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SMART GRID AND ENERGYTECH AS QUALITY MANAGEMENT TOOLS IN ENERGY 4.0

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A B S T R A C T

The article aims to support the decarbonization process and the fight against climate change, as well as contribute to the reduction of global energy and environmental inequality. The purpose of the article is to clarify the causal relationships of quality management in Energy 4.0 and to determine the prospects for improving this management based on Smart Grid and EnergyTech. The study is carried out in the context of geographical regions of the world on the example of 115 countries according to data for 2022, based on the method of regression analysis, analysis of variance and the methodology of game theory. As a result, it has been proved that with the spread of digital technologies, not all, but only some indicators in Energy 4.0 improve, that is, the potential for quality improvement is not fully revealed. The authors have also concluded that the quality in Energy 4.0 is determined by the spread of advanced technology and investment in energy with private participation. The theoretical significance is due to the fact that the compiled econometric model has clarified the scale and nature of the impact of Smart Grid and EnergyTech on quality in Energy 4.0. The practical significance of the conclusions made by the authors is related to the fact that the article has revealed the prospects for the development of Smart Grid and EnergyTech in regions of the world through the prism of the consequences for quality in Energy 4.0 and global inequality. The significance of the authors' recommendations for energy policy is that the developed new approach to energy policy 4.0 makes it possible to improve public quality management system in Energy 4.0 based on Smart Grid and EnergyTech. The managerial significance of the article is expressed in the fact that the authors' recommendations make it possible to improve management information systems in the field of quality in Energy 4.0 and to increase the efficiency of corporate quality management in the practice of energy companies using such tool as Smart Grid and EnergyTech.

1. INTRODUCTION

Energy 4.0 is an energy sector, in which advanced technologies of industry 4.0 are introduced and actively used. In the process of the Fourth Industrial Revolution, there is an intensive digitalization of the economy. With the accumulation of experience in this area, the contradictory nature of digitalization becomes more and more obvious, in particular, manifested in the field of quality in Energy 4.0.

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On the one hand, the introduction of advanced technologies in the energy sector makes it possible to improve the quality of energy supply services provided through “smart” accounting and management of energy supply, strengthening energy security (sufficiency and stability of energy supply), increasing the energy efficiency of economic processes, contributing to the rise in energy availability and its environmental friendliness. Smart Grid and EnergyTech are the tools of quality management in Energy 4.0.

On the other hand, digitalization of the rest of the economy (except the energy sector) may negate the benefits of digitalization for quality in Energy 4.0. Thus, industrial plants raise their capacities in the process of digitalization, thereby increasing the amount of energy consumed. The robotization of the high-tech industry limits the use of energy from renewable sources. Digitalization of services, agriculture and the agro-industrial complex as a whole increases the energy intensity of the economic processes taking place in them.

The problem lies in the imperfection of the approach to state regulation of the digitalization of energy, that is, to energy policy 4.0. A serious drawback of the existing approach is due to the fact that it allows spontaneous digitalization of the economy. The established approach to energy policy 4.0 does not regulate either the order or the proportion of digitalization of energy and non-energy sectors of the economy. Therefore, the digitalization of energy does not keep up with the pace of digitalization of other sectors of the economy, which does not enable to realize the complete potential of quality improvement in Energy 4.0.

The urgency of the problem and the need to solve it is explained by the fact that the insufficiently high quality in Energy 4.0 slows down the process of decarbonization and hinders the fight against climate change. Differences in quality in Energy 4.0 among the countries of the world reinforce global environmental inequality.

Recognizing the high relevance of the problem, this article seeks to strengthen the scientific and methodological basis for its solution and aims to clarify the cause-and-effect relationships of quality management in Energy 4.0 and identify prospects for improving this management based on Smart Grid and EnergyTech.

The chosen purpose determins the logical structure of this article, which includes four research parts. The first part defines the specifics of quality in Energy 4.0 and the technological readiness of geographical regions of the world for Smart Grid and EnergyTech, as well as the scale of global quality inequality in Energy 4.0.
The second part is devoted to the development of an econometric model of the impact of Smart Grid and EnergyTech on quality in Energy 4.0. The third part reveals the prospects for the development of Smart Grid and EnergyTech in regions of the world through the prism of the consequences for quality in Energy 4.0 and global inequality from the standpoint of game theory. In the fourth part, a new approach to energy policy 4.0 is developed to improve quality management in Energy 4.0 based on Smart Grid and EnergyTech.

2. LITERATURE REVIEW

2.1. Smart Grid and EnergyTech: their advantages as innovative quality management tools in Energy 4.0

The fundamental basis of this research is the scientific concept of management information systems in the field of quality in Energy 4.0 (Malek et al., 2023). Smart Grid and Energy Tech are promising quality management tools in this concept, which become more accessible and their capabilities expand as the energy economy is digitalized (Arumugham et al., 2023).

Smart Grid is a “smart” electricity network (Repuri and Darsy, 2023). Its peculiarity lies in the fact that it enables to combine the urban energy infrastructure into a single system, the advantages of which are:

- Transparency: all elements of the energy infrastructure in Smart Grid are equipped with digital sensors and therefore are fully calculated and taken into account in the activities of energy companies. Smart Grid eliminates gaps in energy infrastructure (Yu et al., 2023);
- Integration: disparate objects of energy infrastructure in the Smart Grid form a single network in which they are closely interconnected and actively interact. This provides a synergistic effect in the form of a higher quality of energy supply services (Saleem et al., 2023);
- Predictability: automated corporate accounting and smart analytics in Smart Grid make it possible to accurately predict changes in the volume of electricity consumption (demand), equipment breakdowns, etc. (Alzahrani et al., 2023);
- Controllability: Smart Grid allows continuous automated monitoring of power supply and provides intelligent support for management decision-making process (Al Ka’bi, 2021);
- Continuity and safety: digital sensors transmit information in real time about the state of energy infrastructure facilities. This makes it possible to timely identify the presence of energy infrastructure facilities that are in a pre-emergency and emergency condition and to start the procedure for their maintenance and repair as soon as possible. Thanks to this, the risks of technical failures and power outages

are significantly reduced in Smart Grid (Lesnykh et al., 2023);

- Manageability: In Smart Grid, management commands are automatically transferred from the decision-making center to energy infrastructure facilities through digital sensors receiving information. This accelerates the implementation of management decisions and increases the efficiency of management of energy companies, provides the opportunity for their management to respond to consumer requests in the shortest possible time, guaranteeing high quality of energy supply services (Yarahmadi and Soleimani-Alya, 2021);
- Universal coverage and convenience: in Smart Grid, the opportunities for the development of energy infrastructure are most favorable. This makes it possible to expand the power supply networks and connect new customers to them in an accelerated mode. Due to this, Smart Grid provides mass electrification. In particular, Smart Grid supports the development of urban electric transport, including electric vehicles, by creating and expanding networks of electric charging stations for them (Miroshnyk et al., 2023).

EnergyTech represents high technologies in the energy sector (Martínez et al., 2023; Wang et al., 2023). Their peculiarity lies in the fact that they allow automating the processes of extraction of fuel and energy resources, their distribution and consumption, the advantages of which are:

- "Smart" energy supply management: automated identification of use opportunities for renewable energy, connection of "clean" energy sources (for example, solar panels) and switching to alternative energy sources when "clean" energy is unavailable or inappropriate. Remote activation of machinery and equipment is also carried out to save electricity during periods of downtime of technical equipment (Popkova et al., 2022);
- "Smart" energy consumption metering: "smart" meters allow measuring energy consumption most accurately and reliably, and their readings can be used to determine possibilities for saving energy (Popkova and Sergi, 2023);
- "Smart" monitoring, control and regulation of energy supply: reducing carbon emissions (Popkova, 2023);
- Energy saving: high technologies make it possible to identify, eliminate and prevent leakage (loss) of energy resources during their transportation, including delivery to consumers. Also, high technologies allow to improve the energy efficiency of economic processes – to reduce energy consumption while maintaining and even increasing productivity (Popkova and Sergi, 2021);
- Environmental safety: high technologies in the energy sector, in particular, are used for quick and effective liquidation of the consequences of energy disasters, for example, gas leaks and oil spills (Popkova et al., 2023).

Thus, the numerous advantages listed above indicate that such innovative management tools in the energy sector as Smart Grid and EnergyTech make a serious contribution to improving quality in Energy 4.0.

2.2 Actual problems of digitalization for quality management in Energy 4.0

Energy policy 4.0 refers to government regulation of energy digitalization aimed at improving quality (Wang et al., 2021; Ye et al., 2023). The key drawback of the existing approach to energy policy 4.0 is that it assumes exclusive management of the process of digitalization of the energy economy, while the rest of the sectors of the economy undergoing digitalization remain not covered by the energy management (Xin-gang and Ying, 2023). At the same time, it is important to emphasize that the quality in Energy 4.0 depends not only on the production and distribution of energy, but also on its consumption (Tangsunantham and Pirak, 2023; Tolmachev et al., 2023).

So, for example, the refusal of economic entities among consumers to use energy from renewable sources slows down the transition to "clean" energy, while the environmental friendliness of the energy provided is one of the components of its quality. Uneven character of digitalization of energy and non-energy sectors of the economy, due to the narrowness of energy policy 4.0, reduces the quality in Energy 4.0 and thereby increases the environmental costs and climate risks of the Fourth Industrial Revolution (Popkova and Shi, 2022).

The existing publications do not describe in sufficient detail and do not fully explain the consequences of energy policy 4.0 for quality in Energy 4.0. The uncertainty of these consequences is a gap in the literature and raises the following two research questions (RQs). **RQ_1:** How actively are the advanced technologies, which are widely spread in the process of digitalization, used in Energy 4.0? The target results of the use of advanced technologies, which are widely spread in the process of digitalization, for quality in Energy 4.0 is, firstly, electrification:

- Increasing the availability of electricity for the broad masses of the population – increasing the coverage of households by electricity supply networks (Milin et al., 2022);
- Increasing the share of population with access to clean fuels and technology for cooking (Cary, 2019).

Secondly, it is decarbonization:

- Growth of the share of renewable energy in the structure of energy consumption in the economy (Safina and Khokhlov, 2017; Vechkinzova et al., 2022);
- Reduction of carbon emissions by reducing energy consumption and switching to “clean” energy (Steblyakova et al., 2022).

From published works by authors such as Ha (2022), Li et al. (2021), Sheng and Cao (2023), it follows that the advanced technologies, which are widely spread in the process of digitalization, are used in Energy 4.0 with the same activity as in other sectors of the economy. This means that there must be a positive relationship between the spread of advanced technologies and the noted consequences for quality in Energy 4.0.

In contrast to the above researchers, Dorji et al. (2023), Gwiazdowicz and Natkaniec (2023), Wang et al. (2023) indicate that advanced technologies are introduced and used less actively in the energy sector than in other industries. Based on this, the authors put forward the following hypothesis H_1: with the spread of digital technologies, not all, but only some indicators in Energy 4.0 are improved, that is, the potential for quality improvement is not fully revealed.

RQ_2: Under what conditions does digitalization contribute to quality improvement in Energy 4.0? In their publications, authors such as Li et al. (2022), Mika and Goudz (2021), Nwaigwe (2022) note that digitalization contributes to quality improvement in Energy 4.0 with the active introduction of digital technologies into the energy sector (technological condition).

Однако, Hang et al. (2022), Merrifield and Fowler (2023), Turginbayeva and Domalatov (2019) in their works write that the technological condition is insufficient. They believe that digitalization will contribute to improving the quality in Energy 4.0 if the financial and managerial condition is also met - the influx of private investment and the introduction of private management of energy digitalization projects. This has served as the basis for the hypothesis H_2: quality in Energy 4.0 is determined by the spread of advanced technology and investment in energy with private participation.

In order to find clarifying answers to the RQs posed in the article and to test the hypotheses put forward, the authors carry out econometric modeling of the impact of the spread of digital technologies and investment in energy with private participation on quality in Energy 4.0 in the context of its selected components: 1) the degree of the coverage of households by electricity supply networks; 2) the share of population with access to clean fuels and technology for cooking; 3) the share of renewable energy in in the energy mix and 4) the total carbon emissions.

3. MATERIALS AND METHODOLOGY

3.1 Sampling and control variables

The objects of this research are Smart Grid and EnergyTech as quality management tools in Energy 4.0. The study is carried out in the context of geographical regions of the world defined by UN (2023). The sample includes 115 countries: 17 E. Europe & C. Asia countries (14.78%), 15 East & South Asia countries (13.04%), 14 LAC countries (12.17%), 12 MENA countries (10.43%), 38 OECD countries (33.04%), 19 Sub-Saharan countries Africa (16.52%). Due to this, all the selected geographical regions of the world are represented in the sample.

The study is conducted on the basis of data for 2022 (or the latest data available from official statistics and relevant for 2022). The empirical base of the study is given in the appendix to this article and includes statistical data on the following indicators. Smart Grid and EnergyTech factors:

- Readiness for frontier technologies index, total score (Techno, UNCTAD, 2023);
- Investment in energy with private participation, billion current US$ (Invest, World Bank, 2023a).

Quality in Energy 4.0 is assessed using the results in the field of electrification, measured by indicators:

- Population with access to electricity, % (Electr, UN, 2023);
- Population with access to clean fuels and technology for cooking, % (ClFuels, UN, 2023).

And the results in the field of decarbonization, measured by indicators:

- Renewable energy consumption, % of total final energy consumption (RenEn, World Bank, 2023b);
- Total greenhouse gas emissions, kt of CO_2 equivalent (GrHouse, World Bank, 2023c).

3.1 The order of the study

The purpose is achieved through the solution of four tasks. The first task of the study is to determine the specifics of quality in Energy 4.0 and the technological readiness of geographical regions of the world for Smart Grid and EnergyTech, as well as the scale of global inequality of quality in Energy 4.0. To solve this problem, we find arithmetic averages of indicators characterizing quality in Energy 4.0, as well as indicators characterizing technological readiness for Smart Grid and EnergyTech, in the context of the studied regions of the world.

Using the method of analysis of variance, the coefficients of variation of the arithmetic averages of all studied indicators among the selected geographical regions of the world are calculated. Thus, the global inequality in the field of quality in Energy 4.0 and technological readiness for Smart Grid and EnergyTech in 2022 has been quantified.

The second task is related to the development of an econometric model of the impact of Smart Grid and EnergyTech on quality in Energy 4.0. To solve this problem, the regression analysis method is used. The research model is compiled at the level of the global economy (for the entire sample of 115 countries); it is a system of linear regression equations and has the following form:

$$\begin{cases} Electr=a_1+b_{11}*Techno+b_{12}*Invest; \\ ClFuels=a_2+b_{21}*Techno+b_{22}*Invest; \\ RenEn=a_3+b_{31}*Techno+b_{32}*Invest; \\ GrHouse=a_4+b_{41}*RenEn. \end{cases} \quad (1)$$

The research model (1) is used to test the hypotheses put forward in the article. The hypothesis H_1 is considered proved if not all of the regression coefficients b_{11}, b_{21} and b_{31} are positive. This will indicate that with the spread of digital technologies, not all, but only some indicators in Energy 4.0 are improved, that is, the potential for quality improvement is not fully revealed. The hypothesis H_2 is considered proved if at least some of the regression coefficients b_{12}, b_{22} and b_{32} are positive. This will mean that quality in Energy 4.0 is determined by the spread of advanced technology and investment in energy with private participation.

The third task is to reveal the prospects for the development of Smart Grid and EnergyTech in regions of the world through the perspective of their implications for quality in Energy 4.0 and global inequality. The methodology of game theory is used to solve this task. The applicability and preference of the methodology of game theory for the study of Smart Grid and EnergyTech is confirmed by the existing publications of authors such as Amin et al. (2021), Devi et al. (2023), Naji El Idrissi et al. (2023). Based on the research model (1), the authors determine the necessary growth rate of factor variables to maximize the resulting variables at the level of the global economy through the least squares method.

The predicted values of factor variables in each region are calculated by finding the product of arithmetic averages for the region in 2022 and the obtained growth rate. The resulting values are substituted into the research model (1) and the predicted increase in the dependent variables is determined. The game approach involves the creation and comparison of two alternative scenarios: 1) the scenario of advanced digitalization of Energy 4.0 and 2) the scenario of delayed digitalization of Energy 4.0. Using the method of trend analysis, the predicted implications of each scenario for global inequality in the field of quality in Energy 4.0 are identified.

The fourth task is to develop a new approach to energy policy 4.0 for improving quality management in Energy 4.0 based on Smart Grid and EnergyTech. The authors' approach reflects the subjects and mechanisms of quality management in Energy 4.0, as well as the preferred order of digitalization of economic sectors in the interests of the fullest disclosure of the potential for quality improvement in in Energy 4.0.

4. RESULTS

4.1. Quality in Energy 4.0 and technological readiness for Smart Grid and EnergyTech: the specifics of the world's regions and global inequality

To solve the first task aimed at determining the specifics of quality in Energy 4.0 and technological readiness of geographical regions of the world for Smart Grid and EnergyTech, the arithmetic averages of indicators characterizing quality in Energy 4.0, as well as indicators characterizing technological readiness for Smart Grid and EnergyTech, are calculated by the studied regions of the world (Table 1).

Table 1. Average assessment of quality in Energy 4.0 and technological readiness of the regions of the world for Smart Grid and EnergyTech

Geographical region of the world	Smart Grid and EnergyTech factors		Quality in Energy 4.0			
			Electrification		Decarbonization	
	Readiness for frontier technologies index, total score	Investment in energy with private participation, billion current US$	Population with access to electricity, %	Population with access to clean fuels and technology for cooking, %	Renewable energy consumption, % of total final energy consumption	Total greenhouse gas emissions, kt of CO_2 equivalent
E. Europe & C. Asia	0.56	0.09	99.96	88.30	18.02	238433.14
East & South Asia	0.53	0.75	95.07	60.00	30.64	459988.22
LAC	0.43	0.07	93.69	76.81	28.74	76200.73
MENA	0.56	0.10	99.93	99.46	4.37	227717.56
OECD	0.81	0.11	99.99	99.20	29.67	673067.99
Sub-Saharan Africa	0.25	0.29	54.90	27.68	49.67	174936.76

Source: calculated and compiled by the authors based on materials of UN (2023), UNCTAD (2023), World Bank (2023a), World Bank (2023b), World Bank (2023c).

The results from Table 1 indicate that the technological readiness for Smart Grid and EnergyTech is highest in the countries of East & South Asia and OECD, and the quality in Energy 4.0 as a whole is quite high, but its characteristics vary among the regions of the world.

Using the analysis of variance, the coefficients of variation of the arithmetic averages of all studied indicators among the selected geographical regions of the world are calculated from Table 1 (Table 2).

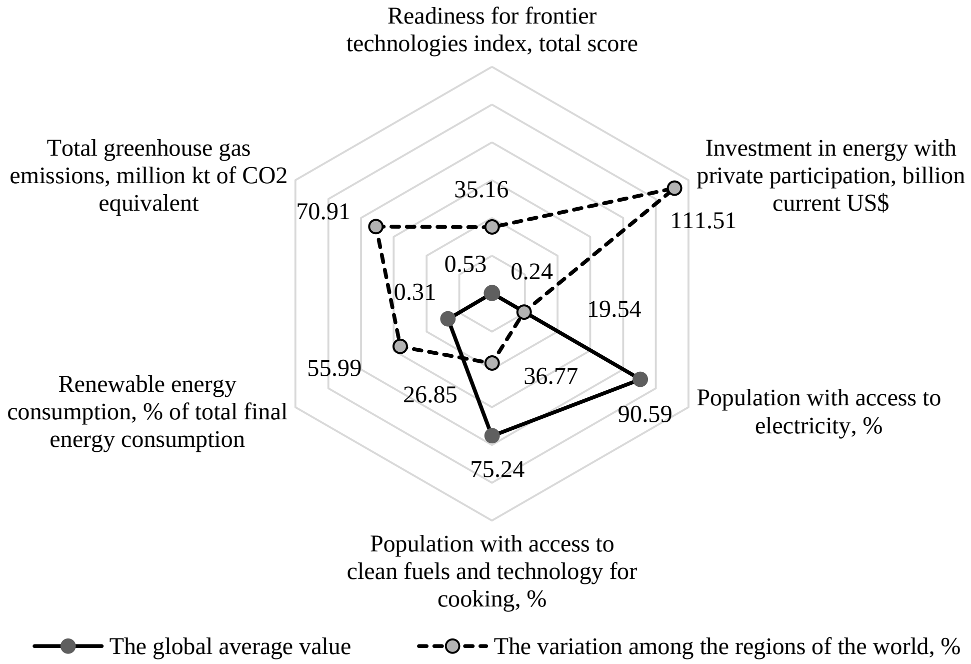

Figure 1. Global quality inequality in Energy 4.0 and technological readiness for Smart Grid and EnergyTech
Source: calculated and constructed by the authors.

The results obtained in Fig. 1 indicate a significant global inequality in the quality in Energy 4.0 (variation from 19.54% to 70.91%) and in the field of technological readiness of the regions of the world for Smart Grid and EnergyTech (variation from 35.16% to 111.51%) in 2022.

4.2. Econometric model of the impact of Smart Grid and EnergyTech on quality in Energy 4.0

To solve the second problem related to the development of an econometric model of the impact of Smart Grid and EnergyTech on quality in Energy 4.0, the authors have carried out a regression analysis of the sample data, the results of which are presented in Tables 2-6.

Table 2. Regression analysis of the dependence of population with access to electricity on Smart Grid and EnergyTech factors

Regression Statistics						
Multiple R	0.6899					
R-Square	0.4759					
Adjusted R-Square	0.4665					
Standard Error	13.6618					
Observations	115					
ANOVA				*Fischer's F-test*		
	df	SS	MS	F-actual	F-critical	Signi-ficance F
Regression	2	18982.4900	9491.2450	50.8516		$1.94*10^{-16}$
Residual	112	20904.3436	186.6459	Passed at α=0.01		
Total	114	39886.8336				
Regression Parameters						
	Coeffi-cients	Standard Error	t-Stat	P-Value	Lower 95%	Upper 95%
Constant	60.2068	3.3492	17.9765	$8.55*10^{-35}$	53.5708	66.8427
Techno	53.5790	5.3130	10.0845	$2.09*10^{-17}$	43.0520	64.1061
Invest	0.5745	1.9471	0.2951	0.7685	-3.2834	4.4324

Source: calculated and compiled by the authors.

According to the results from Table 2, population with access to electricity is 68.99% determined by the influence of Smart Grid and EnergyTech factors in accordance with the following pattern:

$$Electr=60.2068+53.5790*Techno+0.5745*Invest \quad (2)$$

Equation (2) indicates that the share of population with access to electricity grows by 53.5790% with an increase in the readiness for frontier technologies index by 1 point. The share of population with access to electricity rises by 0.5745% with an increase in investment in energy with private participation by 1 billion current US$. Equation (2) is reliable at a significance level of 0.01.

Table 3. Regression analysis of the dependence of population with access to clean fuels and technology for cooking on Smart Grid and EnergyTech factors

Regression Statistics						
Multiple R	0.7758					
R-Square	0.6018					
Adjusted R-Square	0.5983					
Standard Error	19.7877					
Observations	115					
ANOVA				*Fischer's F-test*		
	df	SS	MS	F-actual	F-critical	Signi-ficance F
Regression	1	66877.0946	66877.0946	170.7992		$2.43*10^{-24}$
Residual	113	44245.6033	391.5540	Passed at α=0.01		
Total	114	111122.6980				
Regression Parameters						
	Coeffi-cients	Standard Error	t-Stat	P-Value	Lower 95%	Upper 95%
Constant	20.2137	4.7885	4.2213	4.93E-05	10.7267	29.7006
Techno	100.5006	7.6900	13.0690	2.43E-24	85.2653	115.7358

Source: calculated and compiled by the authors.

According to the results from Table 3, the population with access to clean fuels and technology for cooking is 77.58% determined by the influence of Smart Grid and EnergyTech factors in accordance with the following pattern:

$$ClFuels=20.2137+100.5006*Techno \quad (3)$$

Equation (3) shows that the share of population with access to clean fuels and technology for cooking grows by 100.5006% with an increase in readiness for frontier technologies index by 1 point. Equation (3) is reliable at a significance level of 0.01.

Table 4. Regression analysis of the dependence of renewable energy consumption on Smart Grid and EnergyTech factors

Regression Statistics						
Multiple R	0.3836					
R-Square	0.1472					
Adjusted R-Square	0.1319					
Standard Error	22.6394					
Observations	115					
ANOVA				*Fischer's F-test*		
	df	SS	MS	F-actual	F-critical	Signi-ficance F
Regression	2	9906.1203	4953.0601	9.6637		0.0001
Residual	112	57404.9572	512.5443	Passed at α=0.01		
Total	114	67311.0775				
Regression Parameters						
	Coeffi-cients	Standard Error	t-Stat	P-Value	Lower 95%	Upper 95%
Constant	50.3868	5.5500	9.0786	$4.41*10^{-15}$	39.3901	61.3835
Techno	-38.3734	8.8044	-4.3584	0.0000	-55.8181	-20.9286
Invest	1.3311	3.2266	0.4125	0.6807	-5.0620	7.7241

Source: calculated and compiled by the authors.

According to the results from Table 4, renewable energy consumption is 38.36% determined by the influence of Smart Grid and EnergyTech factors in accordance with the following pattern:

$$RenEn=50.3868-38.3734*Techno+1.3311*Invest \quad (4)$$

Equation (4) indicates that the share of renewable energy consumption decreases by 38.3734% with an increase in the readiness for frontier technologies index by 1 point. The share of renewable energy consumption rises by 1.3311 with an increase in investment in energy with private participation by 1 billion current US$. Equation (4) is reliable at a significance level of 0.01.

Table 5. Regression analysis of the dependence of renewable energy consumption on investment in energy with private participation

Regression Statistics						
Multiple R	0.0502					
R-Square	0.0025					
Adjusted R-Square	-0.0063					
Standard Error	24.3756					
Observations	115					
ANOVA				*Fischer's F-test*		
	df	SS	MS	F-actual	F-critical	Signi-ficance F
Regression	1	169.8045	169.8045	0.2858		0.5940
Residual	113	67141.2730	594.1706	Passed at α=0.60		
Total	114	67311.0775				
Regression Parameters						
	Coeffi-cients	Standard Error	t-Stat	P-Value	Lower 95%	Upper 95%
Constant	28.2235	2.3941	11.7888	0.0000	23.4803	32.9666
Invest	1.8559	3.4716	0.5346	0.5940	-5.0220	8.7338

Source: calculated and compiled by the authors.

The results from Table 5 make it possible to create an alternative regression equation:

$$RenEn=28.2235+1.8559*Invest \quad (5)$$

Equation (5) demonstrates that the share of renewable energy consumption rises by 1.8559 with an increase in investment in energy with private participation by 1 billion current US$. Equation (5) is reliable at a significance level of 0.60.

Table 6. Regression analysis of the dependence of total greenhouse gas emissions on renewable energy consumption

Regression Statistics						
Multiple R	0.1363					
R-Square	0.0186					
Adjusted R-Square	0.0099					
Standard Error	1346051.8657					
Observations	115					
ANOVA				*Fischer's F-test*		
	df	SS	MS	F-actual	F-critical	Signi-ficance F
Regression	1	$3.8738*10^{12}$	$3.8738*10^{12}$	50.8516	2.1380	0.1465
Residual	113	$2.0474*10^{14}$	$1.8119*10^{12}$	Passed at α =0.15		
Total	114	$2.0861*10^{14}$				
Regression Parameters						
	Coeffi-cients	Standard Error	t-Stat	P-Value	Lower 95%	Upper 95%
Constant	596748.1176	194452.5662	3.0689	0.0027	211502.5125	981993.7226
RenEn	-7586.1867	5188.2217	-1.4622	0.1465	-17864.9896	2692.6161

Source: calculated and compiled by the authors.

According to the results from Table 6, total greenhouse gas emissions is 13.63% determined by the influence of renewable energy consumption in accordance with the following pattern:

$$GrHouse=596748.1176-7586.1867*RenEn \quad (6)$$

Equation (6) indicates that total greenhouse gas emissions are reduced by 7586.1867 kt of CO_2 equivalent with an increase in renewable energy consumption by 1%. Equation (6) is reliable at a significance level of 0.15. Thus, the negative value of the regression coefficient b_{31} in the research model (1) (in equation (4)) has confirmed the hypothesis H_1.

Positive values of regression coefficients b_{12} and b_{32} in the research model (1) (in equations (2), (4), (5)) have confirmed the hypothesis H_2.

4.3. Prospects for the development of Smart Grid and EnergyTech in the regions of the world from the perspective of their implications for quality in Energy 4.0 and global inequality: a view from the standpoint of game theory

As part of the solution of the third task, two alternative scenarios have been compiled using the methodology of game theory to reveal the prospects for the development of Smart Grid and EnergyTech in the regions of the world from the perspective of their implications for quality in Energy 4.0 and global inequality.

The scenario of advanced digitalization of Energy 4.0 (Table. 7) has been compiled based on equations (2), (3), (5) and (6). Using the least squares method, the necessary growth rate of factor variables is determined to maximize the dependent variables at the level of the global economy. The required growth rate of readiness for frontier technologies index is 1.38 and the required growth rate of for investment in energy with private participation is 9.24.

Table 7. The scenario of advanced digitalization of Energy 4.0 and its implications for quality

Geographical region of the world	Smart Grid and EnergyTech factors		Quality in Energy 4.0			
			Electrification		Decarbonization	
	Readiness for frontier technologies index, total score	Investment in energy with private participation, billion current US$	Population with access to electricity, %	Population with access to clean fuels and technology for cooking, %	Renewable energy consumption, % of total final energy consumption	Total greenhouse gas emissions, kt of CO_2 equivalent
Arithmetic mean values of indicators in geographical regions of the world						
E. Europe & C. Asia	0.78	0.84	100.00	98.29	29.78	370854.98
East & South Asia	0.74	6.95	100.00	94.18	41.13	284725.02
LAC	0.59	0.68	92.23	79.55	29.49	373068.70
MENA	0.78	0.96	100.00	98.46	30.01	369088.56
OECD	1.12	1.05	100.00	100.00	30.17	367850.42
Sub-Saharan Africa	0.35	2.66	80.38	55.18	33.16	345187.33
The increase in the values of indicators in geographical regions of the world, %						
E. Europe & C. Asia	38.00	824.00	0.04	11.32	65.29	55.54
East & South Asia	38.00	824,00	5.19	56.97	34.22	-38.10
LAC	38.00	824.00	-1.56	3.56	2.60	389.59
MENA	38,00	824.00	0.08	-1.00	587.38	62.08
OECD	38.00	824.00	0.01	0.80	1.68	-45.35
Sub-Saharan Africa	38.00	824.00	46.42	99.32	-33.24	97.32

Source: calculated and compiled by the authors based on the materials

Using the method of trend analysis, Fig. 2 demonstrates the predicted implications of the scenario under consideration for global quality inequality in Energy 4.0.

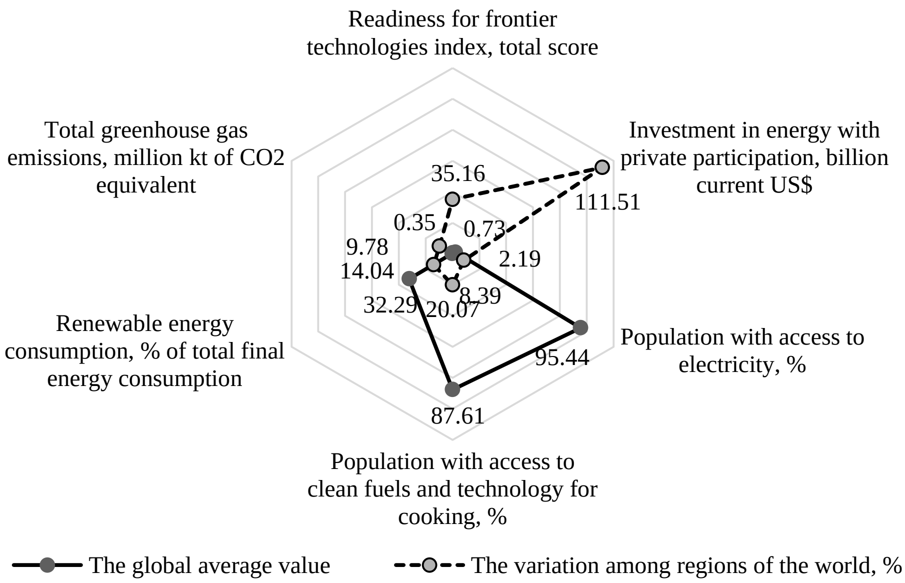

Figure 2. Global quality inequality in Energy 4.0 according to the scenario of its advanced digitalization

Source: calculated and constructed by the authors.

According to Fig. 2, the scenario of advanced digitalization of Energy 4.0 will not only improve its quality, but also significantly reduce global inequality in its quality. Thus, the variation of population with access to electricity will decrease to 8.38%, the variation of population with access to clean fuels and technology for cooking will decline to 20.07%, the variation of renewable energy consumption will fall to 14.04%, and the variation of total greenhouse gas emissions will reduce to 9.78%. The scenario of delayed digitalization of Energy 4.0 (Table 8) is developed based on equations (2), (3), (4) and (6). Using the least squares method, the necessary growth rate of factor variables is found to maximize the dependent variables at the level of the global economy. The required growth rate of the readiness for frontier technologies index is 1.38.

Using the method of trend analysis, Fig. 3 shows the predicted implications of the scenario under consideration for global inequality in the quality in Energy 4.0.

Table 8. The scenario of delayed digitalization of Energy 4.0 and its implications for quality

Geographical region of the world	Smart Grid and EnergyTech factors		Quality in Energy 4.0			
			Electrification		Decarbonization	
	Readiness for frontier technologies index, total score	Investment in energy with private participation, billion current US$	Population with access to electricity, %	Population with access to clean fuels and technology for cooking, %	Renewable energy consumption, % of total final energy consumption	Total greenhouse gas emissions, kt of CO_2 equivalent
Arithmetic mean values of indicators in geographical regions of the world						
E. Europe & C. Asia	0.77	0.09	100.00	97.72	20.91	438100.60
East & South Asia	0.73	0.75	99.79	93.65	23.35	419607.01
LAC	0.59	0.07	91.66	79.12	27.99	384398.60
MENA	0.77	0.10	100.00	97.89	20.87	438452.23
OECD	1.12	0.11	100.00	100.00	7.71	538287.81
Sub-Saharan Africa	0.35	0.29	78.88	54.92	37.52	312141.56
The increase in the values of indicators in geographical regions of the world, %						
E. Europe & C. Asia	38.00	0.00	0.04	10.67	16.06	83.74
East & South Asia	38.00	0.00	4.97	56.08	-23.80	-8.78
LAC	38.00	0.00	-2.17	3.00	-2.62	404.46
MENA	38.00	0.00	0.08	-1.58	378.03	92.54
OECD	38.00	0.00	0.01	0.80	-74.01	-20.02
Sub-Saharan Africa	38.00	0.00	43.69	98.38	-24.46	78.43

Source: calculated and compiled by the authors based the basis on the materials

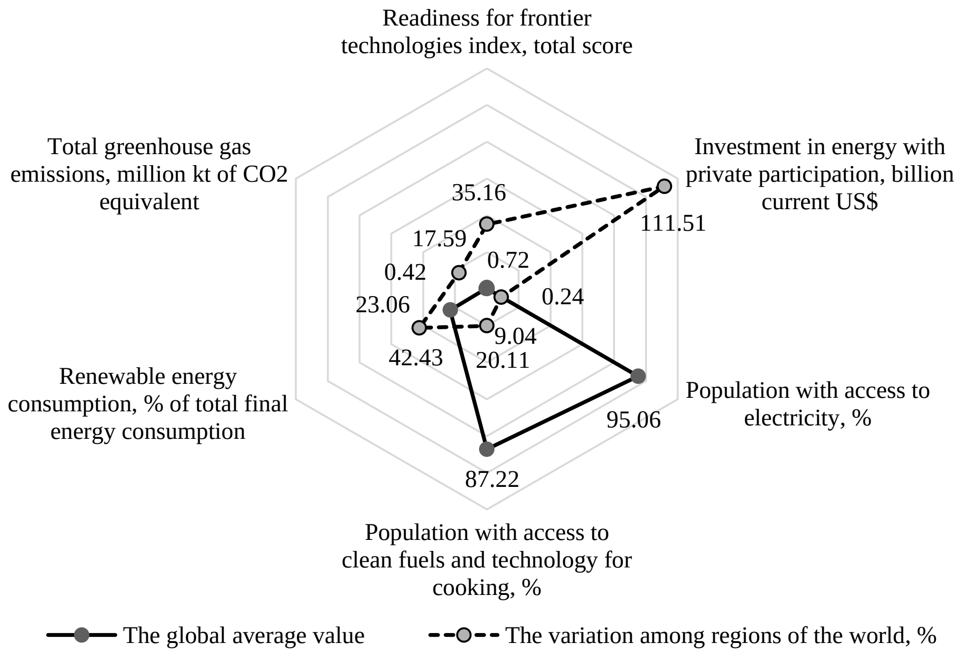

Figure 3. Global quality inequality in Energy 4.0 under the scenario of its delayed digitalization
Source: calculated and constructed by the authors.

According to Fig. 3, the scenario of advanced digitalization of Energy 4.0 will lead to a decrease in its quality, but to some extent will reduce global inequality in its quality.

4.4. The new approach to energy policy 4.0 to improve quality management in Energy 4.0 based on Smart Grid and EnergyTech

To solve the fourth task, aimed at improving quality management in Energy 4.0 based on Smart Grid and EnergyTech, the authors have developed a new approach to energy policy 4.0 (Fig. 4).

The new approach to energy policy 4.0 presented in Figure 4 assumes that the subjects of quality management in Energy 4.0 are not only state regulators, but also private venture and infrastructure investors. The approach involves the use of the mechanism of public-private partnership and the mechanism of infrastructure (technological) support for quality management in Energy 4.0.

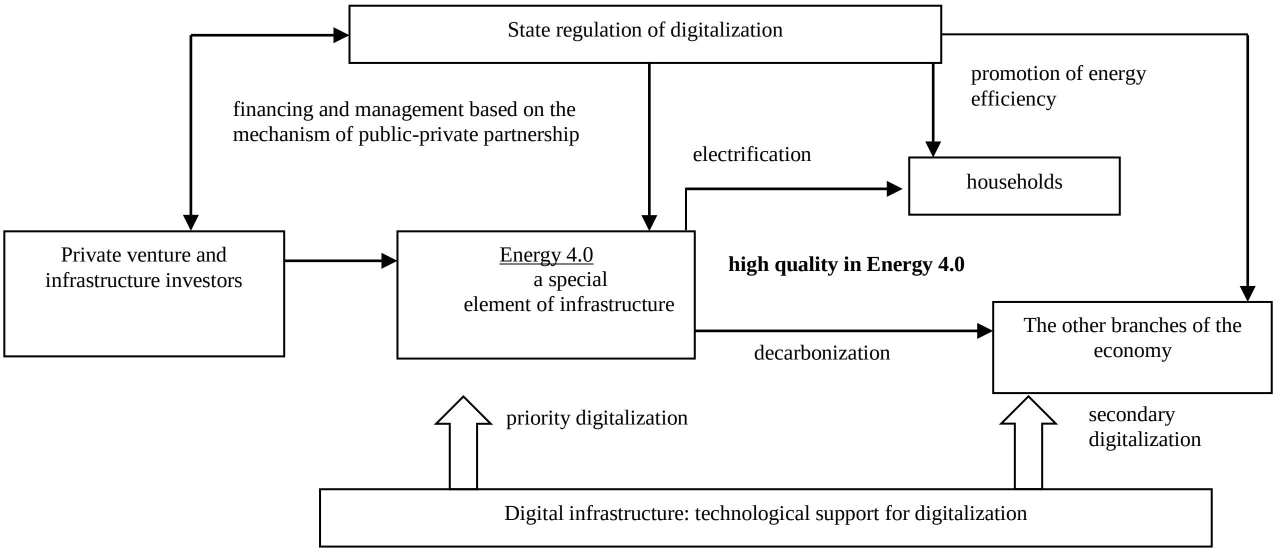

Figure 4. The new approach to energy policy 4.0 to improve quality management in Energy 4.0 based on Smart Grid and EnergyTech
Source: developed by the authors

There is a new order of digitalization of economic sectors in the authors' approach. First, there is a primary digitalization of Energy 4.0, and then there is a secondary digitalization of the rest of the economy. Thanks to the mentioned innovations, the developed approach makes it possible to fully unlock the potential for quality improvement in Energy 4.0 – to increase the level of electrification and the rate of decarbonization.

5. DISCUSSION

The contribution of the article to the literature is explained by the fact that it complements the concept of management information systems in the field of quality in Energy 4.0, offering recommendations for improving quality management using the tools of Smart Grid and EnergyTech. The contribution of the obtained results to the increment of scientific knowledge is justified in Table 9.

As shown in Table 9, the article received a new answer to RQ_1. Unlike Ha (2022), Li et al. (2021), Sheng and Cao (2023), it has been proved that advanced technologies, which are widely spread in the process of digitalization, are used in Energy 4.0 much less actively than in other sectors of the economy. The hypothesis H_1 has been proved in support of the works of Dorji et al. (2023), Gwiazdowicz and Natkaniec (2023), Wang et al. (2023). The contribution of new answers to the increment of scientific knowledge is made through the compiled econometric model of the impact of Smart Grid and EnergyTech on quality in Energy 4.0.

A new answer to RQ_2 has also been received. Unlike Li et al. (2022), Mika and Goudz (2021), Nwaigwe (2022), it has been proved that digitalization contributes to quality improvement in Energy 4.0 while following not only technological condition, but also financial and managerial one, consisting in the influx of private investment and introduction of private management of energy digitalization projects. The hypothesis H_2 has been proved in support of the works of Hang et al. (2022), Merrifield and Fowler (2023), Turginbayeva and Domalatov (2019). The contribution of new answers to the increment of scientific knowledge is made through the developed new approach to energy policy 4.0 to improve quality management in Energy 4.0 based on Smart Grid and EnergyTech.

Table 9. Substantiation of the contribution of the obtained results to the increment of scientific knowledge

The objects to be compared		**Research questions posed in the article (RQs)**	
		RQ_1: How actively are the advanced technologies, which are widely used in the process of digitalization, used in Energy 4.0?	**RQ_2:** Under what conditions does digitalization contribute to quality improvement in Energy 4.0?
Existing literature	Available answers to RQs	The activity of use is the same as in other sectors of the economy	Provided that digital technologies are actively introduced in the energy sector (technological condition)
	References	Ha (2022), Li et al. (2021), Sheng and Cao (2023)	Li et al. (2022), Mika and Goudz (2021), Nwaigwe (2022)
This article	New answers to RQs	In the energy sector, advanced technologies are introduced and used less actively than in other sectors of the economy	Provied that there is an influx of private investment and the introduction of private management of energy digitalization projects (additional: financial and managerial condition)
	The results of testing the hypotheses (H)	The hypothesis H_1 is proved	The hypothesis H_2 is proved
	Confirmation in the literature	Dorji et al. (2023), Gwiazdowicz and Natkaniec (2023), Wang et al. (2023)	Hang et al. (2022), Merrifield and Fowler (2023), Turginbayeva and Domalatov (2019)
	Contribution of the new answers to the increment of scientific knowledge	The econometric model of the impact of Smart Grid and EnergyTech on quality in Energy 4.0 has been developed	The new approach to energy policy 4.0 has been developed to improve quality management in Energy 4.0 based on Smart Grid and EnergyTech

Source: developed and compiled by the authors.

6. CONCLUSION

In accordance with the results of the conducted research, two key conclusions can be drawn. The first conclusion is that with the spread of digital technologies, not all, but only some indicators in Energy 4.0 improve, that is, the potential for quality improvement is not fully revealed. The second conclusion is that quality in Energy 4.0 is determined by the spread of advanced technology and investment in energy with private participation. The theoretical significance of the results obtained in the article is due to the fact that they mathematically describe with high accuracy and explain more fully the implications of energy policy 4.0 for quality in Energy 4.0. The developed econometric model has clarified the scale and nature of the impact of Smart Grid and EnergyTech on quality in Energy 4.0. The existence of a new financial and managerial condition under which digitalization contributes to quality improvement in Energy 4.0, consisting in the influx of private investment and the introduction of private management of projects for energy digitalization, has been substantiated.

The practical significance of the conclusions is related to the fact that the article has revealed the prospects for the development of Smart Grid and EnergyTech in the regions of the world from the perspective of the implications for quality in Energy 4.0 and global inequality. An innovative view from the standpoint of game theory has allowed the authors to justify the preference of the scenario of advanced (compared to other industries) digitalization of Energy 4.0, since this scenario will ensure quality improvement in Energy 4.0 in all regions of the world, as well as reduce global inequality in quality.

The significance of the author' recommendations for energy policy is that the developed new approach to energy policy 4.0 makes it possible to improve public quality management in Energy 4.0 based on Smart Grid and EnergyTech. The managerial significance of the article is expressed in the fact that the authors' recommendations make it possible to improve management information systems in the field of quality in Energy 4.0 and to increase the efficiency of corporate quality management in the practice of energy companies using such tools as Smart Grid and EnergyTech.

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