



# Article Mathematical Description of Energy Transition Scenarios Based on the Latest Technologies and Trends

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**Abstract**: This work, dedicated to a mathematical description of energy transition scenarios, consists of three main parts. The first part describes modern trends and problems of the energy sector. A large number of charts reflecting the latest updates in energy are provided. The COVID-2019 pandemic's impacts on the energy sector are also included. The second part of the paper is dedicated to the analysis of energy consumption and the structure of the world fuel and energy balance. Furthermore, a detailed description of energy-efficient technologies is given. Being important and low-carbon, hydrogen is discussed, including its advantages and disadvantages. The last part of the work describes the mathematical tool developed by the authors. The high availability of statistical data made it possible to identify parameters used in the algorithm with the least squares method and verify the tool. Performing several not complicated steps of the algorithm, the tool allows calculating the deviation of the average global temperature of the surface atmosphere from preindustrial levels in the 21st century under different scenarios. Using the suggested mathematical description, the optimal scenario that makes it possible to keep global warming at a level below 1.7 °C was found.

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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). **Keywords:** decarbonization; renewable energy; energy transition; energy efficiency; hydrogen; carbon capture and storage; mathematical description; parameters identification

# 1. Introduction

Over the last 70 years, carbon dioxide emissions increased by 2.2 times causing climate change. Climate change became one of the most pressing problems mankind has to face. The temperature of the Earth's atmosphere increased by more than 1 °C compared to pre-industrial levels, while the snow on the tops of mountains and poles started to melt and the level of seawater raised. Living organisms are suffering from diseases caused by a high percentage of carbon dioxide in the air. The effects of climate change are being observed in every part of the world. Extreme weather conditions have become more rapid, severe and destructive. Droughts became more frequent in Australia, Brazil, India, the United States and other locations [1]. Many countries, including Indonesia, China, Brazil, the United Kingdom, Pakistan and others suffer from floods. Wildfires destroy large areas of forests. In 2021, 200,000 square kilometers were burned in Russia alone [2]. In 2005, Hurricane Katrina caused almost two thousand deaths and significant economic damage. In September 2017, more than three thousand people lost their lives due to Hurricane Maria [3]. Why is this happening? Is there a way to stop climate change?

For thousands of years, climate changes occurred cyclically due to natural reasons, but the tendency changed in the 1800s. Manufacturing and industry, generating electricity and heat have been the main reason for climate change, mostly due to the burning of fossil fuels. It is a known fact that long-term fossil fuel combustion contributed to the total greenhouse gas emissions. In 1965, the share of fossil fuels in energy consumption was 94%. Today it has decreased to 83%, but this is still too high. The world is in search of alternative heating and energy systems. In 2016, the Paris Climate Agreement of the United Nations was signed by 175 countries. It requires global warming to be maintained at the level of 1.5-2 °C in the 21st century. To achieve this purpose, an energy transition

to sources of energy that are renewable and do not produce harmful pollutants is needed. This transition has already begun, and the share of renewable energy in the total primary energy supply is now more than 15%. Energy agencies suppose that the share of renewable energy in the total primary energy supply could reach up to 65% in 2050 [4,5].

Many energy-efficient technologies that can help reduce carbon emissions exist. "Smart grids", hybrid electric vehicles, solar panels and wind turbines, LED lighting, white roofs, programmable heating devices and energy-saving household appliances are examples of technologies that can help to decrease carbon dioxide emissions. Big data analysis and automated management can also contribute to the keeping of global warming. Section 3 of the article includes a detailed description of energy-efficient technologies.

Dolf Gielen et al. [6] showed that if we apply the electrification of end-uses, energy efficiency technologies and renewable energy together, we can decrease emissions by up to 94%.

Another clean energy source that can be used against global warming is green hydrogen. The share of green hydrogen in the energy balance may increase up to 18% in the 21st century. Many countries already developed their hydrogen strategies.

According to the Center for Climate and Energy Solutions, carbon capture and storage can reduce greenhouse gas emissions by 14% by 2050 [7].

Thus, it is obvious that global warming can be reduced, but this requires decisive actions from policymakers and society. Numerous scenarios of global warming are discussed among scientists, but as a rule, two main scenarios are included in discussions: a conservative scenario and an ambitious scenario. A conservative scenario supposes that recently observed tendencies will remain in the future. BP forecasts that if a conservative scenario will take place, carbon emissions from energy use in 2050 will only be decreased by 10% compared to 2018 [4].

An ambitious scenario, opposite to the conservative scenario, introduces several measures that will significantly (by up to 70%) reduce carbon emissions from energy use by 2050 [4].

A "Net Zero" scenario is also widely discussed. It requires the balance between greenhouse gases produced and removed from the atmosphere.

The authors developed a mathematical tool that allows estimating the deviation of the average global temperature of the surface atmosphere from pre-industrial levels in the 21st century. A large number of available data series and Python programming language made it possible to identify parameters used in the algorithm utilizing the least squares method, and verify the tool.

The algorithm assumes the calculation of various scenarios of population growth and the corresponding scenarios of energy demand, based on the new paradigm of energy consumption that will be introduced in Section 4, scenarios writing for the dynamics of the structure of energy consumption by types of energy sources, the calculation of the dynamics of  $CO_2$  emissions into the atmosphere, the calculation of the dynamics of  $CO_2$  accumulation in the atmosphere, and finally, the calculation of changes in the global average temperature of the surface atmosphere.

Using the suggested mathematical tool, several scenarios of the energy transition were calculated and will be demonstrated. Now, the description of the latest tendencies will be presented.

# 2. The Current State of the Energy Sector

## 2.1. Modern Trends of the Energy Sector

Analyzing statistical data, the authors show the following trends. Primary Energy consumption steadily grows; it has increased 3.5 times since 1965, which is shown in Figure 1. At the same time, decarbonization demonstrates a transition to a carbon-free economy by increasing the share of renewable energy sources (see Figure 2). Fossil fuels' long-term decline continues.



Figure 1. Primary Energy consumption, exajoules [5].



Figure 2. Share of fossil fuels in energy consumption, % [5].

Over the last 50 years, the share of fossil fuels in energy consumption decreased by more than 10%, while the share of renewables increased by 40 times. Although hydropower is good for the environment and water is a renewable resource, the share of energy generated from hydropower only increased from 6% in 1965 to 7% in 2020. This can be explained by expensive dam building, difficulties in finding appropriate locations for dam building and the risk of dam failure [8–10]. The dynamics of changes in the structure of the world fuel and energy balance are shown in Figure 3.

Today, 44% of global  $CO_2$  emissions are generated by the electricity and heat generation sector: 26% by transport and 20% by the industry sector [11]. The technologies allowing to reduce  $CO_2$  emissions are in development. These technologies for the electricity and heat generation sector will be described below. Increasing electrification is observed in the transportation sector – 10 million electric cars are now on the roads [12]. In 2010, approximately 17 thousand electric cars were on the roads. Thus, the number of electric cars has increased by over 600 times in the last 10 years.



Figure 3. The dynamics of changes in the structure of the world fuel and energy balance, calculated by authors using [5].

Now, the "Net-zero emission by 2050" scenario, which assumes that the global carbon emissions from energy use will decrease by over 95% by 2050, is becoming very important, and leading to further development. In leading countries, the share of renewables in primary energy consumption already exceeded 18% in 2020 (see Figure 4).

It should be mentioned that global energy transition to renewable energy cannot be fast. Still, there are countries where the share of coal in primary energy consumption is larger than 50%. The two most populous countries, China and India, are among them, which is demonstrated in Figure 5.



Figure 4. Countries in which the shares of renewables in primary energy consumption are the largest in 2020, % [5].



**Figure 5.** Countries in which the shares of coal in primary energy consumption are the largest in 2020, % [5].

Furthermore, in some countries (Singapore, Trinidad and Tobago, Turkmenistan and Uzbekistan) the share of oil or natural gas in primary energy consumption still exceeds 70% (see Figures 6 and 7).

If we look at the management in the energy sector, we can see a tendency toward decentralization. Today, there are many geographically distributed electricity consumers and producers. The digitalization of the energy sector and AI-driven solutions deployment become very important. Internet of Energy, for example, allows making the transmission of energy more efficient and productive. According to the authors' calculations, energy-efficient technologies make it possible to decrease real energy consumption by up to 50%.

Coming back to the "Net-zero emission by 2050" scenario, it is important to notice that the role of carbon capture and storage technologies (CCS) increases. World capture and storage capacity grew up by 33% compared to 2019. Today, 65 CCS facilities are already functioning in the world [13]. Green hydrogen also starts to play an important role in the decarbonization process. The sector that also becomes significant is the energy storage sector.



**Figure 6.** Countries in which the shares of oil in primary energy consumption are the largest in 2020, % [5].



Figure 7. Countries in which the shares of natural gas in primary energy consumption are the largest in 2020, % [5].

#### 2.2. Changes Observed in 2020

The COVID-19 pandemic impacted the most trends that were observed in 2019 and before. Primary energy consumption and carbon dioxide emissions significantly decreased [14] (see Figure 8). Primary energy consumption in 2020 decreased by 4.3% compared to 2019, from 581.5 exajoules to 556.6 exajoules [5]. Norway, unlike most countries, increased its primary energy consumption by 8.5% in 2020, and China by 2.4%. Carbon dioxide emissions decreased by 6% compared to 2019, from 34,039.8 million tons to 31,983.6 million tons (see Figure 9). Figure 10 shows that electricity generation in 2020 decreased by 0.7% compared to 2019, from 27,001 terawatt-hours to 26,823 terawatt-hours. At the same time, renewable energy demonstrated growth.

Let us consider changes in 2020 for the most important energy sources separately. Thus, coal consumption in 2020 decreased by 4% compared to 2019, from 157.6 exajoules to 151.42 exajoules, which accelerates the general decline of coal consumption since 2015. Oil consumption decreased by 9.5% compared to 2019, from 191.9 exajoules to 173.7 exajoules. Gas consumption decreased by 2% compared to 2019, from 140.5 exajoules to 137.6 exajoules. Renewable energy consumption increased by 10% compared to 2019, from 28.82 exajoules to 31.71 exajoules. Solar energy consumption increased by 20.4% compared to 2019, from 6.3 exajoules to 7.6 exajoules. Hydroelectricity consumption increased by 1.3% compared to 2019, from 37.7 exajoules to 38.1 exajoules. Nuclear consumption decreased by 3.8% compared to 2019, from 24.9 exajoules to 24 exajoules, which has accelerated the general decline of nuclear since 2003. Wind consumption increased by 11.8% compared to 2019, from 12.6 exajoules to 14.13 exajoules. The dynamics of main energy sources consumption are shown in Figure 11.



Figure 8. Primary Energy consumption, exajoules [5].



Figure 9. Carbon dioxide emissions, million tones [5].



Figure 10. Electricity Generation, terawatt-hours [5].



Figure 11. Energy consumption by fuels, exajoules [5].

Despite declines in energy consumption and carbon dioxide emissions in 2020, the situation in general is complex, and requires immediate actions from the global community. The temperature of the Earth's atmosphere continues to increase fast, and this must be changed. It could be changed, and the goals of the Paris agreement could be achieved

by using several technologies and approaches, which will be discussed in the paragraph below. At the COP26 conference, taking place in November 2021 in Glasgow, countries agreed to accelerate the phase-out of coal, which causes 40% of annual CO<sub>2</sub> emissions and a phase-out of fossil fuel subsidies [15]. An accelerated shift away from fossil fuels and towards renewable energy was declared.

# 3. Ways of Reducing Global Warming

Authors consider the following ways of reducing global warming:

- energy-efficient technologies;
- renewable energy;
- green hydrogen;
- CCS technology

#### 3.1. Energy-Efficient Technologies

There is a large set of energy-efficient technologies that contribute to carbon emissions' decrease. In this paragraph, examples of such energy technologies will be described, including energy-saving technologies for the home.

A "smart grid" is determined as an electricity network that utilizes advanced technologies (including AI technologies) for managing electricity transport from all sources to electricity consumers [16]. Because of strong communication between the grid's elements (electricity producers, consumers, storage devices, network infrastructure), the effective functioning of the system is provided [17]. In such a system, an adaptation of the load profile is possible, namely by shifting peak load towards other times in the days with lower load. Moreover, "smart grids" control energy stores such as pumped hydropower stations that allow storing excess energy for days, or even a year. "Smart devices-consumers of energy" make it possible not only to receive electricity, but also to give it to the network if necessary.

Hybrid electric vehicles already reached up to 65% more fuel-efficiency than petrolfueled vehicles. Petrol-fueled vehicles also consume four times more energy compared to pure electric vehicles [18]. In 2019, more than 2 million new electric cars were sold globally [19] (p. 248) (see Figures 12 and 13).



Figure 12. New electric car sales, thousands of vehicles [19] (p. 248).

The use of environmentally friendly renewable solar energy to provide a million homes with energy can reduce carbon dioxide emissions by 4.3 million tons per year [20], by more than 1350 kg in just one household. The use of electricity generated by solar panels allows less electricity consumption from the general network, and reduces costs. Having sufficient capacity in the home system allows to sell the electricity generated by the energy of the sun. Solar panels provide energy independence. There will always be electricity

in a house or an enterprise when the sun is shining in the sky (if there are additional batteries, also at night). Most solar panels are very reliable and designed for more than 20 years, during which the system requires minimal maintenance and does not need high operating costs. Owners of solar power plants can also count on support from the state (subsidies, benefits).



Figure 13. New electric car sales in 2019 by countries, thousands of vehicles [19] (p. 248).

In 2019, more than 65 thousand wind turbines made it possible to avoid 198 million metric tons of carbon dioxide emissions in the US [21]. Today, the most economically feasible is to obtain, with the help of wind generators, not electrical energy of industrial quality, but direct or alternating current (variable frequency), followed by its conversion with the help of heat pumps into heat for heating housing and obtaining hot water. Furthermore, the scheme of the wind generator and control automatics is drastically simplified. A conventional boiler can be used as an energy accumulator for heating and hot water supply. Heat consumption is not so demanding on quality and uninterrupted functioning, so the air temperature in the room can be maintained within a wide range: 19–25 °C, in hot water boilers of 0–97 °C.

White roofs are expected to withstand climate change due to their ability to reflect sunlight. It is obvious that a black roof absorbs the sun's rays and heats up to almost 50 °C above the ambient temperature. Thus, if it is +40 outside the window, it can be up to +90 degrees on the roof. The temperature of the "cold roof" usually rises by only 5–14 °C compared to the environment. Thus, "cold roofs" improve air quality and prevent smog. Air conditioning costs can be reduced by up to 15% in the hot season using "cold roofs". A gentle mode of functioning of the roof provides longer life. It was calculated that a 1000 square feet "cold roof" avoids the emission of 20 tons of CO<sub>2</sub> carbon dioxide in 20 years [22].

LED lighting is environmentally friendly. Unlike fluorescent lamps, LEDs do not contain mercury, so they are not hazardous waste and do not require special utilization. LED lighting products are almost completely made up of recyclable materials. Low power consumption and high efficiency of LEDs lead to energy savings of up to 80% [23]. Long LED life reduces lighting fixture changes and reduces waste.

As about 1/5 of heat loss from the house occurs because of poorly insulated windows, replacing old windows with new ones has the effect of reducing heating costs in the cold season and air conditioning in the hot season [24]. The installation of energy-efficient triple-pane windows ultimately reduces carbon dioxide emissions, both when using individual

heating systems and while reducing the consumption of resources from centralized heating systems. In addition to being positive for the environment as a whole, it could have a positive impact on personal finances in the future, if, for example, taxes on carbon dioxide emissions are introduced.

According to the calculations of scientists from the Lawrence Berkeley Laboratory, the operation of consumer electronics in standby mode consumes from 5 to 10% of all household energy consumption [25]. This leads to approximately 1% of the world's carbon dioxide emissions into the atmosphere. For example, when a printer finishes printing and goes into sleep mode, power consumption drops, signaling it to disconnect from the mains. Turning off one of the devices does not affect the rest of the extension sockets in any way – they continue to work in the mode that the consumer needs.

Mechanical thermostats make it possible to set the temperature, which will remain unchanged until someone manually changes the set parameter. Unlike mechanical thermostats, programmable devices provide more flexibility: the users can program time intervals for different temperatures. If there are no people in the house during the period from 8 am to 6 pm, then there is no point in maintaining comfortable temperature conditions during this period. You can lower the temperature, say, to 18 °C, and by the time people arrive, the automation itself will again increase the temperature. This temporary temperature reduction results in additional savings of up to 30% [26].

Heat pumps are developed to heat and cool buildings utilizing energy transfer from a cooler space to a warmer space (or opposite) applying the refrigeration cycle without external power usage. Heat pumps need less energy than air conditioners. Correctly installed heat pumps are characterized by 300% efficiency [27].

On average, household appliances, including washing machines, dryers, dishwashers, refrigerators, freezers, air purifiers and humidifiers, will account for 20% of total home electricity costs. ENERGY STAR devices are helping to reduce this percentage. An ENERGY STAR qualified appliance will consume 10–50% less energy each year than its inefficient equivalent [28].

It is also should be mentioned that big data collection and analysis, automated management and AI-driven processes can significantly reduce energy consumption.

Thus, many examples of energy-efficient technologies were provided. It is obvious that such technologies save much energy and prevent carbon dioxide emissions. According to the calculations of the authors, energy efficiency can decrease global real energy consumption by 50%.

Although energy-efficient technologies allow using less energy, they also have their disadvantages and limitations. Since energy-efficient technologies are usually new, they are expensive. Implementation of these technologies may take many years, since it is not possible to replace the current machines and industry with the new technologies fast. Some green technologies are still immature, and some are not really green. Therefore, life-cycle assessments are undertaken and studies on the overall energy harvest are on the way [29–33]. Some of the technologies, for example, solar panels and wind turbines, are dependent on weather conditions, and cannot be used everywhere. Therefore studies on spatial and temporal distribution of solar and wind potentials are currently being undertaken [34–40].

#### 3.2. Renewable Energy

Renewable energy is energy that is produced using renewable sources including sun, wind, water, geothermal heat and other sources. It is known that historically, only renewable energy was available for people until much cheaper energy sources, including coal, oil and gas, replaced renewable energy sources, causing a large number of environmental disasters and global warming [41]. The temperature of the Earth's atmosphere has increased quicker from 1970 than in any other half-century period during the last 2000 years or more [42]. Now, when global surface temperature has already increased by more than 1 °C compared to the pre-industrial level, mankind is in search of ways to stop

global warming and not to permit new disasters. Dolf Gielen et al. demonstrated in [6] that energy efficiency and renewable energy could become the solution to the problem. The share of renewable energy in the total primary energy supply already exceeded 15%. According to Dolf Gielen et al. [6], if we apply electrification of end-uses, energy efficiency technologies and renewable energy together, we can reduce emissions by up to 94%. Dolf Gielen et al. suppose that the share of renewable energy in the total primary energy supply can reach up to 63% in 2050 [6]. BP assumes that by 2050 the share of renewable energy in primary energy consumption can reach 44% in the Rapid scenario and 60% in the Net Zero scenario [4]. IRENA, in [43], describes a Transforming Energy Scenario in which the share of renewable energy in energy demand will exceed 65% by 2050.

Renewable energy is practically endless, and requires lower maintenance. Renewable energy can also save money. We already talked about the benefits of using solar panels and wind turbines in the paragraph above. The advantage that can be considered as the main advantage is that the renewable energy generation process almost does not contaminate the air and water. Renewable energy reduces carbon dioxide and decentralizes power generation [43]. However, renewable energy depends on the climate and geographical zone, requires energy storage and has a high cost. The amount of power generated using renewable energy technology is still small, due to the deplorably still unprofessional management of its volatility. Besides that, solar panels, for example, require a lot of space to install [44], which, however, is possible – especially in large countries [45]. A long time is needed for renewable energy to become reliable and be used everywhere, and therefore this highly needed task must be most quickly started in every country now.

#### 3.3. Hydrogen

Today, hydrogen is already used at an industrial scale across the world. It is mostly needed in industry—it is used for the production of ammonia and methanol, refining and treating metals, including steel, in the oil refining process, in food processing and for NASA space programs [46]. Many power plants produce electricity using hydrogen in fuel cells. Hydrogen fuel cells are also installed in cars. Furthermore, hydrogen can be used for heating buildings. Baxi, Viessmann and Worcester Bosch already have prototypes, and test 100% hydrogen-ready boilers [47] (now these boilers are compatible with natural gas). In 2018, Viessmann introduced a highly efficient cutting-edge heating device (Vitovalor PT2, Viessmann, Allendorf, Germany) that provides hot water and heating, applying advanced fuel cell technology to convert hydrogen into energy [48]. Hydrogen is useful in power generation; it allows to store renewable energy. Along with ammonia, it helps gas turbines to improve their power system flexibility.

Global demand for pure hydrogen shown in Figure 14 has been increasing in the last few decades.



Figure 14. Global demand for pure hydrogen, Mt, 1975–2018 [49].

Hydrogen ( $H_2$ ) itself is not available on Earth and should be produced. Electrolysis and steam-methane reforming are the main ways to extract hydrogen from a variety of sources [50]. Electrolysis allows separating the oxygen from hydrogen atoms by passing a high current of electricity through water. Today there are two main disadvantages of this technology: it is expensive, and it burns fossil fuels.

95% of hydrogen is produced by the steam-methane reforming process, in which carbon and hydrogen are separated in methane [51]. This method also suggests greenhouse gases emission that contributes to global warming.

Today, approximately 120 million tons (14.4 exajoules) of hydrogen are produced annually [52]. Two-thirds of this is pure hydrogen, and the remaining part is a mixture with other gases.

Increasing interest in hydrogen is explained by its advantages. Hydrogen can be produced from different sources, including biomass, coal, gasoline, methane, water and so on. Today, approximately 95% of all hydrogen is generated from natural gas and coal [53]. Hydrogen carries energy. Hydrogen can store energy, and if produced from a renewable energy source (then called green hydrogen), it can be considered equivalent to renewable energy – however, if produced from fossil energy, this non-green hydrogen must be considered as fossil fuel, as its creation emitted CO<sub>2</sub>, even if H<sub>2</sub> at the time of its combusting has a small environmental impact. Hydrogen energy is very efficient. Hydrogen can provide a sustainable production system (in the case of using electrolyzers powered by renewable energy).

Hydrogen also has disadvantages. Hydrogen extraction is very expensive, using both electrolysis and steam reforming. Although hydrogen is a renewable source, its extraction today is not environmentally friendly; it requires fossil fuels and produces emissions. As hydrogen has a low volumetric energy density, it should be compressed to a liquid state for storage, which is difficult. Hydrogen can be dangerous because it is highly flammable and has a volatile substance. There always is a risk of exploding a hydrogen station. Hydrogen is not able to perform well in some conditions and temperatures.

Although hydrogen is widely used today, it is far away from reaching its full potential as an energy source. Still, many research is required to provide cheap and sustainable green hydrogen energy from renewable energy sources only (via hydropower, solar panels or wind farms) without producing emissions, or at least using carbon capture storage (CSS) systems that help to avoid carbon from being released. Another problem is that today, there is no ready infrastructure for hydrogen energy usage. For example, vehicles and service stations should be significantly changed to conform to hydrogen requirements.

It should be mentioned that hydrogen can be grey, blue or green, depending on how it is produced. Grey hydrogen is the least environmentally friendly hydrogen. It is obtained from fossil fuels - mostly by dividing natural gas into hydrogen and carbon dioxide. It was calculated that from 1 kg of produced grey hydrogen, approximately 10 kg of carbon dioxide are emitted into the atmosphere [54]. Unfortunately, now a major part of the produced hydrogen is grey hydrogen. When blue hydrogen is produced, natural gas is also divided into hydrogen and carbon dioxide. Carbon dioxide is then can be captured and stored, but it is very expensive and highly unusual under present circumstances. Another problem is that the storage reservoirs are limited. This makes it impossible to widely use blue hydrogen. The hydrogen can also be green. It is produced through the above-mentioned electrolysis of water when electricity is generated by zero-carbon sources only. This technology allows reducing CO<sub>2</sub> emissions, but it is still very expensive. In 2015, the cost of production of 1 kg of green hydrogen was \$6 [55]. During the last five years, the green hydrogen production cost has been reduced to \$3 per kilogram, going by information of the European Commission's July 2020 hydrogen strategy [56]. For comparison, 1 kg of produced grey hydrogen costs \$1.80, while blue hydrogen costs \$2.40. The United States Department of Energy expects that in 2025, the green hydrogen production cost will be reduced to \$2 per kilogram, and in this case, green hydrogen can become competitive against other non-renewable sources [53].

The European Union, Canada, South Korea, Australia, the Netherlands, Norway, Chile and other countries have already developed their hydrogen strategies. European Union's strategy focuses on hydrogen produced from renewable energy sources. The strategy consists of three stages. Stage one supposes that electrolyzers' capacity will be increased up to 6 GW by 2024. Stage two aims to increase electrolyzers' capacity up to 40 GW by 2030. EU also plans to produce up to 10 million tons of renewable hydrogen per year by 2030 [57]. For the third stage (after 2030), large-scale renewable hydrogen production is planned.

Canada's Hydrogen Strategy, released on December 16, 2020, includes a plan of significant clean hydrogen production, and also analyzes a way of achieving a net-zero emissions scenario by 2050. Before 2025, the infrastructure and foundations for the hydrogen economy should be prepared. The years 2025–2030 aim to make the hydrogen sector diverse, and stimulate its growth. After 2030, the sector is supposed to expand. Canada targets to provide up to 30% of end-use energy using hydrogen, which will be the top global clean low-carbon hydrogen [58]. A hydrogen export is also planned.

The National Green Hydrogen Strategy of Chile was rolled out in November 2020. By 2025, it aims to produce 5 GW using electrolysis capacity, and by 2030, to develop the cheapest green hydrogen in the world [59].

South Korea set a target to produce 6.2 million fuel cell electric vehicles powered by hydrogen that do not produce harmful emissions, and open 1200 refilling stations by 2040. Furthermore, 15 GW of fuel cells in South Korea will be supplied for power generation.

Since in Australia, renewable energy became cheaper than electricity generated by new coal-fired and gas-fired power stations, it is planned that the "hydrogen valley", that will be constructed in New South Wales, will substitute its current coal industry [60].

BP supposes that hydrogen use may reach up to 60 EJ by 2050 [61]. The share of green hydrogen in the structure of the world fuel and energy balance for the 21st century calculated by authors is presented in Figure 15. The curve was calculated using a logistic function, the parameters of which were identified based on current statistics and BP's forecast of hydrogen use [61]. Furthermore, to construct this logistic function, the following facts and projections were used. Today, the share of green hydrogen is less than 1% of the total hydrogen produced. In the next decades, an exponential increase (up to 60% per year) of green hydrogen production is expected [62]. By 2050, green hydrogen production may reach up to 150–200 million metric tons according to the Transforming Energy Scenario described in [63,64]. More optimistic green hydrogen demand projections of 500 million tons per year also exist [65]. In general, most reports suggest that hydrogen produced from renewable energy sources only will account for 10–25% of power consumption in the 21st century [66–68].



**Figure 15.** The share of green hydrogen (%) in the structure of the world fuel and energy balance for the 21st century (ambitious scenario) (calculated by authors).

It is important to again notice that the hydrogen that authors mention and use in their calculations is green hydrogen produced using renewable energy sources only, unlike grey and blue hydrogen that can be obtained using coal or natural gas.

#### 4. Mathematical Description

# 4.1. Methodology

To find a combination of parameters that allow maintaining the temperature below 2 °C compared to the pre-industrial level, the tool developed by authors and described in [69] was used.

The key features and assumptions of this mathematical tool are the following [69]. The average global per capita energy consumption  $e_w$  will stabilize at the level of 1.8 toe (tonnes of oil equivalent) per year in the 21st century. Thus, the nominal global energy demand  $E_w$  in the year *t* will change in direct proportion to the global population  $N_w(t)$ :

$$E_w(t) = e_w \cdot N_w(t) \tag{1}$$

Several scenarios of the world's population are considered:

- 7.4 billion people by the year 2100 (using the model with lags described in [70]);
- 9.3 billion people by the year 2100 (using the model with lags [70]);
- 10 billion people by the year 2100 (using the model of sustainable evolutionary growth according to Kapitsa [71]); and
- 11 billion people by the year 2100 (according to the UN scenario [72]).

The population development scenarios are presented in Figure 16.





Figure 16. Scenarios of the world's population in the 21st century.

The real global energy consumption is calculated using the obtained nominal global energy consumption and energy efficiency coefficient, introduced by Plakitkin [73] (shown in Figure 17), which reflects the level of technological development of power engineering. This coefficient works for developed countries as well as for developing countries (with a time lag). Plakitkin calculated that in 1900 the coefficient was 0.1 (or 10%), and projected that it will be 0.5 in 2050 and 0.9 in 2200. Using statistical data and projected points, Plakitkin created and verified a model described by the logistic curve allowing to calculate energy efficiency coefficient for every year of the 21st century. Energy-efficient solutions that were described above can significantly decrease energy consumption growth. The performed calculations show that real world energy consumption can be decreased by up to 50%, compared to the nominal energy consumption.



Figure 17. Energy use coefficient (percentage).

The dynamics of real global energy consumption in the 21st century are presented in Figure 18.





Figure 18. Dynamics of real global energy consumption in the 21st century.

Two scenarios of changes in the structure of the world fuel and energy balance for the 21st century (conservative and ambitious) are calculated. The conservative scenario is based on the idea that technologies, social behavior and government policies will not change, and stay at the level of the recent past. The ambitious scenario assumes significant changes in energy efficiency and the structure of the world fuel and energy balance (including increased hydrogen share) and CCS technologies usage.

The value of the global capacity of different energy sources are calculated using an approximating logistic function of the form [74]

$$E_r(t) = E_{r1} + \frac{E_{r2}}{1 + r_{ES} \cdot exp[-\vartheta_{ES}(t - T_0)]}$$
(2)

where  $E_r(t)$  is the projected growth of energy capacity of a resource;  $E_{r1}$ ,  $E_{r2}$ ,  $r_{ES}$ ,  $\vartheta_{ES}$  are constant parameters to be identified. The parameters are calculated using the least squares method, based on statistical data for years from 2000 to 2019 and scenario values for solar and wind power plants presented in the IRENA report [75]. The dynamics of changes



in the structure of the world fuel and energy balance for the 21st century are shown in Figures 19 and 20.





**Figure 20.** The dynamics of changes in the structure of the world fuel and energy balance (shares in energy consumption) for the 21st century (ambitious scenario) (for Coal, Oil, Gas, Solar Power Plants (SPP), Wind Power Plants (WPP), Hydrogen, Nuclear Power Plants (NPP) and Hydro energy).

Based on outlooks of energy agencies [4,5,46,52,75–78], we assume that the share of hydro energy in the world fuel balance will be constant (7%), and the share of bioenergy will increase up to 8.5%.

Adding coal, oil and gas we obtain the value of consumption of fossil hydrocarbon fuels  $E_{wff}(t)$ .

The next step is to calculate the values of anthropogenic carbon dioxide emissions. For this purpose, the global average carbon intensity coefficient  $c_c(t)$ , is determined using the Marland-Rotti equation [79]

$$c_c = \frac{0733E_s + 0.586E_j + 0.398E_g}{E_c}$$
(3)

where  $E_c$  is the total volume of consumption of hydrocarbon fuels; and  $E_s$ ,  $E_j$ ,  $E_g$  are the consumption of solid (coal), liquid (oil) and gaseous (natural gas) fuels (in tfe).

To calculate the values of anthropogenic carbon dioxide emissions, the average carbon intensity coefficient  $c_c(t)$  is multiplied by the value of consumption of fossil hydrocarbon fuels  $E_{wff}(t)$ :

$$C_w(t) = c_c \cdot E_{wff}(t) \tag{4}$$



#### 4.2. Results

The results of the calculations are shown in Figures 21 and 22.

**Figure 21.** Dynamics of reduction of anthropogenic emissions of carbon dioxide (CO<sub>2</sub>) into the atmosphere in the 21st century under the conservative scenario of the energy transition.



**Figure 22.** Dynamics of reduction of industrial  $CO_2$  emissions into the atmosphere under the ambitious energy transition scenario using CCS technology.

It should be mentioned that the ambitious scenario also assumes CCS technology usage. In the "Blue Map" scenario [80], it is shown that if we start to develop and widely use CCS technologies now,  $CO_2$  emissions can be decreased by 19% by 2050. The detailed

mathematical description of the CCS technology usage was described by authors in [69]. Every year, 26 CCS facilities capture approximately 40 Mt of carbon dioxide [81]. However, it is important to notice that CCS technology has limitations. Not all power plants have the required equipment for CCS installation. It was calculated that one billion US dollars would be needed to prepare one plant for CSS, which is very expensive and cannot be used everywhere [82]. It is obvious that not every country in the world will have sufficient CO<sub>2</sub> storage capacity [83]. Furthermore, the risk of leakages and environmental contamination exists. All these limitations were taken into consideration.

As soon as the emissions of carbon dioxide (CO<sub>2</sub>) into the Earth's atmosphere  $C_w$  are calculated (using Formulas (1)–(4)), it is possible to obtain carbon accumulation  $C_{\Sigma}(T)$  in the Earth's atmosphere in the 21st century using the formula

$$C_{\Sigma}(T) = \int_{T_0}^{T} C_w(t) dt - 3, 1(T - T_0)$$
(5)

where  $T_0 = 2020$ ;  $2020 \le T \le 2100$  (see Figure 23).



The accumulation of carbon in the atmosphere at an average rate of improvement in energy efficiency, billion tons

**Figure 23.** Dynamics of carbon accumulation in the Earth's atmosphere in the 21st century under the ambitious scenario of energy transition using CCS technology.

Terrestrial ecosystems and oceans absorb some part of the carbon. A. Tarko estimates this part as 3.1 Gt per year [84] (p. 177).

To estimate the deviation of the average global temperature, Tarko suggested the following formula [84]

$$T_g = \begin{cases} 2,5\{1 - \exp[-0,82(z-1)]\}, & z \ge 1; \\ -5,25z^2 + 12,55z - 7,3, & z < 1. \end{cases}$$
(6)

where  $T_g$  is the deviation of the global average temperature of the atmosphere from the present value (+15 °C), due only to the greenhouse effect caused by anthropogenic carbon dioxide emissions.

$$z = 1 + \frac{C_{\Sigma}}{C_0}$$

$$C_0 = 867Gt.$$
(7)



**Figure 24.** Dynamics of the deviation of the average global temperature of the surface atmosphere in the 21st century under the implementation of the conservative scenario of the energy transition, as well as the application of CCS technology in coal power engineering.

The ambitious scenario will keep global warming in the 21st century at the level of 1.7 °C (see Figure 25).



Deviations of the global average temperature from the value in 2020 at an average rate of improvement in energy efficiency, °C

**Figure 25.** Dynamics of the deviation of the average global temperature of the surface atmosphere in the 21st century in the implementation of the ambitious scenario of the Great Energy Transition, as well as the application of CCS technologies in coal energy.

# 5. Conclusions

In this work, modern trends and problems of the energy sector were discussed. The structure of the world fuel and energy balance was studied and calculated for the 21st century. Furthermore, a detailed explanation of energy-efficient technologies was given. Green hydrogen, as a temporary and possibly clean energy carrier, was also analyzed.

The large volume of statistical data describing historical and latest trends in the energy sector made it possible to develop and verify the tool that allows estimating the deviation of the average global temperature of the surface atmosphere from pre-industrial levels in the 21st century. To perform calculations, all the parameters of the tool were identified using the least squares method. The algorithm includes the following steps:

- calculation of various scenarios of growth in the population of the world;
- calculation of the corresponding scenarios for the development of the dynamics of energy demand, based on the new paradigm of energy consumption;
- scenarios writing for the dynamics of the structure of energy consumption by types of energy sources (coal, oil, gas, renewable energy sources, nuclear energy, hydropower);
- scenarios writing for the dynamics of demand for organic fossil fuels (coal, oil, gas);
- scenarios writing for the dynamics of changes in the structure of hydrocarbon energy sources (coal, oil, gas);
- calculation of the dynamics of CO<sub>2</sub> emissions into the atmosphere during the combustion of hydrocarbon fuels, taking into account structural changes in the consumption of organic fossil fuels (coal, oil, gas), as well as the use of technologies for carbon capture and storage (CCS);
- calculation of the dynamics of CO<sub>2</sub> accumulation in the atmosphere, taking into account non-industrial CO<sub>2</sub> emissions (due to deforestation and soil erosion) and absorption of part of the emissions by oceans and terrestrial ecosystems; and
- calculation of changes in the global average temperature of the surface atmosphere.

Calculations showed that the conservative scenario is only able to keep global warming at a level of 2 °C compared to the pre-industrial level.

Using big data and the developed tool authors could find a scenario that allows keeping global warming at the level of  $1.7 \,^{\circ}$ C. It became possible due to the usage of:

- renewable energy;
- energy-efficient technologies;
- CCS technology; and
- green hydrogen.

Since the developed tool makes it possible to calculate different scenarios and find appropriate parameters for these scenarios, in the future, the tool will be used for search of a scenario that will allow keeping global warming at the level of 1.5 °C, which is the ambitious goal of the Paris agreement. Furthermore, the authors plan to perform a detailed study of CCS technology, and make calculations for different countries of the world.

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# Abbreviations

CCS	Carbon Capture and Storage;
CO <sub>2</sub>	carbon dioxide;
EJ	exajoule;
GW	gigawatt;
LED	a light-emitting diode;
Mt	megaton;
NPP	Nuclear Power Plants
SPP	Solar Power Plants;
Toe	tonnes of oil equivalent;
UN	United Nations;
WPP	Wind Power Plants.

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