 2. Relative contribution of different sources to global electricity production in 2022. *Source:* Dickert C. What Electricity Sources Power the World? September 10, 2023. https://elements.visualcapitalist. com/what-electricity-sources-power-the-world/ (accessed on 10.04.2024).

Let us now turn to the terminology used by the UN: "Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed. Sunlight and wind, for example, are such sources that are constantly being replenished. ... Fossil fuels – coal, oil and gas – on the other hand, are non-renewable resources that take hundreds of millions of years to form. Fossil fuels, when burned to produce energy, cause harmful greenhouse gas emissions, such as carbon dioxide" [2].

It would seem that everything is clear: mankind must urgently switch to renewable energy sources. In reality, everything is not so simple and obvious [3].

Figure 2 shows that in 2022, coal continued to lead global electricity generation (35%). It was followed by natural gas (23%) and hydropower (15%). This is not accidental: the main advantage of such energy carriers as oil, gas and coal is their high energy density (12 kWh/kg in the case of gasoline [4] versus the current energy density of a car battery of about 0.26–0.27 kWh/kg [5]). To repeat: it is generally accepted that the use of fossil energy sources leads to huge emissions of CO_2, a greenhouse gas believed to cause global warming with all its negative consequences[1].

Another disadvantage of fossil fuels is the low energy efficiency (less than 28%) characteristic of internal combustion engines, in contrast to the very high efficiency of

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[1] To be fair, there are other opinions on this, but in the present article we will assume that this statement is true.

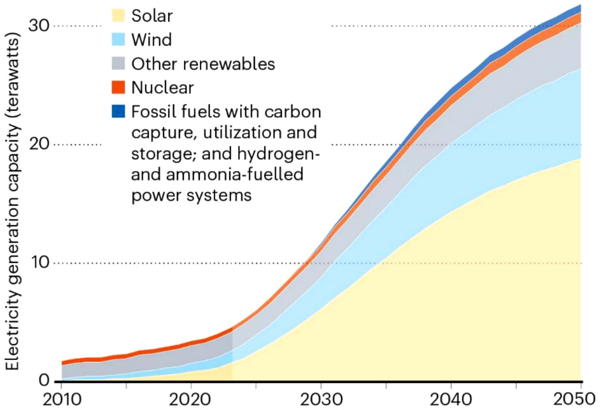

Figure 3. Expected dynamics of electricity generation using various sources to keep the average temperature increase on the planet by 2050 within 1.5 °C [8]

the electric motor, exceeding 93%, which allows significant energy savings [6].

Similarly, there is, for example, a huge difference in efficiency between gas boilers and heat pumps: using the latter helps to save energy and reduce CO_2 emissions. Except that installing a heat pump is very expensive [7].

So, to save our planet and humanity from the negative effects of climate change, it is necessary to reduce greenhouse gas (GHG), especially CO_2, emissions, i.e. to carry out so-called decarbonization. This requires new alternative technologies that fulfil a number of requirements:

- high energy density,
- no CO_2 emissions, and
- greater energy efficiencies [8].

The proportion of the world population living in cities will increase from the actual 55% to 68% in 2050, thus, urban decarbonization becomes all-important to avoid the undesirable impact on the climate [9].

The decarbonization process implies the gradual involvement of renewable sources in energy production. Figure 3 shows the expected energy production dynamics using various sources to keep the average temperature increase on the planet by 2050 within 1.5 °C. As we can see, the main hope is for accelerated development of solar and wind energy. Later on, we will come back to this issue.

3. Global energy generation and consumption

Not for all countries, tackling global warming is a top energy policy priority, as recorded in the final document of the G20 Energy Transitions Ministers' Meeting in Goa, India, 22 July 2023: "The energy sector's contribution to global GHG emissions is significant. Given that fossil fuels currently continue to play a significant role in the global energy mix, eradication of energy poverty, and meeting the growing energy demand, the importance of making efforts towards phasing down unabated fossil fuels, in line with different national circumstances was emphasized by some members while others had different views on the matter that abatement and removal technologies will address such concerns" [10]. Serious differences of opinion were also evident at the recently concluded COP28 UAE – United Nations Climate Change Conference in Dubai [11].

To understand the source of the controversy, one needs only look at Figs 4 and 5 which reflect the catastrophic

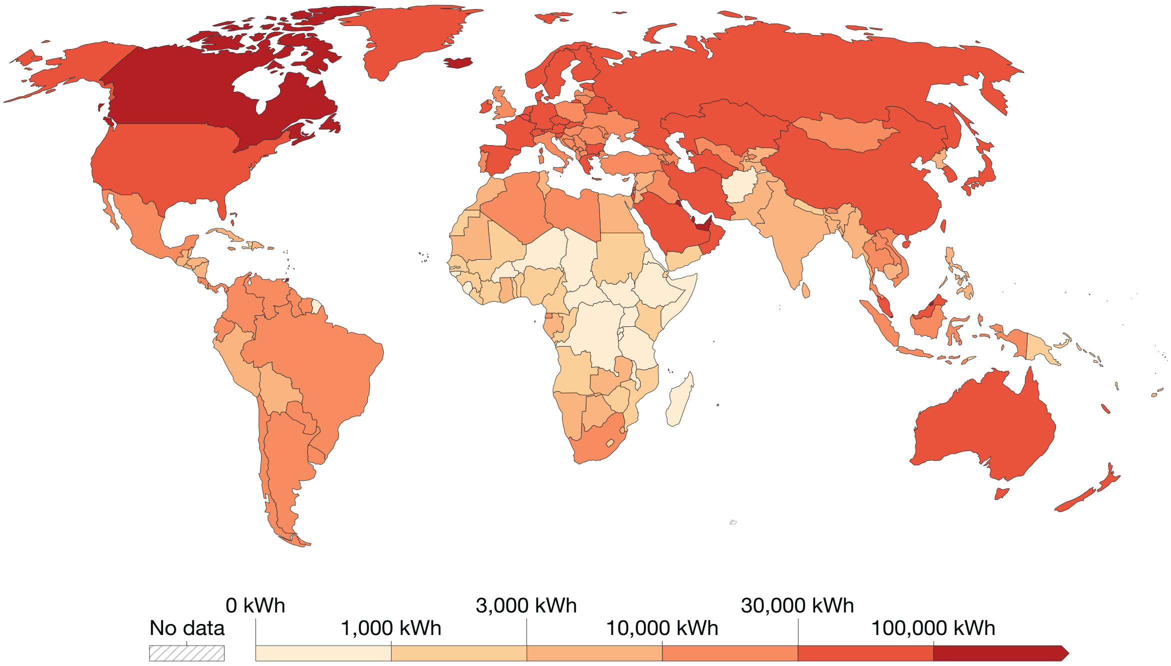

Figure 4. Energy use per person in different countries in 2022. *Source:* Our World in Data. https://ourworldindata.org/energy#explore-data-on-energy (accessed on 10.04.2024).

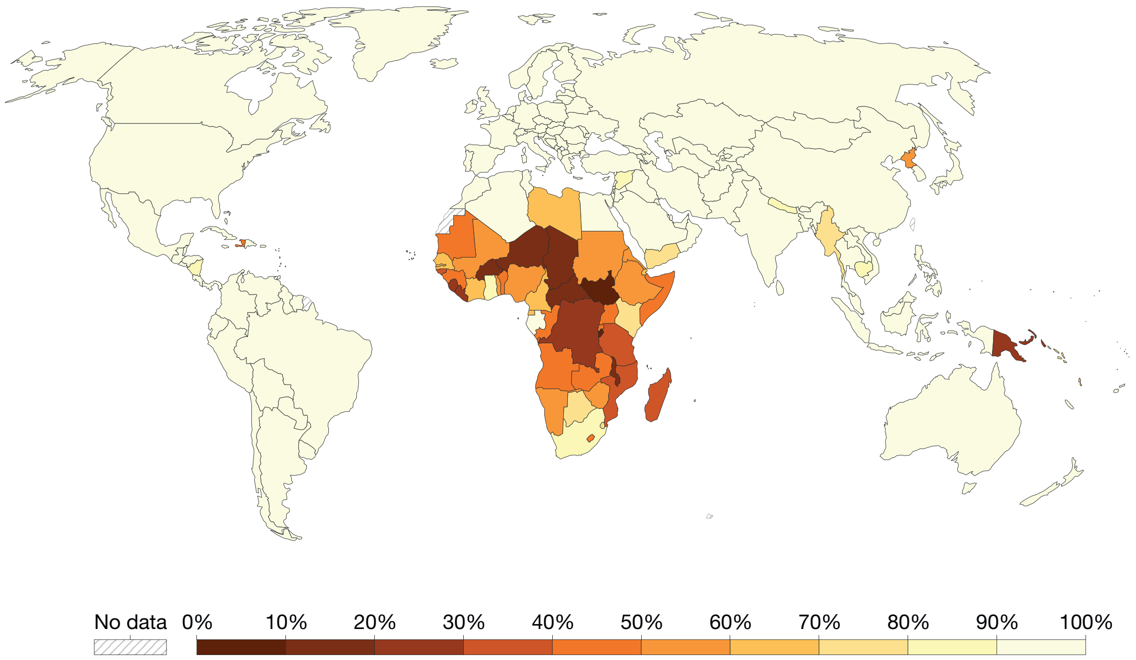

Figure 5. Access to electrical energy in different countries in 2020. *Source:* Our World in Data. https://ourworldindata.org/energy#-explore-data-on-energy (accessed on 10.04.2024).

situation of energy consumption and access to electricity in many countries in Africa, Asia and Oceania. Figure 6 shows that while the total energy consumption in North American and European countries has not grown for decades, the Asia-Pacific region shows an explosive growth in annual primary energy consumption [12].

Now let us look at the development of alternative (i.e. renewable) energy production in different countries (Fig. 7).

We see that some countries are increasing renewable energy production while others are reducing it. The most mixed picture is found on the European continent. Figure 8 tells us that the rate of renewable energy innovation, as measured by the number of patents granted, has only grown in China over the past two decades, with China far outpacing the rest of the world after 2008.

An interesting and telling exception is Sweden, where GNP per capita growth since 1995 has been achieved with a slight decrease in energy consumption (Fig. 9).

By the way, thinking activity also requires energy expenditure and a lot of it: with an average brain weight of 1350 g, it consumes from 9–10% at rest to 25% (some

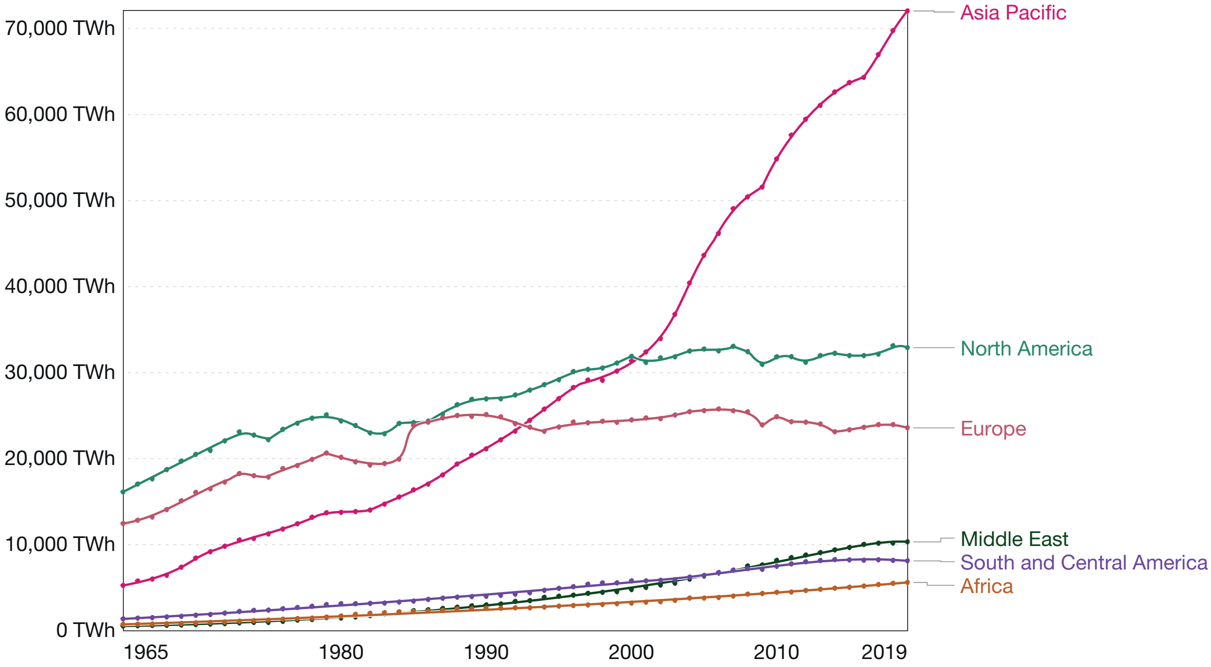

Figure 6. Annual primary energy consumption by world region [12]

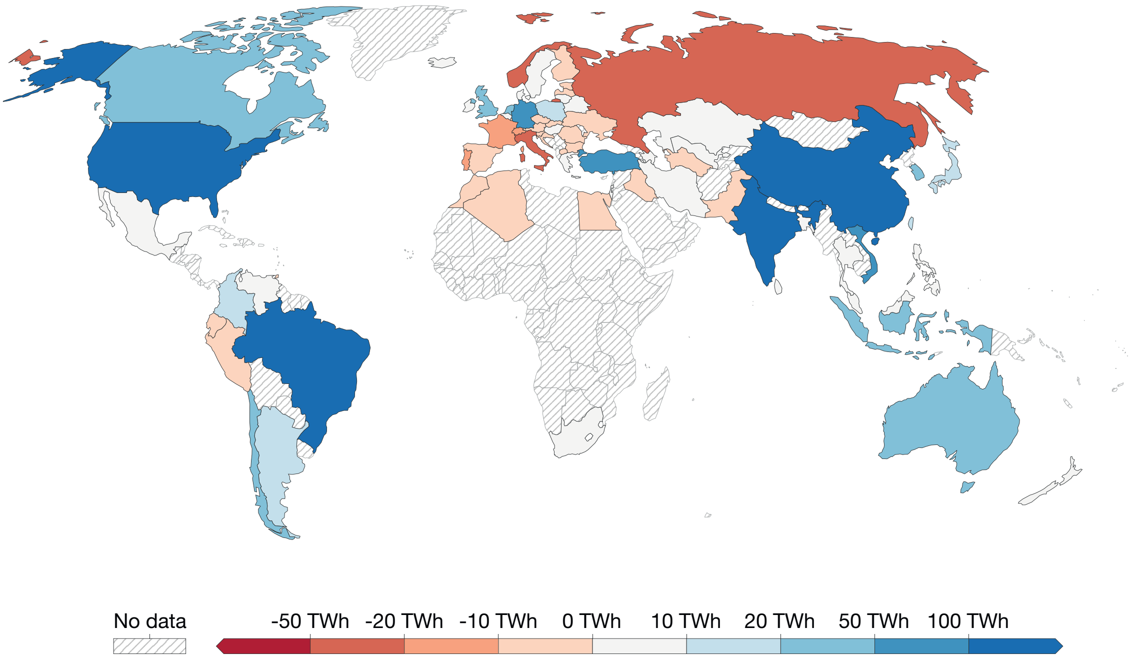

Figure 7. Change in annual renewable energy production by country in 2022 compared to 2021. *Source:* Energy Institute Statistical Review of World Energy. 2023. https://www.energyinst.org/statistical-review (accessed on 10.04.2024).

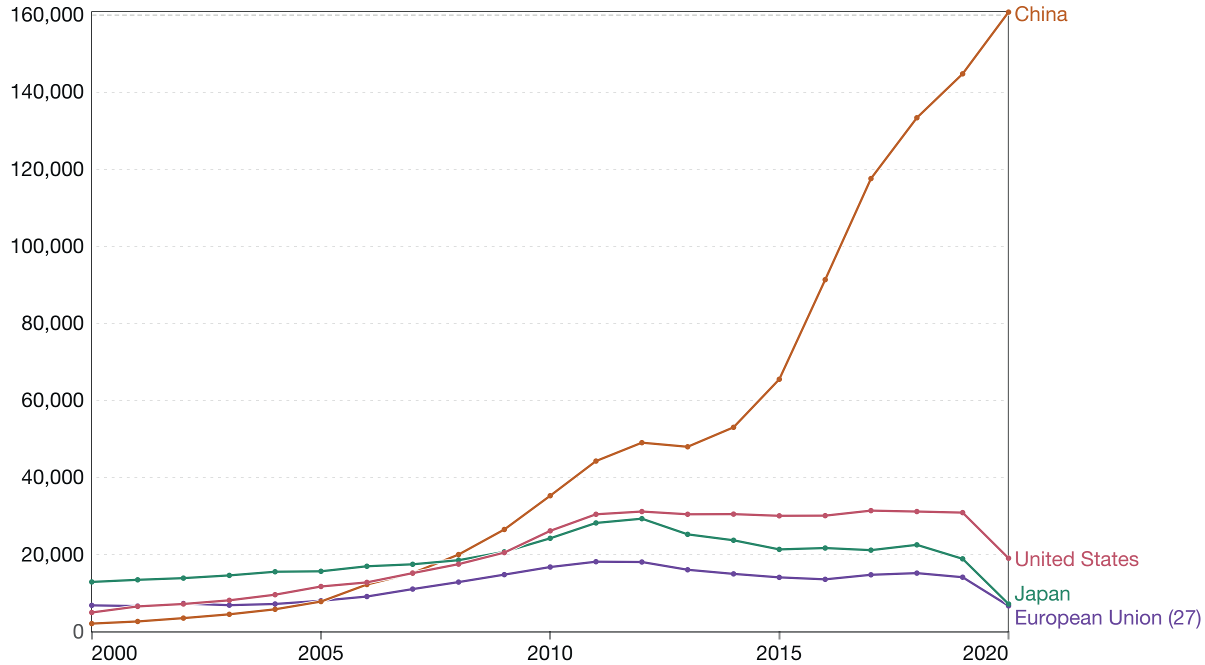

Figure 8. Number of renewable energy patents by country since 2000. *Source:* Our World in Data. https://ourworldindata.org/grapher/patents-for-renewables-by-country?tab=chart (accessed on 10.04.2024).

sources say up to 60% [13]) in periods of maximum activity from the total energy of the human body at an average weight of 75 kg (a 55-fold difference in weight!). In the rat brain, 25% of energy is used to maintain vital body functions, and 75% is used to process information [14]. Importantly, this means that mental work is much more labour-intensive than physical work. Besides, the brain is not a CMOS processor and consumes not only energy but also nutrients and produces metabolic products that need to be utilized.

What is the case with electronic "brains" in this sense? In Ref. [15], direct quantitative data on the impact of computing power on areas like Chess and Go or weather prediction, protein folding, and oil exploration have been considered, with the fundamental result that processing power explains 49–94 % of the performance gains in these applications. Note: to obtain linear growth in these areas, an exponential boost in computing power according to Moore's Law is required [15]. Thus, the keeping of the latter has been extremely important for progress, and

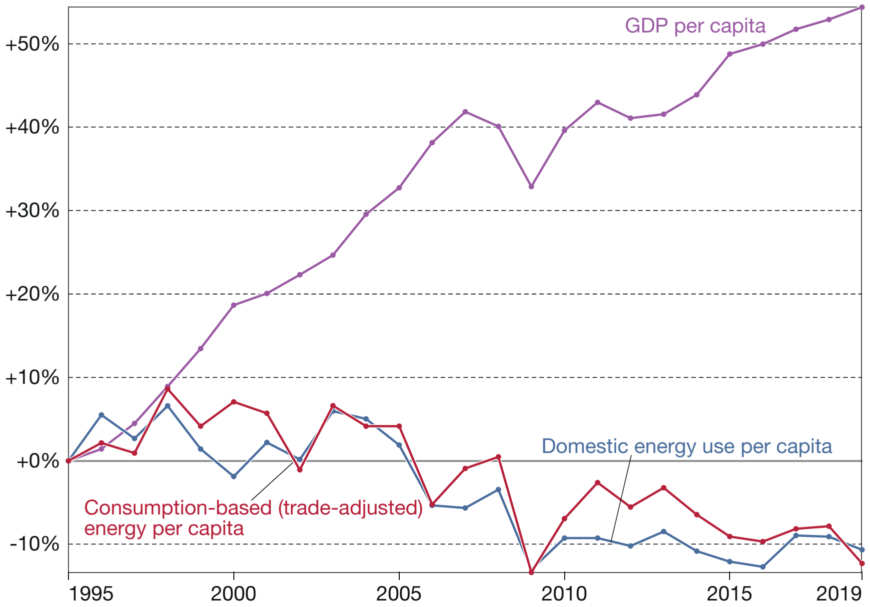

Figure 9. Change in energy use versus changes in GNP per capita in Sweden since 1995. *Source:* Our World in Data. https://ourworldindata.org/grapher/change-energy-gdp-per-capita (accessed on 10.04.2024).

the performance gains in many areas become economically unsustainable when Moore's Law comes to nought. The situation has deteriorated dramatically over the last decade: while global demand for computing power doubled every 24 months until 2012, then the doubling period suddenly shortened to about 2 months [16]. Thus, the growing demand for computing power is far outpacing the improvements achieved through Moore's Law scaling [17].

What's even more interesting is that machine learning (ML) tends, in the limit, to consume all the power produced in the world, and this development model is costly, inefficient and unsustainable. The power consumption figures are becoming daunting. At the 2022 Design Automation Conference, a slide was shown (Fig. 10) that puts the power consumption of ML systems in perspective, approaching the world's energy production.

Another well-known computerised energy eater is cryptocurrency mining. It is estimated that bitcoin alone devours 127 TWh per year, which exceeds the energy consumption of many countries, e.g. Norway. In the United States, cryptocurrency business emits between 25 and 50 million tons of CO_2 per year – comparable to the emissions from the burning of diesel fuel by American railways [18]. To produce this amount of electricity, 100 coal-fired power plants are needed. That's enough energy to charge more than 200 million all-electric cars travelling 10,000 km a year, and in 2022 there were only 26 million such cars in the world [19].

Another cause for concern is Bitcoin's water footprint which has skyrocketed recently. As compared with 2020, in 2021 it grew by a factor of 2.66, from 591 Gl to 1,574 Gl (from 5,231 l to 16,279 l per transaction, respectively). Bitcoin's water footprint is estimated to be 2,237 Gl in 2023 [20].

In 2020, about 50% of the worldwide bitcoin farms were in China [21], with electricity produced from coal-burning power stations being inexpensive, and the government tried to reduce this by shutting down bitcoin mining in September 2021. As of the end of 2023, the USA is the world leader in cryptocurrency mining [22].

We can cite other data that are in agreement with the described trend [23]: In 2022, the Internet consumed 800 TWh of electricity, and the need for energy is likely to double by 2030.

Power and cooling infrastructure costs have now exceeded the cost of raw IT equipment [24]. Lisa Su, CEO of AMD, forecasted that we will use half of a nuclear power plant's energy just for a single supercomputer operation in 2035 [25]. Leopold Aschenbrenner, a former OpenAI employee, predicts in his recent review that

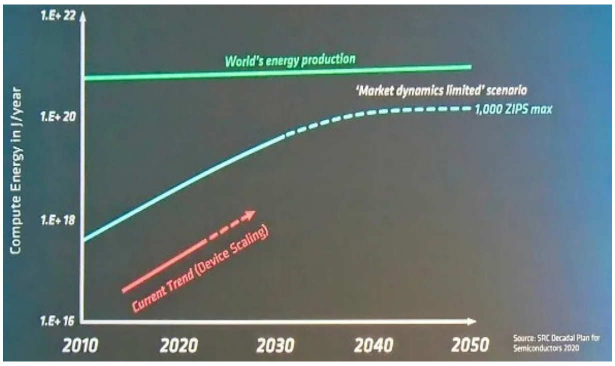

Figure 10. Projection of energy expenditure on computing compared to its global production up to 2050. *Source:* Bailey B. AI power consumption exploding. August 15, 2022. Semiconductor Engineering. https://semiengineering.com/ai-power-consumption-exploding/?cmid=1c9a6ebe-071d-4b5f-9433-f084336b9289 (accessed on 10.04.2024).

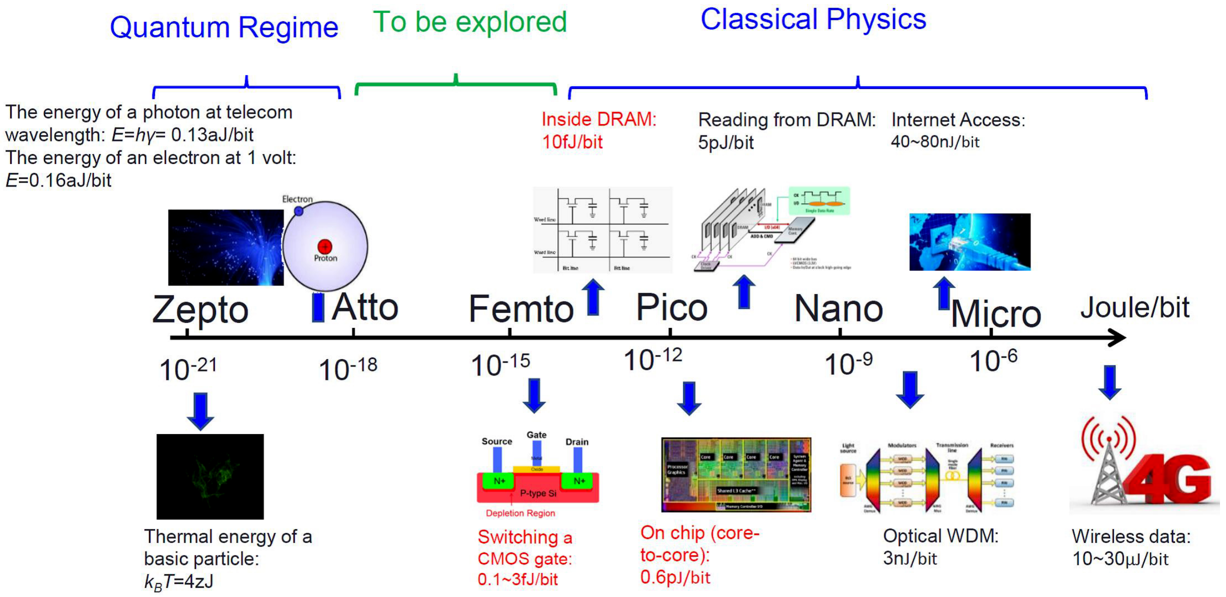

Figure 11. Optoelectronic technologies for low-energy information processing and communications (Figure plotted by Alan Wang according to the data from D.A.B. Miller, 2017 [27])

by 2030, data centres will require energy comparable to the entire electricity generation in the United States to train models [26]. He, incidentally, compares the project to develop an artificial general intelligence (AGI) with the Manhattan Project and considers it a priority for US national security.

To understand where savings can be made, it is interesting to look at the orders of magnitude of energy costs associated with different technologies (Fig. 11) [27].

To summarize: energy consumption is frighteningly high and growing. So what are the possible solutions?

Obvious answers:

– to produce more (negative consequences: global warming, pollution[2]);

– to consume less (be careful, on this path, it is possible to slow down technological progress and reduce the standard of living of the population).

With regard to the first point, it is time to return to the analysis of P.L. Kapitza [1], attracting information that appeared after 1975.

4. Energy technologies

The Umov–Poynting vector **U** describes the energy flux density. In a medium, **U** is restricted by the expression $\mathbf{U} < \mathfrak{v}F$, where $\mathfrak{v}$ is the deformation propagation velocity, and F may be any elastic or thermal energy [1]. The formalism is also applicable to other types of energy.

Looking ahead, we note that, when we seek high-power applications, the restrictions on the Umov–Pointing vector exclude many energy technologies that are otherwise quite effective! But let us go in order, following P.L. Kapitza[3].

Geothermal energy. Its advantages include inexhaustible energy reserves and the ability to generate energy 24 h a day, 365 days a year. The main disadvantage is the limitations imposed by the low thermal conductivity of rocks resulting in a low energy flow density.

Hydro energy is generated by damming rivers and utilizing tides and allows efficient conversion of gravitational energy into mechanical energy. In addition, hydroelectric power plants allow for rapid variation in the power delivered to the grid, compensating for the volatility of other sources. The main disadvantage is that damming rivers is favourable only in mountainous regions where the potential energy per unit area of the water reservoir is high. On plains, dams do not justify themselves either economically or environmentally, especially when it comes to flooding fertile land. What concerns tidal energy, tidal power plants are only profitable in places where the tides are high enough, and there are not many such places.

Wind power is environmentally safe (nowadays there are some doubts, which we will not dwell on now). The obvious drawbacks are insufficient energy flow density and instability of the generated power.

Thanks to large uranium reserves, *nuclear energy* can meet the energy needs of mankind for millennia. However, the safe storage of nuclear waste is problematic (an example: the Kyshtym disaster). The threats of reactor accidents (examples: Chalk River, Three Mile Island,

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[2] According to a study performed just before the COP28 conference, eight million people worldwide die yearly from air pollution. Even worse: experts affirm the crisis is getting deeper. *Source:* Martin V.St. At COP28, a growing sense of alarm over the harms of air pollution. December 6, 2023. Inside Climate News. https://insideclimatenews.org/news/06122023/cop28-growing-alarm-air-pollution-harms/?et_rid=35096604&et_cid=5059919 (accessed on 10.04.2024).

[3] References will be inserted as a rule only to information sources which have appeared after Kapitza's paper [1] and bear new information.

Chornobyl, Fukushima – all at least partially caused by human error), large-scale plutonium proliferation and the associated risk of nuclear terrorism, as well as sabotage or war are always present. Increased international control may be a possible solution.

P.L. Kapitza considered nuclear power to be the most promising [1]. In past decades, the opposite trend has prevailed in some countries, but quite recently, at the 21 March 2024 Nuclear Energy Summit in Brussels, EU leaders reaffirmed the value and potential role of nuclear power in achieving the EU's climate goals [28].

Thermonuclear fusion is an inexhaustible source of energy due to deuterium reserves in the oceans. In addition, virtually no radioactive waste is generated, there is little danger in the event of reactor failure, and no explosives are produced for the bomb. Unfortunately, the plasma is heated by the application of an electric field, so almost all the energy goes to the electrons, which, because of their low mass, transfer energy poorly to the ions in collisions. Most of the electrons' energy is lost to bremsstrahlung.

It should be noted that despite considerable efforts worldwide since the middle of the last century, there is still no fusion plant that produces more energy than it consumes to operate. For 70 years now, thermonuclear energy has remained the "energy of the future". And estimates show that fusion will hardly be a competitive technology even beyond 2040 [29].

Direct transformation of chemical energy into mechanical energy (as it occurs in muscles) is a clean technology. However, energy density is limited by the slow diffusion processes in biological membranes or on the surface of muscle fibres. This is why the Industrial Revolution happened – machines replaced human and animal muscle power.

Fuel cells also represent a clean technology (no emission of CO_2), directly transforming chemical energy released during the oxidation of hydrogen into electrical energy. Even more, it exhibits high efficiency for obtaining electrical energy (above 65% for proton-exchange membrane fuel cells and even greater than 85% for solid oxide fuel cells) [30]. On the other hand, the rate of diffusion processes in electrolytes is very low, and hydrogen is still expensive.

There are various technologies to obtain hydrogen. The most widespread is the electrolysis of water producing hydrogen and oxygen. In addition, according to a recent model developed by the U.S. Geological Survey (USGS), the natural hydrogen produced by water reacting with rocks deep inside the Earth could be enough to meet growing global demand for thousands of years [31].

It is important to note that hydrogen meets modern requirements for possible fuels, having an energy density of 33.3 kWh/kg [4] (against 12 kWh/kg for gasoline). Roughly speaking, 50 kWh is needed to produce one kg of hydrogen by electrolysis, which, as indicated above, contains 33.3 kWh of energy. This defines an average energy efficiency of approximately 65% [30]. Various hydrogen-based energy carriers have gained strategic importance: pressurized and liquid hydrogen, methanol, ammonia, liquid organic hydrogen carriers, etc., which facilitates their transportation and use [30].

Solar energy for water splitting and hydrogen generation is another clean technology (but there are doubts). Unfortunately, there still is no viable technology for industrial applications [32].

Solar energy for photovoltaics is the Holy Grail Cup for power engineers. It is considered a clean technology (but there are doubts – the technology of silicon solar cell production uses highly toxic substances, and the issue of solar panels recycling as they reach the end of their useful life is getting ever more challenging [33]). Other drawbacks are low energy density, variability of insolation in time and on the Earth's surface, and long distances between solar farms (e.g., in the Sahara) and industrial sites (e.g., in Europe).

Earlier the high cost of solar energy was a serious problem (in 1975 even P.L. Kapitza did not know how to make it economically viable [1]). But now the price barrier has been broken (Fig. 12). What's more, in 2023, solar PV module prices have fallen by 45% and are now cheaper than at any time in history [34]. It's gone so far that solar panels are now used as garden fencing [35]. The International Energy Agency predicts that there will be a global supply of solar panels of 1100 GW by the end of 2024, tripling demand and leading to an estimated 40% drop in prices by 2028 [36].

In 2022, photovoltaics accounted for 4.5% of global electricity production (see Fig. 2), making it the third most important source of renewable energy after hydro and wind power. The share of these three types of energy is expected to grow exponentially in the medium term and reach 40% by 2035 and 45% by 2050 [37]. Overall, renewable energy is expected to account for 90% of energy production in the mid-21st century, of which about half will be solar energy [38].

The first solar cell (SC) invented in 1954 was based on a *p–n* junction [39], and the working principle of most

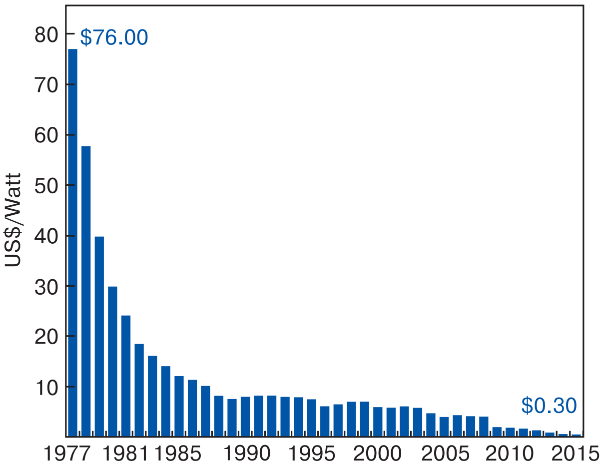

Figure 12. Development of prices per watt for conventional solar cells (c-Si) since 1977. *Source:* Solar cell. https://en.wikipedia.org/wiki/Solar_cell (accessed on 10.04.2024).

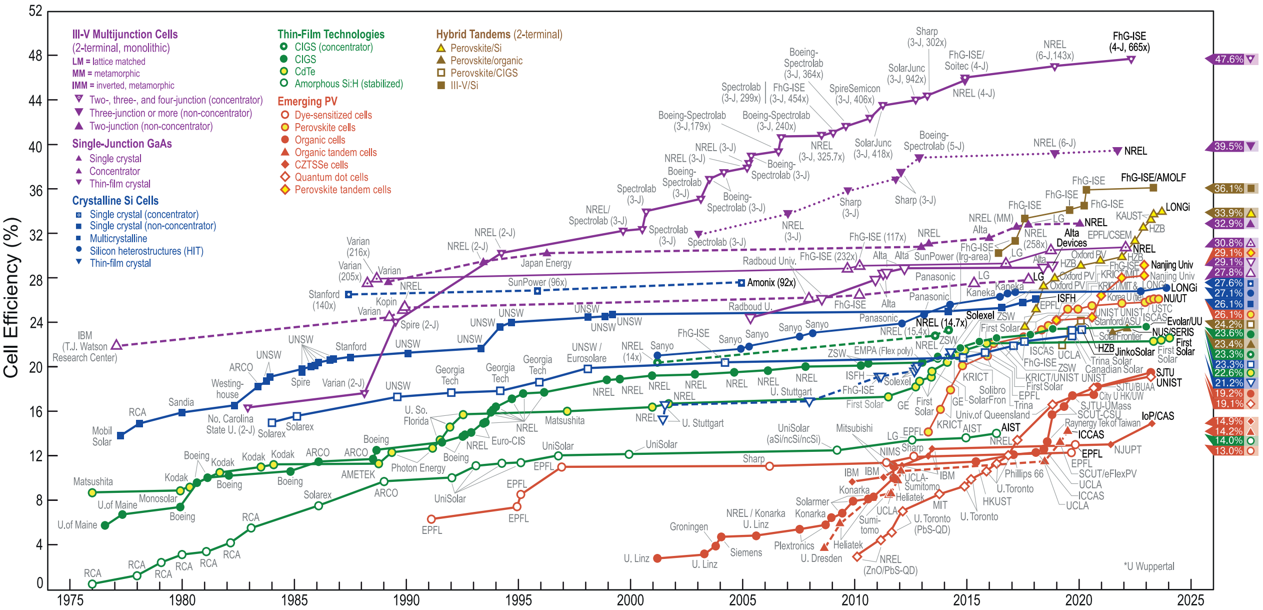

Figure 13. Over the past ten years, the maximum efficiency of multi-junction cells has increased from about 35% to 47.1%. The best laboratory designs need about two years to arrive on the market. *Source:* Photovoltaic Research. https://www.nrel.gov/pv/cell-efficiency.html (accessed on 10.04.2024).

of today's SCs is still the same. Since then other technologies like heterojunctions, anti-reflection coatings, thin-film absorbers, solar concentrators, integration of different bandgap junctions, i.e. multijunction and intermediate band-based SCs, as well as use of novel materials such as perovskites, have pushed up the efficiency. As a result, silicon-based technology still accounts for ca. 97% of the global solar market [36].

To conquer the main drawback of solar energy, its intermittency, the scientific community spent several decades investigating Space-based solar power (SBSP), in which orbiting satellites would collect energy 24/7 and 365 days.

In June 2023, Caltech's space solar power project (SSPP) team announced that their space prototype called the space solar power demonstrator (SSPD-1) transmitted the produced energy to microwave receivers installed on a roof of the Caltech campus in Pasadena, California. According to Science Alert [40], the experiment – known as the Microwave Array for power-transfer low-orbit experiment (or MAPLE) – is one of three research projects being carried out aboard SSPD-1. The platform is based on low-cost silicon technologies. However, a report, published by NASA's Office of Technology, Policy and Strategy (OTPS) in January 2024, communicated that space-based solar power designs are 12 to 80 times more expensive than their land-based counterparts [41].

In order not to be further distracted by a detailed description of the state of affairs in SC research and development, I will only show the historical development of the record values of quantum efficiency of SCs, starting from 1975 (Fig. 13).

5. Energy-saving electronic technologies

Energy costs for processing and transmitting data around the world are high, so there is an urgent need to develop respective energy-efficient devices.

Tensor processing units (TPUs) and graphics processing units (GPUs) use the traditional von Neumann architecture: Information processing and storage are performed by different processor blocks: computation – in cores, storage – in main memory, one memory block for several dozens or hundreds of cores. This requires frequent data exchange between cores and memory, which causes a relatively high power consumption and low energy efficiency (energy per frame) of data processing: typical values of heat dissipation from a modern GPU are 200–300 W with a performance of about 10^{13} operations (multiplication-addition/write to buffer/erase, etc.) per second (10 TFLOPS).

So what are the ways to reduce energy consumption in IT? Here are a few possibilities.

5.1. NorthPole

In 2023, a chip with a neural-inspired architecture, called NorthPole, has been proposed [42]. It exhibits higher performance, energy efficiency, and area efficiency than other similar devices. Unlike analogue in-memory computing, NorthPole is a purely digital system which can tailor the bit precision, resulting in the optimization of power usage.

5.2. Transistor-free compute-in-memory architecture

The compute-in-memory (CIM) architectures are characterized by the elimination of the data transfer between processor and memory, thus accelerating computing and minimizing energy consumption. But even in a CIM architecture, transistors degrade data access time due to the need for a large number of wires in the chip circuitry, thus wasting more time, space, and energy than is desirable for neuromorphic computing (see below).

The transistor-free CIM design proposed recently [30] is simple, small, and quick, ensuring very low energy consumption. This architecture performs three computational tasks, viz., search, storage, and neural network operations, which is fundamental for artificial intelligence (AI) applications.

5.3. Semiconductor spintronics

Another alternative to conventional electronics is to utilize the properties of spin rather than charge. This field, known as semiconductor spintronics [43], has existed for a few decades, and it promises energy-efficient quantum computing and data storage, as well as other possibilities, compared to similar electronics. However, despite several advances, progress in semiconductor spintronics has been almost as slow as in fusion energy [4].

5.4. Quantum computing

Quantum computing is based on swapping digital bits for qubits. Quantum computers can be used in quantum cryptography, quantum machine learning, molecular modelling and other areas where conventional processors are inefficient. On the other hand, quantum computers are unlikely to replace classical computers in a number of traditional applications. To date, quantum computers have not yet left the laboratory, so their total contribution to global energy consumption is negligible.

5.5. Neuromorphic engineering

The main path of computer technology development is undoubtedly the transition to the neuromorphic architecture of computing systems [44], which has the following advantages:

– convergence of information processing and storage units (i.e. CIM);

– matrix-vector multiplication by memristors for energy-efficient artificial intelligence systems [45];

– hardware execution of weighting factors between neurons (synaptic analogues) based on arrays of memristors, multilevel or even analogue cells of electrically rewritable memory (ReRAM);

– operating at low frequencies while maintaining computational speed (biological neural networks operate at very low frequencies (from units to hundreds of hertz) compared to traditional processors);

– the ability to (self-)learn, i.e. to self-organise or fine-tune additional multi-digit or analogue synaptic scales for target tasks (computer vision, hearing, autonomous control, etc.).

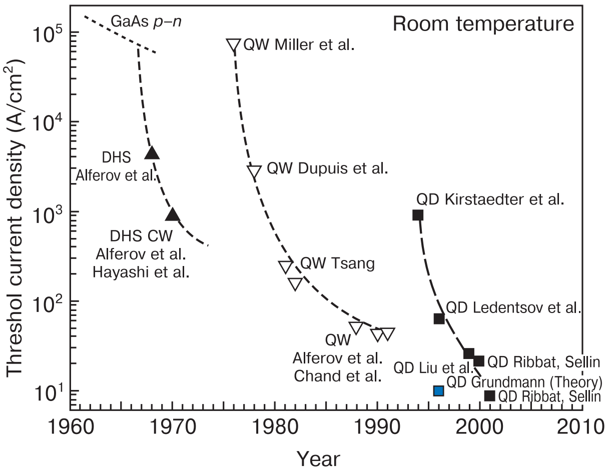

Figure 14. Historical development of the threshold current density of heterostructure lasers [46]

5.6. “Green” photonics

"Green" photonics is the development and application of optoelectronics technology with record high energy efficiency (see Fig. 11). An example is the history of the decrease in the threshold current density of semiconductor lasers during the transition from *p–n* homojunctions to heterostructures, then to quantum wells and finally to quantum dots, see Figure 14 [46].

5.7. Edge Intelligence

Integration of data-driven approaches with power hardware onboard for system monitoring, dynamic adaptation, and prognostic health management (PHM) can be achieved by mission-profile-centric design techniques collectively referred to as "Edge Intelligence" [47]. The application of these techniques promises improved effectiveness and sustainability. These methods can be extended well beyond power converters or even electronics in general as shown by the project “CAREER: Enhancing the State of Health and Performance of Electronics via in-situ Monitoring and Prediction (SHaPE-MaP) – Toward Edge Intelligence in Power Conversion, 2023” recently funded by the U.S. National Science Foundation [48].

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[4] Another, more successful branch of spintronics is magnetic memory technology based on spin-dependent scattering and tunnelling of electrons. The discovery in 1988 of giant magnetoresistance (GMR) in Fe/Cr superlattices by Albert Fert and Peter Grünberg won the 2007 Nobel Prize in Physics. This discovery led to a revolution in hard disc drive technology. Even earlier, in 1975, Michel Jullière discovered the tunnelling magnetoresistance (TMR) effect in the Fe/GeO/Co structure. In 2007, TMR devices with magnesium oxide instead of germanium oxide completely displaced GMR devices in the magnetic storage market.

5.8. Power converters with Edge Intelligence

On the way to the Green World, power converters are playing an increasing role in energy systems. According to the US Department of Energy, by 2030 more than 80% of electricity will go through power converters [49]. One such system is called "Sustainable Agriculture". Figure 15 shows an agricultural energy system based on power converters, implementing clean energy technologies including "agrovoltaics" [50], storage, water treatment, and grid energy management [47].

6. Energy harvesting

Energy harvesting (EH) or energy scavenging is the process of extracting otherwise wasted energy from sources such as wind, electromagnetic waves, solar light, parasitic vibrations or body motion, to name just a few.

Currently, countless Internet of Things (IoT) devices are powered by batteries. However, the devices could either scavenge energy on their own or receive it from outside. This would allow them to operate virtually perpetually [51].

There are several energy harvesting technologies for low-power applications.

Light, heat, wind, vibrations, radio waves and other energy sources have seen limited use in small devices so far [52, 53].

To get an idea of the power required, it is worth looking at the power consumption of medical implants, Table 1 [54].

Table 1. Power consumed by medical implants [54]

Implant type	Power consumption (μW)
Heart pacemaker	30–100
Heart defibrillator	30–100
Nero pacemaker	30 – ~1000
Pump for medicament feed	100–2000
Cochlear implants	10000

The most typical technology for harvesting dispersed energy is the use of the *piezoelectric (PE) effect*. The corresponding energy is generated by a coupling between mechanical deformation and electrical polarization in

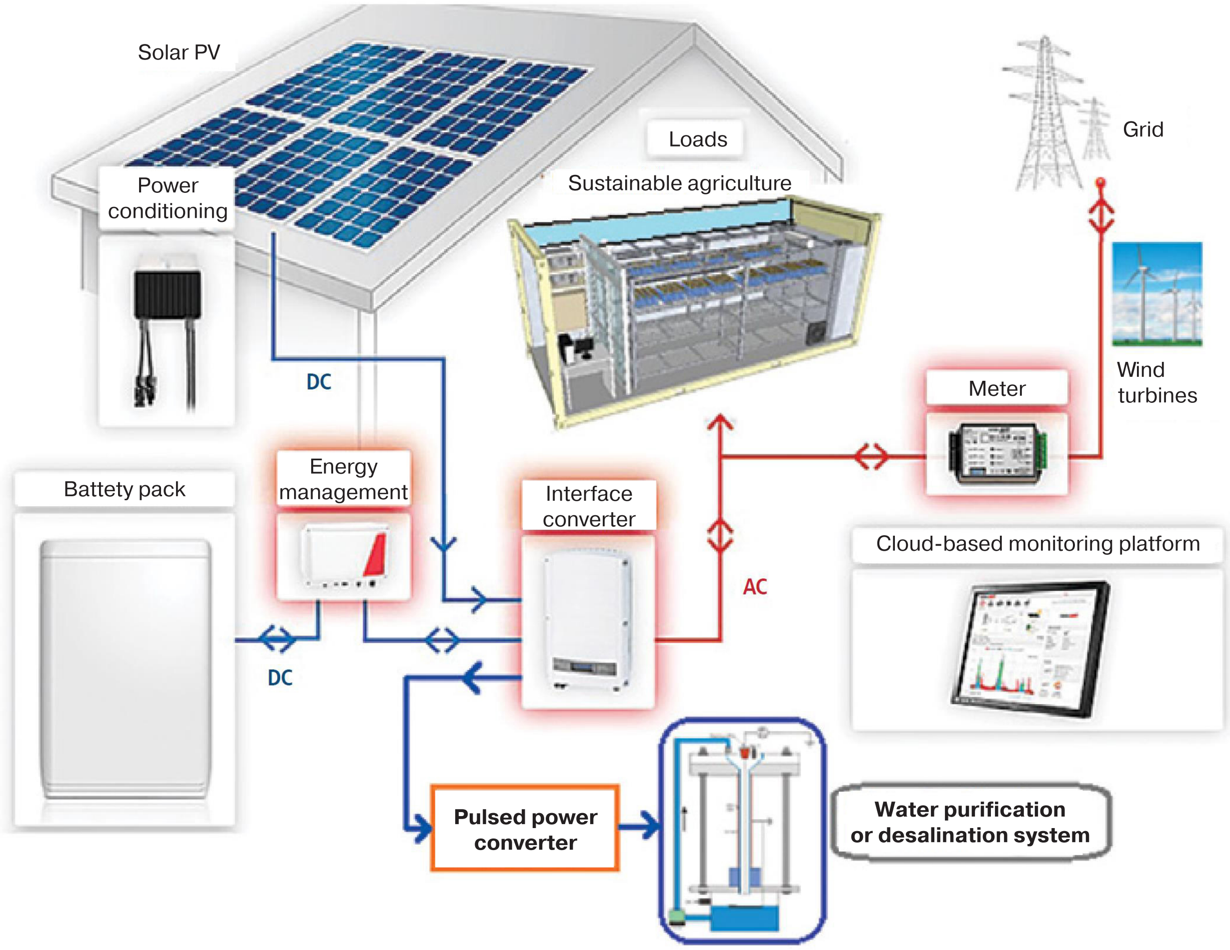

Figure 15. An example of a sustainable agricultural system combining power electronics, clean energy technologies, agriculture loads, and water purification/desalination facilities with the grid [47]

certain crystals. The required deformation can arise from a wide variety of sources such as periodic and aperiodic motion, seismic or motor vibrations, acoustic noise, and many others. (Here we should not forget about the law of conservation of energy – a piezoelectric generator in the sole of running shoes will make a runner expend more muscle energy).

This source can deliver energy for miscellaneous EH applications. The smallest generators (up to 50 μW) could supply energy to ultra-low-power modules [55–57]. However, there is currently no successful commercial product powered by piezoelectric EH [58].

*Ambient radiofrequency (RF) radiatio*n exists in both natural and man-made environments. However, the power obtainable from most ambient RF sources is very low. A thinkable solution is antenna farms which can collect sufficient energy [59]. Note, however, that the antennas must be located in the far-field radiation zone – in the near-field they will simply "suck" energy from the source.

Thermoelectric generators (TEGs) comprise junctions of two different materials subjected to a temperature gradient. The thermoelectric EMF does not exceed 100 to 200 μV/K per junction [60]. Multiple junctions can be connected in series or parallel. TEG-based devices are being developed with an ever-smaller footprint [61]. Materials operating in higher temperature gradients are being developed. On the other hand, there are biomedical applications where high temperatures are not admissible. Here, novel materials that combine a high electrical and low thermal conductivity thus improving thermoelectric EMF are being actively searched for.

Pyroelectric nanogenerators. The change of spontaneous polarization of a material with temperature fluctuation leads to the appearance of reversed charges at opposite ends of a pyroelectric crystal. The phenomenon is called the pyroelectric (PyE) effect and is specific to anisotropic dielectric crystals with certain symmetries. It can be observed in single crystals, ceramics, composites, inorganic films, organic materials, and polymers. The pyroelectric materials are necessarily also piezoelectric.

PyE nanogenerators consist of three parts: a bottom metal electrode, a middle layer made of a PyE material, and an upper electrode connected to the heat source [62].

The PyE effect has traditionally been used for the manufacturing of sensitive infrared radiation detectors, shock wave sensors, and precise voltage and temperature variation meters. Recently also the potential of the PyE effect for thermal energy harvesting has been recognized [63].

Biomechanical sources. A part of the mechanical and thermal energy produced by the human body can be harvested [60]. A strap around the knee can produce ca. 2.5 W which is enough to power e.g. a cell phone [64].

Even such ultra-low-power sources as the human breath propelling a mini wind turbine, or voice box vibrations can be harnessed [60].

Triboelectric nanogenerators (TENGs) can transform mechanical energy present in the environment into electrical energy by combining the effects of contact electrification and electrostatic induction. Recently, the output electrical current of TENGs has improved dramatically, changing from AC to DC, increasing from ~nA to ~μA and even ~mA, and raising power density from ~mW/m^2 to ~W/m^2. Semiconductor DC TENGs have appeared in researchers' fields of vision to adapt to the trend of miniaturization and integration with current semiconductor electronic devices, which are more appropriate for developing small electronic devices than traditional polymer TENGs [65–67].

Beta-voltaic generators. Radioactive isotope-based power supplies offer advantages such as small size, light weight, wide operating temperature range, long lifetime and high reliability. Beta-voltaic cells can be manufactured in a single technological process together with semiconductor MEMSs [68].

Magnetoelectric and hybrid devices. The direct magnetoelectric effect (MEE) consists of the appearance of electric polarization in a material exposed to a magnetic field. The MEE is much more pronounced in composite materials than in single-phase ones (i.e., multiferroics), so only the former ones have found application in EH. Composite ME materials include both PE and magnetostrictive (MS) materials. The mechanism of direct MEE is as follows: The MS material is strained due to magnetostriction in an applied magnetic field. Part of this elongation / compression is then transferred to the PE component, resulting in the induction of macroscopic electric polarization due to the PE effect. The harvesting of the energy of strayed AC magnetic fields by MEE can be combined with other harvesting mechanisms, such as the PE mechanism [69].

Another example of hybrid devices can be *electromagnetic-triboelectric generators* that convert the energy of mechanical movement into electricity [70].

Embedded systems are becoming ever more common in our daily lives. Programmable microchips that underpin household appliances, computers and security systems can be powered, at least in part, by EH systems instead of batteries or supercapacitors [60].

Some interesting developments have been occurring also in other areas, e.g., biology. Back in 2008, researchers working at MIT studied the potential difference between plants and their surrounding soil [71]. Here are more examples: other researchers from MIT have placed a tiny gas turbine engine in a silicon chip the size of a coin. The resulting device can last 10 times longer than a battery of the same weight, powering laptops, mobile phones, radios and other electronic devices [72]. DARPA researchers have even proposed chip-sized fusion reactors [73].

The main property of the future is its unpredictability, so we don't know exactly which energy-harvesting technology will win the market, but research is ramping up to overcome the limitations of conventional batteries.

7. Conclusions

So, for the first time in its history, humanity is faced with the need to limit the use of the most efficient energy sources – fossil fuels. Climate change (global warming) is influenced not by the energy produced (we cannot yet directly heat the environment), but by the associated greenhouse effect caused by greenhouse gas emissions. Note that not all countries are willing to pay a higher price for energy from alternative (renewable) sources, primarily because they are severely short of energy as such.

Of the technologies reviewed by P.L. Kapitza in 1975 [1], nuclear power has maintained and strengthened its position in an increasing number of countries, after being vigorously fought against in some others. Kapitza's doubts about the cost-effectiveness of solar power were resolved by the impressive decline in the price of solar panels. Many other alternative technologies, as Kapitza had foreseen, have not moved beyond niche applications. In addition, in the last decade, methods of collecting dissipated energy (harvesting) have been actively pursued, but here we are talking about low and ultra-low power.

In terms of energy consumption, electronics and telecommunications have come to the forefront. New paradigms, such as neuromorphic computing, attowatt optoelectronics, etc., are being actively sought worldwide to enable technological progress without increasing energy consumption.

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