frontiers | Frontiers in Energy Research

TYPE Opinion
PUBLISHED 20 September 2022
DOI 10.3389/fenrg.2022.923784



OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

RECEIVED 19 April 2022
ACCEPTED 15 August 2022
PUBLISHED 20 September 2022

CITATION
Vorozheykina TM, Averin AV, Semenova EI and Semenov AV (2022), Scenarios of the alternative energetics development in the age of the fourth industrial revolution: Clean energy prospects and policy implications. *Front. Energy Res.* 10:923784. doi: 10.3389/fenrg.2022.923784



# Scenarios of the alternative energetics development in the age of the fourth industrial revolution: Clean energy prospects and policy implications

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KEYWORDS

**alternative energy, clean energy, energytech, the fourth industrial revolution, industry 4.0, high technology**

## Introduction

The Fourth Industrial Revolution is a global challenge of the modern times for sustainable and environmental development of energy economics. On the one hand, the leading technologies of the fourth technological mode (Industry 4.0) are often characterized by large energy efficiency, which allows reducing the specific energy consumption (energy efficiency of production and consumption).

On the other hand, ubiquitous automation raises the total need of economy for energy, since economic functions, which were earlier based on manual (or conventionally manual) labor (which energy intensity is minimal) now become automated, and, therefore, require more energy. Thus, for example, quick growth of energy consumption in the world economy was observed in 2014, when electric power consumption reached 3,131.68 kWh per capita (as compared to 2,274.94 kWh per capita in 2009) (World Bank, 2022).

In the existing literature, much attention is paid to the energy efficiency of advanced technologies in industry 4.0, in particular, industrial robots. In the works of Aubin et al. (2022), Huang et al. (2022), Luan et al. (2022), Nonoyama et al. (2022), Ntsiyin et al. (2022), Wang et al. (2022) note the cost-effectiveness of energy efficiency of industrial robots. In this regard, the robotization of the economy is considered as an energy-neutral process.

In the available works of Anthopoulos and Kazantzi (2022), Dreher et al. (2022), Fang et al. (2022), Xuan and Ocone (2022), another key technology of Industry 4.0–artificial intelligence (AI) received a positive assessment from the standpoint of energy efficiency. In particular, it was noted that AI has a great potential for use in the energy sector, contributing to its optimization.

In their research, Cui et al. (2022), Ng et al. (2021), Popkova et al. (2021), Popkova and Sergi (2021), Tabor et al. (2018), Taghizadeh-Hesary et al. (2022), Zaidan et al. (2022) point out that Industry 4.0 technologies, which are widely used in the context of the Fourth Industrial Revolution, support the transition to "clean" energy.

Accordingly, the state regulation of sustainable energy development in the publications of Chen et al. (2022), Deng et al. (2022), Inshakova et al. (2022), Iqbal and Bilal (2021), Liu et al. (2022), Nyenno et al. (2021) is recommended to be implemented through promoting the use of advanced technologies of industry 4.0 in the context of the Fourth Industrial Revolution.

Nevertheless, the existing publications are limited to the current situation and do not disclose in sufficient detail the future prospects for the development of alternative and clean energy in the era of the Fourth Industrial Revolution, which is a research gap. This article is intended to fill the identified gap. The main purpose of the research is to identify scenarios for the development of alternative and clean energy in the age of the Fourth Industrial Revolution and to elaborate recommendations for economic policy.

This purpose is achieved by coping with the following tasks: 1) to review international practices and to carry out the mathematical economic modeling of the impact of the Fourth Industrial Revolution on the energy economy; 2) To compile, describe and compare forecast scenarios for the development of the energy economy in the age of the Fourth Industrial Revolution; 3) To elaborate recommendations for economic policy on the development of clean and alternative energy in the age of the Fourth Industrial Revolution.

The object of research is the driving force of the Fourth Industrial Revolution–the world's top 10 countries in terms of the degree of automation, according to the International Federation of Robotics. (2022). For these countries, the analysis is carried out, scenarios are developed and their practical relevance is assessed. The main results obtained consist, firstly, in the compilation of an econometric model (in the form of a simultaneous-equation system) of the impact of the Fourth Industrial Revolution on the energy economy, which mathematically describes the consistent patterns of development of clean energy with the development of automation. Secondly, in the identification of prospects and making recommendations for the development of alternative (clean) energy in the age of the Fourth Industrial Revolution.

The significance of the results for science is that the article has clearly substantiated and dramatically illustrated, through the example of international practices, the conflict between the interests and practices of development of alternative (clean) energy and the interests and practices of automation. The significance of this new input is that, given the absolute consistency, acute importance for humanity, and the equivalence of all 17 UN SDGs, the article has demonstrated the high complexity of the simultaneous implementation of SDG7 and SDG9 due to the contradiction between the essence of sustainable energy (a reduction of energy consumption and the transition to clean energy) and the Fourth Industrial Revolution (an increase in the energy intensity of the economy and the consumption of fossil fuels with the development of automation).

The practical applicability of the results is attributable to the fact that the identified scenarios allow for the most complete, accurate, and reliable assessment of the implications of managerial decision-making and state regulation of the energy economy for the period until 2030 (which is the focus of the SDGs). The practical relevance of the authors' conclusions and recommendations is that for the first time they have justified the need for joint development and consistent implementation of the energy and innovative technology policy of the state. This will offer an advantage in the form of the balanced development of clean energy and automation–using the possibilities of the Fourth Industrial Revolution.

A literature review is singled out in the structure of the article after this Introduction. It is followed by a review of international practices and modeling of the impact of the Fourth Industrial Revolution on the energy sector (the first stage of research). Further, scenarios for the development of the energy sector in the age of the Fourth Industrial Revolution are compiled (the second stage of research). Subsequently, recommendations are made for economic policy on the development of clean and alternative energy in the age of the Fourth Industrial Revolution (the third stage of research). The work ends with the discussion followed by the conclusion.

## Literature review

The issues of the Fourth Industrial Revolution have become particularly relevant since the middle of the last decade. In their works, Bragança et al. (2019), Contreras (2020), Hayhoe et al. (2019), and Jin (2019) point to automation based on Robotics and Artificial Intelligence (AI) as the main features of Industry 4.0.

The history of industrial revolutions is inextricably connected with the evolution of the energy economy. Thus, the First Industrial Revolution was accompanied by the advent of the steam engine (steam-powered engine), the wide-scale installation of gas lamps, more efficient mining, and improved coal handling (McNeill, 2019; Tainter and Taylor, 2019). The Second Industrial Revolution was crowned by the advent of the internal combustion engine Peter and Mbohwa. (2018). The Third Industrial Revolution was marked by the development of the power-generating industry (Matizamhuka, 2018).

The fundamental distinction between the Fourth Industrial Revolution and them is that it is implemented against the background of the global sustainability initiative which is

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expressed in the 17 UN SDGs and has designated the development of clean energy as a priority (Alimhan et al., 2019). Like all industrial revolutions, the fourth revolution increased the energy intensity of the economy, but it has been interpreted negatively for the first time (Ignatov and Korolev, 2019). In this regard, the process of the development of Industry 4.0 is a way to achieving a balance between the interests of automation and the interests of the sustainable development of the energy economy (Tijani et al., 2018).

The relationship between Industry 4.0 and alternative energy has been pointed out in numerous literature sources. The critical analysis has made it possible to identify several main emerging issues in this relationship. These issues include, firstly, low power and unstable volume of production of clean (wind, solar) energy. Hence, the transition to clean energy implies a reduction in energy consumption and dictates the strict framework for energy consumption in the economy, which contradicts the idea of economic growth in general and automation in particular (Mangla et al., 2020; Mascarenhas et al., 2020).

Secondly, the total automation that is taking place in the context of Industry 4.0 significantly increases the energy intensity of each economic process, causing an exponential increase in energy consumption (Matsunaga et al., 2022; Seixas et al., 2018). Thirdly, the fundamental idea of creation and the advantage of smart enterprises consists in continuous production and distribution. This calls for a continuous supply of a large amount of energy, which is impossible using clean energy alone (Ang et al., 2017; Huang et al., 2017; Junker and Domann, 2017).

Nonetheless, Li. (2022), Matsunaga et al. (2022), and Saikia et al. (2020) write in their works that the mentioned contradiction can be overcome since high technologies of Industry 4.0 are not only high-performance but also energy-saving. Hargreaves et al. (2022), Kang and Reiner (2022) cite the relevant experience of particular countries that are leading in terms of the development of Industry 4.0 - the United Kingdom and China respectively - as evidence of this effect.

According to the results of the literature review, it can be concluded that the existing publications have recognized the close relationship between Industry 4.0 and clean energy, but the nature of this relationship is interpreted in the available literature in different ways. The lack of a clear idea of the consistent patterns of progress in clean energy and automation, as well as prospects for the development of the energy economy in the age of the Fourth Industrial Revolution, is a gap in the literature.

To fill in the identified gap, this article contains a comprehensive study of the international best practices of the world's top 10 countries in terms of the degree of automation, constituting the driving force of the Fourth Industrial Revolution, and these practices are used as the basis for modeling a consistent pattern and compiling forecast scenarios for the development of alternative energy in the age of the Fourth Industrial Revolution.

## Methodology

In this article, the study is carried out in three successive stages. In the first stage, international practices are examined and the impact of the Fourth Industrial Revolution on energy is modeled. The method of regression analysis is used to carry out the mathematical economic modeling of the consistent patterns of development of clean energy (Alternative and nuclear energy, Renewable electricity output, Renewable energy consumption, and Fossil fuel energy consumption based on statistics from the World Bank. (2022) in the age of the Fourth Industrial Revolution (under the influence of factors of Robot Density in the manufacturing industry based on statistics from the International Federation of Robotics. (2022) and The global AI index based on statistics from Tortois (2022).

In the second stage of research, scenarios for the development of the energy economy in the age of the Fourth Industrial Revolution are compiled. To this end, arithmetic means and standard deviations have been used as the basis for making the forecasts of changes in each of the above variables using the Monte Carlo technique. Previously obtained economic and mathematical (regression) dependencies are used as the basis for determining the probable (forecast) combinations of achievements in the field of clean energy and the field of automation based on Robotics and AI. Two alternative scenarios are considered within this framework.

The first scenario involves further unrestricted automation in the context of the freedom of proliferation of technologies of Industry 4.0 in the age of the Fourth Industrial Revolution. The best possible values of automation indicators are substituted into the regression models for its quantification. The second scenario is associated with the preservation of the current trend of the development of alternative and clean energy. To quantify it in regression models, the least-squares method is used for determining the values of automation indicators with the best possible values of clean energy indicators.

In the third stage of research, recommendations are made for economic policy on the development of clean and alternative energy in the age of the Fourth Industrial Revolution. Framework recommendations are provided for the balanced implementation of the energy and innovative technology policy of the state. In addition, specific recommendations are made for the adaptation of relevant policy papers to modern requirements in the world's top 10 countries in terms of the degree of automation through the example of South Korea as a developed country and China as a fast-growing country.

## Review of international experience and modeling of the influence of the fourth industrial revolution on energy

To conduct the research, this article has formed a sample of the top 10 countries in the world in terms of automation

TABLE 1 The world experience in implementation of robots and AI and energy development.

| Country | Robot density in the manufacturing industry, robots installed per 10.000 employees | The global AI index, score 0–100 | Alternative and nuclear energy (% of total energy use) | Renewable electricity output (% of total electricity output) | Renewable energy consumption (% of total final energy consumption) | Fossil fuel energy consumption (% of total) |
|---|---|---|---|---|---|---|
| | rb | Ai | ANE | REO | REC | FFE |
| Republic of Korea | 932 | 38.60 | 15.96 | 1.89 | 3.18 | 81.03 |
| Singapore | 605 | 38.67 | 0.19 | 1.82 | 0.73 | 90.58 |
| Japan | 390 | 30.53 | 3.09 | 15.98 | 7.39 | 93.03 |
| Germany | 371 | 36.04 | 12.86 | 29.23 | 15.80 | 78.86 |
| Sweden | 289 | 29.85 | 43.24 | 63.26 | 52.48 | 25.12 |
| United States | 255 | 100.00 | 11.87 | 13.23 | 10.11 | 82.43 |
| China | 246 | 62.92 | 5.11 | 23.93 | 13.12 | 87.67 |
| Denmark | 246 | 30.87 | 11.75 | 65.51 | 35.33 | 64.93 |
| Italy | 224 | 24.45 | 6.33 | 38.68 | 17.07 | 79.95 |
| Netherlands | 209 | 36.35 | 3.37 | 12.44 | 7.38 | 93.46 |
| Arithmetic mean | 376.70 | 42.83 | 11.38 | 26.60 | 16.26 | 77.71 |
| Standard deviation | 228.23 | 22.60 | 12.30 | 22.94 | 15.96 | 20.32 |

Compiled by the authors based on the materials of International Federation of Robotics (2022), Tortois (2022), World Bank. (2022).

according to the International Federation of Robotics. (2022), which are the leaders of the Fourth Industrial Revolution. Statistics on robotics (International Federation of Robotics, 2022), AI development (Tortois, 2022), and energy (World Bank, 2022) have been collected for these countries. The study is based on the most relevant data for 2020–2021. The energy data dates from 2015 to 2019 (the most up-to-date available data have been collected), but given the relative stability of energy development, they generally reliably/acceptably reflect the situation for 2020–2021. The factual basis of the study is given in Table 1.

Based on the international experience given in Table 1, the following system of equations describing the patterns of energy development in the conditions of the Fourth Industrial Revolution was obtained using the regression analysis method:

$$\begin{cases} ANE = 14.15 - 0.0010rb - 0.06ai \\ REO = 67.34 - 0.06rb - 0.42ai \\ REC = 38.53 - 0.03rb - 0.23ai \\ FRE = 62.07 + 0.02rb + 0.22ai \end{cases} \quad (1)$$

According to formula (1), the spread of advanced technologies of Industry 4.0 (robots and AI) under the influence of the Fourth Industrial Revolution leads to a decrease in the share of alternative and clean energy, as well as an increase in the dependence of the economy on fossil energy. The correlation in all four equations turned out to be quite high and amounted to, respectively 10.24, 67.89, 53.46, 28.55%, which indicates the reliability of the resulting system of equations.

## Scenarios of energy development in the era of the fourth industrial revolution

Alternative scenarios have been compiled to determine the prospects for the development of energy in the era of the Fourth Industrial Revolution. For this purpose, the Monte Carlo method has been used to make forecasts of changes in each of the variables in Table 1 based on arithmetic averages and standard deviations. Based on the resulting system of Eq. 1, the relationships of among variables are taken into account.

The first scenario assumes further unlimited automation along with the freedom of dissemination of Industry 4.0 technologies in the context of the Fourth Industrial Revolution. In this case, the most likely values of Industry 4.0 technologies are the following: an increase in robotization to 452.58 per 10 thousand industrial workers (+20.14% with a probability of 20%) and an increase in the activity of using AI to 49.94 points (+16.61% with a probability of 16%). Substitution of the obtained values of factor variables into the system of Eq. 1 showed that this scenario will be associated with the following implications for the energy sector:

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→ Reduction of the share of alternative and nuclear energy by 4.17% (to 10.90%);
→ Decrease in the share of renewable electricity output by 28.44% (up to 19.03%);
→ Decline of renewable energy consumption by 25.47% (up to 12.12%);
→ Growth of the share of fossil fuel energy consumption by 3.63% (up to 80.53%).

The fullest possible fulfillment of the potential of automation in Industry 4.0 has been used as a criterion in the development of this scenario. A special thing about the practical implementation of this scenario is the accelerated robotization and the spread of AI, which, unfortunately, occurs at the expense of clean energy and critically increases the energy intensity of the economy, threatening the onset of the energy crisis.

The second scenario is connected with the preservation of the current trend in the development of alternative and clean energy. In this case, the most likely values of energy development indicators turned out to be the following:

→ Increase in the share of alternative and nuclear energy by 49.42% (up to 17% with a 20% probability);
→ Increase in the share of renewable electricity output by 9.03% (up to 29% with a probability of 25%);
→ The growth of renewable energy consumption by 66.75% (up to 27.11% with a probability of 17%);
→ Reduction of the share of fossil fuel energy consumption by 12.74% (to 67.81% with a probability of 14%).

Based on the dependencies from the system of Eq. 1 by the least squares method, it was found that the implementation of this scenario would require a complete abandonment of the use of AI, as well as the limitation of robotics by 8.52% (up to 344.60 robots per 10 thousand industrial workers). The fullest possible fulfillment of the potential of the development of clean energy has been used as a criterion in the development of this scenario. A special thing about the practical implementation of this scenario is the rapid pace of decarbonization. However, unfortunately, decarbonization is contrary to the interests of economic growth and slows down the innovative and technological development of the economy.

The third scenario is the balanced development of clean energy and high technologies in EnergyTech This is an alternative to the two radical scenarios described above, which are based on a clear opposition of clean energy and high technology. EnergyTech is the most optimal scenario, as it allows developing both clean energy and advanced technologies of industry 4.0 at the same time. The current practice of using robots and AI does not allow quantifying the parameters of this scenario. It is the least likely, but it deserves the closest attention.

## Recommendations for economic policy on the development of clean and alternative energy in the context of the fourth industrial revolution

To improve economic policy, it is expedient to take into account the impact of the proposed scenarios on political decision-making by state bodies, as well as the possible implications of scenarios. In the first scenario (unrestricted automation), the economic implications are associated with the accelerated rate of economic growth and increased labor productivity. However, the social implications consist in the growth of unemployment and the imbalance of the labor market, while the environmental implications consist in the critical increase in the energy intensity of the economy and the exacerbation of climate change issues.

In the second scenario (development of alternative and clean energy), the social implications consist in stable employment and improvement of the quality of life. In contrast, the environmental implications consist in a decrease in the energy intensity of the economy and decarbonization. However, the economic implications are associated with a slowdown in the rate of economic growth and scientific-technological progress.

In the third scenario (EnergyTech), all the implications are balanced, so this scenario is preferable. The economic implications are associated with moderate economic growth and a gradual increase in labor productivity. The social implications consist in the relative stability of the labor market, while the environmental implications consist in the implementation of the plan for decarbonization of the economy and the gradual reduction of its energy intensity.

To implement the EnergyTech scenario in practice, the following applied recommendations for improving the state economic policy are proposed. Firstly, it is the increase of public financing and the stimulation of private investment in energy saving of high technologies. The revealed quantitative dependencies 1) indicate that by now energy-saving high technologies have not been common due to their high cost. Therefore, high technologies with low energy efficiency prevail. Additional funding will help solve this problem.

Secondly, it is the support for the development of EnergyTech. High technologies should be developed not only in economic sectors, but also in the energy sector itself. This will increase the amount of energy generated, as well as allow for a more flexible combination of clean/alternative energy and fossil fuels. Thirdly, it is necessary to tighten the norms and standards of energy efficiency for high-tech industries and enterprises. High technologies (in particular, robots and AI) should be implemented in practice only if they contribute to the development of clean energy or energy neutrality.

The framework recommendations for the development of clean and alternative energy in the age of the Fourth Industrial Revolution for economic policy allow for the adaptation of specific policy papers to modern requirements in each particular country. To make the authors' recommendations more specific, the consistent implementation of the "pledge to achieve carbon neutrality by 2050" (European Parlament, 2022) and "The Development Strategy of the Smart Robot Industry Under the Framework of South Korea Industry 4.0" (Market Prospects, 2022) is proposed in South Korea.

In China, the consistent implementation of "The new 5-year plan for the robotics industry" (The Robot Report, 2022) and the "roadmap for decarbonization with five guiding principles, dozens of measures, and emission targets for 2025, 2030, and 2060" (Climate Dialogue, 2022) is recommended. The abovementioned examples of South Korea as a developed country and China as a fast-growing country will be useful in the adaptation of relevant policy papers in other countries to up-to-date requirements by analogy with these countries, especially in the world's top 10 countries in terms of the degree of automation included in the sample of this research.

## Discussion

The contribution of the article to the literature is to fill the scientific gap by highlighting the future prospects for the development of alternative and clean energy in the era of the Fourth Industrial Revolution. Unlike Aubin et al. (2022), Huang et al. (2022), Luan et al. (2022), Nonoyama et al. (2022), Ntsiyin et al. (2022), Wang et al. (2022), it was found that robotization is characterized by insufficiently high energy efficiency, as it causes an increase in the dependence of the economy on fossil fuels.

In contrast to Anthopoulos and Kazantzi (2022), Dreher et al. (2022), Fang et al. (2022), Xuan and Ocone (2022), it was proven that the use of AI hinders the development of clean and alternative energy. Unlike Cui et al. (2022), Ng et al. (2021), Popkova et al. (2021), Popkova and Sergi (2021), Tabor et al. (2018), Taghizadeh-Hesary et al. (2022), Zaidan et al. (2022), t was justified, that the technologies of industry 4.0, which are becoming widespread in the conditions of the Fourth Industrial Revolution, not only do not support, but also slow down the transition to "clean" energy.

Unlike Chen et al. (2022), Deng et al. (2022), Inshakova et al. (2022), Iqbal and Bilal (2021), Liu et al. (2022), Nyenno et al. (2021), direct state regulation of sustainable energy development is recommended. For the balanced development of clean energy and high technologies, progress in the field of energy technologies was proposed and appropriate recommendations were developed.

The practical significance of the results obtained is that they clearly identified the contradiction between clean energy and high technologies–outlined the problem areas and offered the authors' vision of ways to solve them. In further research, it is necessary to study this problem more deeply, as well as to work out in more detail the prospects and recommendations for the development of EnergyTech for the balanced progress of clean energy and high technologies.

The novel nature of the discovery of the obvious conflict between clean energy and automation in the context of the "decade of action" consists in the evidence of the contradiction (antagonism) and complexity of the simultaneous implementation of SDG7 and SDG9. It promotes existing views on the development of alternative energy in the age of the Fourth Industrial Revolution by justifying the need for the consistent development and joint implementation of the economic policy of decarbonization and automation of the economy.

## Conclusion

The main conclusions and results of this research are as follows. The review of international practices and the results of the econometric modeling of the impact of the Fourth Industrial Revolution on the energy economy have shown that the proliferation of high technologies of Industry 4.0 (Robotics and AI) leads to the decreasing share of alternative and clean energy, as well as the growing dependence of the economy on fossil energy. With an independent implementation of energy and innovative technology policies, there are two prospective alternative scenarios for the development of the energy economy in the age of the Fourth Industrial Revolution.

The first scenario involves further unrestricted automation in the context of the freedom of proliferation of technologies of Industry 4.0 in the age of the Fourth Industrial Revolution. This will enable the accelerated rate of economic growth and increased labor productivity but will cause a critical increase in the energy intensity of the economy and exacerbate the climate change issues. The second scenario is associated with the preservation of the current trend of the development of alternative and clean energy. This will reduce the energy intensity of the economy and ensure decarbonization while critically slowing down the rate of economic growth and scientific-technological progress.

Consistent development and joint implementation of the energy and innovative technology policy have been proposed to improve the economic policy. As a result, this will enable a third, more promising scenario of the development of energy in the age of the Fourth Industrial Revolution. This optimal scenario will make it possible to achieve the balanced development of clean energy and high technologies in EnergyTech. The economic implications are associated with moderate economic growth and a gradual increase in labor productivity. The social implications consist in the relative stability of the labor market, while the environmental implications consist in the implementation of the plan for decarbonization of the economy and the gradual reduction of its energy intensity.

## Author contributions

Conceptualization, TV; Formal analysis, AS.; Methodology, TV; Project administration, S; Resources, AS and TV.; Writing – review and editing, ES and TV.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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