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TECHNO-ECONOMIC ASSESSMENT OF IMPLEMENTING THE PROTECTION OF SOLAR BATTERIES IN SPACECRAFT POWER SYSTEMS

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Abstract. *Sustainable development of the space activity will only be made possible once space users will be implementing technologies and practices that are capable of ensuring the use of energy efficient technologies. The presented study employs a method of creating a fuzzy cognitive map of protection of solar batteries in spacecraft power systems. A cognitive model has been developed for the purpose of determining the level of protection of solar batteries in spacecraft power systems. The paper contains an elaborated scenario which reflects the system's response under complex maximum mitigation of influence from the most substantial concepts. As a conclusion, practical implementation of the method enables to anticipate the degree of protection of solar batteries in spacecraft power systems and contributes to the implementation of the required mechanisms of prevention, protection and access control on corresponding levels of energy infrastructure.*

Keywords: *solar battery, spacecraft, cognitive modelling, energy efficient technology, payback period.*

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Introduction

A possible area for the use of solar energy in the 21st century consists in the creating orbital power plants with solar batteries which accumulate the solar energy and convert it into microwave or laser emission directed towards the Earth where it is collected by special antennas and eventually transformed into the electric energy.

One of the efficient sources of energy in the space activity is the use of solar energy. In space, with no atmosphere, clouds and day-night change cycles, ten times more solar energy is projected per unit area than reaches the Earth's surface. However, extreme factors of solar batteries operation in space formulate the necessity for thorough substantiation of parameters for their selection.

An important issue in the development of solar energy is the high cost of energy. Improvement of the reliability, durability and safety of solar cells are the main ways to reduce the cost of energy. A significant, still unsolved problem is the failure of individual solar cells in the solar systems for generating power. Up to 30% of damage occurs due to the presence of individual defective solar cells (Nakashidze et. al., 2020). This leads to a significant reduction in the generating capacity of the entire power generation system, or until its complete failure. In order to solve this problem, it is possible to use switching elements with a positive temperature coefficient of resistance, in particular, thin films based on polymer nanocomposites with wire fillers, which are capable of blocking damaged solar cells.

This puts into the foreground a scientific search in the domain of development of energy efficient technologies, determination of electrothermal protection of solar batteries in spacecraft power systems, reduction of failures, etc.

The purpose of the present paper is to substantiate the improved methodology of techno-economic assessment of implementing the protection of solar batteries in spacecraft power systems.

According to the specified purpose of the paper the following tasks must be resolved: to conduct an analysis of technical and economic indicators that impact the performance efficiency of solar batteries in spacecraft power systems; to develop a cognitive model for determining the degree of impact of threats on the level of protection of solar batteries in spacecraft power systems; to study the structural properties of the elaborated cognitive model; to conduct a scenario modeling for the purpose of defining a relative change in the level of protection of solar batteries in spacecraft power systems.

Literature Review

The formation of a strategy for the development of industrial enterprises on the basis of energy saving is a process that allows studying the possible behavior of energy suppliers in order to choose the most acceptable energy supply option for a certain period of time (Bowen, 2018).

The real possibility of choosing suppliers of energy products, taking into account the need for them to ensure an adequate level of reliability of energy supply in the case of the lowest costs is associated with the formation of a competitive market in the energy sector and with the possibility of buying electricity in the wholesale market (Prunariu & Tulbure, 2017).

The development strategy of industrial enterprises on the basis of energy conservation, which is functional in nature, should be aimed primarily at the imp lementation of a general strategy for the development of an industrial enterprise, at the same time taking into account the state of the internal environment and its possible dynamics (Brady, 2017).

That is why in the case of forming a development strategy for industrial enterprises on the basis of energy conservation, the limitations imposed by the adopted general development strategy of an enterprise on the number of personnel of energy services, the amount of material resources allocated to them and investments to maintain the necessary proportions in the development of the energy sector and core production should be taken into account (Quintana, 2017).

The wide interdependence of individual power plants, the use of fuel and energy resources and the use of technological processes in manufacturing implies an objective need to optimize decisions made in the process of shaping the development strategy of industrial enterprises based on energy saving, taking into account the impact they will ha ve on the economic performance of the enterprise and product competitiveness (Muelhaupt et. al., 2019).

Despite a growing number of current studies within the presented scope, there still remains little to no research effort conducted on the issue of improving the methodology of the techno-economic assessment of implementing the protection of solar batteries in spacecraft power systems. This primarily concerns the issue of determining the implementation of methodology which will enable to trace the interrelation of impact of corresponding technical and economic indicators.

An issue of evaluation of a cumulative impact of threats upon the system and the possibility to determine risks under different scenarios of realization of multiple threats remains vital for conducting an assessment of implementing the protection of solar batteries in spacecraft power systems.

A solution to this issue is possible by means of resorting to the methods of statistical analysis, among others the correlation and regression analysis. However, these methods require complex calculations, significant scope of experimental data, long period of time for processing it and does not ensure the possibility to work with quality factors that are being expertly defined (Pekkanen, 2019). In this regard it is worth drawing attention to the cognitive approach based on creating fuzzy cognitive maps (FCM).

A priority in selecting FCM relates to their simplicity, constructiveness and clearness in visualization; identification of cause-and-effect relations between the elements of a complex system which are otherwise complicated to conduct a qualitative analysis upon by traditional methods; use of knowledge and experience by the experts in the subject area, adaptability to uncertainties in the source data and requirements of the researched problem (Chow, 2020). Furthermore, it is well worth noting the simplicity of expanding the factors by means of introducing additional vertices and arcs to the graph of the cognitive map.

These problems may be solved with the help of the methods of cognitive modeling (Drobyazko et. al., 2021). Cognitive models are developed by an expert or a group of experts in the researched subject area on the basis of the theoretical, statistical and expert information related to the object of research. The adequacy of the model is determined by the comprehensiveness of the body of initial knowledge; the model can be adjusted and refined in the process of research and employment being in itself a source of structured knowledge (Czerny et. al., 2018).

Methods of cognitive modeling are based on the use of FCMs with their inherent relative ease of interpretation, integration with the methods of assessing the results of the analysis, clearness, flexibility, constructiveness, adaptability to uncertainties in the source data, absence of need for preliminary specification of data and reciprocal influence relations (Weinzierl, 2018).

FCM of a complex system (problem) constitutes a directed graph with its vertices (concepts) representing system variables and its arcs – cause-and-effect relations between concepts, moreover the weights of such relations determine the degree of influence of concepts upon one another (Maclay & Mcknight, 2020).

A cognitive map is a model of representation of experts' knowledge on the laws of development and properties of the studied situation while their multiplicity is determined through various types of expert definition of the strength of cause-and-effect relations and significance of factors on the cognitive map.

Results

To develop an FCM which identifies the safety status of protection of solar batteries in spacecraft power systems it is of prime importance to form a set of concepts that prove to be the most substantial from the standpoint of studying the presented problem. Resulting from the survey and the harmonization of views by experts in the given subject area the following concepts have been identified.

C1. Cost of delayed decisions. Potential savings equal the same potential costs if the company does not implement corresponding systems of technical protection of solar batteries.

C2. Maintenance accessibility in emergency situations. Emergency situations in the process solar batteries operation in the conditions of space include: failure of battery opening, fire, space weather, solar cycles, etc. Impossibility to conduct repairs of solar batteries, particularly solar arrays of the truss structure of the ISS, renders spacecrafts fully or partially unpowered.

C3. Service life of solar batteries. Whereas solar batteries on the Earth have a service life of 3-5 years, in the conditions of space a service life of monocrystalline solar batteries is extended to 20 years. Taking into consideration the economic aspect, it is necessary to account for the given payback period in the calculated changes in cost in the operation and maintenance (O&M) (Hilorme & Horbach, 2021).

C4. Cost of solar batteries. Production costs may be defined through adding up the manufacturing costs (costs for development, testing and assembly), costs of operation and maintenance (O&M).

C5. Operational reliability. Operational reliability is manifested in technical characteristics of photovoltaic modules: electrical, mechanical and thermal properties of the model. Operational reliability has a direct impact on the conversion efficiency of solar batteries.

C6. Weight and dimensional parameters. Ensuring a substantial reduction in weight and dimensional characteristics. Due to the use of reusable launch vehicles to transport solar batteries into the orbit, there emerges an issue of the existing maximum value of useful payload of a spacecraft. It is therefore the use of energy efficient technical means of electro-thermal protection is based on their functional capacity to ensure significant reductio in weight and dimensional paraments of solar batteries and their reusability. For instance, the usage of the polymeric posistor nanocomposites of the PolySwitch technology.

C7. The given payback period in the changes in cost in the operation and maintenance (O&M). New equipment may require more or less O&M works. It should be noted that costs that are accounted for in the calculation of this indicator have the following components: the cost of solar batteries, the cost of delivery into orbit and O&M costs (Dron’ et. al., 2022). Each cost component is attributed to different contractors.

Having formulated the list of concepts, it is essential to determine the value of the force of reciprocal influence between each pair of concepts by means of processing the data obtained through the expert survey. For this purpose, the authors propose to specify a fuzzy linguistic scale that represents an ordered set of linguistic values (terms) for assessment of occurrence of possible consequences obtained as a result of influence of one of the concepts on another. Each of these values will be assigned a corresponding specific numeric range which belongs to the interval [0;1] for positive feedback and the interval [-1;0] for negative feedback (Table 1).

Table 1
Linguistic scale for assessing possible consequences of reciprocal influence of concepts

Range of values	Linguistic terms (feedback)
(0.85;1]	positive very strong
(0.6;0.85]	positive strong
(0.35;0.6]	positive medium
(0.15;0.35]	positive weak
(0;0.15]	positive very weak
0	no influence
(0;-0.15]	negative very weak
(-0.15;-0.35]	negative weak
(-0.35;-0.6]	negative medium
(-0.6;-0.85]	negative strong
(-0.85;-1]	negative very strong

Source: author’s development

An FCM that illustrates multiple cause-and-effect relations and the pattern of interaction between the identified factors is represented in the Figure 1.

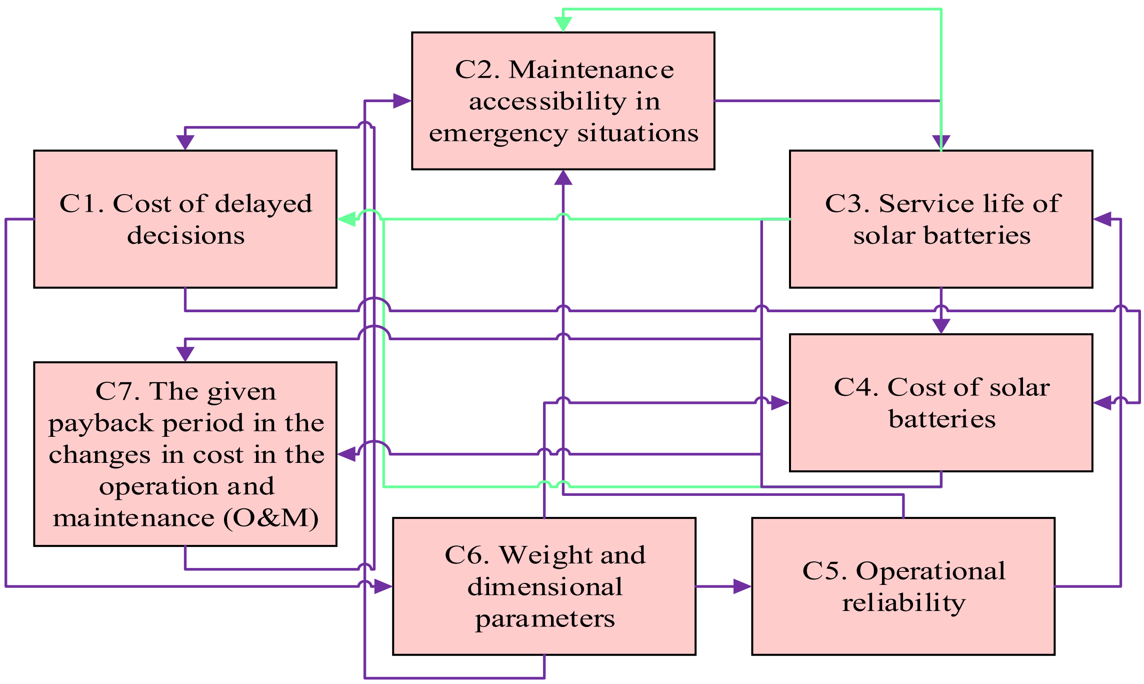

Figure 1. Fuzzy cognitive map of interaction between the identified factors
Source: author’s development

To determine the complexity of the developed FCM a calculation of the density of links will be conducted. The number of concepts according to the model – 7, the number of links – 15, the density of links is 0.08. This indicates a sufficient complexity of the developed cognitive model.

To conduct an analysis of FCM it is imperative to take into consideration an entire scope of indirect reciprocal influence of concepts. For this purpose, an adjacency matrix is elaborated on the basis of the previously developed cognitive map (Table 2).

Table 2
Adjacency matrix of the fuzzy cognitive map

Concept	C1	C2	C3	C4	C5	C6	C7
C1	0	0	-0.38	-0.15	0	0	+0.85
C2	0	0	-0.55	0	+0.86	+0.22	0
C3	0	+0.92	0	0	+0.88	0	0
C4	+0.75	0	+0.94	0	0	+0.64	0
C5	+0.18	0	0	0	0	0	0
C6	0	0	0	0	0	0	0
C7	0	0	+0.92	+0.95	0	0	0

Source: author's development

Having analyzed the values of the presented indicators it is possible to determine the most significant concepts of the examined system: C5 – operational reliability; C4 – cost of solar batteries; C3 – service life; C7 – the given payback period in the changes in cost in the operation and maintenance (O&M). It is furthermore expedient to note that lowest influence on the operation of the grid is demonstrated by the concept under C6 - weight and dimensional parameters.

To obtain forecasts related to the development of the situation a relative change of system's concepts with the maximum value of influence of the most significant concepts must be determined факторів (Drobyazko & Hilorme, 2021). To specify, corresponding scenarios will be modelled. As an instance, a Scenario «How will the state of the system change under the maximum increase in the value of the concept C3 «Service life of solar batteries» will be examined. The calculations will be conducted on the basis of the data in Table 2.

As a consequence of maximum increase in the value of influence of the service life of solar batteries the cost of delayed decision is reduced by 0,02, the maintenance accessibility in emergency situations - by 0,05, operational reliability is increased by 0.06 while the cost of solar batteries is increased by 0,04 (Figure 2).

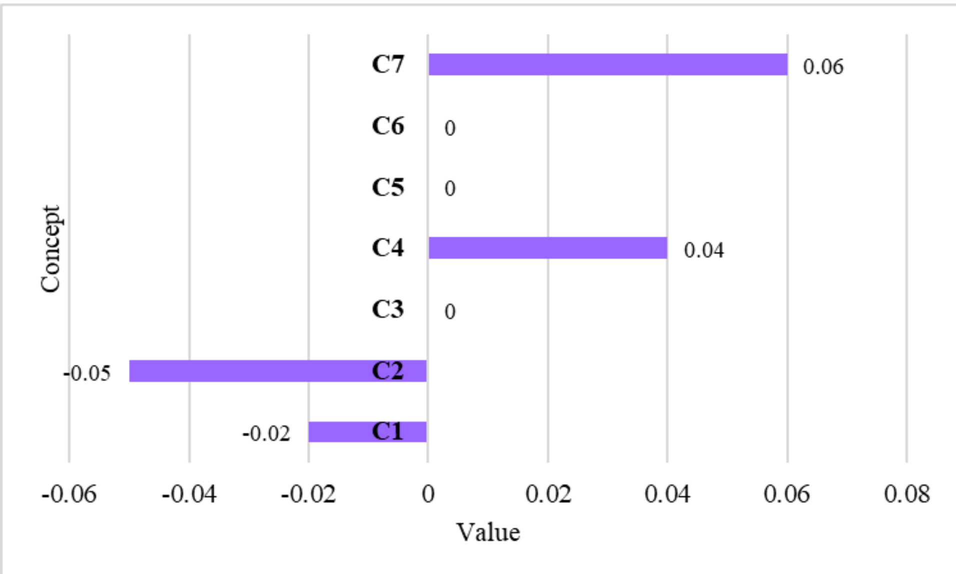

Figure 2. Scenario depicting the reaction of the system to maximum increase in the value of influence of the concept C3 «Service life»

Source: author's development

According to calculations (Figure 2) the most substantial influence under the maximum increase in the value of concept C3 «Service life» is exerted upon the concept C7 «The given payback period in the changes in cost in the operation and maintenance (O&M)».

Profitability indicators cannot be determined without considering supplementary conditions: qualifications of operation and maintenance personnel, operational conditions of energy-intensive equipment, etc. (Hilorme, 2020). The rate, at which energy savings would allow initial capital investments (investments into energy efficiency) to be recouped, must become the primary factor for assessment of the energy modernization as compared to other types of investment. Concurrently, the estimation of the period of delay in the management decision making must be economically justified – how long the actual delay persists (from the concept to making a decision). The management must understand the problem of the «energy efficiency potential» and the cost of delayed decisions.

Discussion

An effective investment project in energy saving should be evaluated, created, selected from a number of possible before it starts to be implemented. As for most difficult controversial issues, it is impossible to immediately select the most optimal investment project, if you do not realize the potentially available opportunities for their risks, requirements and benefits. For a more detailed picture of energy consumption, which will allow to evaluate energy saving projects that are planned to be implemented at industrial enterprises, it is worthwhile to introduce energy management.

In order to determine the effectiveness of an investment project in energy saving, it is necessary to define evaluation criteria. We propose to determine the three components of the coordinate system of the management decision-making plan for an energy saving project: x-value (combination of consumer and business), y-technical capability, z- degree of risk, they in turn have several levels of subcriteria. Thus, value is a compositional characteristic that is a synergy of customer value and business value. Thus, the subcriteria of value are four main characteristics: Cost; Lifetime performance; Security; Reliability.

Quantitative values can be determined by calculating the weighted average distortion coefficient along the axes of the coordinate plane. Thus, the project on energy saving and creation of protection of solar cells against overloads based on polymer nanocomposites has the following investment characteristics: high consumer value, high technical capabilities and medium risk.

We consider the dominant hierarchy of criteria for investment projects on energy saving for industrial enterprises built from the top (from a management point of view) through intermediate levels (criteria on which subsequent levels depend) to the lowest level, which is usually a list of alternatives. The hierarchy is considered complete if each element of a given level functions as a criterion for all elements of a level, stands below. We apply the hierarchy analysis method to determine the strategy of transition to an alternative type of energy carrier.

In order to implement the strategy for the development of industrial enterprises on the basis of energy saving, we are guided by the following criteria: cost; lifetime performance; security; reliability.

In our case, the maximum, taking into account all the criteria, is the estimate of the first alternative-solar energy, which has the highest priority value. On the other hand, the solution of this problem gives us the opportunity to allocate the available resources among alternative options according to their priorities. The next priority is the alternative-the use of biofuel, then-the use of secondary energy resources and in the fourth position-the use of wind energy.

As for the other criteria for the efficiency of an investment project on energy saving-the degree of risk and technical capabilities – we can also highlight the corresponding sub- criteria. Thus, the criterion “degree of risk” has the following hierarchies of criteria of the third order: incompleteness (fuzzy license for the production and sale of energy from alternative energy sources, lack of standards, premature offer from the supplier, fuzzy payment model for use); loss of control (lack of leadership, inconsistency of corporate policy); legal and regulatory issues (compliance with regulatory documents); security issues (data protection, lack of energy audit). The criterion "technical capability" – ease of integration, ease of migration, technological stack and the like.

Conclusion

The paper incorporates a developed cognitive model for the purpose of determining the level of protection of solar batteries in spacecraft power systems. A proposed model allows to define the most substantial threats from the standpoint of studying the presented problem and to analyze a relative change in the level of protection of the studied systems. A structural and topological analysis of the developed fuzzy cognitive map is being undertaken with its results attesting to its sufficient density, complexity and democratic mapping. The paper goes on to define the concepts that posses the highest structural significance, while simultaneously a scenario modeling is conducted within the scope of the paper, resulting in the identification of the change in the indicator of service life under maximum positive influence of such concepts.

The findings of the presented research enable to forecast the operational behavior of solar batteries in spacecraft power systems which, in its turn, contributes to the implementation of required mechanisms of prevention, protection and access control on the corresponding levels of energy infrastructure.

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