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# Blockchain, sustainability and clean energy transition

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ABSTRACT

The digital economy's neo-industrialization self-accelerates resource consumption and wide automatization inevitably envisage a technological leap. The article contributes conceptually and empirically to a systemic vision of blockchain to sort out climate change challenges and clean energy transition and simultaneously increase the productivity and efficiency of good practices. This vision covers the popularization of ecological initiatives, waste reduction, organization of sustainable investments, control over responsibilities on both fighting and forecasting climate change and clean energy transition. By embracing the notion of blockchain as a problem-solving tool for climate change and clean energy transition, the paper draws and investigates the experiences of the 36 digitally developed and 25 digitally developing economies. It also examines the effectiveness of alternative practices in Industry 4.0. The paper's findings represent a systematic vision of implementing blockchain initiatives to solve climate change and clean energy transition. An energy-efficient model with a blockchain opens up massive opportunities for ecological monitoring, supports energy transition and ameliorates economic sustainability. Since the blockchain potential is not fully unlocked, a model expanding the use of blockchain in education to train green personnel and in science to support climate innovations is proposed.


## 1. Introduction

Responsible innovations are a strategic direction for hastening economic development [1–4]. The transition to Industry 4.0 contributed significantly to implementing responsible innovations [5]. A prominent place is solving climate change problems envisages environmental protection, increased production's eco-efficiency, responsible consumption, growth of resource efficiency, reduced waste, and removed environmental harm [6–8] (see Tables 6–7, Figs. 3–5).

The importance and urgency of the problem of climate change are emphasized in Refs. [9–11]; and [12]. The influence of Industry 4.0 on climate change is contradictory, so we must thoroughly study its role in responsible innovations [13–15]. On the one hand, the digital economy's neo-industrialization speeds up its growth, thus stimulating the consumption of resources and increasing waste – proportionally to the volume of production and consumption [16]. Something inevitably connected wide automatization to the growth of energy consumption. Industry 4.0 envisages a technological leap [17]. New resource- and energy-efficiency technologies develop, alternative possibilities for the safe use of production and consumption waste, and opportunities for ecological monitoring and control of economic activities appear [18,19].

Although SDG 7 (transition to clean energy) and SDG 13 (combating climate change) are closely related in the existing literature [20–23]. However, exclusive application mechanisms for the systemic implementation of these goals have not been developed, which hinders progress towards these goals.

This article aims to identify the potential of sustainable blockchain technologies to ensure the systematic practical

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implementation of SDG 7 and SDG 13. This paper explores blockchain as an advanced tool to contribute to the climate change and clean energy transition problem-solving and combating practices technology of Industry 4.0. It provides practical recommendations for today's issues.

Conceptually, the paper hypothesizes that smart and sustainable technologies enable the clean energy transition. The basis for offering the view was the results of the studies by Refs. [24–27]and), [28]. The following paragraphs solve these tasks: evaluate the current contribution of blockchain to clean energy transition; consider successful examples of using blockchain in climate change fights; employ a systemic vision of a perspective model of using blockchain to clean energy transition.

This study draws on a sample of 36 developed and 25 developing economies in 2021 (a list of countries of developed and developing countries is in the IMD ranking of the most competitive digital economies). We did not cut the list of developed nations down to 25 to be able to cover their experience entirely due to the highest prevalence of blockchain technologies in these countries. The final paragraph concludes the paper.

## 2. Literature review

The theory of climate economics defines the fundamental principles for applying economic tools to combat climate change and the study of the climatic costs of economic growth. This laid the foundations for the use of digital technologies, in particular, blockchain technology, for bringing economic activities in line with sustainable development goals.

The central aspect of this paper is the notion of sustainability, which is painstaking through the lens of the UN's Sustainable Development Goals (SDGs). In the Decade of Action context, sustainability is treated as a society and economy's environmental friendliness toward the environment, reflected in the seventeen SDG systems. The path to achieving sustainability lies through solving the climate change problem and clean energy transition. Clean energy facilitates decarbonisation, which, in turn, ensures the improvement of the state of the environment. In the existing literature, selected issues of the use of blockchain in the fight against climate change and the transition to clean energy were researched.

[29] suggested creating blockchain networks for solar PV electric vehicle charging stations as a promising innovation supporting the fight against climate change and the transition to clean energy [30]. developed a coupling mechanism that improves the prospects of innovations ecosystem of clean energy in smart agriculture based on blockchain technology.

[31] recommended expanding the use of blockchain in the climate-responsible finance sphere to slow global warming [32]. revealed a severe barrier to blockchain development through the example of the food service industry – resistance to blockchain adoption. The scholars substantiated the significant role of restraint of public pressure and increased awareness of climate change for the more active use of blockchain in the fight against climate change and the transition to clean energy.

[33] presented a conceptual vision of climate-smart agriculture using intelligent techniques, blockchain and the Internet of Things. The advantage of using blockchain in this conceptual vision is the more active involvement of interested parties in agricultural company management [34]. proved that the implementation of blockchain allows for reducing damage to climate (climate costs of economic growth) from the economy and decreasing mortality (raising the quality and lifespan of the population). The scholars suggested using non-fungible tokens and bitcoins to reduce carbon emissions (decarbonisation) and mortality.

The concept of sustainable development and combating climate change underpins the theoretical basis of this study. It is also explored in Refs. [35–46]. Limitation of the capabilities of the existing approach to the fight against climate change is noted in Refs. [47–61]; and [62].

Climate change and the many barriers on the path of its solution are explored by Refs. [63–74]; and [75].

Despite intensive efforts of the extant works towards climate change issues, it has not yet found a highly effective and universal means to stop climate change and, at a maximum, ensure reverse climate change. Technological aspects of problem-solving, in particular, blockchain-based, are considered in the works of [76–78]; and [79]; and [80]. Practical issues of climate change and management of these processes, including the use of Industry 4.0 technologies, are disclosed by Refs. [63,71,81–87].

The need, best practices, successful examples and current issues of the clean energy transition are discussed in Refs. [88–96]. The benefits of using smart sustainable technologies for the clean energy transition are described in the writings of [97–100].

We note the focused attention of modern scientists to the prospects for resorting to digital technologies to solve the climate change problem and clean energy transition. At the same time, research concentrates on formulating hypotheses, while their verification requires additional empirical research. Thus, a widespread belief was formed that the advanced technologies of Industry 4.0 can contribute to solving the problem of climate change and clean energy transition. Deeper cause-and-effect relationships, limitations of the capabilities of Industry 4.0 technologies in solving the problem of climate change and clean energy transition, and details on individual digital technologies, particularly on the blockchain, are unclear.

Using promising technologies of Industry 4.0 for solving climate change and clean energy transition is recognized in the existing literature. However, the experience and perspectives of blockchain here need to be further explored. They carried most of the current research out at an intellectual level. Simultaneously, the applied aspects of using blockchain to combat climate change and clean energy transition are poorly studied. There is also a lack of applied developments on blockchain implementation to combat climate change and clean energy transition. This article is intended to fill in these gaps at the level of empirical science.

A critical appraisal of the literature revealed shortcomings, such as the lack of knowledge of blockchain technology and its potential to combat climate change and move countries through a clean energy transition. We overcome these shortcomings in this article.

## 3. Methodology

We evaluate our hypothesis by analyzing the experience of blockchain in 36 developed and 25 digitally developing economies. The countries were selected in the sample according to the criterion of the most significant prevalence of blockchain technologies (use of Big data and analytics, as well as cybersecurity), according to the criterion of different income levels - high incomes (developed countries), incomes above and below the world average (developing countries), as well as by the criterion of striving to cover different geographic regions - America (USA), Europe (Denmark, Sweden, Switzerland, and Russia), Asia (UAE, China, Malaysia, and Qatar), Australia (Australia, New Zealand), Africa (South Africa). Including the sample of both developed and developing countries ensured a representative and robust sample.

An additional criterion was the progress in implementing the SDGs. Including countries with various sustainable development levels in the sample allowed the in-depth study of the differences in their fight against climate change and the relationship between the development of sustainable technologies and the transition to clean energy. The sample is ultimately robust for our purposes.

Table 1 shows the high difference between developed and developing countries' digital competitiveness. Therefore these countries need to be studied separately to consider their characteristics. According to the International Organization for Standardization (ISO) materials, blockchain is a digital technology of big data processing distributed among blocks within a register, ensuring data protection [103]. There are no separate statistics on blockchain applications in the digital economy, but they could be assessed indirectly.

Therefore, this article examines the typical characteristics of the digital economy highlighted by Ref. [101]: Talent; training and education; scientific concentration; regulatory framework; capital; technological framework; adaptive attitudes; business agility; IT integration. They function as factor variables (sst). The resulting variables reflecting the clean energy transition (CET) are the Population with access to clean fuels and technology for cooking (%) ($CET_1$); $CO_2$ emissions from fuel combustion for electricity and heating per total electricity output ($MtCO_2/TWh$) ($CET_2$); Share of renewable energy in total primary energy supply (%) ($CET_3$), the values of which are taken from Ref. [5].

For the first time, the new model allows measuring the level of development of smart and sustainable technologies (through indicators of the digital economy) as a mechanism to ensure a clean energy transition (using UN indicators, 2022). With this model, this article contributes to the literature by quantifying the contribution of smart and sustainable technologies to the clean energy transition and describing the patterns of clean energy transition under the influence of blockchain development. Consequently, the original model of the study is:

$$\textbf{\textit{Model 1}} \quad CET = a + \sum_{i=1}^{n} b_i * sst_i$$

where n is purely factorial variables (sst), equal to 9 (i.e., IMD distinguishes 9 indicators of digital competitiveness, which are the factor variables examined in this paper). The hypothesis is proven for positive regression coefficients ($bi > 0$) in the equations for $CET_1$ and $CET_3$, as well as negative regression coefficients ($bi < 0$) in the equations for CET2. The initial statistical data are in Table 1.

## 4. Results: the current contribution of blockchain to solving climate changes

Based on the sample, we obtain the following multiple linear regression equation (Tables 2–6). The correlation is high in all accepted regression models. They are significant at a significance level of 0.1, except for the $CET_2$ model for developing countries (Table 3).

The regression analysis results identify the prospects for optimizing smart, sustainable technologies in the clean energy transition in developing digital economies (Table 2) and developed digital economies (Table 4). The benefits of the transition from optimizing smart sustainable technologies in developing digital economies are defined in Tables 3 and in developed digital economies - in Table 5.

In developing digital economies, an increase in the level of development is recommended.

- Talent by 10.97%;
- Scientific concentration by 63.66%;
- Regulatory framework by 28.26%;
- Capital by 71.50%;
- Technological framework by 14.34%;
- Adaptive attitudes by 17.67%;
- Business agility by 21.46%;
- IT integration by 61.62%.

This achieves the following benefits for the clean energy transition.

- Increase in population with access to clean fuels and technology for cooking from 83.12% to 100% (+20.3%);
- Reducing $CO_2$ emissions from fuel combustion for electricity and heating per total electricity output from 1.49 $MtCO_2/TWh$ to 0.59 $MtCO_2/TWh$ (−60.26%);
- Optimizing the share of renewable energy in the total primary energy supply is not available due to the lack of statistical data (but it is possible).

In developed digital economies, it is recommended to increase the level of development.

- Talent by 96.17%;
- Training and education by 96.52%;
- Regulatory framework by 96.29%;
- Capital by 85.55%;
- Technological framework by 96.30%;
- Adaptive attitudes by 96.20%;
- Business agility by 96.64%;
- IT integration by 24.26%.

This achieves the following benefits for the clean energy transition.

- Growth of the population with access to clean fuels and technology for cooking from 95.51% to 100% (+4.70%);
- Reducing $CO_2$ emissions from fuel combustion for electricity and heating per total electricity output from 4.01 $MtCO_2/TWh$ to 0 $MtCO_2/TWh$ (−409.22%);
- Increase the share of renewable energy in the total primary energy supply from 25.45% to 48.59% (+137.57%).

The results obtained based on econometric modelling revealed significant potential for using smart, sustainable technologies for a clean energy transition and systematic achievement in the practice of SDG 7 and SDG 13. Blockchain is one of the most promising smart sustainable technologies.

### 4.1. Successful examples of using blockchain to solve climate change and clean energy transition

Consider successful international practice examples to determine the directions of the blockchain (Table 3). Let us consider the future trends of using blockchain to solve climate change and clean energy transition. *The first problem* is the popularization of ecological initiatives. Blockchain could help solve this problem of marketing support for fighting environmental pollution and climate change. A successful example of a practical implementation of this direction is the Treelion app, which combines cryptocurrencies and eco-products [104].

This ensures standardization and certification of ecological products and the possibility to track it along the whole added value chain – from the manufacture of raw materials to final consumption. Full-scale information support production, distribution, and eco-transparency, ensuring the public character of the signs of violating ecological principles and risks for climate change based on blockchain. This motivates all economic subjects to consider whether their economic practices are eco-friendly and join successful environmental initiatives.

**Table 1**
Statistics of smart and sustainable technologies and clean energy transition in digitally developed and developing economies in 2021.

| Country | The category of the country | Population with access to clean fuels and technology for cooking (%) | $CO_2$ emissions from fuel combustion for electricity and heating per total electricity | Share of renewable energy in total primary energy supply (%) | Talent | Training and education | Scientific concentration | Regulatory framework | Capital | Technological framework | Adaptive attitudes | Business agility | IT integration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Argentina | Developing | 98.400 | 1.230 | n/a | 62 | 46 | 48 | 57 | 63 | 56 | 50 | 43 | 59 |
| Botswana | Developing | 64.080 | 2.717 | n/a | 53 | 48 | 63 | 63 | 56 | 64 | 63 | 46 | 63 |
| Brazil | Developing | 95.590 | 0.661 | n/a | 63 | 58 | 21 | 51 | 59 | 51 | 40 | 42 | 49 |
| Bulgaria | Developing | 88.650 | 0.901 | n/a | 54 | 53 | 46 | 55 | 53 | 42 | 45 | 61 | 53 |
| China | Developing | 59.260 | 1.407 | n/a | 12 | 35 | 63 | 15 | 27 | 28 | 19 | 3 | 32 |
| Croatia | Developing | 92.700 | 1.158 | n/a | 61 | 42 | 34 | 56 | 50 | 41 | 39 | 64 | 58 |
| Cyprus | Developing | n/a | 1.319 | n/a | 56 | 29 | 29 | 47 | 54 | 52 | 27 | 50 | 33 |
| India | Developing | 41.040 | 1.462 | n/a | 38 | 43 | 47 | 52 | 4 | 62 | 55 | 36 | 51 |
| Indonesia | Developing | 58.370 | 2.015 | n/a | 48 | 64 | 44 | 50 | 25 | 55 | 57 | 26 | 60 |
| Jordan | Developing | 99.060 | 1.186 | n/a | 34 | 33 | 62 | 38 | 41 | 53 | 61 | 28 | 54 |
| Kazakhstan | Developing | 95.340 | 2.104 | n/a | 45 | 14 | 54 | 22 | 51 | 47 | 32 | 6 | 44 |
| Malaysia | Developing | 96.300 | 1.426 | n/a | 30 | 9 | 32 | 35 | 31 | 15 | 29 | 27 | 31 |
| Mongolia | Developing | 42.800 | 3.425 | n/a | 60 | 39 | 61 | 58 | 62 | 60 | 37 | 63 | 62 |
| Peru | Developing | 75.060 | 0.938 | n/a | 59 | 41 | 60 | 49 | 43 | 58 | 54 | 39 | 56 |
| Philippines | Developing | 43.220 | 1.398 | n/a | 55 | 61 | 56 | 62 | 40 | 49 | 60 | 37 | 57 |
| Qatar | Developing | 98.490 | 1.926 | n/a | 19 | 54 | 59 | 27 | 24 | 16 | 26 | 17 | 28 |
| Romania | Developing | 85.880 | 1.162 | n/a | 50 | 59 | 43 | 40 | 61 | 40 | 42 | 57 | 50 |
| Russia | Developing | 98.250 | 1.519 | n/a | 44 | 6 | 24 | 39 | 58 | 45 | 44 | 56 | 48 |
| Saudi Arabia | Developing | 95.960 | 1.383 | n/a | 32 | 34 | 64 | 30 | 15 | 35 | 46 | 35 | 24 |
| Singapore | Developing | n/a | 0.946 | n/a | 2 | 13 | 11 | 5 | 14 | 2 | 11 | 12 | 7 |
| South Africa | Developing | 84.750 | 1.818 | n/a | 58 | 62 | 53 | 59 | 36 | 61 | 59 | 59 | 55 |
| Thailand | Developing | 74.430 | 1.393 | n/a | 39 | 56 | 36 | 29 | 19 | 22 | 53 | 34 | 43 |
| UAE | Developing | 98.510 | 1.505 | n/a | 1 | 25 | 52 | 2 | 11 | 5 | 15 | 10 | 10 |
| Ukraine | Developing | 95.730 | 1.210 | n/a | 46 | 18 | 55 | 46 | 55 | 57 | 56 | 45 | 61 |
| Venezuela | Developing | 96.160 | 1.165 | n/a | 64 | 52 | 49 | 64 | 64 | 63 | 64 | 52 | 64 |
| Australia | Developed | n/a | 1.533 | 7.102 | 8 | 37 | 18 | 17 | 17 | 27 | 14 | 55 | 21 |
| Austria | Developed | n/a | 0.936 | 30.187 | 15 | 5 | 15 | 26 | 32 | 38 | 21 | 18 | 11 |
| Belgium | Developed | n/a | 1.035 | 7.756 | 20 | 31 | 20 | 18 | 20 | 37 | 22 | 38 | 26 |
| Canada | Developed | n/a | 0.904 | 16.374 | 9 | 10 | 5 | 13 | 9 | 29 | 17 | 20 | 14 |
| Chile | Developed | 92.280 | 1.201 | 24.273 | 36 | 51 | 57 | 33 | 38 | 36 | 24 | 54 | 39 |
| Colombia | Developed | 91.790 | 0.934 | 26.022 | 57 | 50 | 58 | 61 | 49 | 59 | 58 | 47 | 46 |
| Czech Republic | Developed | 97.130 | 1.179 | 10.725 | 28 | 45 | 30 | 44 | 29 | 32 | 35 | 32 | 36 |
| Denmark | Developed | n/a | 0.990 | 36.931 | 5 | 4 | 17 | 4 | 13 | 6 | 4 | 7 | 1 |
| Estonia | Developed | 92.890 | 1.595 | 23.161 | 29 | 8 | 45 | 28 | 33 | 20 | 20 | 25 | 25 |
| Finland | Developed | n/a | 0.622 | 34.126 | 10 | 19 | 10 | 11 | 10 | 14 | 7 | 21 | 2 |
| France | Developed | n/a | 0.537 | 10.682 | 23 | 27 | 12 | 10 | 21 | 17 | 48 | 33 | 22 |
| Germany | Developed | n/a | 1.130 | 14.633 | 21 | 17 | 6 | 25 | 23 | 43 | 23 | 15 | 20 |
| Greece | Developed | 94.290 | 1.216 | 12.827 | 42 | 55 | 35 | 43 | 52 | 50 | 43 | 51 | 41 |
| Hungary | Developed | n/a | 1.410 | 10.311 | 43 | 47 | 42 | 36 | 45 | 21 | 62 | 62 | 42 |
| Iceland | Developed | n/a | 0.098 | 90.139 | 35 | 22 | 39 | 14 | 26 | 3 | 31 | 16 | 27 |
| Ireland | Developed | n/a | 1.163 | 11.127 | 18 | 32 | 26 | 19 | 35 | 34 | 12 | 14 | 19 |
| Israel | Developed | n/a | 0.920 | 2.865 | 27 | 3 | 9 | 31 | 28 | 26 | 25 | 31 | 13 |
| Italy | Developed | n/a | 1.089 | 18.236 | 40 | 60 | 25 | 42 | 48 | 44 | 36 | 19 | 38 |
| Japan | Developed | n/a | 1.123 | 6.248 | 47 | 21 | 13 | 48 | 37 | 8 | 18 | 53 | 23 |
| Korea Rep. | Developed | 96.680 | 1.076 | 2.364 | 26 | 16 | 3 | 23 | 16 | 7 | 2 | 5 | 16 |
| Latvia | Developed | 95.280 | 1.088 | 41.374 | 24 | 30 | 51 | 34 | 46 | 18 | 51 | 48 | 37 |
| Lithuania | Developed | n/a | 3.765 | 20.363 | 25 | 15 | 37 | 32 | 30 | 30 | 47 | 24 | 34 |
| Luxembourg | Developed | n/a | 106.183 | 7.405 | 33 | 20 | 38 | 8 | 8 | 25 | 38 | 22 | 12 |
| Mexico | Developed | 85.350 | 1.451 | 8.850 | 51 | 57 | 50 | 54 | 57 | 54 | 52 | 41 | 52 |
| Netherlands | Developed | n/a | 1.245 | 7.177 | 4 | 28 | 16 | 7 | 3 | 10 | 6 | 8 | 6 |
| New Zealand | Developed | n/a | 0.738 | 41.841 | 14 | 36 | 33 | 24 | 22 | 23 | 16 | 30 | 18 |

(*continued on next page*)

**Table 1** (*continued*)

| Country | The category of the country | Population with access to clean fuels and technology for cooking (%) | $CO_2$ emissions from fuel combustion for electricity and heating per total electricity | Share of renewable energy in total primary energy supply (%) | Talent | Training and education | Scientific concentration | Regulatory framework | Capital | Technological framework | Adaptive attitudes | Business agility | IT integration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Norway | Developed | n/a | 0.197 | 54.588 | 16 | 11 | 22 | 1 | 6 | 12 | 8 | 11 | 8 |
| Poland | Developed | n/a | 1.900 | 9.347 | 41 | 44 | 28 | 53 | 47 | 31 | 28 | 44 | 45 |
| Portugal | Developed | n/a | 0.881 | 23.162 | 22 | 38 | 27 | 21 | 44 | 46 | 30 | 58 | 30 |
| Slovak Republic | Developed | 96.580 | 1.119 | 9.905 | 52 | 49 | 40 | 60 | 42 | 39 | 49 | 60 | 40 |
| Slovenia | Developed | 96.170 | 0.860 | 16.659 | 37 | 23 | 31 | 45 | 39 | 33 | 41 | 40 | 35 |
| Sweden | Developed | n/a | 0.197 | 40.782 | 7 | 2 | 4 | 3 | 5 | 13 | 5 | 13 | 5 |
| Switzerland | Developed | n/a | 0.533 | 22.456 | 3 | 7 | 8 | 9 | 12 | 11 | 10 | 4 | 4 |
| Turkey | Developed | n/a | 1.279 | 15.947 | 49 | 63 | 41 | 41 | 60 | 48 | 34 | 29 | 47 |
| United Kingdom | Developed | n/a | 1.104 | 12.493 | 11 | 26 | 7 | 20 | 18 | 19 | 9 | 23 | 9 |
| USA | Developed | n/a | 1.145 | 7.915 | 13 | 24 | 2 | 12 | 1 | 9 | 1 | 1 | 3 |

*Source*: authors based on [101,102].

*The second problem* is the reduction of production and consumption waste. Blockchain could help to solve this problem through automatized monitoring and quotas on environmental pollution. A successful example of this direction's practical implementation is [105]; based on smart contracts supported by the World Economic Forum.

Responsible blockchain includes ecological parameters in economic contracts between corporations and public-private partnerships. Using blockchain in smart contracts to specify each economic operation's ecological parameters is promising. This raises the awareness of interested parties of the implemented project's environmental effectiveness and simplifies its control.

*Third problem*: organization of sustainable investments. Blockchain could help solve this problem by providing transparency about the climate consequences of financial deals. A successful example of this direction's practical implementation is the Mitigation token (MITO) by DAO ICPI and trading carbon units by Laszlo Giric in the Poseidon project [106].

Mitigation token is a recent approach to quotas on natural resources and ecological costs. This allows for finding the characteristics of each economic activity indicator, which has consequences for climate change (consumption of energy resources, production waste). Due to this, the implications for the environment become controlled, predictable, and manageable.

Another successful example of growing popularity is green obligations. In Russia (as well as in other EAEU countries), a blockchain-ecosystem DAO IPCI (Integral Platform for Climate Initiatives) appeared in 2017 and was approved and supported by the Russian President's counsellor on the issues of climate change Aleksandr Bedritsky, the World Bank, Framework Convention on Climate Change, UN FCCC, and the UN Green Climate Fund (GFC). The Russian blockchain ecosystem sets quotas on industrial corporations' pollution emissions and quotas on energy consumption [107].

*The fourth problem is* control over responsibilities in fighting climate change and the clean energy transition. Blockchain could help solve this problem through technical support to conclude smart contracts and control their practical implementation. A successful example of practical implementation of this direction is blockchain oracles based on the Internet of Things, promoted by the Global Commission on Adaptation and used by Apple, Google, Morgan Stanley, PepsiCo, and Walmart [108].

Blockchain oracles are apps for intelligent analytics of data from the Internet or other sources – e.g., the Internet of Things. Blockchain oracles allow for figuring out the signs of violation of smart contracts, which helps control them. AI's application enables blockchain oracles to determine mismatches in companies' ecological reports, e.g., a repeat of ecological advantages without information on environmental costs.

*Fifth problem*: forecasting climate change and clean energy transition. Blockchain could help collect climate change factors and guarantee their reliability, correctness, and preservation. A successful example of practical implementation is projects Ascribe, Factom, and Cloud of Siberia, supported by corporations, particularly Facebook [109].

In this process, a key role belongs to the Centers of data processing – analytical platforms that process big data on climate change from various sources (citizens, organizations, the Internet, or government). These Centers allow for figuring out the evolution of separate climate change indicators, taking them into account systematically, building climate change forecasts, and supplying academic decision support. The critical role here is the blockchain as a technology supporting the systemic character of data.

Blockchain projects, organized according to the blockchain principle, stimulate big data in climate change. Blockchain

**Table 2**
Results of regression analysis for the resulting variable CET1 in developing countries.

| Regression statistics | | | | | | |
|---|---|---|---|---|---|---|
| Multiple R | | | | | | 0.785648 |
| R-square | | | | | | 0.617242 |
| Normalized R-square | | | | | | 0.387587 |
| Standard error | | | | | | 15.6006 |
| Observation | | | | | | 25 |
| Analysis of variance | | | | | | |
| | df | SS | MS | F | | Significance F |
| Regression | 9 | 5,887.151 | 654.1279 | 2.687696 | | 0.043757 |
| Surplus | 15 | 3,650.68 | 243.3787 | | | |
| Total | 24 | 9,537.832 | | | | |
| | *Coefficients* | *Standard error* | *t-statistics* | *P-Value* | *Lower 95%* | *Upper 95%* |
| Y-intersection | 97.84334 | 14.46363 | 6.764785 | 6.36E-06 | 67.01484 | 128.6718 |
| Talent | 0.347614 | 0.577761 | 0.601657 | 0.556387 | −0.88385 | 1.579082 |
| Training and education | −0.16742 | 0.252477 | −0.66313 | 0.517312 | −0.70557 | 0.370718 |
| Scientific concentration | −0.15928 | 0.279386 | −0.57011 | 0.577045 | −0.75478 | 0.436217 |
| Regulatory framework | −0.46185 | 0.594142 | −0.77734 | 0.449046 | −1.72823 | 0.804534 |
| Capital | 0.886648 | 0.341074 | 2.599578 | 0.020116 | 0.159666 | 1.61363 |
| Technological framework | −0.31539 | 0.441293 | −0.7147 | 0.485767 | −1.25599 | 0.6252 |
| Adaptive attitudes | 1.054932 | 0.440664 | 2.393958 | 0.030179 | 0.115678 | 1.994185 |
| Business agility | 0.031679 | 0.328429 | 0.096456 | 0.924435 | −0.66835 | 0.731708 |
| IT integration | −1.42515 | 0.605665 | −2.35303 | 0.032685 | −2.71609 | −0.13421 |

*Source*: authors

**Table 3**
Results of regression analysis for the resulting variable CET2 in developing countries.

| Regression statistics | | | | | | |
|---|---|---|---|---|---|---|
| Multiple R | | | | | | 0.579194 |
| R-square | | | | | | 0.335466 |
| Normalized R-square | | | | | | −0.06325 |
| Standard error | | | | | | 0.612478 |
| Observation | | | | | | 25 |
| Analysis of variance | | | | | | |
| | df | SS | MS | F | | Significance F |
| Regression | 9 | 2.840556 | 0.315617 | 0.841357 | | 0.591396 |
| Surplus | 15 | 5.626933 | 0.375129 | | | |
| Total | 24 | 8.467489 | | | | |
| | Coefficients | Standard error | t-statistics | P-Value | Lower 95% | Upper 95% |
| Y-intersection | 0.841548 | 0.56784 | 1.482015 | 0.159038 | −0.36878 | 2.051871 |
| Talent | −0.00731 | 0.022683 | −0.3224 | 0.751598 | −0.05566 | 0.041034 |
| Training and education | −0.00462 | 0.009912 | −0.46563 | 0.648172 | −0.02574 | 0.016512 |
| Scientific concentration | 0.018686 | 0.010969 | 1.703568 | 0.109084 | −0.00469 | 0.042065 |
| Regulatory framework | 0.009228 | 0.023326 | 0.395619 | 0.697956 | −0.04049 | 0.058946 |
| Capital | −0.00841 | 0.013391 | −0.62805 | 0.539416 | −0.03695 | 0.020131 |
| Technological framework | 0.005136 | 0.017325 | 0.296453 | 0.77095 | −0.03179 | 0.042064 |
| Adaptive attitudes | −0.0281 | 0.0173 | −1.62413 | 0.125171 | −0.06497 | 0.008777 |
| Business agility | 0.004001 | 0.012894 | 0.310277 | 0.76062 | −0.02348 | 0.031484 |
| IT integration | 0.023472 | 0.023778 | 0.987104 | 0.339248 | −0.02721 | 0.074154 |

*Source*: authors

technologies forecast and control climate change based on big data, reducing the consumption of resources, energy, and production waste, popularising ecological initiatives, and stimulating the fight against climate change in business and society.

The findings' managerial and political economy implications include the desirability of expanding existing blockchain practices to combat climate change. The countries most acutely experiencing the problem of climate change (developing countries, for example, China, and lagging countries, for example, African countries) need to pay attention to the blockchain as a promising tool in the fight against their climate change problems.

### *4.2. Cost of technology input, the cycle of benefits and adaptability of technology operations*

Regarding economic value, it is necessary to spotlight the cost of technology input, the cycle of benefits and the adaptability of technology operations. We shall investigate the likelihood of the broad application of blockchain in climate governance in countries with different economic development levels and the technology cycle length. The official international statistics on blockchain focus on Bitcoin – the most popular practice of using blockchain with precise quantitative measuring. To assess the cost of technology

**Table 4**
Results of regression analysis for the resulting variable CET1 in developed countries.

| Regression statistics | | | | | | |
|---|---|---|---|---|---|---|
| Multiple R | | | | | | 0.635722 |
| R-square | | | | | | 0.404142 |
| Normalized R-square | | | | | | 0.197883 |
| Standard error | | | | | | 14.96165 |
| Observation | | | | | | 36 |
| Analysis of variance | | | | | | |
| | df | SS | MS | F | | Significance F |
| Regression | 9 | 3,947.513 | 438.6126 | 1.959395 | | 0.087181 |
| Surplus | 26 | 5,820.126 | 223.851 | | | |
| Total | 35 | 9,767.639 | | | | |
| | Coefficients | Standard error | t-statistics | P-Value | Lower 95% | Upper 95% |
| Y-intersection | 106.6256 | 6.245561 | 17.07222 | 1.2E-15 | 93.78768 | 119.4636 |
| Talent | −0.4785 | 0.383238 | −1.24859 | 0.222943 | −1.26626 | 0.309251 |
| Training and education | −0.20645 | 0.257311 | −0.80235 | 0.429627 | −0.73536 | 0.322458 |
| Scientific concentration | 0.008743 | 0.259824 | 0.033649 | 0.973414 | −0.52533 | 0.542818 |
| Regulatory framework | 0.589364 | 0.366389 | 1.608573 | 0.119787 | −0.16376 | 1.342488 |
| Capital | −0.63826 | 0.391411 | −1.63066 | 0.115018 | −1.44281 | 0.166298 |
| Technological framework | −0.11286 | 0.257888 | −0.43762 | 0.665275 | −0.64295 | 0.417239 |
| Adaptive attitudes | 0.354847 | 0.28512 | 1.244554 | 0.224398 | −0.23123 | 0.94092 |
| Business agility | 0.309668 | 0.21196 | 1.460973 | 0.156004 | −0.12602 | 0.745357 |
| IT integration | −0.25711 | 0.622375 | −0.41311 | 0.682911 | −1.53642 | 1.022198 |

*Source*: authors

**Table 5**
Results of regression analysis for the resulting variable CET2 in developed countries.

| Regression statistics | | | | | | |
|---|---|---|---|---|---|---|
| Multiple R | | | | | | 0.695434 |
| R-square | | | | | | 0.483628 |
| Normalized R-square | | | | | | 0.304884 |
| Standard error | | | | | | 14.61154 |
| Observation | | | | | | 36 |
| Analysis of variance | | | | | | |
| | df | SS | MS | F | | Significance F |
| Regression | 9 | 5,198.937 | 577.6596 | 2.705704 | | 0.022771 |
| Surplus | 26 | 5,550.921 | 213.497 | | | |
| Total | 35 | 10,749.86 | | | | |
| | *Coefficients* | *Standard error* | *t-statistics* | *P-Value* | *Lower 95%* | *Upper 95%* |
| Y-intersection | −2.31825 | 6.09941 | −0.38008 | 0.706975 | −14.8558 | 10.21927 |
| Talent | 1.071634 | 0.374269 | 2.863269 | 0.008181 | 0.302312 | 1.840956 |
| Training and education | 0.075557 | 0.25129 | 0.300675 | 0.766053 | −0.44098 | 0.59209 |
| Scientific concentration | 0.415287 | 0.253744 | 1.63664 | 0.113755 | −0.10629 | 0.936865 |
| Regulatory framework | −0.48164 | 0.357815 | −1.34605 | 0.189906 | −1.21714 | 0.253862 |
| Capital | −0.63236 | 0.382251 | −1.6543 | 0.11009 | −1.41809 | 0.153369 |
| Technological framework | 0.417789 | 0.251853 | 1.658861 | 0.109161 | −0.0999 | 0.93548 |
| Adaptive attitudes | 0.373954 | 0.278448 | 1.342994 | 0.190881 | −0.1984 | 0.946312 |
| Business agility | 0.04069 | 0.207 | 0.196571 | 0.845692 | −0.3848 | 0.466184 |
| IT integration | −1.07463 | 0.607811 | −1.76804 | 0.088789 | −2.324 | 0.174741 |

*Source*: authors

input of blockchain, we use the statistics on the cost to mine 1 Bitcoin according to Ref. [110] as of August 5, 2022.

To assess the benefits and adaptability of blockchain to technology operations, the correlation analysis reveals the connection between the cost of mining 1 Bitcoin and the outcomes of the 17 SDGs in 2022. We set up a sample of 162 countries for which are available the cost to mine 1 Bitcoin and statistical accounting of the results of the achievement of the UN SDGs. Countries in the sample are listed in the appendix. The average cost to mine 1 Bitcoin follows the categories of countries distinguished by the United Nations in terms of income, the rate of socio-economic development and geographical location (Fig. 6).

As shown in Fig. 6, the highest cost to mine 1 Bitcoin in 2022 was in countries of Oceania: USD 50,481.1. In countries of LAC, the cost to mine 1 Bitcoin equals USD 48,448.1, in countries of Sub-Saharan Africa – USD 32,110.7, in countries of the OECD – USD 31,585.7, in countries of East & South Asia – USD 27,449.4, in countries of E. Europe & C. Asia – USD 22,055.7, and in countries of MENA – USD 15,980.2. On average, in developing countries, the cost to mine 1 bitcoin in 2022 was USD 32,754.2, which is 3.70% higher than in developed countries (by the example of countries of the OECD): USD 31,585.7. The correlation between the cost to mine 1 Bitcoin (USD) and the results for the SDGs in 2022 is in Fig. 7.

**Table 6**
Results of regression analysis for the resulting variable CET3 in developed countries.

| Regression statistics | | | | | | |
|---|---|---|---|---|---|---|
| Multiple R | | | | | | 0.650342 |
| R-square | | | | | | 0.422945 |
| Normalized R-square | | | | | | 0.223195 |
| Standard error | | | | | | 15.33067 |
| Observation | | | | | | 36 |
| Analysis of variance | | | | | | |
| | df | SS | MS | F | | Significance F |
| Regression | 9 | 4,478.811 | 497.6457 | 2.117375 | | 0.065398 |
| Surplus | 26 | 6,110.768 | 235.0295 | | | |
| Total | 35 | 10,589.58 | | | | |
| | Coefficients | Standard error | t-statistics | P-Value | Lower 95% | Upper 95% |
| Y-intersection | 28.71552 | 6.399605 | 4.487076 | 0.00013 | 15.56094 | 41.87009 |
| Talent | −0.03832 | 0.39269 | −0.09759 | 0.923003 | −0.84551 | 0.768861 |
| Training and education | −0.26858 | 0.263658 | −1.01868 | 0.317743 | −0.81054 | 0.273374 |
| Scientific concentration | 0.66379 | 0.266232 | 2.493276 | 0.01935 | 0.116542 | 1.211039 |
| Regulatory framework | −0.54149 | 0.375426 | −1.44233 | 0.161148 | −1.31319 | 0.23021 |
| Capital | 0.45149 | 0.401065 | 1.12573 | 0.270564 | −0.37291 | 1.27589 |
| Technological framework | −0.34159 | 0.264248 | −1.29269 | 0.207489 | −0.88476 | 0.20158 |
| Adaptive attitudes | −0.10077 | 0.292152 | −0.34491 | 0.732937 | −0.70129 | 0.499762 |
| Business agility | −0.20964 | 0.217188 | −0.96526 | 0.343307 | −0.65608 | 0.236793 |
| IT integration | 0.140574 | 0.637725 | 0.22043 | 0.827258 | −1.17029 | 1.451437 |

*Source*: authors

**Table 7**
Systematization of the future directions of using blockchain to solve the problems of climate change and clean energy transition.

| Problem of climate change | Prospective direction of using blockchain | Successful practical example |
|---|---|---|
| Popularization of ecological initiatives | Marketing support for fighting environmental pollution and climate change | Treelion app, which combines cryptocurrencies and eco-products |
| Reduction of production and consumption waste | Automatized monitoring and quotas for environmental pollution | Responsible blockchain PricewaterhouseCoopers based on smart contracts |
| Organization of sustainable investments | Provision of transparency of climate consequences of financial deals | Mitigation token (MITO) by the initiative of DAO ICPI and trading carbon units by the initiative of Laszlo Giric in the Poseidon project |
| Control over observation of responsibilities on fighting climate change and clean energy transition | Technical support for the conclusion of smart contracts and control over their practical implementation | Blockchain oracles based on the Internet of Things, promoted by The Global Commission on Adaptation, and applied by Apple, Google, Morgan Stanley, PepsiCo, and Walmart |
| Forecasting climate change and clean energy transition | Collection of information on the factors of climate change and the guarantee of their reliability, correctness, and preservation | Projects Ascribe, Factom, and Clouds of Siberia, supported by corporations, in particular, Facebook. |

*Source*: Authors based on [104,106–109]; and [105].

Results in Fig. 1 show that the reduction of cost and, accordingly, an increase in the affordability of Bitcoin leads to the improvement of the following results in the sphere of sustainable development (Fig. 2).

- Fight against poverty (correlation with SDG 1: 18.4%);
- Fight against hunger (correlation with SDG 2: 19.7%);
- Healthcare (correlation with SDG 3: 6.3%);
- Improvement of the quality of education (correlation with SDG 4: 1.0%);
- Improvement of gender equality (correlation with SDG 5: 1.4%);
- Development of clean energy (correlation with SDG 7: 5.1%);
- Industry, innovation and infrastructure (correlation with SDG 9: 11.1%);
- Reduced inequalities (correlation with SDG 10: 6.0%);
- Development of sustainable territories (correlation with SDG 11: 4,0%);
- Preservation of ecosystems on land (correlation with SDG 15: 0.1%);
- Improvement in the effectiveness of institutions (correlation with SDG 16: 19.1%);
- Development of partnership for sustainable development (correlation with SDG 17: 8.9%).

To determine the specific features of developed and developing countries, let us consider coefficients of correlation in each of these categories in isolation (Fig. 8).

As shown in Fig. 8, developing countries have more benefits of blockchain in the fight against poverty (correlation of −20.72% vs. −11.56% in developed countries), the fight against hunger (correlation of −24.26% vs. missing effect in developed countries), healthcare (correlation of −9.94% vs. missing effect in developed countries), improvement of the quality of education (correlation of −2.53% vs. missing effect in developed countries), improvement of gender equality (correlation of −3.48% vs. missing effect in developed countries), industry, innovations and infrastructure (correlation of −19.37% vs. −0.20% in developed countries), reduction of inequality (correlation of −9.25% vs. missing effect in developed countries), development of sustainable territories (correlation −6,13% compared to missing effect in developed countries), preservation of ecosystems on land (correlation of −3.49% vs. missing effect in developed countries) and

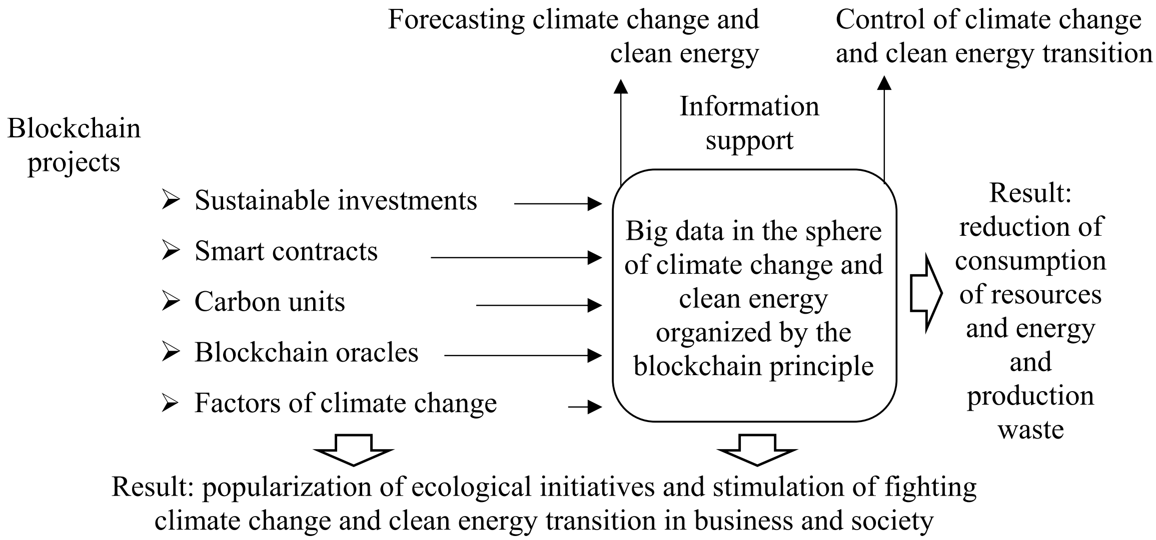


**Fig. 1.** perspective model of using blockchain to Address climate change and clean energy transition.
*Source*: authors

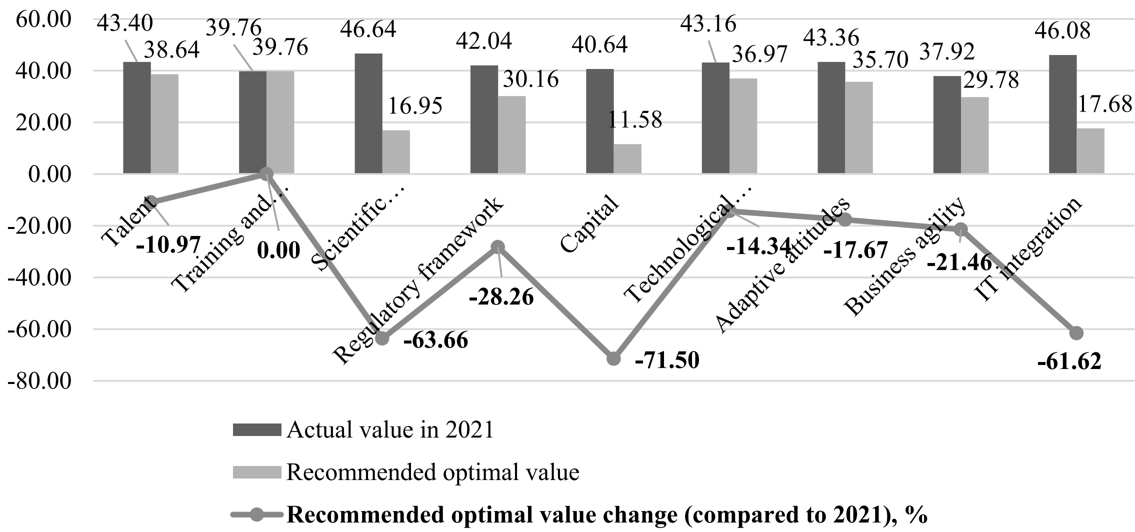


**Fig. 2.** Prospects for optimizing the use of smart sustainable technologies in the interests of clean energy transition in developing digital economies.
*Source*: authors

improvement in the effectiveness of institutions (correlation of −28.32% vs. missing effect in developed countries).

In developed countries, more vivid benefits of blockchain are observed with the development of clean energy (correlation of −12.31% vs. −5.59% in developing countries), development of responsible production and consumption (correlation −5.11% vs. missing effect in developing countries) and preservation of water eco-systems (correlation of −13.58% vs. missing effect in developing countries). In the sphere of partnership for sustainable development in developed and developing countries, the advantages of blockchain are approximately equal: the correlation is −11.66% and −9.84%, accordingly.

Thus, the results allowed for quantitative analysis of the cost of applying blockchain to manage sustainable development in developing countries. The results showed that the cost of using blockchain in developing countries is 3.70% higher than in developed countries – this difference is insignificant. Blockchain is more closely connected with the development of clean energy in developed countries (correlation in absolute value: 12.31%, and in developing countries: 5.59%). Therefore, blockchain has a significant potential to support the energy transition, solve climate change, and increase economic systems' sustainability. However, this potential is not fully developed because of climate and energy policy imperfection.

### 4.3. Climate and energy policy implications

The following future-oriented policy recommendations are offered based on the results obtained, accelerating the transition to clean energy and improving the sustainability of economic systems based on blockchain. The recommendations are divided into three management blocks. The recommendations fit in the context of the Decade of Action and the UN Agenda for Sustainable Development. Though the recommendations support all seventeen SDGs with

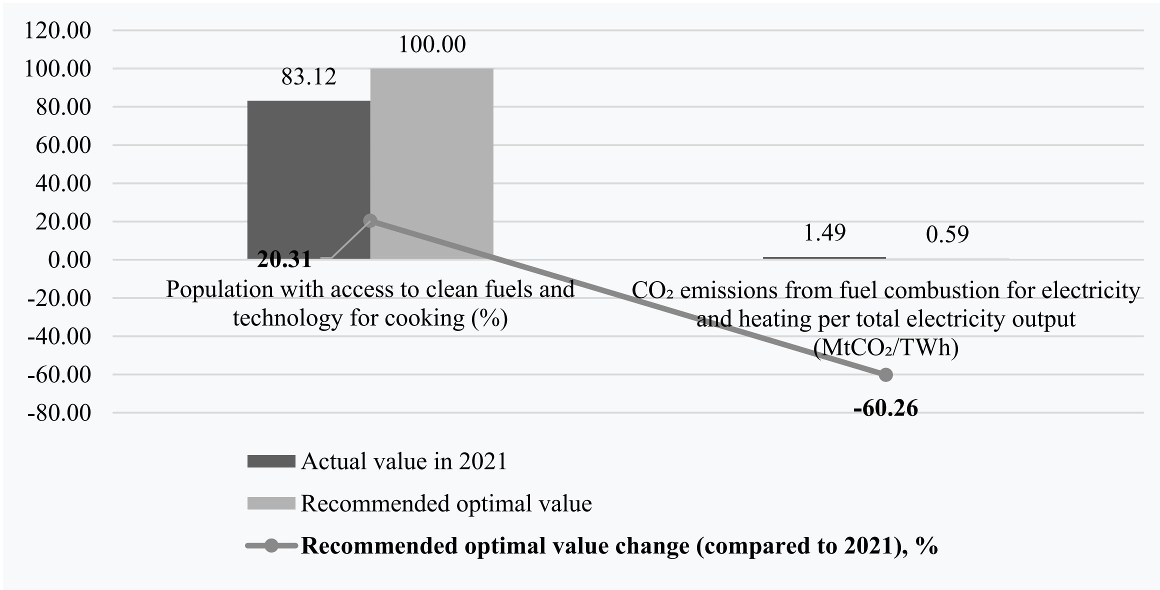


**Fig. 3.** Benefits for clean energy transition from optimizing the use of smart sustainable technologies in emerging digital economies.
*Source*: authors

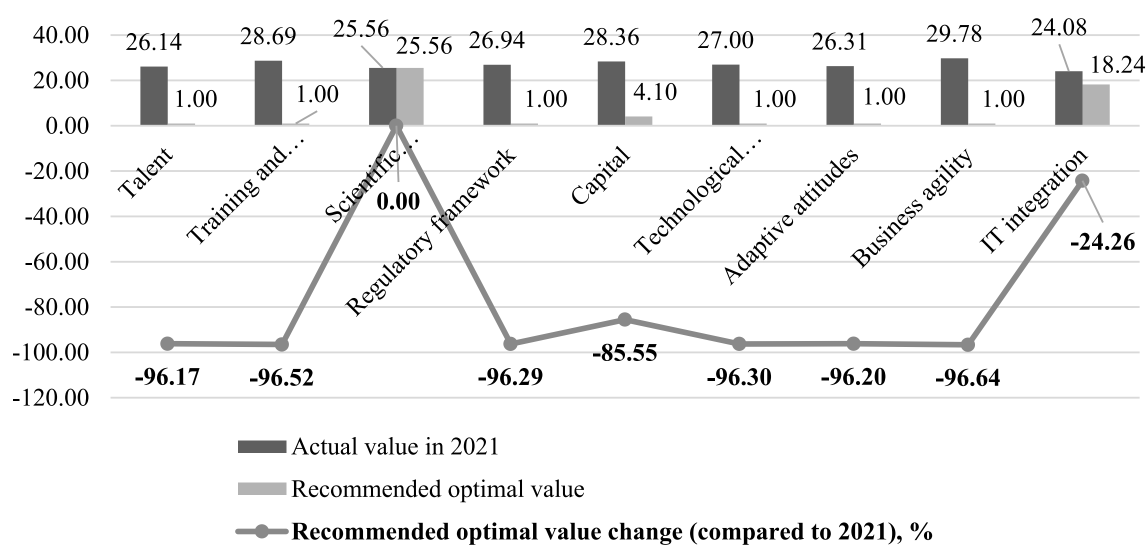


**Fig. 4.** Prospects for optimizing the use of smart sustainable technologies in the interests of clean energy transition in developed digital economies.
*Source*: authors

particular attention to SDG 7, SDG 13, SDG 14 and SDG 15, each block is focused on certain SDGs.

1st block: education for training green personnel and science supporting climate innovations in the energy sphere. This block is to ensure the development of “talent”, “scientific concentration” and “technological framework” and to support the practical implementation of SDG 4, SDG 8 and SDG 9. Recommendations in this block are as follows.

- Popularization of environmental initiatives and marketing support of the fight against environmental pollution and climate change based on standardization and certification of eco-friendly products and their tracking along the entire chain of added value with the help of blockchain (on the example of the application Treelion);
- Forecasting of climate change and the transition to clean energy with the help of blockchain (by the example of big data on climate change, organized by the principle of blockchain).

2nd block: environmentally responsible production and consumption of energy. This block is to ensure the development of a “regulatory framework”, “adaptive attitudes”, “business agility” and “IT integration” and support the practical implementation of SDG 11 and SDG 12. Recommendations in this block are as follows.

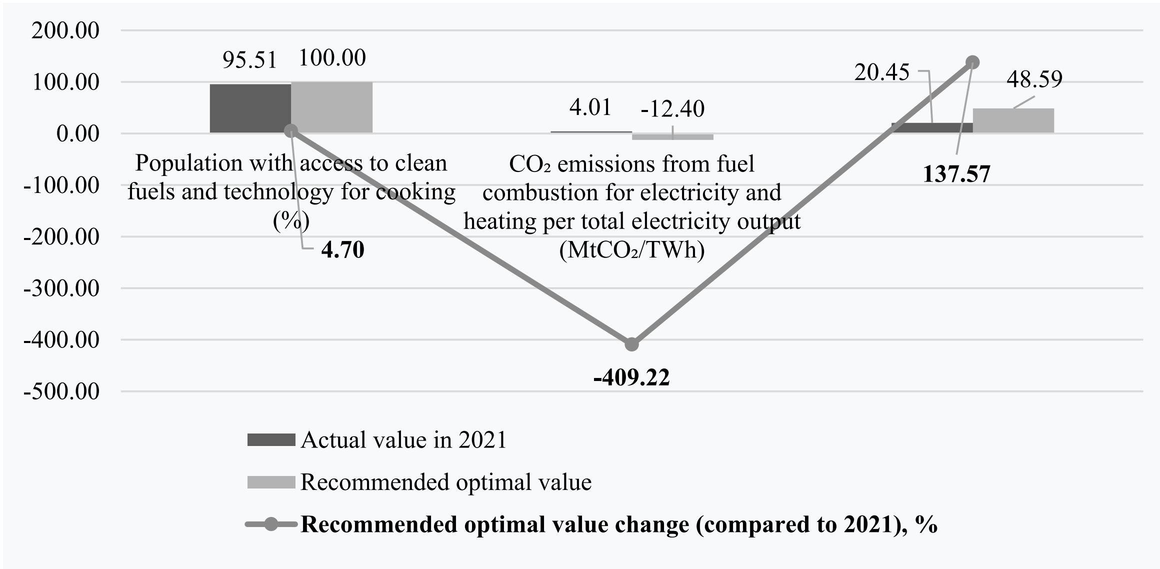


**Fig. 5.** Benefits for the clean energy transition from optimizing the use of smart sustainable technologies in advanced digital economies.
*Source*: authors

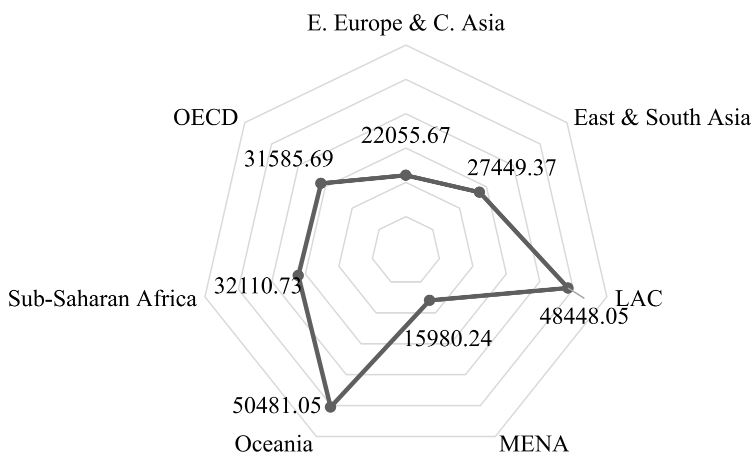


**Fig. 6.** Average cost to mine 1 bitcoin (USD).
Source: Authors.

– Automatized monitoring and quotas for environmental pollution to reduce production and consumption waste with the help of blockchain (on the example of smart contracts);
– Control over the execution of smart contracts and automatized monitoring of environmental accounting of companies to guarantee the execution of duties in the fight against climate change and transition to clean energy (on the example of blockchain oracles based on the Internet of Things).

3rd block: green finance supporting the fight against climate change and clean energy development. This block ensures the development of “capital” and supports the practical implementation of SDG 10, SDG 16 and SDG 17. Recommendations in this block are as follows.

– Organization of sustainable investments through the introduction of quotas on natural resources, environmental costs and their dissemination between all economic subjects to increase the transparency of climate consequences of financial deals with the help of blockchain (on the example of tokens and trade of carbon units);
– Dissemination of green bonds based on blockchain (for example, quotas for pollutant emissions by industrial corporations and quotas for energy consumption).

## 5. Conclusions

This article contributes to a thoughtful understanding of a new systemic vision of implementing blockchain initiatives to solve climate challenges and assist clean energy transition to maximize the beneficial effect. Based on the unique experience of the 36 digitally developed and 25 developing economies, it has been shown that smart and sustainable technologies enable the clean energy transition. By embracing the perspectives of using

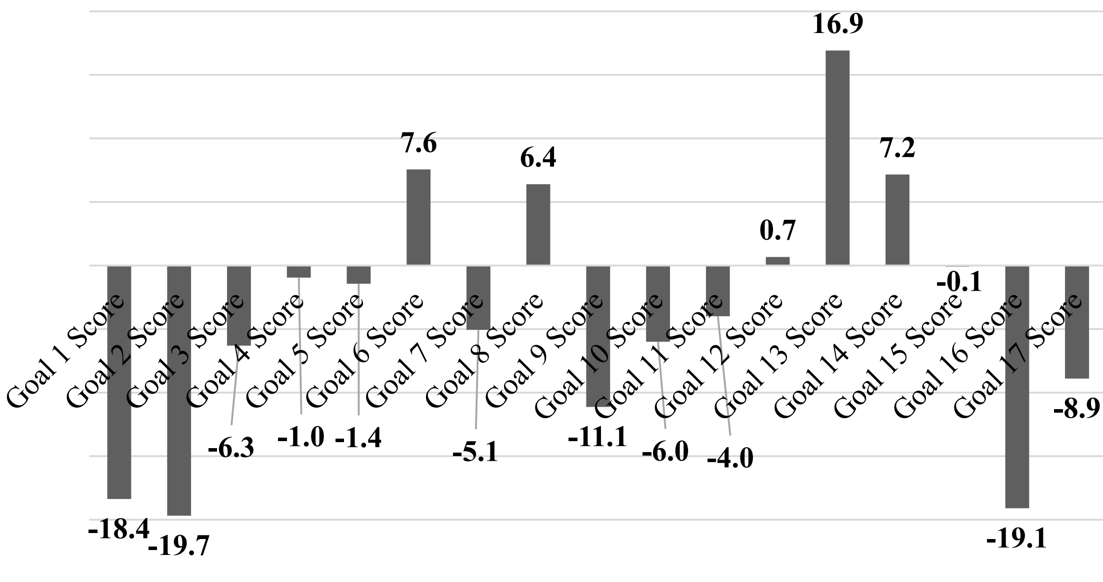


**Fig. 7.** Correlation between the cost to mine 1 bitcoin (USD) and the results in the SDGs, %.
Source: Authors.

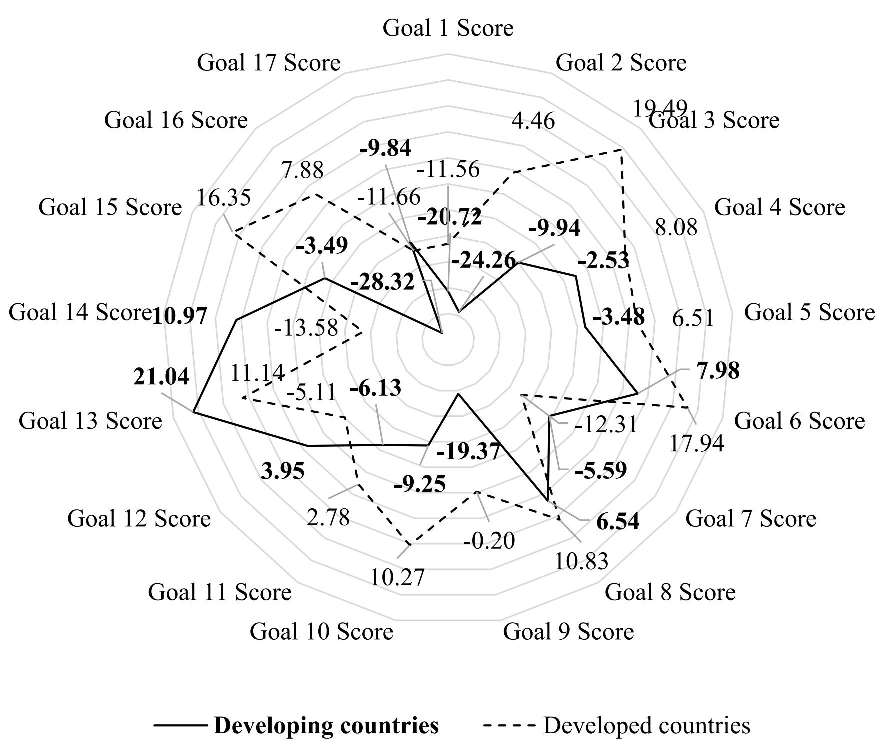


**Fig. 8.** Correlation between the cost to mine 1 bitcoin (USD) and the results in the SDGs in developed and developing countries, %.
Source: Authors.

blockchain as a progressive technology of Industry 4.0 able to improve the performance progressively and, accordingly, the effectiveness of climate change and clean energy transition practices cover three key directions.

1. Execution of blockchain projects (sustainable investments, smart contracts, carbon units, blockchain oracles, and climate change factors);

2. Formation of an extensive database and its organization based on blockchain guarantees reliability, preservation, and safety;
3. Blockchain technologies forecast and control climate change and clean energy transition during big data analytics.

Many successful cases of using blockchain to solve climate change and clean energy transition are available worldwide.

– the Treelion app combines cryptocurrencies and eco-products, supported by PricewaterhouseCoopers, based on smart contracts backed by the World Economic Forum.
– the Mitigation token (MITO) by DAO ICPI and trading carbon units by Laszlo Giric in the Poseidon project;
– the blockchain-ecosystem DAO IPCI in Russia was approved and supported by the Russian President's counsellor on the issues of climate change, the World Bank, Framework Convention on Climate Change, UN FCCC, and the UN Green Climate Fund (GFC);
– the Blockchain oracles – apps for intelligent analytics of data from the Internet or other sources – e.g., Internet of Things, promoted by the Global Commission on Adaptation, and used by Apple, Google, Morgan Stanley, PepsiCo, and Walmart;
– the Centers for data processing based on blockchain, successful examples of practical implementation include Ascribe, Factom, and Cloud of Siberia, supported by corporations, particularly Facebook.

Through the chosen inductive analysis, a model depicting the study's outcomes and its relationships with the blockchain projects to solve climate change clean energy transition. We develop a model for comprehensively implementing projects with systemic management and extracting a synergic effect. This new model ultimately benefits from a comprehensive impact on climate change and clean energy transition by collecting and analyzing data, regularly monitoring the severity of mounting climate change and clean energy transition forecasting and stimulating the environmental responsibility of producers and consumers. The importance of the findings for policymaking is about this extra practice that would be ubiquitous and maximize the contribution of blockchain to achieve SDG 7 and SDG 13.

## Author contributions

Elena G. Popkova: Conceptualization, Writing- Original draft preparation, Software; Aleksei V. Bogoviz: Data curation, Methodology; Svetlana V. Lobova: Visualization; Natalia G. Vovchenko: Investigation; Bruno S. Sergi: Writing- Reviewing and Editing.

## Declaration of competing interest

The authors declare no competing interests.

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