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DESIGN OF MICROGRIDS AS A COST ECONOMY ENERGY SAVINGS SIMULATION MODEL: MONTE CARLO METHOD

Straka, M.
Institute of Logistics and Transport, BERG Faculty, Technical University of Kosice,
Park Komenskeho 14, 042 00 Kosice, Slovak Republic, EU
E-Mail: martin.straka@tuke.sk

Abstract
The article examines the creation of a Cost Economy Energy Savings Simulation Model (CEESS Model) as an economic scenario generator for energy-independent structures using the Monte Carlo method. The CEESS model is a continuous simulation model created on the ExtendSim simulation system platform. The problem is related to the constantly changing environmental parameters for the purpose of energy security for buildings as modern, energy-independent and self-sufficient systems. In terms of the implementation of the defined part of the research, a logistical approach was applied: system analysis, coordination, algorithm work, planning, efficiency. We define logistics as a system, principle, philosophy of management of flows. The numerous simulation experiments carried out show that the return on investment of the option with an initial investment of 5000 euros is in the range of 2422 to 4978 days, the return on investment of the option with an initial investment of 10000 euros is in the range of 4233 to 7902 days and the return on investment of the option with an initial investment of 15000 euros is in the range of 5691 to 10073 days.

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Key Words: Energy Savings Simulation Model, Monte Carlo Method, Local Energy Systems, Microgrids, Simulation, ExtendSim

1. INTRODUCTION

Renewable and distributed energy sources that are interconnected into microgrids will shape the future of energy systems. Traditional centralized energy systems, in which the user, the customer is without the possibility of any influence on the course and implementation of production, distribution and economic processes, are acquiring strong competition in the form of decentralized energy systems. Decentralization of energy systems means the geographical dispersion of electricity production and the replacement of a few large sources of energy production with a larger number of smaller sources of energy production. The described state and development in this area has been made possible only by the development of new energy systems based on alternative and renewable energy sources. By 2050, a significant number of households in the European Union will already be producing renewable energy, and they will be part of energy communities or form an independent, self-sufficient energy microgrid [1].

In connection with this, we define a problem that is related to constantly changing environmental parameters for the needs of energy security for buildings as modern, energy-independent and self-sufficient systems. The aim of the solution is to create a computer simulation model, a Cost Economy Energy Savings Simulation Model (CEESS Model) as a generator of economic scenarios for energy-independent structures using a solution based on the Monte Carlo method. The process for solving a defined problem and achieving the goal using a computer simulation model is examined in this article.

According to papers by Micallef et al. [2], Mehraban and Eslami [3] and Zheng et al. [4] the microgrid concept has evolved from its humble origins in simple remote electrification applications in rural environments to complex architectures. Microgrids are key enablers to the integration of higher penetrations of renewables in the energy sector. Economic operation is a

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fundamental issue for microgrids. Conventionally, hierarchical control is commonly utilized to deliver economic operations for microgrids.

Under the influence of various unpredictable or improbable events in recent years, such as the COVID-19 pandemic, the war in Ukraine, the economic or energy crisis, the importance of an economically efficient solution for securing energy-dependent and independent structures has become a priority of society. Already during the construction or purchase of a real estate structure, it should be clear under what conditions and associated costs it is possible to achieve economically effective energy security solutions for the structure. The solution of the defined problem depends on a number of changing parameters, which, however, have a stable representation, for example, the development of environmental temperatures over time, and also development of weather, the thickness and quality of materials of an energy-independent structure and also their thermal resistance, dimensions of the structure, the number of people using the structure, etc. The described state is subject to a solution using continuous computer simulation in the ExtendSim simulation environment and by applying the Monte Carlo method. This paper examines the possibility of creating a continuous simulation model, which takes into account the described state of uncertainty of the environment in which the studied structure will be located as an economically efficient energy-independent structure.

2. LITERATURE REVIEW

The use of the Monte Carlo method has a wide application in various areas that depend on random variables, whether in various areas of economics, production, game theory, but also in the field of simulation, probability, forecasting and others. The Monte Carlo method is a suitable method for solving both probabilistic and deterministic tasks. The essence of the method is often the repetition of random experiments, for example, using the generation of random numbers that represent the studied random states, phenomena, activities, events and processes. The basic goal of using the Monte Carlo method is to determine a solution, a result with a certain probability value if solution of the task by analytical means is lengthy, difficult, or impossible. Globally, this is a statistical estimate of probability. In certain solutions to tasks, it is better to obtain a solution or result that is not completely accurate, but has only a certain probability value, than to have no result at all [5].

The Monte Carlo method is the most widely used method in terms of solving various research, application and practical tasks, and also theoretical and educational tasks, which are focused on random but also deterministic phenomena, states, activities and events [5]. The importance and use of the Monte Carlo method is also evidenced by numerous articles and publications published by authors from all over the world, who use it to solve various research and practice tasks.

Zakeri and Syri [6] use the Monte Carlo method for the large-scale deployment of intermittent renewable energy, which may entail new challenges in power systems and more volatility in power prices in liberalized electricity markets. Life cycle costs and levelized cost of electricity delivered by electrical energy storage is analysed, employing the Monte Carlo method to consider uncertainties. Zhou et al. [7] use the Monte Carlo method to solve a distributed energy system as a multi-input and multi-output energy system with substantial energy, economic and environmental benefits. The authors employ a two-stage decomposition-based solution strategy to solve the optimization problem with a genetic algorithm performing the search on the first stage variables and a Monte Carlo method examining uncertainty in the second stage.

The Monte Carlo method solution approach can also be used to solve tasks in the field of logistics to solve optimal fleet capacities [8], in the field of electrical engineering to solve the increase in the power of a parabolic receiver [9, 10], or as a predictive control model for solving the energy management problems of plug-in hybrid electric buses [11], also for solving the deviation between the forecast and actual energy consumption of a building [12] and solving other tasks.

Using the Monte Carlo method to define energy production, based on renewable or alternative energy sources for different applications is also examined by other authors in various workplaces around the world [13-17].

3. METHODOLOGY

The CEESS model is a continuous simulation model that generates economic scenarios for structures studied from the energy perspective, which are generated based on defined parameters and system evolution over time. The parameters for setting up the system take into account the statistical development of temperatures over time, and also the development of the weather, the thickness and quality of materials of the structure being studied from the energy perspective and also their thermal resistance, the dimensions of the structure, the number of people using the structure, production of energy from photovoltaic panels, etc. The Monte Carlo method is used to define random parameters such as weather and temperature development on a defined day, the output of photovoltaic panels on a defined day, market inflation development over time and more. The calculation and assessment of heat demand for heating and energy demand for the studied structure is the basis for the development of economic scenarios as a means of deciding on investments in modern energy technologies.

The energy crisis, environmental pollution and global warming are important issues for our world [18-20]. The environmental protection is one of the most important socio-cultural topics. Protecting and supporting the healthy environment is an important basis for preserving human existence [21-23]. Hybrid energy systems provide one such optimistic sustainable solution for power generation in a grid integrated system as well as for stand-alone applications [24-27].

3.1 Calculation of the energy needs of the studied structure

The calculation of the total energy demand of the structure studied, Eq. (1), consists of several partial calculations such as the heat loss of the structure, the amount of energy needed to heat water and the amount of energy needed for heating.

$$Q_{(S,total)} = Q_S + Q_P + Q_W \text{ [W per hour]} \tag{1}$$

where:

$Q_{(S,total)}$ – total energy demand of the object,
Q_S – energy loss of the object,
Q_P – energy required to heat water,
Q_W – energy required for heating.

The heat loss of the structure, Eq. (2), (heat that escapes from the structure and needs to be supplied to the structure, caused by the quality of materials, ventilation, location of the structure) consists of parts of the heat losses of the roof, walls, windows, doors, floors and heat loss caused by infiltration by ventilation, opening and closing windows and doors, Eqs. (3), (4).

$$Q_S = Q_{(S,roof)} + Q_{(S,walls)} + Q_{(S,windows)} + Q_{(S,doors)} + Q_{(S,floors)} + Q_{inf} \text{ [W per hour]} \tag{2}$$

where:

$Q_{(S,roof)}$ – heat loss through the roof,
$Q_{(S,walls)}$ – heat loss through the walls,
$Q_{(S,windows)}$ – heat loss through the windows,
$Q_{(S,doors)}$ – heat loss through the doors,
$Q_{(S,floors)}$ – heat loss through the floors,
Q_{inf} – heat loss by infiltration.

$$Q_{(S,subject)} = L_{subject} \times S_{subject} \times \Delta t / R_{subject} \text{ [W per hour]} \tag{3}$$

where:
$L_{subject}$ – coefficient taking into account the orientation of roof, walls, windows, doors, floors to the cardinal points,
$L_{north} = 1.1$, $L_{south} = 1.0$, $L_{east} = 1.05$, $L_{west} = 1.05$,
$L_{southwest} = 1.025$, $L_{southeast} = 1.025$, $\underline{L_{northwest}} = 1.075$, $L_{northeast} = 1.075$,
$S_{subject}$ – area of roof, floors, walls, windows, doors [m^2],
Δt – temperature difference [°C]; $\Delta t = |t_{outside} - t_{inside}|$,
$R_{subject}$ – thermal resistance of solid and transparent parts of peripheral constructions [m^2 K / W];
$R_{subject} = B / k$,
B – thickness of material [m],
k – thermal conductivity coefficient of the material [W / (mK)],
$k_{roof} = 2.0,\ 1.1,\ 0.45$ $k_{walls} = 2.0,\ 1.0,\ 0.5$ $k_{windows} = 2.5,\ 1.9,\ 1.3$
$k_{doors} = 2.5,\ 1.9,\ 1.3$ $k_{floors} = 1.0,\ 0.5,\ 0.2$

$$Q_{inf} = 0.33 \times K \times V \times \Delta t \text{ [W per hour]} \tag{4}$$

where:
K – coefficient, air exchange rate, living rooms $K = 0.3$, rooms with heating $K = 0.8$, kitchen and bathroom $K = 1$,
V – room volume [m^3].

The amount of energy required to heat water and the amount of energy required to heat the studied structure can be calculated using the Eqs. (5) and (6).

$$Q_P = m \times c \times \Delta t \times \eta \text{ [kWh per month]} \tag{5}$$

where:
m – weight of liquid,
c – specific heat capacity of water; 4190 [J / (kgK)],
Δt – temperature difference [°C]; $\Delta t = |t_{output} - t_{input}|$
η – heating efficiency.

$$Q_W = Q_S \times k_S \text{ [W per hour]} \tag{6}$$

where:
k_S – coefficient of safety, depends on the region and requirements for thermal comfort.

3.2 A formalized scheme of the CEESS model

The CEESS model as a generator of economic scenarios for structures studied from the energy perspective depends on parameters of the development of the system over time, such as the development of environmental temperatures in a given location over time, and also weather development, thickness and quality of materials of the structure studied from the energy perspective and also their thermal resistance, the dimensions of the structure, the number of people using the structure, the production of energy from photovoltaic panels, market conditions, prices, inflation, etc. (see Fig. 1). The influence of the defined parameters is continuous, 24 hours a day, 7 days a week and over many years.

From the point of view of creating a CEESS computer simulation model, it is advisable to create a formalized diagram in the first phase and then a block diagram, which will be transformed into a specific simulation system. Since a logistical project approach is applied in the creation of the simulation model, the examined structures represent the system with its elements. Elements that have a direct impact on the calculation of the energy intensity of the structure studied depend on the quality of building elements such as roof, walls, windows, doors, floor, amount of hot and cold water, energy needed for heating, infiltration, etc., the qualities of which affects the heat transfer of materials and the heat loss of the structure.

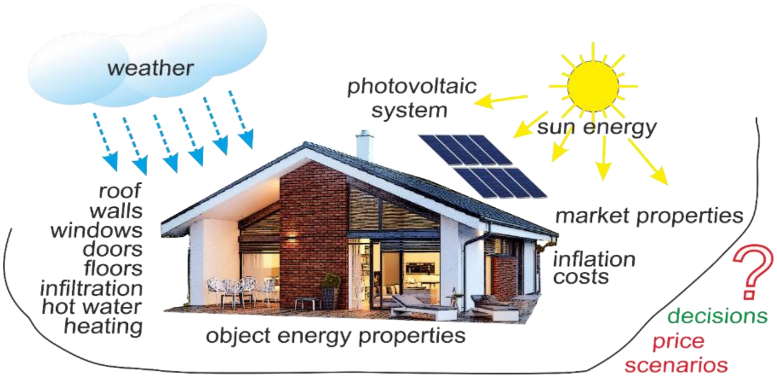


Figure 1: System and elements of the microgrid studied.

By evaluating direct elements and elements that are random in nature or whose development can be statistically estimated such as weather, inflation and costs, it is then possible to build a model that is able to generate price scenarios for the needs of making decisions in terms of return on investment, investments in the quality of building materials, energy system, etc. The elements of the studied system are arranged in a sequence of steps, creating an algorithm that represents a formalized scheme of defined parameters and the procedure for performing calculations (see Fig. 2).

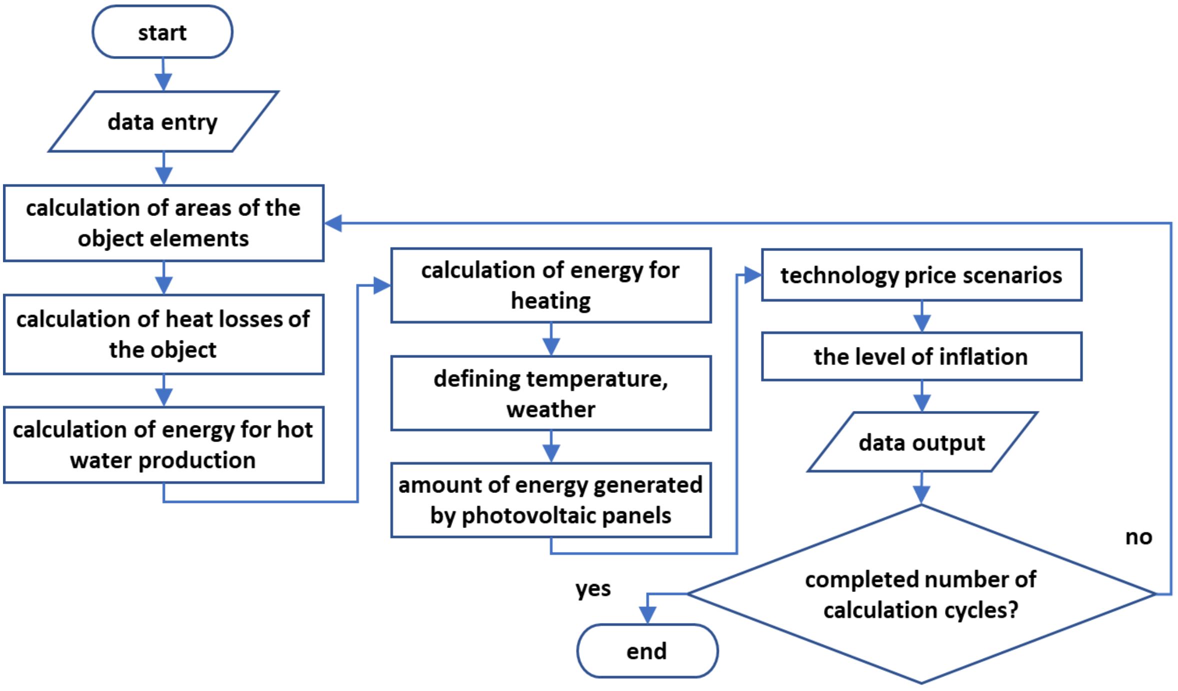


Figure 2: Procedure for performing calculations and steps of creating a CEESS simulation model.

3.3 Block diagram and continuous simulation model design of the CEESS model

The creation of the CEESS computer simulation model in ExtendSim consists of two parts. The first part is represented by the block diagram of the simulation system concerned (see Fig. 3). The second part is the created computer simulation model itself, used for conducting research into the generation of economic scenarios of structures studied from the energy perspective (see Fig. 4). An interesting feature of the model created is that each element of the block diagram, or blocks of the computer simulation model, represent subroutines with their calculations. In the ExtendSim simulation system, these are *“Hierarchical blocks, structures”* [28].

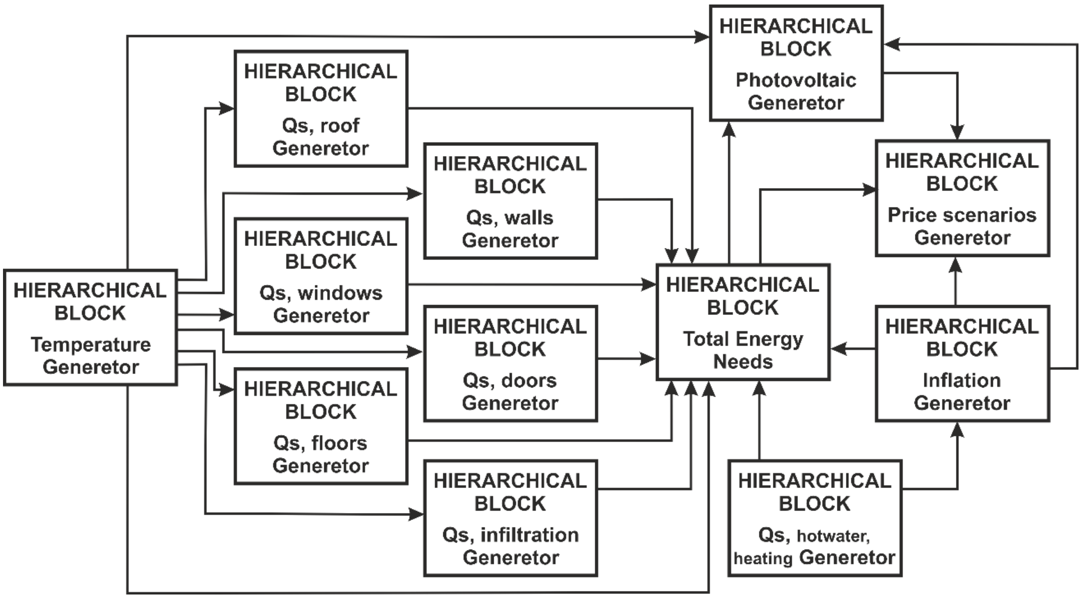


Figure 3: CEESS block diagram of a simulation model.

The parts of the computer simulation model are characterized by a sequence of blocks that are connected by connectors that unambiguously determine the direction of flows. The basic characteristics of the individual blocks of the model are defined by the position, icon and name of the block, block connectors, connecting lines, dialogs with operands and flows [28].

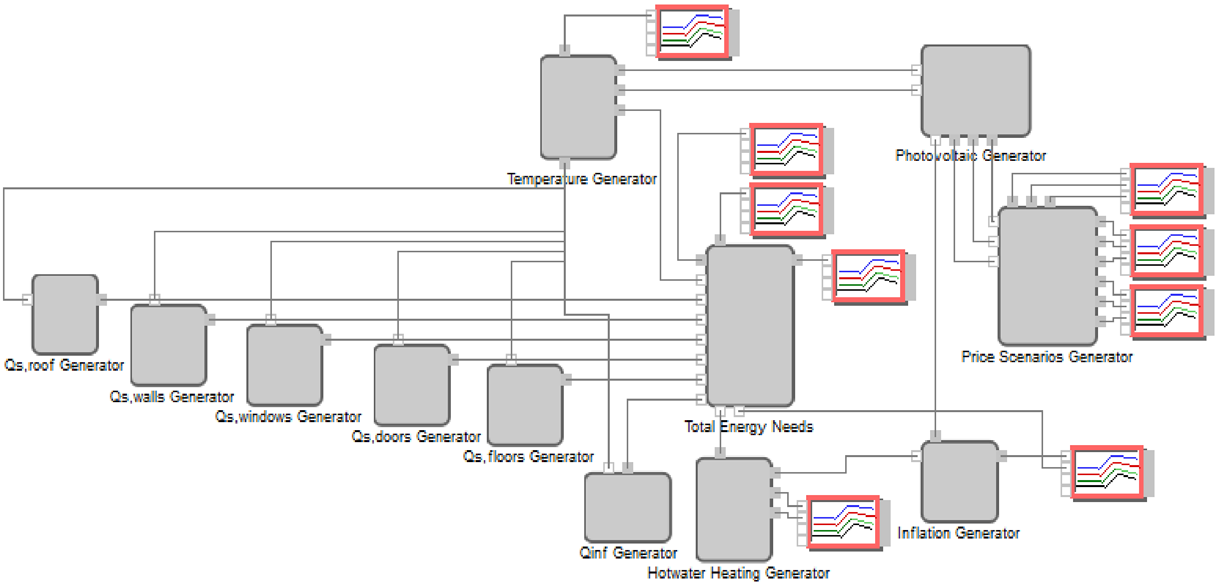
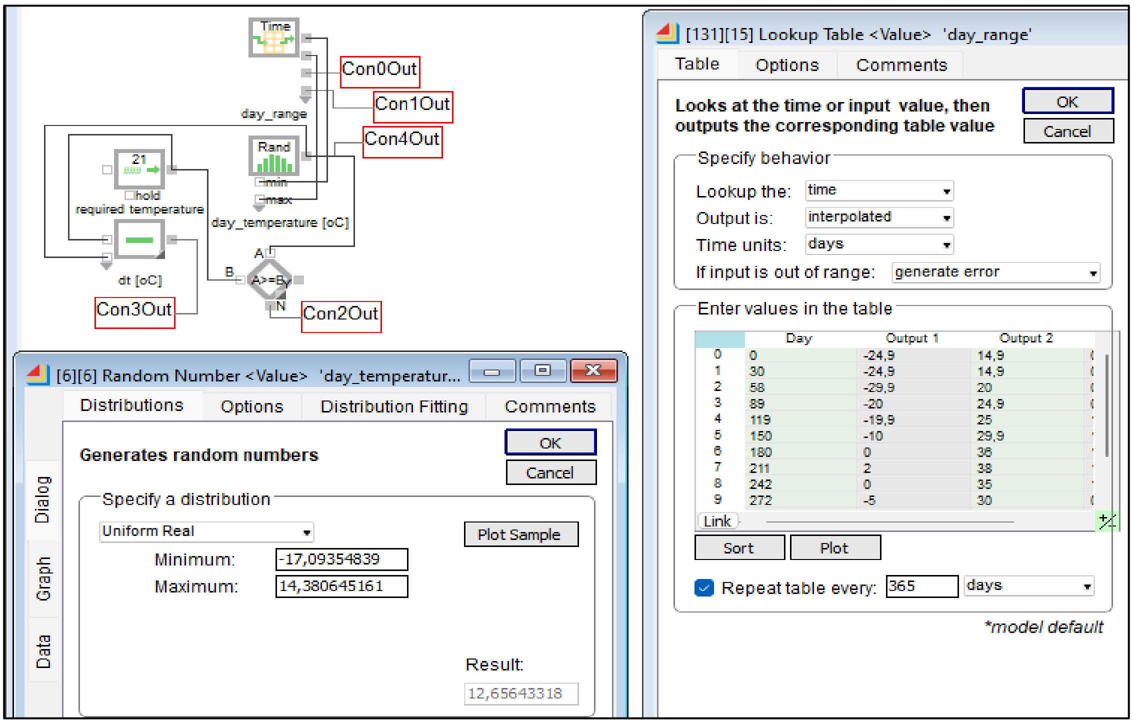


Figure 4: Computerized ExtendSim simulation of the CEESS model, created from *"Hierarchical blocks, structures"*.

The created Cost Economy Energy Savings Simulation Model in the ExtendSim simulation system has its own specifics, just like any functional model. In terms of difficulty and scope, it is not possible to describe all the details of a given continuous simulation model. The relationships / Eqs. (1), (2), (3), (4), (5), (6), by which it is possible to calculate the energy intensity of the studied structure, form the core of the CEESS model generators in the sections *"QS,roof Generator", "QS,walls Generator", "QS,windows Generator", "QS,doors Generator", "QS,floors Generator", "Qinf Generator" and "Hotwater Heating Generator".* For this reason, the description of the CEESS model as a functional computer simulation model will focus on parts that are significant in design and based on the Monte Carlo method. The main influence on the creation, generation of economic scenarios, and also on the calculation of the energy intensity of the studied structure is the variable conditions of weather and temperature in the region and the related amount of electricity produced through photovoltaic panels and the development of inflation on the market. The individual defined parts use the principles of the Monte Carlo method for their functional side.

The development of weather and temperature in the given region has a random character, which is limited by extreme values, which are recorded as statistics and are available on the website of the Slovak Hydrometeorological Institute for decades [29]. These data form the basis of the *"Temperature Generator"* setting and are input parameters for generating values based on the Monte Carlo method (see Fig. 5). The development of weather and temperature in a defined region directly affects the production of electricity generated through photovoltaic panels and also the calculation of the energy demands of the studied structure. The amount and values of electricity that a photovoltaic panel is able to generate in a period under specific defined conditions are known and form the basic input values for generating energy for individual days and time and form the basis of the Monte Carlo method-based *"Photovoltaic Generator"* setting (see Fig. 6). Inflation/deflation, as an economic parameter, is also characterized by uncertainty. The development of inflation/deflation depends on a number of factors. In terms of creating a simulation model as a functional system and incorporating the parameter in question into the system, the inflation/deflation setting is realized as a statistical indicator (see Fig. 7) based on the Monte Carlo method. In principle, any parameter that is random in nature and about which some statistical indicators are known can be realized in a computer simulation in a similar manner based on the Monte Carlo method.



[6][6] Random Number <Value> 'day_temperatur...

Distributions | Options | Distribution Fitting | Comments

Generates random numbers

OK
Cancel

Specify a distribution

Uniform Real

Plot Sample

Minimum: -17,09354839

Maximum: 14,380645161

Result: 12,65643318

[131][15] Lookup Table <Value> 'day_range'

Table | Options | Comments

Looks at the time or input value, then outputs the corresponding table value

OK
Cancel

Specify behavior

Lookup the: time

Output is: interpolated

Time units: days

If input is out of range: generate error

Enter values in the table

	Day	Output 1	Output 2
0	0	-24,9	14,9
1	30	-24,9	14,9
2	58	-29,9	20
3	89	-20	24,9
4	119	-19,9	25
5	150	-10	29,9
6	180	0	36
7	211	2	38
8	242	0	35
9	272	-5	30

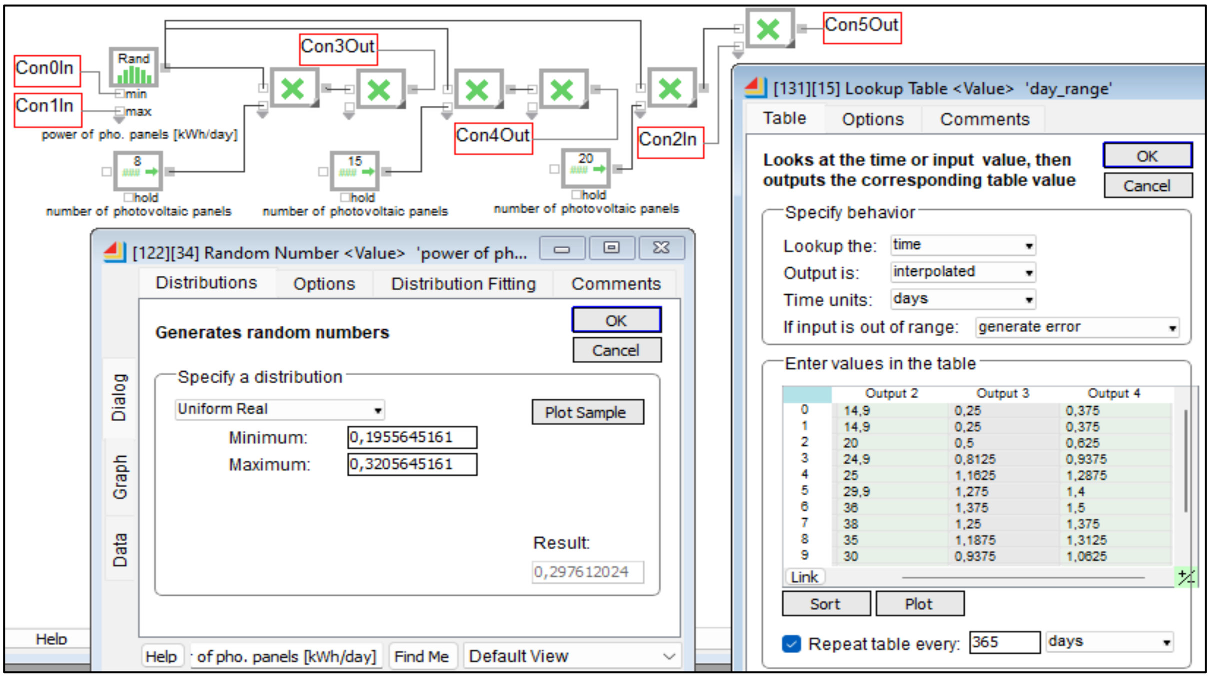
Link

Sort
Plot

☑ Repeat table every: 365 days

*model default

Figure 5: Hierarchical block *"Temperature Generator"* of the CEESS model with a setting that generates temperature development for a specific time based on the Monte Carlo method.



[122][34] Random Number <Value> 'power of ph...

Generates random numbers

Specify a distribution

Uniform Real

Minimum: 0,1955645161

Maximum: 0,3205645161

Result: 0,297612024

[131][15] Lookup Table <Value> 'day_range'

Looks at the time or input value, then outputs the corresponding table value

Specify behavior

Lookup the: time

Output is: interpolated

Time units: days

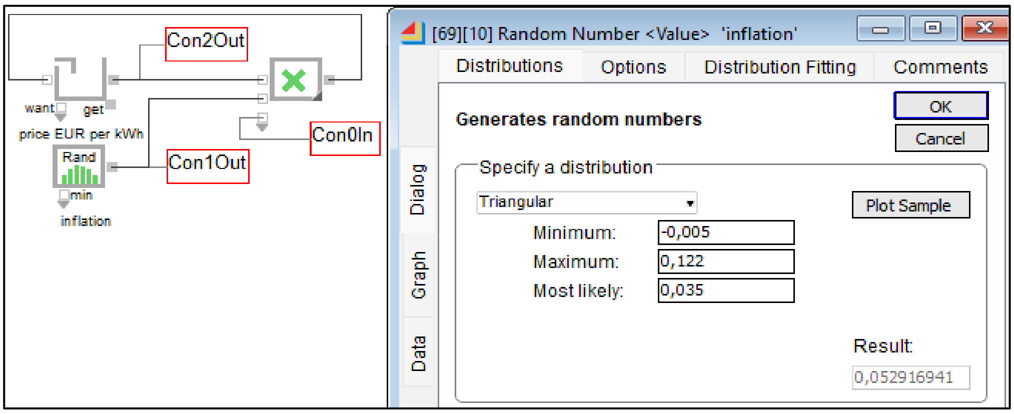
If input is out of range: generate error

Enter values in the table

	Output 2	Output 3	Output 4
0	14,9	0,25	0,375
1	14,9	0,25	0,375
2	20	0,5	0,625
3	24,9	0,8125	0,9375
4	25	1,1625	1,2875
5	29,9	1,275	1,4
6	36	1,375	1,5
7	38	1,25	1,375
8	35	1,1875	1,3125
9	30	0,9375	1,0625

☑ Repeat table every: 365 days

Figure 6: Hierarchical block *"Photovoltaic Generator"* of the CEESS model with a setting that generates energy for a specific time based on the Monte Carlo method.



[69][10] Random Number <Value> 'inflation'

Generates random numbers

Specify a distribution

Triangular

Minimum: -0,005

Maximum: 0,122

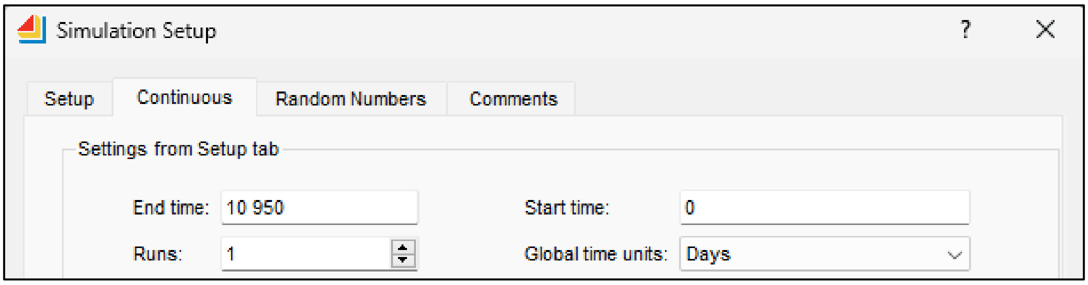
Most likely: 0,035

Result: 0,052916941

Figure 7: Hierarchical block *"Inflation Generator"* of the CEESS model with a setting that generates the development of inflation/deflation for a specific day based on the Monte Carlo method.

4. RESULTS AND DISCUSSION

Since it is a continuous simulation, the control of simulation time is limited to the cyclical sequence of mathematical calculations. In the CEESS model studied, the system was set to perform calculations for 30 years with a global time unit of one day (see Fig. 8).



Simulation Setup

Settings from Setup tab

End time: 10 950

Start time: 0

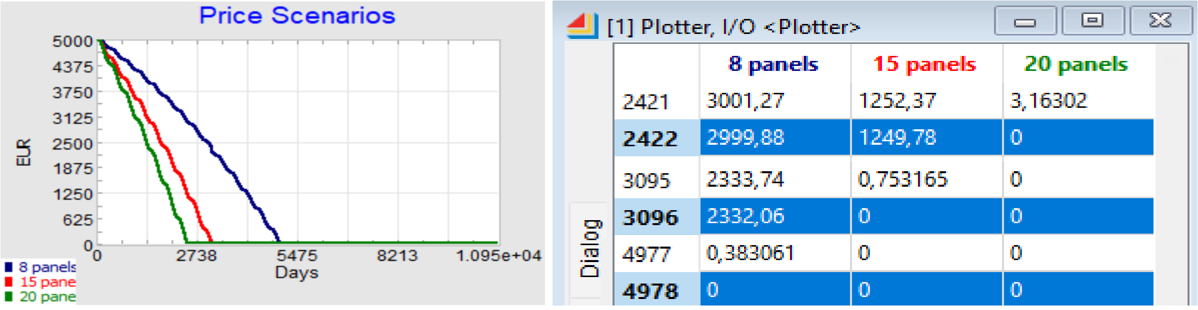
Runs: 1

Global time units: Days

Figure 8: Setting the start and end of continuous simulation calculations in the CEESS model.

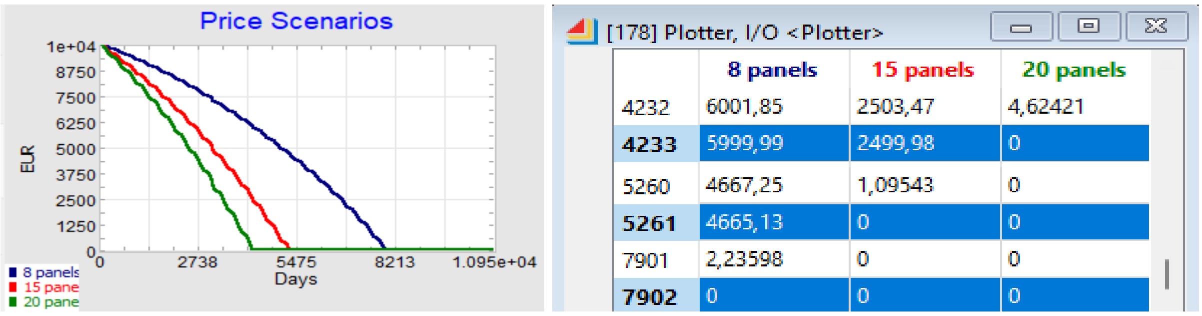
To create economic scenarios and generate more outputs at the same time, the CEESS model uses three groups of photovoltaic panels and three investment groups as a basis. Groups of photovoltaic panels are formed with 8, 15 and 20 pieces. Investment groups in technology are at investment levels of 5, 10 and 15 thousand euros. For each energy-active group, economic scenarios are generated, which in the form of graphs record the return on investment, taking into account all the parameters and constraints defined above.

The results of the simulation show that the return on investment of the option with an initial investment of 5000 euros is in the range of 2422 – 4978 days (see Fig. 9), the return on investment of the option with an initial investment of 10000 euros is in the range of 4233 – 7902 days (see Fig. 10) and the return on investment of the option with an initial investment of 15000 euros is in the range of 5691 – 10073 days (see Fig. 11). The results are valid for a specifically defined number of photovoltaic panels and size of investment.



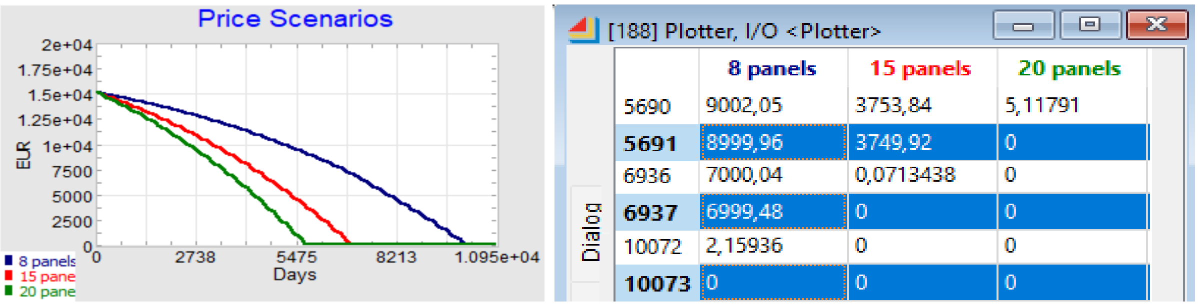
	8 panels	15 panels	20 panels
2421	3001,27	1252,37	3,16302
2422	2999,88	1249,78	0
3095	2333,74	0,753165	0
3096	2332,06	0	0
4977	0,383061	0	0
4978	0	0	0

Figure 9: Generated scenarios of economic return after numbers of days in the CEESS model, option with an investment of 5000 euros.



	8 panels	15 panels	20 panels
4232	6001,85	2503,47	4,62421
4233	5999,99	2499,98	0
5260	4667,25	1,09543	0
5261	4665,13	0	0
7901	2,23598	0	0
7902	0	0	0

Figure 10: Generated scenarios of economic return after numbers of days in the CEESS model, option with an investment of 10000 euros.



	8 panels	15 panels	20 panels
5690	9002,05	3753,84	5,11791
5691	8999,96	3749,92	0
6936	7000,04	0,0713438	0
6937	6999,48	0	0
10072	2,15936	0	0
10073	0	0	0

Figure 11: Generated scenarios of economic return after numbers of days in the CEESS model, option with an investment of 15000 euros.

The current economic situation and the development of alternative energy technologies on the market provide scope for research and development of similar models aimed at generating scenarios of economic return on investment in the purchase of such technologies. Niekurzak and Kubinska-Jabcon [30] also discuss this evaluation of investments in photovoltaic panels in their paper. It follows from the results of their paper that an installation of the technology can achieve a Net Present Value (*NPV*) of EUR 6,000 over 20 years at a discount rate $r = 0$ assuming that the electricity price is EUR 0.15/kWh. In their paper, Vögele and Rübbelke [31] state that for an assessment of the profitability of investments in photovoltaics (and other renewable energy technologies), additional costs caused by the fluctuation in the productivity of photovoltaic power plants and by the need for backup capacities have to be taken into account. From the results of the research by Kittner et al. [32] it also follows, that distributed mini-grids with penetrations of solar photovoltaics of up to 50 % of annual generation can exceed the energy return on energy invested with some fossil-based traditional centralized grid systems.

There are a number of authors with similar or identical results. No author or authors used the possibilities of continuous simulation using the ExtendSim simulation system to solve the defined problem.

5. CONCLUSION

The Cost Economy Energy Savings Simulation Model (CEESS Model) created as a generator of economic scenarios for energy-independent objects using the Monte Carlo method is a continuous simulation model created on the ExtendSim simulation system platform. The CEESS model is the result of independent research and development in the field of modelling and simulation of local energy systems microgrids in industry and their impact on the rest of the electricity system. From the number of simulation experiments carried out it follows that the return on investment of the option with an initial investment of 5000 euros is in the range of 2422 – 4978 days, the return on investment of the option with an initial investment of 10000 euros is in the range of 4233 – 7902 days and the return on investment of the option with an initial investment of 15000 euros is in the range of 5691 – 10073 days. The results are valid for the above-defined number of photovoltaic panels and the size of the investment. The given parameters can be changed according to the needs and requirements of the studied system. The CEESS model is the result of independent research and development in the field of modelling and simulation of local microgrid energy systems in industry and their impact on the rest of the electricity system. The defined problem, connected with constantly changing environmental parameters for the needs of energy security of buildings such as modern, energy-independent and self-sufficient systems, has led to the creation of a continuous simulation model for generating economic scenarios as a means of deciding on investments in modern energy technologies.

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