APPLICATION OF SYSTEM ANALYSIS IN THE DEVELOPMENT OF GREEN ENERGY IN UKRAINE

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This research is devoted to an overview of the use of system analysis in the context of green energy development in Ukraine. The article focuses on systems analysis methods as an important tool for solving complex problems related to planning, choosing between several alternatives, types of renewable energy, optimisation and implementation of projects in this field. An illustrative project example demonstrates the practical application of these methods. The article describes the process of completing the stages of systematic analysis, such as collecting and analysing information on the state of the country's energy sector, building a production model for presenting knowledge based on the collected facts, necessary actions and proposals; forecasting and making the most rational decisions based on expert assessment and objective analysis methods. The article also explores the use of mathematical tools based on a systematic approach and methods of mathematical modelling.

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Introduction

Ukraine's energy sector has taken a significant damage during the military conflict, which has created the need to restore and modernise the infrastructure. The aggressor state, Russia, is using energy as a weapon in this war through direct attacks on Ukraine's energy infrastructure, which highlights the need for secure energy supply and resilient energy systems. The Kyiv School of Economics (KSE) analytical team estimates that damages in Ukraine's energy sector as of May 2024 amounted to more than $16.1 billion (KSE Institute, 2024a). Expanding renewable energy production in the country leads the way to Ukraine's energy independence and will be a strategically important step in the country's recovery. Several recent studies have explored the integration of renewable energy and system analysis in the Ukrainian context, affirming the relevance of this topic. One notable study conducted by researchers at ETH Zurich mapped Ukraine's energy infrastructure and highlighted the country's vast potential for solar and wind energy development. Their geospatial analysis emphasized the importance of decentralizing the energy grid, which would make it more resilient to both war and future crises (Doronina et al., 2024)

Among other factors, climate change and the growing need for sustainable development are causing countries to look for alternatives to traditional energy sources. At the same time, Ukraine has considerable potential for green energy development. The use of systems analysis can help to use this potential and expedite the development process. Therefore, the exploration of the role of systems analysis in this context is extremely relevant.

Green energy development requires an integrated approach due to its complex nature. Solving this problem involves not only the construction of green energy objects, but also the consideration of various factors such as geographical conditions, climate, resource availability, infrastructure and economic opportunities. This process becomes extremely complex due to the correlation and co-dependence of different factors, which makes a systems analysis useful and appropriate to effectively solve the problem and achieve optimal results.

The purpose of the article is to research and develop an illustrative example of the application of systems analysis methods to emphasise its effectiveness and importance in solving complex problems of green energy development in Ukraine.

Materials and Methods

The approach began by collecting and processing data on the country's energy sector, which had been severely impacted by the ongoing war. Various renewable energy alternatives (solar, wind, hydro, and geothermal) were examined using system models, decision trees, and mathematical tools such as linear programming and simplex method. Expert assessments and the analytical hierarchy process were employed to evaluate the feasibility and potential outcomes of different renewable energy sources.

Results and Discussion

Systems analysis is based on the systems approach, which is based on the idea that the functioning of any part or element of a system affects the functioning of its other parts or elements and the system as a whole. We will use systems analysis to study the complex system of the energy sector, identifying the connections between subsystems and the system as such, with the environment, the metasystem – a larger external system, which includes the system under research, because any system is in a certain environment, therefore, when analysing it, it is necessary to consider the impact of external factors.

There is no single standard methodology for applying system analysis. We will propose and consider our approach, taking into account the specifics related to the subject area and the general principles of integrity, consistency, unity of elements and interdependence of parts and the whole.

We have already defined the goal and objectives of the study – the ultimate goal is to solve a number of issues to ensure the development of the country's green energy sector.

Let's proceed to the next stage of the analysis – collecting and processing information. The Ukrainian energy sector has become one of the key targets of Russian attacks. According to the World Bank, more than 50% of Ukraine's energy infrastructure has been damaged. The most vulnerable were large thermal power plants and CHPs. Green energy, which accounted for more than 13% of the production structure before the war and was increasing its capacity, was not an exception. According to the Energy Charter Secretariat, 13% of solar generation capacity is located in the occupied territories, and 8% has been damaged or destroyed; about 80% of wind generation is occupied and part of it has been damaged by attacks; 2% of bioenergy capacity is under occupation, and at least 4 biogas plants have been reported to have been destroyed (KSE Institute, 2024 b). The stability of the energy system can be improved through reserve, autonomous and decentralised energy supply, especially from renewable sources. This means the use of solar, wind, hydro, biomass and biogas energy. The construction of a large number of small generation facilities is the basis for decentralising the energy system.

The next stage will be to identify the structure of the object (energy sector), describe Its characteristics and conditions of existence. The energy sector is a key industry segment of the economy that provides energy to all spheres of society. The conditions for the energy sector have deteriorated recently: access to resources, economic stability, and, ultimately, the geopolitical context have all had a negative impact. However, Ukraine has everything necessary to overcome these challenges. Technological progress, environmental requirements and resources are in good condition. Considering the subsystem of our interest, the renewable energy sector of Ukraine, we can say that the following types of renewable energy are currently actively developing: solar energy (including solar installations for private households), wind energy, bioenergy, and hydroenergy. The amount of capacity of a particular type of renewable energy facility follows in the same order.

Let us proceed directly to the methods of system analysis, going through the following stages: studying the object with the help of models and informal methods; refining hypotheses about the mechanism of the object's functioning, adjusting models; developing decisions on the management of the system object; predicting the consequences of the implementation of the developed management decisions, choosing the most rational ones for practical implementation.

We will build a production model of knowledge representation in the subject area "Renewable Energy Sector of Ukraine".

Target action: "Development of renewable energy", "financing of the process". Sub-target actions: selecting the type of renewable energy, selecting the geography of the location of renewable energy facilities, according to the natural potential of a particular region (Barylo et al., 2020). Let's consider the conditions for action. Choosing the type and geography of location: availability of resources in general and specific ones, potential capacity. To be specific, let's assume we have four alternative types of renewable energy (solar, wind, hydro, and geothermal).

Define facts (F), actions (A) and proposals (P):

Facts: (F1): The entrepreneur wants to develop the green energy sector. (F2): The entrepreneur has the financing. (F3): Solar energy provides the most capacity of all other types of energy. (F4): Wind energy is second after solar energy. (F5): Geothermal is not developed but has potential. (F6): Hydro had a share of 3% of electricity from renewable energy sources in 2021.

Actions: (A1): The entrepreneur chooses the type of energy. (A2): Entrepreneur chooses solar. (A3): Entrepreneur chooses wind. (A4): Entrepreneur chooses geothermal. (A5): Entrepreneur chooses hydropower. (A6): Entrepreneur selects a location for a particular type. (A7): The entrepreneur obtains financing. (A8): The entrepreneur chooses a location for solar: the largest part of solar radiation falls in the south of the country (Odesa, Mykolaiv, Kherson, Zaporizhzhia, Donetsk regions). (A9): The entrepreneur chooses a location for wind: the offshore wind is more powerful and constant than the onshore wind, wind turbines on the coast of the southern territories of Ukraine generate much more green electricity, but it makes sense to locate them in the west (Lviv and Ternopil regions) and in the centre, if we look at the map of wind flows. (A10): The entrepreneur chooses a location for hydropower: The main cascades of hydroelectric power plants are the Dnipro cascade and the Dniester cascade. (A11): The entrepreneur chooses a location for geothermal: The most suitable conditions for the development of hydrothermal resources are in the Precarpathian region (Lviv, Ivano-Frankivsk), the Dnipro-Donetsk Rift (Chernihiv, Poltava, Sumy, Kharkiv) and the Black Sea coast (Kherson and Odesa). (A12): Decision-making.

Proposals: (P1): If (F1) and (F2), then (A1). (P2): If (F3) and (A1), then (A2). (P3): If (F4) and (A1), then (A3). (P4): If (F5) and (A1), then (A4). (P5): If (F6) and (A1), then (A5). (P6): If (A2 or A3 or A4 or A5), then (A6). (P7): If (A6), then (A7). (P8): If (A7 and A2), then (A8). (P9): If (A7 and A3), then (A9). (P10): If (A7 and A4), then (A11). (P11): If (A7 and A5), then (A10). (P12): If (A8 or A9 or A10 or A11), then (A12).

The next stage is to build a decision tree, a graphical model for analysing decisions under risk. To make a decision after building the decision tree, we calculate the expected profits.

The entrepreneur does not know which type or types of renewable energy to choose. The results will show a successful or unsuccessful implementation. The entrepreneur assumes that there is a 90% chance that the development of solar energy will be successful with a profit of $8 billion, 70% for wind energy with a profit of $7 billion, 40% for geothermal with a profit of $4 billion, and 50% with a profit of $3 billion for hydro. There is a 10% chance that the development of solar energy will be unsuccessful with a loss of $5 billion, 30% for wind energy with a loss of $6 billion, 60% for geothermal with a loss of $10 billion, and 50% with a loss of $5 billion for hydro. For each type, investments are required: $4 billion for solar, $3 billion for wind, $3 billion for geothermal, and $2 billion for hydro.

The result of the decision tree is obtained by determining the expected value for each possible solution: Solar energy: $2.7 billion; wind energy: $100 million; geothermal energy: -$7.4 billion; hydropower: -$3 billion (Figure 1).

To summarise, when choosing a solution with the highest expected value, it is most appropriate for an entrepreneur to choose solar and wind energy.

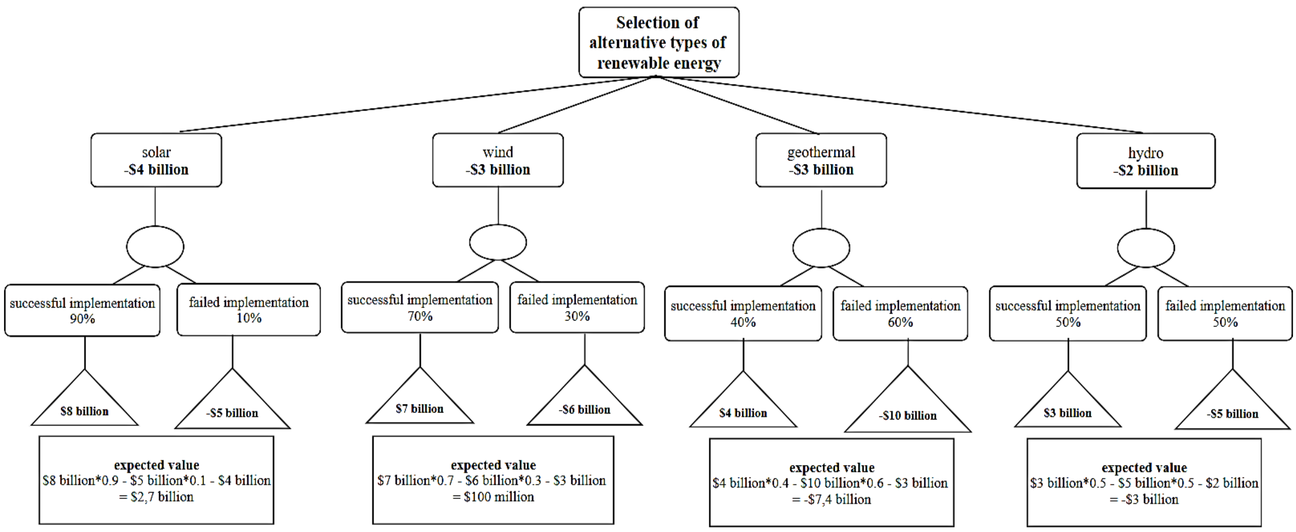

Figure 1. The decision tree (*Source:* author's research)

We will also form a generalised expert assessment of alternative types of renewable energy to decide on the key ones for their further development.

The analysis was carried out by 4 experts who assigned appropriate ranks to each option in accordance with their personal opinion on the feasibility of using each alternative. Selection of the expert group:

– Energy engineer: a specialist with knowledge of the energy sector and an understanding of the production, transmission and use of energy from various sources, including renewable energy sources.
– Ecologist: a specialist with knowledge of the environmental impacts and sustainability of different types of energy, able to assess the environmental aspects of different alternatives.

– Economist: a specialist in economics who can analyse the costs, economic efficiency and benefits of developing different types of renewable energy.
– Political analyst: a specialist who understands the political context and legal aspects that affect the development of renewable energy, such as legislation, regulation and geopolitical factors.

This composition of the expert group will allow to cover different aspects and benefits of different types of renewable energy, which will contribute to a more objective and balanced decision.

First, we calculated the sum of the scores assigned to each alternative. Then we divided this sum by the number of experts – 4 – and then calculated the arithmetic mean rank. Based on the average ranks, we build the final ranked series based on the principle that the higher the average rank, the more advantageous the alternative is. A3 has the lowest rank, equal to 3, so it gets rank 4 in the final ranked sequence. The next highest value is 4, for A4, and it gets rank 3. A2 has a rank of 2 with a value of 8, and A1 has a rank of 1 with a value of 9 (Table 1).

Table 1. The process of expert assessment

	solar	**wind**	**geothermal**	**hydro**
№ of expert	**Alternatives**			
	A1	**A2**	**A3**	**A4**
1	9	6	2	4
2	7	9	4	1
3	9	7	1	6
4	10	8	5	3
Sum of ranks	**35**	**30**	**12**	**14**
Mean arithmetic rank	8.75	7.5	3.0	3.5
Final rank	9	8	3	4
General view of the ranked series	A3<A4<A2<A1			

Source: author's research

We can see that the result is the same as in the decision tree, with solar and wind power remaining the most preferred alternatives.

Using the results above, we will apply the analytical hierarchy method, a mathematical tool of the systems approach to decision making, to make the final choice between solar and wind energy.

The advantage of the analytical hierarchy method is that it uses a pairwise comparison to determine the relative weight of different factors, and then applies them at each level of the factors to calculate the overall weight. From this, an objective score can be calculated for each alternative.

The importance of each factor is ranked in relation to the others, for example: resource availability is a much less important factor than economic benefits. Resource availability is slightly more important than technological potential. Resource availability is a much more important factor than energy production potential. Economic benefit is a much more important factor than resource availability. Economic benefit is a much less important factor than technological potential. Economic benefit is a much less important factor than energy production potential, and so on (Table 2).

Calculating the ratings: Now we need to calculate the total weight for each factor. This is called the "priority vector". This is the total weight for each criterion. This result indicates that the resource availability influences the final result by 34% and is the most influential factor. Economic profit has an impact on the final result of 22%. Technology potential influences the final result by 17%. Energy production potential influences the final result by 27% (Table 3).

Table 2. A pairwise comparison of the factors

	Resource availability	Economic profit	Technology potential	Energy production potential
Resource availability	1.00	0.20	4.00	6.00
Economic profit	5.00	1.00	0.14	0.20
Technology potential	0.25	7.00	1.00	0.17
Energy production potential	0.17	5.00	6.00	1.00
Total	6.42	13.20	11.14	7.37

Source: author's research

Table 3. Normalisation of values of factors and priority vector calculation

	Resource availability	Economic profit	Technology potential	Energy production potential	Priority Vector
Resource availability	0.16	0.02	0.36	0.81	0.34
Economic profit	0.78	0.08	0.01	0.03	0.22
Technology potential	0.04	0.53	0.09	0.02	0.17
Energy production potential	0.03	0.38	0.54	0.14	0.27
Total	1.00	1.00	1.00	1.00	1.00

Source: author's research

Let's compare each alternative based on the lowest level criteria in our decision-making hierarchy, repeating the previous steps. We see the following: there are more solar energy resources than wind energy. The economic profit will be greater if we choose solar. The factor of technology potential is higher in the case of wind energy. The energy production potential is higher for solar energy (Table 4). Finally, the priority vector of each factor is multiplied by the score of each alternative, and summed up by row to obtain the final score. With a score of 0.71 for solar and 0.29 for wind, we make a choice for solar (Table 5).

This approach allowed us to systematically compare two green energy alternatives and choose the most optimal development path, taking into account various criteria and their importance.

Finally, we apply linear programming methods by making mathematical modelling to optimise the use of limited resources.

Let us consider a scenario where an entrepreneur in Ukraine wants to build solar panels on a piece of land he owns.

We will formulate a linear programming problem to optimise the implementation of a solar power system. Consider different types of solar panels with different output power, cost, and space requirements. The task is to maximise the total output power of the solar panels.

Table 4. Pairwise comparison of alternatives by factors

Resource availability	solar	wind	Priority Vector
solar	0.75	0.75	0.75
wind	0.25	0.25	0.25
Total	1	1	1

Technology potential	solar	wind	Priority Vector
solar	0.2	0.2	0.2
wind	0.8	0.8	0.8
Total	1	1	1

Economic profit	solar	wind	Priority Vector
solar	0.86	0.86	0.86
wind	0.14	0.14	0.14
Total	1	1	1

Energy production potential	solar	wind	Priority Vector
solar	0.88	0.88	0.88
wind	0.13	0.13	0.13
Total	1	1	1

Source: author's research

Table 5. Final Scores

Energy type / Aspect	Resource availability	Economic profit	Technology potential	Energy production potential	Overall Priority
solar	0.75	0.86	0.20	0.88	0.71
wind	0.25	0.14	0.80	0.13	0.29
	0.34	**0.22**	**0.17**	**0.27**	

Source: author's research

Let's define the following variables:
x_1, x_2, x_3 – number of solar panels of type 1, 2 and 3, accordingly.
Parameters:
P_1, P_2, P_3 – output power per one panel of type 1, 2 and 3, accordingly.
C_1, C_2, C_3 – cost of one panel of type 1, 2 and 3 accordingly.
S_1, S_2, S_3 – space required for one panel of type 1, 2 and 3, accordingly.
B – the total budget available for the project.
A – total space available for panel placement.

Let's describe the problem using a mathematical model:

$$Z = P_1 * x_1 + P_2 * x_2 + P_3 * x_3 \to max, \quad (1)$$

on condition that:

$$C_1 * x_1 + C_2 * x_2 + C_3 * x_3 \leq B; \quad (2)$$

$$S_1 * x_1 + S_2 * x_2 + S_3 * x_3 \leq A; \quad (3)$$

$$x_1, x_2, x_3 \geq 0. \quad (4)$$

In this model, the target function Z represents the total power output to be maximized. The first constraint ensures that the total cost does not exceed the budget, and the second constraint ensures that the panels do not require more space than is available. Non-negativity constraints are standard in all linear programming problems, meaning that we cannot have a negative number of panels.

Let's look at realistic values for the parameters of a solar power project in Ukraine, given a budget of $4 billion. P_1, P_2, P_3 – let's assume that the average output power is 250 W, 300 W and 350 W, accordingly. C_1, C_2, C_3 – based on the current market situation (*Solar market prices* ...), we estimate the costs at $200, $240, and $280, accordingly. S_1, S_2, S_3 – taking into account the average area required (*What area is required* ...), we will allocate 1.6 m², 1.8 m² and 2.0 m² per panel. B – the total budget is $4 billion. A – let's say there is a large amount of land, such as 1,000,000 square metres, available for solar panel installation. Given these parameters, we can find the optimal number of solar panels to maximise the power output within the $4 billion budget. We will do this using the simplex method. For the first iteration, let's reduce the system of inequalities to a system of equations by adding additional variables – move to the canonical form. In the first inequality, we define the base variable x_4. In the second inequality, we define the base variable x_5.

$$Z = 250 * x_1 + 300 * x_2 + 350 * x_3 + 0 * x_4 + 0 * x_5 \to max, \quad (5)$$

on condition that:

$$200 * x_1 + 240 * x_2 + 280 * x_3 + x_4 = 4\,000\,000\,000; \quad (6)$$

$$1{,}6 * x_1 + 1{,}8 * x_2 + 2 * x_3 + x_5 = 1\,000\,000; \quad (7)$$

$$x_1, x_2, x_3, x_4, x_5 \geq 0. \quad (8)$$

Let's solve the system of equations with regard to the base variables: x_4, x_5. Assuming that the free variables are equal to 0, we have the first optimal plan: $X_0 = (0{,}0{,}0{,}4000000000{,}1000000)$.

The current reference plan is not optimal because the index row contains negative coefficients. Let's recalculate the simplex table by selecting the solving column and solving row, finding the solving element at their intersection (Table 6).

Table 6. Representation of the simplex table

Coefficients of basic variables	Basic variable	x_1	x_2	x_3	x_4	x_5
x_4	3860000000	-24	-12	0	1	-140
x_3	500000	0.8	0.9	1	0	0.5
Z	175000000	30	15	0	0	175

Source: author's research

$X_1 = (0{,}0, 500000, 3860000000, 0)$.

There are no negative values in the index row, so this table determines the optimal plan for the problem. The optimal plan can be written as follows: $x_1 = 0,\ x_2 = 0,\ x_3 = 500000$.

$$Z = 250 * 0 + 300 * 0 + 350 * 500000 = 175000000. \tag{9}$$

Analysis of the optimal plan: the optimal plan includes an additional variable x_4, which means that if this plan is implemented, there are underutilised resources of the first type in the amount of 3,860,000,000. A value of 30 > 0 in the column x_1 means that the use of x_1 is not profitable. A value of 15 > 0 in column x_2 means that the use of x_2 is not profitable. A value of 0 in column x_3 means that the use of x_3 is profitable. Thus, it is profitable for an entrepreneur to choose panels of type 3 under the given conditions.

Based on the results of all the steps we have taken, we conclude that it is profitable for an entrepreneur to choose solar energy if he wants to develop the renewable energy sector in Ukraine. Based on the results of the expert evaluation method, the decision tree method and the analytical hierarchy method, it is the most rational choice and will bring him a profit of USD 2.7 billion with an initial investment of USD 4 billion, and has an advantage over wind energy when considering the criteria of resource availability, economic profit, technology potential, energy production potential.

Conclusion

This study illustrates how systems analysis can be used to overcome the complex problems associated with energy sector management with a focus on green energy development. Following these steps allowed us to gain a deeper understanding of the subject area, analyse information and systematise our knowledge. We identified green energy development strategies to optimise the use of available resources. The methodology used takes into account various factors, such as the current state of infrastructure, available resources, the potential of different types of renewable energy, and other circumstances, to determine the optimal plan for green energy development.

Conflict of interest

The authors state no conflict of interest.

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