This paper reports an approach to optimizing the structure of a hybrid solar energy system (HSES), used in the task of automated design, under two modes: independent and connected to the network. The proposed HSES includes a solar energy system (SES), an energy storage system (ESS) powered by rechargeable batteries (RBs), a set of diesel generators (DGs), and a network-connecting system. This paper has identified models of the HSES elements' power and proposed a control algorithm based on rules that assess the state of the system during operation.

The energy models in conjunction with the control algorithm make it possible to model the system's operation stage over a predefined time interval. The proposed approach is based on solving a multicriteria optimization problem (MCO). MCO takes into consideration the minimization of system costs and the total cost of the system, minimizing fuel use, maximizing reliability, and minimizing the use of non-renewable energy sources. A solution to the MCO problem is based on using a Pareto-optimal solution search algorithm, underlying which is the NSGA-II genetic algorithm employing the proposed set of cross-breeding, mutation, and breeding operators. The devised procedure makes it possible to determine the structure of HSES, which includes a set of the number of solar panels, RBs, and DGs. The result is three variants of HSES for a household for two people (Kyiv, Ukraine), under an autonomous mode and in the regime connected to the electricity grid. Given the possibility of selling electricity at a green tariff during the year, the reported solution makes it possible to reduce the estimated cost of the system by up to 45 %. The use of simulation has helped conduct a detailed analysis of the system's performance throughout the year

Keywords: hybrid solar energy system, multicriteria optimization, automated design

UDC 004.896:621.311.243
DOI: 10.15587/1729-4061.2021.234202

MULTICRITERIA OPTIMIZATION IN THE PROBLEM OF COMPUTER-AIDED DESIGN OF HYBRID SOLAR ENERGY SYSTEMS

Victor Sineglazov
Doctor of Technical Sciences, Professor,
Head of Department*
Denis Karabetsky
Corresponding author
Postgraduate Student*
E-mail: karabetsky@gmail.com
Olena Chumachenko
Doctor of Technical Sciences, Professor
Department of Technical Cybernetics
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
Peremohy ave., 37, Kyiv, Ukraine, 03056
*Department of Aviation Computer-Integrated Complexes
National Aviation University
Liubomyra Huzara ave., 1, Kyiv, Ukraine, 03058

Received date: 11.03.2021
Accepted date: 19.05.2021
Published date: 29.06.2021

How to Cite: *Sineglazov, V., Karabetsky, D., Chumachenko, O. (2021). Multicriteria optimization in the problem of computer-aided design of hybrid solar energy systems. Eastern-European Journal of Enterprise Technologies, 3 (2 (111)), 67–78. doi: https://doi.org/10.15587/1729-4061.2021.234202*

1. Introduction

Renewable energy sources (RES) have become the main sources of clean electricity, which has made it possible to reduce greenhouse gas emissions and abandon non-renewable forms of energy. Even though fossil fuel sources are readily available, there is no certainty that they will last for a long time, so their resource is not infinite. Consequently, environmental factors come to the fore as fossil fuel consumption increases and the environment degrades. The task of protecting the environment can only be solved by controlling pollution and reducing the use of fossil fuels.

Because the availability of solar energy (SE) is unstable, its combination with other sources, including sources of non-renewable energy, is quite a promising direction.

Hybrid systems have recently become increasingly popular as they may be used both under network and autonomous modes. Autonomous systems allow them to be implemented in remote areas where there is no access to the electricity grid. Systems running under a network mode can also improve the overall quality of social objects.

A hybrid solar energy system (HSES) is a system that uses a solar energy system (SES) to convert solar energy (SE) into electricity, in combination with traditional energy sources. Conventional energy sources may be the city's electricity grid (for the sale and purchase of electricity) and diesel generators (DGs) using diesel fuel.

The introduction of energy storage systems (ESSs) powered by rechargeable batteries (RBs) increases the penetration level of RES and improves reliability by balancing the grid [1].

Connecting ESSs is increasingly complicating the process of designing HSES, as there is an additional task of managing the flux of energy. The modeling process is also complicated as the use of RBs and DGs requires a control system to provide for the energy balance [1]. Poorly designed systems can have serious drawbacks, including the inability to meet the energy demand of the system's consumers in critical situations, such as during peak periods.

The classic statements of problems on building automated design systems are far from the real conditions of the object's operation. Possible failures in the provision of electricity, weather variability are not taken into consideration, which predetermines redundancy of both the equipment used and the software, which causes additional costs.

Thus, it is a relevant task to devise new approaches to solve these problems, both in stating the problem and solving it using mathematical modeling. That makes it possible to evaluate the work of the system during the design phase, which enables optimization of the choice of a set of technical tools and software for a built system.

2. Literature review and problem statement

Due to the growing interest in HSES and other types of hybrid systems utilizing RES, the number of studies into optimal configuration is also growing. There are many literary sources that examine hybrid systems that use renewable energy. Options for the integration of various RES, ESS are detailed in work [1].

Many approaches to building HSES based on solving a multicriteria optimization problem (MCO) using evolutionary algorithms employing different environmental and feasibility criteria have been proposed [2 5]. Despite the use of detailed mathematical models HSES elements to improve the quality of the calculation of criteria, special attention is paid to the development and implementation of management system algorithms in the optimization procedure. Such a step significantly improves the quality of modeling and makes it possible to take into consideration the features of the system.

Work [6] formalizes many different criteria that are used in the design, including technological, economic, and environmental. Simultaneously taking into consideration a large number of criteria makes it much more difficult to find the optimal structure of HSES, so choosing and optimizing the number of criteria is a separate task. Accordingly, the authors only define methodological approaches to solving the problem of finding the optimal configuration.

Study [7] reports HSES, which is optimized taking into consideration the capital cost of the system and fuel costs by using the algorithm of a swarm of particles. However, the authors focused only on the assessment of economic criteria, which is a clear disadvantage, as additional consideration of many factors of reliability of the system is required. This approach was used by the authors of work [8] who used an algorithm to solve MCO based on linear programming. The optimization problem was solved taking into consideration the economic restrictions and limitations imposed on the purchase and sale of electricity. The GSPP model introduced included the use of DGs to meet demand during peak periods, as well as to compensate for the lack of energy generation by the photovoltaic system. The authors reported the results of their simulation, which included the operation of all components of the hybrid system.

The authors of [9] conducted a study into the use of a set of economic and environmental criteria in the design of systems based on SE, taking into consideration the connection to the city's electricity grid. However, the use of ESS was not considered. The availability of this system has a huge impact on the design results, as well as on the values of the criteria used.

Work [10] used the HOMER (USA) software package to improve economic and technical factors when designing hybrid power grid systems for a large hotel comprising 15 buildings. Although the projected system was considered to improve the quality of the grid, the use of ESS was not addressed.

The authors of [11] optimized the structure of HSES using various meta-heuristic algorithms, taking into consideration a number of feasibility studies. The set of criteria included minimizing the total annual cost of the system and maintenance costs, minimizing the likelihood of power loss. Even though the cited work describes in detail the approach to simulation, as well as its results, the proposed solution has a significant drawback. The set of the criteria chosen was generalized as one complex objective function. Accordingly, that approach does not make it possible to cover all the Pareto-optimal solutions when solving a multicriteria problem.

Our review of the above studies [2–11] allows us to argue that the multicriteria optimization methods, owing to their good performance considering trade-offs, are widely used for the design of HSES. The most popular approach proposed to solve such problems is the use of genetic and evolutionary algorithms to solve MCO, in the design of many hybrid energy systems.

Although studies [2–4, 7, 11] are looking at HSES that operate under an autonomous mode, they can also be connected to the network to improve reliability. In some situations, this approach can lead to economic benefits from the sale of renewable electricity and lower the cost of the system.

In many practical tasks, design variables must be consistent with an available elemental base (for example, information from the solar panel specification) and, therefore, cannot accept arbitrary values. The limitations that need to be met to solve the problem are termed project limitations and are formed based on the task set. The design restrictions of the system function as boundaries imposed on optimization parameters and are, therefore, the key to finding the best solution [12].

The systematization of the results of the above studies allows us to believe that the design of the GSPP requires that the cost of the system should be minimal, environmental standards should be met, the system should be reliable, provided the load requirements are met. The HSES should also be able to connect to the network, so its optimal configuration may differ in view of the additional reserve.

3. The aim and objectives of the study

The aim of this work is to optimize the structure of HSES, providing for the possibility of working both under autonomous and independent modes while taking into consideration technological, economic, and environmental goals, by using automated design approaches.

To accomplish the aim, the following tasks have been set:

– to build the models of HSES elements taking into consideration the parameters for the optimization procedure, as well as formalize a set of criteria for solving technological, economic, and environmental goals;

– to develop an algorithm to manage HSES elements and construct appropriate simulation models to check the performance of the predefined HSES structure;

– to perform the structural and parametric synthesis of HSES using MCO based on genetic algorithms in order to confirm the feasibility of the proposed approach to solve applied tasks.

4. The study materials and methods

The development of new approaches to HSES design involves the use of different theoretical methods in many fields of science and technology. Automated systems that implement the functions of computer-aided design (CAD) apply information system theory based on object-oriented analysis, including mathematical modeling, systems analysis, and optimization techniques.

The development of HSES CAD employs a set of numerical and analytical models describing elements of the system, as well as a unit to solve an optimization problem based on certain quality criteria. Having an optimization solution unit can significantly reduce design time.

The MATLAB (USA) software package is used for mathematical modeling. The HSES control algorithm includes a set of rules for managing system elements to meet load requirements. Simulation interval and discreteness are the parameters; in the current study, set to equal 1 year and 1 hour, respectively. Energy losses and the effectiveness of the elements are taken into consideration by using efficiency factors. In a numerical model of the environment (temperature and light), load requirements are represented in the form of time series, which are set for the entire simulation interval. The models of RBs, solar panels, DGs are represented in an analytical form.

The optimization problem is solved using multicriteria conditional optimization methods applying genetic algorithms to find Pareto-optimal solutions. The software package for the implementation of MCO is the JMetal library (open-source software). The solution test, simulation, obtaining information about the state of HSES elements over time at the predefined discretion are carried out by integration with the software package MATLAB (USA).

5. Results of the study into resolving a task of the computer-aided design of hybrid solar energy systems

5. 1. Constructing the mathematical models of structural elements and quality criteria for the hybrid solar energy system

The basic structure of HSES (Fig. 1) consists of a set of the following units: solar energy system (SES), diesel generator(s), SSE, a network, and consumers connected to a single AC bus. HSES is controlled by a system that acquires information from all units about their current status and, based on these data, monitors meeting the restrictions imposed. The condition of the units is the information about the internal characteristics of the unit (the state of RB charge, the requirement of the load of the consumer unit) and external characteristics (measurements of the consumed/generated power).

ESS includes a set of rechargeable batteries (RBs), as well as a set of bidirectional converters to perform the functions of battery charge and discharge. It is used to store instantly excess energy, which can be subsequently used if there is an insufficient supply or lack of energy from the main sources.

The diesel generator acts as a reserve unit, activated by a signal from the control strategy unit, providing the system with energy by utilizing diesel fuel.

Consumers are a set of energy requirements, formed from analyzing devices of the end-users of the system.

The control system executes the functions of control (acquiring and analyzing telemetry status data) of HSES elements, coordinating and managing them to meet consumer demand, protect the system from overload, and optimize the performance of the generation system. Control logic is implemented by a control algorithm.

Solar panels (SPs) are widely used due to their safety and lack of pollution. Assuming that the photovoltaic array combines N_s panels sequentially and N_p in parallel, the maximum power output can be calculated using [13, 14]:

$$P_{\mathrm{SP}}(t)=N_s N_p P_{\mathrm{SP,STC}} f_{\mathrm{SP}} \frac{G(t)}{G_{\mathrm{STC}}}\times$$
$$\times\left(1+K_{\mathrm{T}}\left(T_{\mathrm{C}}(t)-T_{\mathrm{C,STC}}\right)\right), \tag{1}$$

where $P_{\mathrm{SP,STC}}$ is the power under standard test conditions (STC) according to the specification of solar panels; f_{SP} is the power loss factor that includes power loss factors due to panel contamination, partial shading conditions, etc.; K_T is the temperature factor of change in power (panel characteristics), $T_C(t)$ is the current temperature of solar panels; $T_{C,\mathrm{STC}}$ is the temperature during STC (25 °C); $G(t)$ is the current solar radiation; G_{STC} is the constant of solar radiation during STC.

A model of the environment. Because the SP operation modeling requires solar radiation and environmental temperature values, the proposed model includes the predefined time series, limited by the service life of the system [15]. Similarly, the values for the time series can be generated synthetically [16].

An example of a time series of solar radiation (Fig. 2) and ambient temperature (Fig. 3) for the city of Kyiv in 2015, acquired using the PVGIS software package developed by the European Commission.

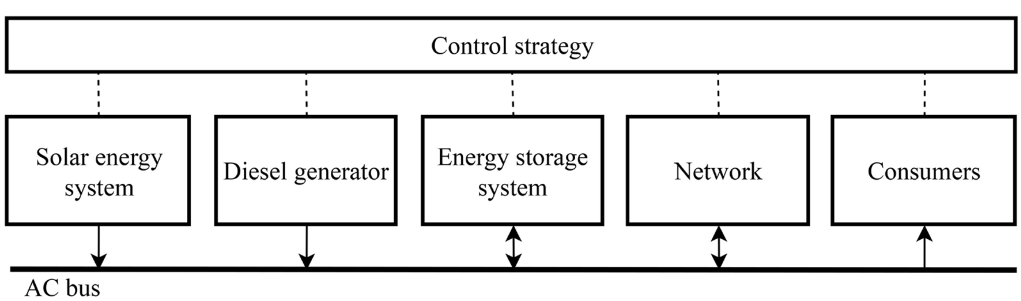

Fig. 1. Structure of the hybrid solar energy system

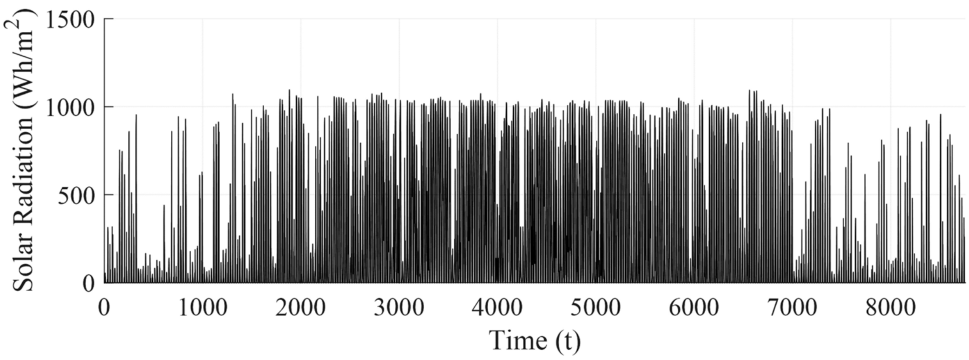

Fig. 2. Acquired solar radiation for 1 year

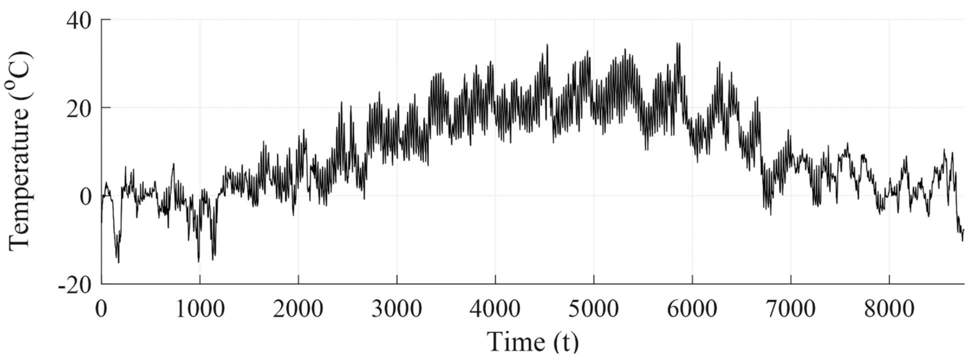

Fig. 3. Ambient temperature over 1 year

Energy storage system. Rechargeable batteries (RB) are often used in HSES as a storage element. The power of charge and discharge depends not only on the load requirements but also on the charge state [17]. The state of charge (SoC) is the level of the charge of RB relative to its capacity, the unit of SoC is the percentage, where 0 % denotes that the RB is fully discharged, and 100 % – fully charged. During the simulation, the SoC can be calculated using the following formula:

$$S_{\mathrm{BAT}}(t)=S_{\mathrm{BAT}}(t-1)+\frac{E_{\mathrm{BAT}}(t)}{N_{\mathrm{BAT}}C_{\mathrm{BAT}}U_{\mathrm{BAT}}}\eta_{\mathrm{BAT}}, \quad (2)$$

where $E_{\mathrm{BAT}}(t)$ is the flow of energy to/from a rechargeable battery (positive when charging and negative when discharged), η_{BAT} is the efficiency of charge/discharge, N_{BAT} is the number of RBs, C_{BAT} is the capacity of each RB, U_{BAT} is the rechargeable battery voltage.

The battery model maintains the SoC value between the lower limit ($S_{\min}$) and the upper limit ($S_{\max}$) to ensure that the battery is safe and running. Accordingly, the power of the rechargeable battery charge and discharge is determined from [20]:

$$P_{\mathrm{BAT}}^{\mathrm{dchrg}}(t)=\min\left\{0,\frac{N_{\mathrm{BAT}}U_{\mathrm{BAT}}C_{\mathrm{BAT}}}{\Delta t}\left(S_{\min}-S_{\mathrm{BAT}}(t)\right)\right\}, \quad (3)$$

$$P_{\mathrm{BAT}}^{\mathrm{chrg}}(t)=\max\left\{0,\frac{N_{\mathrm{BAT}}U_{\mathrm{BAT}}C_{\mathrm{BAT}}}{\Delta t}\left(S_{\max}-S_{\mathrm{BAT}}(t)\right)\right\}, \quad (4)$$

where N_{BAT} is the number of batteries, C_{BAT} is the capacity of each battery, U_{BAT} is the battery voltage.

Since the quantity of the charge/discharge cycles, the depth of discharge, causes a gradual degradation of a rechargeable battery, it is possible to apply the estimate for a battery service life given in work [21].

A *diesel generator* usually acts as a backup energy source; its fuel consumption D_f is determined from [22]:

$$D_f(t)=\left(\alpha P_{\mathrm{DG}}(t)+\beta P_{\mathrm{DG,R}}\right)N_{\mathrm{DG}}, \quad (5)$$

where $P_{\mathrm{DG,R}}$ and $P_{\mathrm{DG}}(t)$ are the rated and actual power, α and β – fuel consumption coefficients, N_{DG} is the number of diesel generators.

A load model. Similar to the ambient temperature as well as solar radiation, the load data may be represented by time series limited by the system's lifespan [22]. It is also possible that the time series are generated by software using the Artificial Load Profile Generator (ALPG) tool developed at the University of Twente. An example of the generated series for a two-person apartment is shown in Fig. 4.

The economic criterion adopted in this article is the total cost of the system. The total cost of the system is defined as the sum of all costs for the purchase of HSES elements, their installation, maintenance, the cost of non-renewable resources used in the system operation; it is expressed in the following form:

$$C_{\mathrm{HSES}}=C_{\mathrm{elem}}+C_{\mathrm{maint}}+C_{\mathrm{fuel}}+C_{\mathrm{net}}, \quad (6)$$

where C_{elem} is the cost of HSES elements, C_{maint} is the cost of maintenance and replacement of elements, C_{fuel} is the cost of fuel, C_{net} is the cost of working with the network.

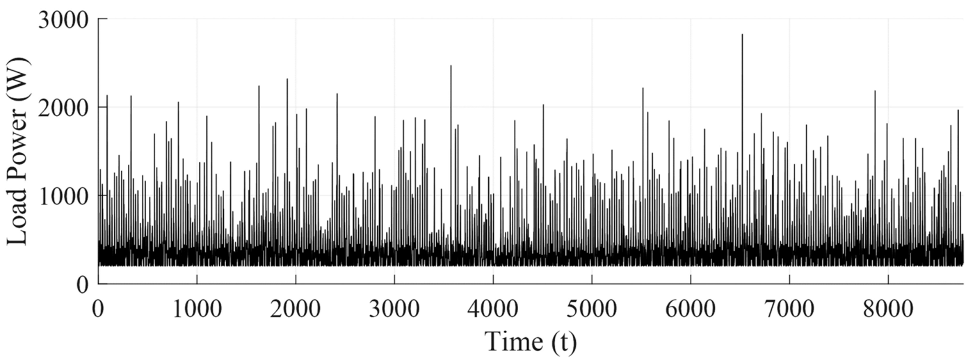

Fig. 4. Instantaneous permissible load over 1 year

The cost of all elements of the system is determined in the following form:

$$C_{\text{net}} = N_{\text{SP}}C_{\text{SP}} + N_{\text{DG}}C_{\text{DG}} + N_{\text{BAT}}C_{\text{BAT}} + C_{\text{acc}}, \quad (7)$$

where N_{SP}, C_{SP} is the number and cost of solar panels, N_{DG}, C_{DG} is the number and cost of diesel generators, N_{BAT} and C_{BAT} is the number and cost of rechargeable batteries, C_{acc} is the cost of accessories (DC converters, inverters, etc.).

The cost of fuel required to operate a diesel generator is determined from the following formula:

$$C_{\text{fuel}} = \sum\nolimits_t D_f(t) C^{1}_{\text{fuel}}, \quad (8)$$

where $D_{\text{fuel}}(t)$ is the fuel consumption over time t; C^{1}_{fuel} is the cost of fuel.

The standard HSES operation depends on the service life of the solar panels and involves maintenance (periodic contact cleaning of panels from dirt). In the event of a failure – replacement of equipment, which requires additional costs.

The cost of working with the network is the total cost of buying and selling electricity, taking into consideration the restrictions on the acceptability of tariffs and tariff zones:

$$C_{\text{net}} = \sum\nolimits_t C_{\text{net}}(t), \quad (9)$$

$$C_{\text{net}}(t) = \begin{cases} C^{T1}_{\text{net}} E_{\text{net}}(t) & P_d(t) > 0,\ t \in T_{T1} \\ C^{T2}_{\text{net}} E_{\text{net}}(t) & P_d(t) > 0,\ t \in T_{T2}, \\ C^{GT}_{\text{net}} E_{\text{net}}(t) & P_d(t) < 0, \end{cases} \quad (10)$$

where $C_{\text{net}}(t)$, $E_{\text{net}}(t)$ is the cost and volume of electricity over time t; C^{T1}_{net}, C^{T2}_{net}, C^{GT}_{net} are the purchase (two-zone tariffs: T1 – day, T2 – night) and electricity sale tariffs (GT – green tariff), $P_d(t)$ is the power deficit.

The cost of maintenance and replacement of elements:

$$C_{\text{maint}} = \sum\nolimits_t \sum\nolimits_i C_{\text{maint},i}(t), \quad (11)$$

where $C_{\text{maint},i}$ is the cost of servicing an HSES element over the predefined time t.

The environmental criterion can be calculated on the basis of emissions of working fuel residues from DG. CO_2 emissions are one of the environmental criteria associated with the operation of a backup power source for a diesel generator. The calculation of emissions is as follows [24]:

$$CO_{2,em} = \sum\nolimits_t P_{\text{DG}}(t) K, \quad (12)$$

where K is the emission coefficient (g/kW), P_{DG} is the power (W) of the diesel generator at a time t.

Another environmental criterion is the amount of non-renewable energy used, this is the energy derived from the network, as well as when using the diesel generator(s):

$$E_{NRE} = \sum\nolimits_t E^{+}_{\text{net}}(t) + E_{\text{DG}}(t), \quad (13)$$

where E^{+}_{net} is the electricity bought from the network, E_{DG} is the energy generated by diesel generators.

The reliability of electricity supply to consumers plays a vital role because renewable energy is not permanent in nature. Accordingly, when HSES is connected to the consumer's energy network, the technical goal would be to minimize energy shortages. Energy deficit is a criterion used to measure the reliability of a system that measures the amount of energy shortage over the entire period of operation:

$$E_{\text{d}} = \sum\nolimits_t E_{\text{load}}(t) - E_{\text{avail}}(t), \quad (14)$$

where E_{load} is the energy needed by consumers (load), E_{avail} is the energy available in HSES that is provided by the energy storage system, SES, and DGs.

5. 2. Developing an algorithm to control the elements of the hybrid solar energy system

Under an autonomous mode, the system is not connected to the network. The energy generated by photovoltaic panels is directly supplied to the load. If the energy generated exceeds the overall load requirements, excess energy would accumulate in the batteries. If HSES cannot meet the load requirements, the batteries would be used to maintain power based on the depth of the discharge. If there is still a shortage of electricity, diesel generators are used as an additional source of energy. This mode implies an additional restriction, $E_{\text{net}}(t)=0$, which limits a link to the electricity grid.

Under a mode of connection to the electricity grid, when the energy produced exceeds the required amount, and the batteries are charged to the maximum, excess energy would be sold to the network to make a profit and compensate for the cost of HSES. If the energy generated cannot meet the load, then, similar to the case of an autonomous mode, rechargeable batteries and a diesel generator are used. If batteries with a diesel generator cannot cover the energy shortage, the necessary power would be purchased from the electricity grid, taking into consideration the favorable tariff zone and tariff restrictions.

Based on the description of HSES modes of operation, a control system algorithm is proposed, with a set of predefined rules; the pseudo-code of the algorithm is given below.

Initialize the simulation (enter parameters and restrictions imposed)
For each t at step Δt in the interval $[0; T]$
SES power calculation: $P_{SP}(t)$
If $P_{SP}(t)>P_{load}(t)$ (there is excess capacity)
Use the charge of the energy storage system
Charge power assessment: $P_{BAT}(t)$
Assess the new SoC: $S_{BAT}(t)$
If $S_{BAT}(t)<S_{max}$
    Charge RB
Otherwise
    Calculate and sell non-used energy to the grid: $E_{net}(t)$
    Calculate sales profit: $C_{net}(t)$
Otherwise (no excess power)
Assess power shortage $P_d(t)$
If $P_d>0$ (there is a shortage)
    Use the discharge of energy storage system
    Assess discharge power: $P_{BAT}(t)$
    Assess new SoC: $S_{BAT}(t)$
    If $S_{BAT}(t)>S_{min}$
        Discharge RB
        Adjust power shortage: $P_d(t)=P_d(t)-P_{BAT}(t)$
If $P_d(t)>0$ (there is a shortage)
    Use diesel generator $P_{DG}(t)$
    Adjust power shortage: $P_d(t)=P_d(t)-P_{DG}(t)$
If $P_d(t)>0$ (there is a shortage)
    Purchase the shortage from the grid
    If $C_{net}(t)<C_{net}^{max}$ (tariff is acceptable)
        Purchase electric power $P_{net}(t)$
        Calculate $E_{NRE}(t)$
        Adjust power shortage: $P_d(t)=P_d(t)-P_{net}(t)$
Calculate the resulting energy shortage $E_d(t)$
Calculate the maintenance and wear of HSES elements.

Our control algorithm makes it possible to link all energy models and models of the state of HSES elements. As a result of this integration, it becomes possible to perform simulations for the time period T at the predefined discreteness (step) Δt.

5. 3. Structural-parametric synthesis of hybrid solar energy systems using multicriteria optimization

The main criteria for MCO in the design process are the total cost of the system (C_{HSES}), the amount of CO_2 emission (EM_{DG}), the total energy deficit (E_d), and non-renewable energy (E_{NRE}) use.

As a result, the MCO problem takes the following form:

$$\text{minimize}\left(C_{HSES}, EM_{DG}, E_d, E_{NRE}\right), \tag{15}$$

optimization procedure parameters: N_{SP}, N_{BAT}, N_{DG}; taking into consideration the restrictions imposed on HSES elements:

$$S_{min} \le S_{BAT}(t) \le S_{max}, \tag{16}$$

$$\left|P_{BAT}(t)\right| \le P_{BAT,chrg}, \tag{17}$$

$$\left|P_{BAT}(t)\right| \le P_{BAT,dchrg}, \tag{18}$$

$$P_{DG}(t) \le P_{DG,R}, \tag{19}$$

$$C_{net}(t) \le C_{net}^{max}, \tag{20}$$

where $S_{BAT}(t)$ is the state of RB charge – must be within the specified limits(S_{min}; S_{max}), $P_{BAT}(t)$ is the instantaneous power of the charge/discharge of RB – should not exceed the allowable maximum charge ($P_{BAT,chrg}$) and discharge ($P_{BAT,dchrg}$) power, $P_{DG}(t)$ is the power of the diesel generator – should not exceed its rated power ($P_{DG,R}$), $C_{net}(t)$ is the tariff for the purchase of electricity at time t – should not exceed the maximum allowable tariff ($C_{net,max}$).

There are many stochastic multicriteria optimization algorithms, such as NSGA-II and SPEA2, which store the archives of the best found species at the Pareto border. These two algorithms directly compete, are equipped with a mechanism to support diversity, and use the principle of elitism. However, the NSGA-II algorithm has less computational complexity.

The constructed series of models, the HSES control system algorithm were used to build a simulation system in the MATLAB environment. The NSGA-II genetic algorithm with a population size of 100 was employed to solve the MCO problem.

The genetic algorithm of non-dominant sorting II (NSGA-II) has the following features: it uses the principle of elitism, close distance, and emphasizes non-dominant solutions. The NSGA-II algorithm is detailed in paper [11].

The crossing operator selected is an integer imitating binary crossover with the following parameters: the distribution index is 20, the speed is 0.8. The operator of the mutation selected is an integer polynomial mutation with a distribution index of 20 and a speed of 0.33. The selection of species was carried out by using binary tournament breeding.

HSES is designed using historical environmental data for Kyiv (Ukraine). Using the PVGIS software package developed by the European Commission, we acquired time series for 2015 regarding solar radiation (Fig. 2) ambient temperature (Fig. 3). Using the ALPG tool developed at the University of Twente, a temporary series of powerful requirements for an apartment with two adult residents was generated, which is shown in Fig. 4.

The set of input parameters for the optimization phase includes information on the cost and maintenance of HSES elements (Table 1), the parameters of the HSES element base (Table 2).

Table 1

Information about the cost of elements in the hybrid solar power system

Element	Cost per piece	Maintenance (monthly)
Solar panels	200	5
Rechargeable batteries	100	10
Diesel generator	800	20
Converter	300	10
Inverter	350	10

The optimization task of finding the optimal structure of HSES under a network mode is solved in two variants: with activated and deactivated restriction (20), which regulates the maximum allowable tariff for electricity purchase. If this restriction is deactivated, HSES under a network mode can freely compensate for the energy deficit by buying electricity. If this restriction is activated and set at the border of the day and night zone of tariffs (Table 2), then HSES would compensate the deficit only at night as the daily tariff would be unacceptable for purchase.

Table 2

Settings for the configuration of elements in the hybrid solar energy system

Parameter	Value
SES parameters	
Power loss coefficient (f_{SP})	0.85
Panel power at STC ($P_{SP,STC}$)	320 W
Power change temperature coefficient (K_T)	–0.35 %/°C
ESS parameters	
RB capacity (C_{BAT})	225 Ah
Voltage on rechargeable battery (U_{BAT})	12 V
Conversion efficiency of energy storage system (η_{BAT})	0.98
SoC minimal level (S_{min})	10 %
SoC maximal level (S_{max})	95 %
DG parameters	
Diesel generator rated power ($P_{DG,R}$)	1,000 W
Fuel consumption coefficient (α)	0.08
Fuel consumption coefficient (β)	0.25
Diesel generator emission coefficient $\left(K_{CO_2}\right)$	2.8
Diesel fuel cost (C_{fuel})	1 %/l
Electricity network parameters	
Electricity purchase, daytime tariff $\left(C_{net}^{T1}\right)$	0.062 USD/kWh
Electricity purchase, nighttime tariff $\left(C_{net}^{T2}\right)$	0.031 USD/kWh
Electricity purchase, maximal price $\left(C_{net}^{max}\right)$	0.04 USD/kWh
Electricity sale, green tariff $\left(C_{net}^{T3}\right)$	0.15 USD/kWh
Simulation parameters	
Time simulation (T)	8,760 h
Simulation step (Δt)	1 h

As mentioned above, in order to optimize HSES under an autonomous mode, it is necessary to activate the additional restriction $E_{net}(t)=0$.

After the optimization procedure, we derived the solutions given in Table 3.

Table 3

HSES structural optimization results

N_{SP}	N_{BAT}	N_{DG}	C_{HSES}	EM_{DG}	E_d	E_{NRE}
Autonomous mode						
19	7	2	15,780	950	0	339,470
Network mode $\left(C_{net}^{max}=1\ \$/kWh\right)$						
14	6	0	8,523	0	0	483,924
Network mode $\left(C_{net}^{max}=0{,}04\ \$/kWh\right)$						
4	1	2	7,726	4,935	1,773	1,762,618

The corresponding Pareto sets, formed as a result of the optimization procedure, are shown in Fig. 5–7.

As each intermediate solution during the optimization simulates the year of operation, Fig. 8–10 illustrate the results of the above solutions.

The data in the above results include the time series of the instantaneous power of each subsystem: SES, DGs, ESS, ES; that allows the designer to evaluate the HSES performance.

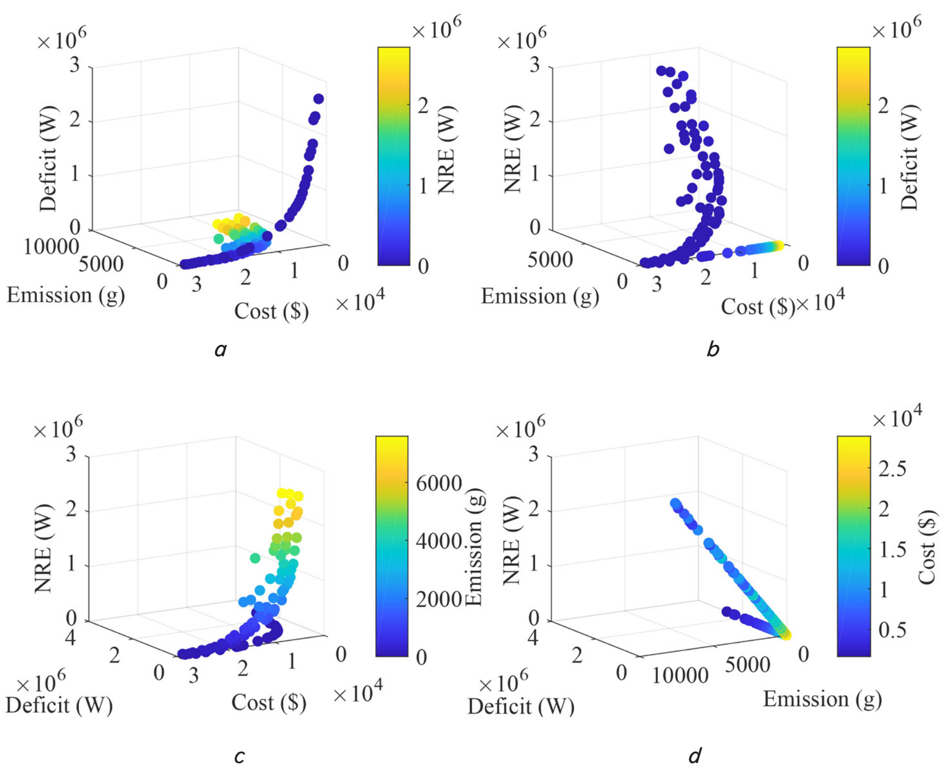

Fig. 5. Mapping the Pareto set (optimization of the hybrid solar energy system for an autonomous mode): *a* – the space of criteria cost – CO_2 emission – energy deficit; *b* – the space of criteria cost – CO_2 emission – the use of non-renewable energy; *c* – the space of criteria cost – energy deficit – the use of non-renewable energy; *d* – the space of criteria CO_2 emission – energy shortage – the use of non-renewable energy

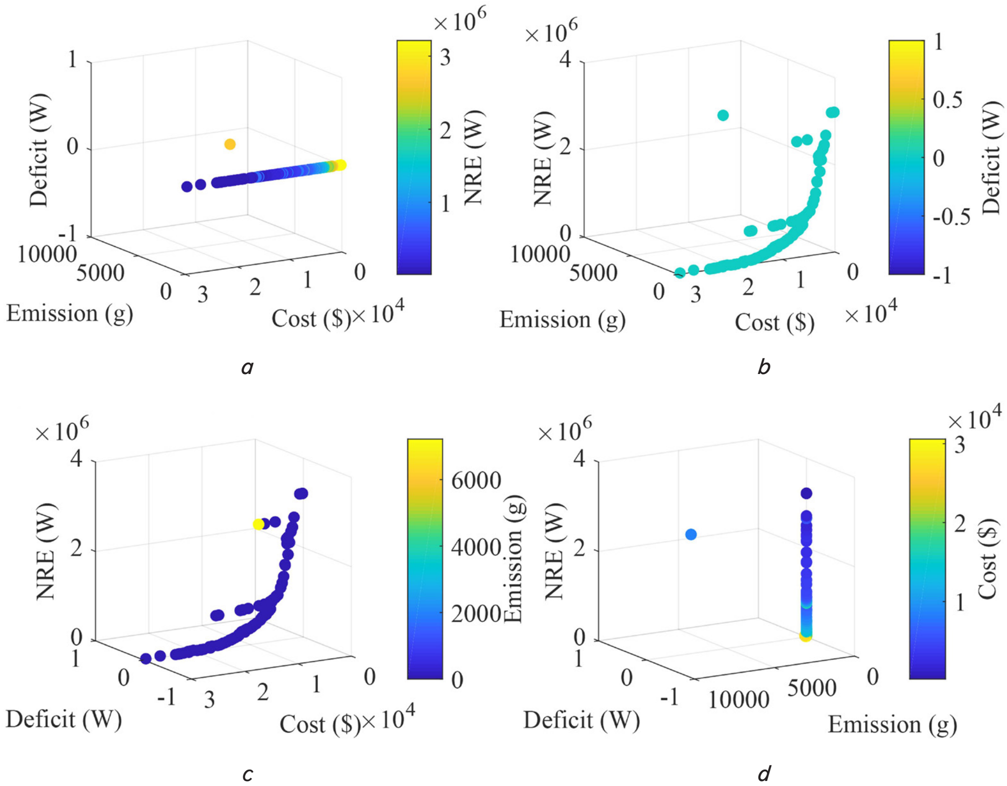

Fig. 6. Mapping the Pareto set (optimization of the hybrid solar energy system for the network mode without restrictions on the purchase of electricity): *a* – the space of criteria cost – CO_2 emission – energy deficit; *b* – the space of criteria cost – CO_2 emission – the use of non-renewable energy; *c* – the space of criteria cost – energy deficit – the use of non-renewable energy; *d* – the space of criteria CO_2 emission – energy shortage – the use of non-renewable energy

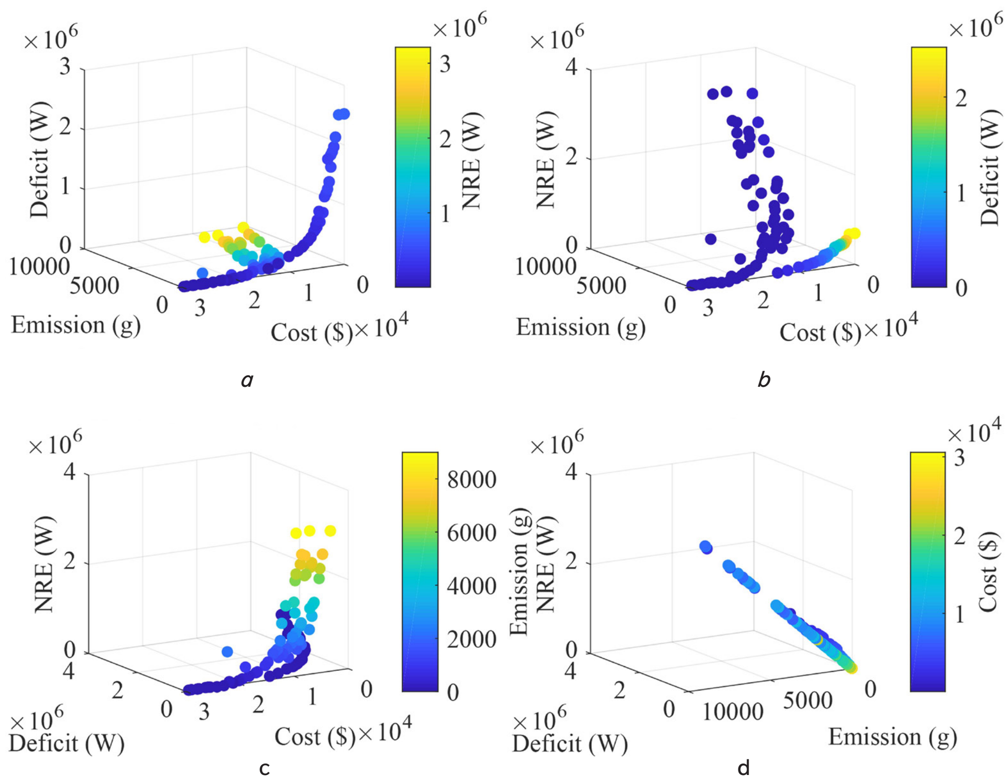

Fig. 7. Mapping the Pareto set (optimization of the hybrid solar energy system under a network mode with restrictions on the purchase of electricity at daytime tariff): *a* – the space of criteria cost – CO_2 emission – energy deficit; *b* – the space of criteria cost – CO_2 emission – the use of non-renewable energy; *c* – the space of criteria cost – energy deficit – the use of non-renewable energy; *d* – the space of criteria CO_2 emission – energy shortage – the use of non-renewable energy

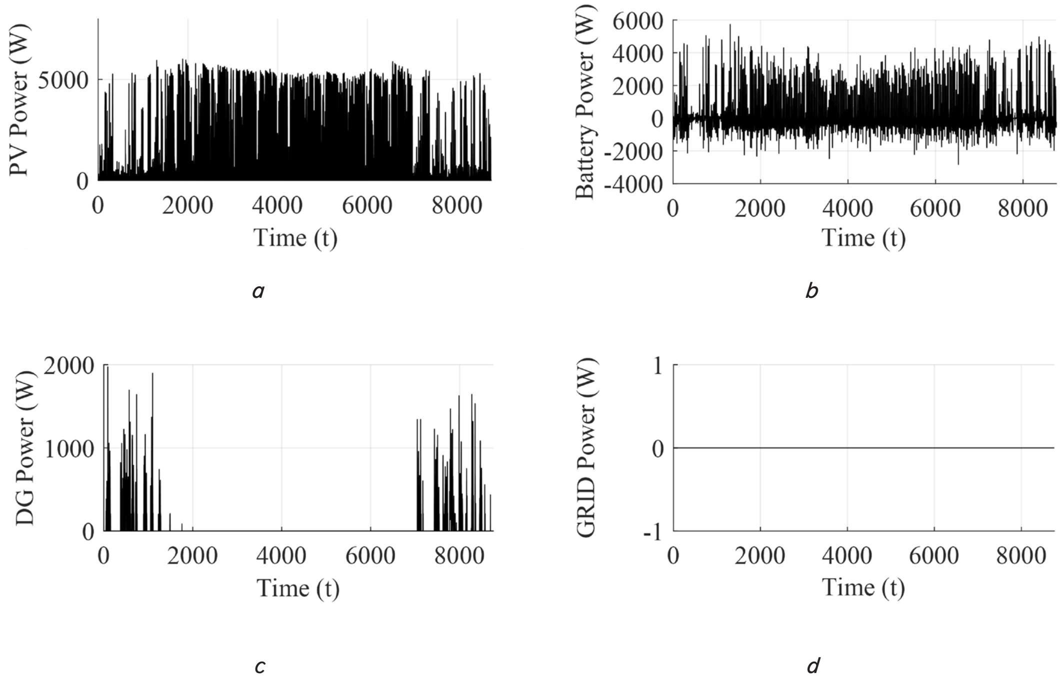

Fig. 8. Simulating a year of the hybrid solar energy system operation (proposed solution for an autonomous mode):
a – the power of the solar energy system;
b – the power of the energy storage system;
c – the actual power of the diesel generator;
d – the power of interaction with the power grid

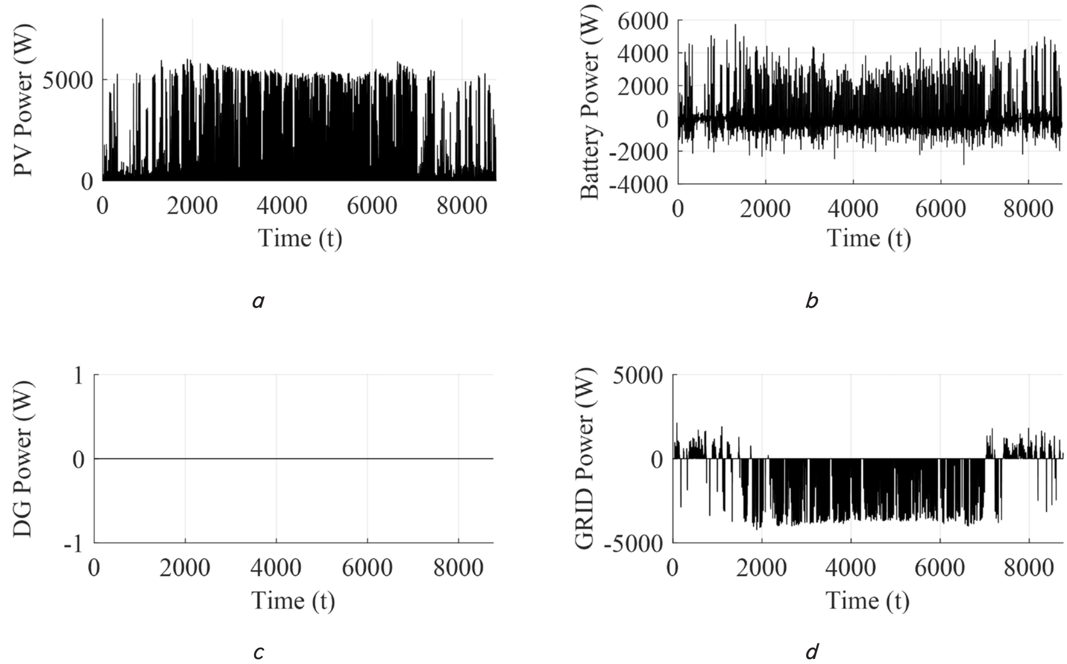

Fig. 9. Simulating a year of the hybrid solar energy system operation
(proposed solution for a network mode without restrictions on the purchase of electricity):
a – the power of the solar energy system;
b – the power of the energy storage system;
c – the actual power of the diesel generator;
d – the power of interaction with the power grid

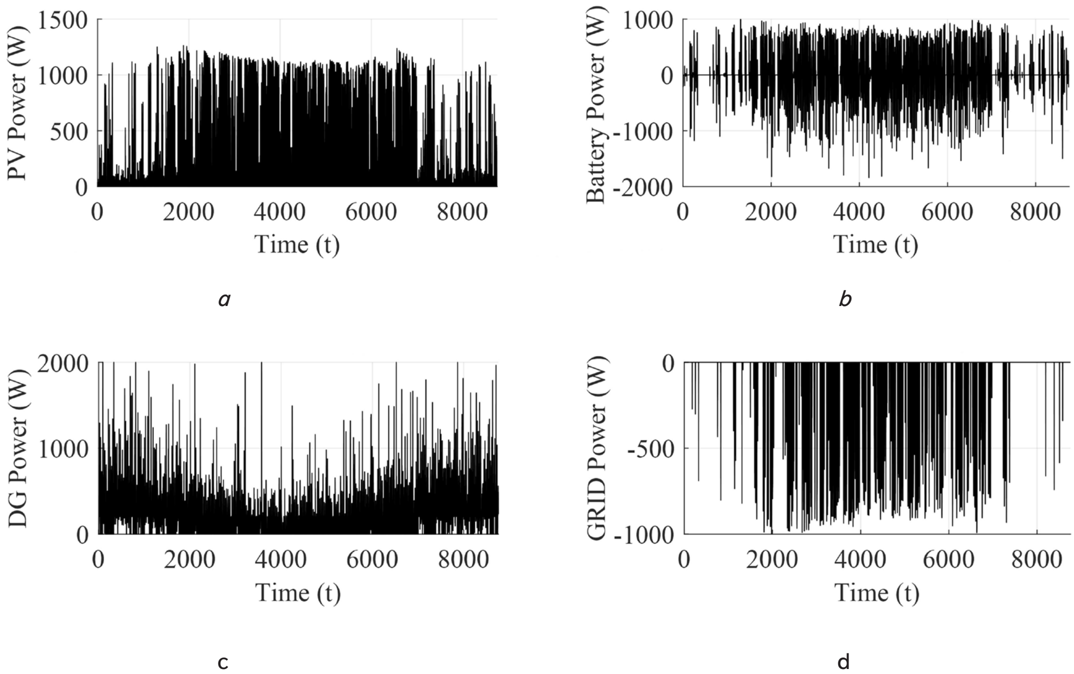

Fig. 10. Simulating a year of the hybrid solar energy system operation (the proposed solution for a network mode with a limit on the purchase of electricity at daytime tariff):
a – the power of the solar energy system; *b* – the power of the energy storage system;
c – the actual power of the diesel generator; *d* – the power of interaction with the power grid

6. Discussion of results of using the multicriteria optimization in the task of automated design of solar energy systems

Our results are explained by the following. The introduction of additional criteria such as minimizing energy shortages, minimizing the use of non-renewable energy sources, minimizing the cost of the system, minimizing CO_2 emissions. The models and time series make it possible to take into consideration seasonal, statistical, operating conditions, based on historical data. The energy models, provided that there is an algorithm of HSES control, make it possible to conduct mathematical modeling of the system operation so that it is possible to accurately assess the criteria. The use of MCO with a genetic algorithm makes it possible to derive Pareto-optimal points, which allows the designer to justify his/her preferences on the received solution.

The results of the structural optimization of HSES, given in Table 3, show that the proposed automated design procedure using the multicriteria optimization approach makes it possible for the designer to find the sub-optimal structures of HSES. The Pareto sets resulting from MCO, shown in Fig. 5–7, make it possible to find such an optimal structure of HSES in which the value of each criterion characterizing the system cannot be improved without compromising others. The designer, based on these data, may make decisions by assessing the set of criteria for choosing the optimal structure, based on the original tasks.

For example, when designing HSES in a remote area under an independent mode, it is preferable that HSES should not face a shortage of energy with CO_2 emissions not exceeding the strict threshold, taking into consideration budget constraints. The result of analyzing the derived Pareto-set (Fig. 5) reveals that, in order for the projected system to face no energy deficit during operation, it is necessary to exceed the budget. This condition cannot be met, so, accordingly, the search for a solution shifts towards the search for a compromise through the deterioration of other criteria, including environmental. The results of the energy simulation are shown in Fig. 8 for the selected optimal structure of HSES under an autonomous mode. If it is possible to connect to the power grid and sell electricity for profit, a new Pareto-set (Fig. 6) was calculated while maintaining the design parameters. Based on the analysis, a new sub-optimal solution was selected; the results of the energy simulation are shown in Fig. 8. This solution is relatively cheap, it does not use DGs, as the network is the main backup source, which makes it possible to remove all CO_2 emissions and energy shortages. The use of a non-renewable energy source is still present as the compensation for energy scarcity comes from the grid. To check the possibility of additional reduction in the cost of the system, by prohibiting the purchase of electricity at daytime tariff (the purchase is possible only at night at nighttime tariff), an additional limitation is introduced; the analysis of the Pareto set (Fig. 7) reveals that a compromise solution cannot be found for the design parameters set. The reduction in cost is possible only by taking into consideration the return of the use of DGs, partial abandonment of SE to reduce the cost of the system and the deterioration of all environmental criteria. The results of the simulation of the resulting solution are shown in Fig. 10.

A series of new criteria have been used to solve the automated design task. Both dynamic and static models, time series describing the variability of operating conditions and performance (energy requirements) of consumers were employed as our mathematical models. Implementing the new approach to automated design has allowed us at the design stage to model possible scenarios in the hybrid solar energy system operation, namely, the energy balance of all elements of the system. To solve a multicriteria optimization problem, the Pareto-optimization has been used, allowing the designer to determine the most optimal structure of the system within the task at hand.

The proposed Automated Design Tool (CAD), using an MCO based on the NSGA-II genetic algorithm, has the advantage of quickly calculating multiple solutions, allowing the sorting and analyzing of any solutions without any delay.

The obvious limitations of the HSES CAD are the detailed models used, as well as the set of the initially predefined criteria. Detailing models limits the accuracy of the simulation but, on the other hand, reduces the time of calculations and is a kind of parity.

It should be noted that the proposed search method, given the MCO solution features, does not produce the best solution but only the so-called suboptimal. This fact shows a clear limitation of the approach, which requires that designers should understand the tasks set when designing to make an analytical decision.

These limitations are also the flaws in the current study. Any CAD is required to provide maximum flexibility during the design phase in order to assess the impact of different parameters on the design result. Since the set of criteria, the MCO algorithm, the HSES control algorithm, the HSES elements models are strictly set, this factor deprives CAD of the desired flexibility. In the long term, more detailed models should be suggested, which would make it possible to choose between speed and accuracy during the design phase. A database of criteria should be introduced, as well as alternative control algorithms and HSES models.

The current work can be advanced through a comparative study of MCO algorithms, the speed of operation, and the impact on the results to be obtained. The experimental part could improve the software and mathematical component of the HSES CAD, to remove all the above-mentioned restrictions. The direction of further development of CAD should be focused on determining the exact set of criteria from the database according to the objectives set.

7. Conclusions

1. A set of key criteria has been formalized, which include the set of project objectives, including minimizing the cost of the system by accounting for depreciation and amortization, increasing reliability by minimizing energy shortages, minimizing environmental impacts by reducing CO_2 emissions, and prioritizing the use of renewable energy. The built models of HSES elements take into consideration the parameters of the design procedure, which makes it possible to solve the task of structural and parametric synthesis in the future and thus improve the energy efficiency of the developed system.

2. An algorithm for managing HSES elements has been developed, which includes a set of rules of system performance taking into consideration two possible modes of operation: an autonomous mode and the regime when it is connected to the electricity grid. The specificity of ESS operation (control of the level and maximum power of charge/discharge), control of the energy balance (connection, disconnection, and tracking the state of energy sources according to energy requirements), accounting for tariff zones when interacting with the electricity grid have all been considered. The introduction of the control system algorithm makes it possible to derive a solution to the problem of HSES structural and parametric synthesis close to the optimal one.

3. Using the constructed mathematical models and the developed control algorithm, we have searched for the optimal configuration involving the application of MCO with a set of predefined criteria and limitations. To solve the problem of structural and parametric synthesis, the genetic algorithm NSGA-II is used, which has the advantage of quickly calculating a set of the Pareto-optimal configurations for their subsequent analysis. The developed automated design tool has allowed us to determine the optimal structure of HSES for a household for two people (Kyiv, Ukraine), consisting of 19 SPs, 7 RBs, and 2 DGs. The solution includes an estimated cost of USD 15,780, no energy shortage, 950 grams of CO_2 emissions, and the use of 340 kWh of non-renewable energy. If it is possible to sell electricity at a green tariff within a year, it is possible to reduce the estimated cost of the system to USD 8,523 (by 45 %). This solution implies meeting all the energy requirements when using 14 SPs, 6 RBs, and 0 DG. Since DG is not used, there is no CO_2 emission but the use of non-renewable energy increases to 483 kWh due to the reduction of SES and SSE.

References

1. Farret, F. A., Godoy Simoes, M. (2017). Integration of renewable sources of energy. John Wiley & Sons, 688.
2. Aziz, A., Tajuddin, M., Adzman, M., Ramli, M., Mekhilef, S. (2019). Energy Management and Optimization of a PV/Diesel/Battery Hybrid Energy System Using a Combined Dispatch Strategy. Sustainability, 11 (3), 683. doi: https://doi.org/10.3390/su11030683
3. Zheng, X.-K., Li, K., Wang, R., Zhang, T. (2017). Operation Management of a Hybrid Renewable Energy Systems Base on Multi-Objective Optimal under Uncertainties. 2017 IEEE International Conference on Energy Internet (ICEI). doi: https://doi.org/10.1109/icei.2017.18
4. Ma, G., Xu, G., Chen, Y., Ju, R. (2016). Multi-objective optimal configuration method for a standalone wind–solar–battery hybrid power system. IET Renewable Power Generation, 11 (1), 194–202. doi: https://doi.org/10.1049/iet-rpg.2016.0646
5. Song, Y., Liu, Y., Wang, R., Ming, M. (2019). Multi-Objective Configuration Optimization for Isolated Microgrid With Shiftable Loads and Mobile Energy Storage. IEEE Access, 7, 95248–95263. doi: https://doi.org/10.1109/access.2019.2928619
6. Upadhyay, S., Sharma, M. P. (2014). A review on configurations, control and sizing methodologies of hybrid energy systems. Renewable and Sustainable Energy Reviews, 38, 47–63. doi: https://doi.org/10.1016/j.rser.2014.05.057
7. Abedini, M., Moradi, M. H., Hosseinian, S. M. (2016). Optimal management of microgrids including renewable energy scources using GPSO-GM algorithm. Renewable Energy, 90, 430–439. doi: https://doi.org/10.1016/j.renene.2016.01.014

8. Delgado, C., Dominguez-Navarro, J. A. (2014). Optimal design of a hybrid renewable energy system. 2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER). doi: https://doi.org/10.1109/ever.2014.6844008
9. Bernal-Agustín, J. L., Dufo-López, R. (2006). Economical and environmental analysis of grid connected photovoltaic systems in Spain. Renewable Energy, 31 (8), 1107–1128. doi: https://doi.org/10.1016/j.renene.2005.06.004
10. Caballero, F., Sauma, E., Yanine, F. (2013). Business optimal design of a grid-connected hybrid PV (photovoltaic)-wind energy system without energy storage for an Easter Island's block. Energy, 61, 248–261. doi: https://doi.org/10.1016/j.energy.2013.08.030
11. Cho, J.-H., Chun, M.-G., Hong, W.-P. (2016). Structure Optimization of Stand-Alone Renewable Power Systems Based on Multi Object Function. Energies, 9 (8), 649. doi: https://doi.org/10.3390/en9080649
12. Eriksson, E. L. V., Gray, E. M. (2017). Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems – A critical review. Applied Energy, 202, 348–364. doi: https://doi.org/10.1016/j.apenergy.2017.03.132
13. Singh, R., Bansal, R. C. (2019). Optimization of an Autonomous Hybrid Renewable Energy System Using Reformed Electric System Cascade Analysis. IEEE Transactions on Industrial Informatics, 15 (1), 399–409. doi: https://doi.org/10.1109/tii.2018.2867626
14. Hosseinalizadeh, R., Shakouri G, H., Amalnick, M. S., Taghipour, P. (2016). Economic sizing of a hybrid (PV–WT–FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: Case study of Iran. Renewable and Sustainable Energy Reviews, 54, 139–150. doi: https://doi.org/10.1016/j.rser.2015.09.046
15. Olatomiwa, L., Mekhilef, S., Huda, A. S. N., Sanusi, K. (2015). Techno economic analysis of hybrid PV –diesel–battery and PV –wind–diesel–battery power systems for mobile BTS: the way forward for rural development. Energy Science & Engineering, 3 (4), 271–285. doi: https://doi.org/10.1002/ese3.71
16. Aguiar, R., Collares-Pereira, M. (1992). TAG: A time-dependent, autoregressive, Gaussian model for generating synthetic hourly radiation. Solar Energy, 49 (3), 167–174. doi: https://doi.org/10.1016/0038-092x(92)90068-l
17. Singh, R., Bansal, R. C., Singh, A. R. (2018). Optimization of an isolated photo-voltaic generating unit with battery energy storage system using electric system cascade analysis. Electric Power Systems Research, 164, 188–200. doi: https://doi.org/10.1016/j.epsr.2018.08.005
18. Bokopane, L., Kusakana, K., Vermaak, H. J. (2015). Optimal energy management of an isolated electric Tuk-Tuk charging station powered by hybrid renewable systems. 2015 International Conference on the Domestic Use of Energy (DUE). doi: https://doi.org/10.1109/due.2015.7102981
19. Bakhtiari, H., Naghizadeh, R. A. (2018). Multi-criteria optimal sizing of hybrid renewable energy systems including wind, photovoltaic, battery, and hydrogen storage with ε-constraint method. IET Renewable Power Generation, 12 (8), 883–892. doi: https://doi.org/10.1049/iet-rpg.2017.0706
20. Coppitters, D., De Paepe, W., Contino, F. (2020). Robust design optimization and stochastic performance analysis of a grid-connected photovoltaic system with battery storage and hydrogen storage. Energy, 213, 118798. doi: https://doi.org/10.1016/j.energy.2020.118798
21. Díaz, G., Gómez-Aleixandre, J., Coto, J., Conejero, O. (2018). Maximum income resulting from energy arbitrage by battery systems subject to cycle aging and price uncertainty from a dynamic programming perspective. Energy, 156, 647–660. doi: https://doi.org/10.1016/j.energy.2018.05.122
22. Ramesh, M., Saini, R. P. (2020). Effect of different batteries and diesel generator on the performance of a stand-alone hybrid renewable energy system. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1–23. doi: https://doi.org/10.1080/15567036.2020.1763520
23. Yusoff, Y., Ngadiman, M. S., Zain, A. M. (2011). Overview of NSGA-II for Optimizing Machining Process Parameters. Procedia Engineering, 15, 3978–3983. doi: https://doi.org/10.1016/j.proeng.2011.08.745
24. Ming, M., Wang, R., Zha, Y., Zhang, T. (2017). Multi-objective optimization of hybrid renewable energy system using an enhanced multi-objective evolutionary algorithm. Energies, 10 (5), 674. doi: https://doi.org/10.3390/en10050674
25. Nujoom, R., Wang, Q., Mohammed, A. (2018). Optimisation of a sustainable manufacturing system design using the multi-objective approach. The International Journal of Advanced Manufacturing Technology, 96 (5-8), 2539–2558. doi: https://doi.org/10.1007/s00170-018-1649-y