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MATHEMATICAL MODEL FOR HOUSEHOLD OFF-GRID SIMULATION (OFF-GRID SYSTEM SIZING)

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The paper presents the results of the research, which was initiated in our previous publication. The main goal of the research is to develop and validate our own multi-objective simulation tool for determination of optimal mix and sizing of off-grid and grid-connected microgrid systems. The first version of the developed model was tailored specifically for simulation of household off-grid system, which consisted of solar photovoltaics (PV), micro wind turbine, electric batteries, and backup power generator. Proposed algorithms are based on simulation of mentioned resources and hourly electric loads of off-grid system with the objective to reduce unsupplied energy volumes and total system costs. Several alternatives were considered with different configurations of the off-grid system and dispatching strategies of available resources. The developed model was validated with calculations of real off-grid system and results were compared to those, which were made in the previous publication, using Homer Pro software.

Keywords: *Annual costs of system, dispatch strategy, microgrid equipment sizing, off-grid system, RES fraction.*

1. INTRODUCTION

In recent years, microgrid systems either when operated in an off-grid or a grid-connected mode have been recognized as one of the most suitable, cost-effective, and sustainable solutions for commercial, industrial, and residential electrification applications [1], [2]. Decreasing costs of renewable energy technologies, fluctuating fossil fuel prices, environmental concerns and security of electricity supply are the main reasons for looking towards the development of emerging microgrid systems [3].

However, research on such systems still must be examined. For instance, microgrids have challenges regarding determination of proper equipment sizing, the voltage and frequency disturbance problems in unpredictable weather conditions, difficulties with monitoring and managing local power generation and loads, along with constrains related to designing protection devices to cope with bi-directional power flows and so on [1]. Within this paper, our focus is on autonomous household scale microgrid equipment sizing problems.

The microgrid equipment sizing is understood as quantification of the power capacities for renewable generators (solar, wind, etc.), as well as for backup power generator and determination of the power (kW) and energy (kWh) capacities of a battery energy storage system (BESS). The proper sizing of the microgrid may reduce the risk of oversize system equipment, which could lead to higher initial capital costs. On the other hand, it may reduce the risk of undersize equipment, which can lead to the poor power supply reliability [4]. Moreover, environmental and social aspects are no less important. Therefore, it is necessary to consider how to minimize emissions, how to promote socially acceptable system development, which includes issues with land use, visual impact, acoustic noise, etc.

According to literature review, several types of methods and different indicators might be considered in the evaluation process of such microgrid equipment. The sizing methods can be classified as classical methods, software tools, hybrid methods and most recently also artificial intelligence methods as shown in Table 1. In the most common cases, four types of indicators are identified which further describe the performance of microgrid: economic indicators (LCOE, LCC, ACS, NPV etc.), reliability indicators (LPSP, LOLP, EENS, etc.), environmental indicators (CE, LCA, EE), and social indicators (HDO, JC, SA, etc.) [5], [6].

In addition to the review mentioned above, some articles have summarised the latest trends of algorithm and indicators, and future overall challenges of microgrid sizing methodologies. For example, ant colony (ACO), firefly algorithm (FA), particle swarm optimization (PSO) and genetic algorithm (GA) and their performance were comprehensively analysed by [7] regarding how to select an appropriate algorithm to solve non-linear problems in the context of storage-based off-grid systems under different alternatives. The results reveal that FA performs better, with the least relative error. Other paper [2] evaluated sizing of an autonomous microgrid considering droop control. Results indicated that a competitive total cost could be obtained if the droop parameters were calculated considering the microgrid sizing results. Electric system cascade extended analysis was developed in [8]. In it, the LPSP, LCC and the LCOE together with tri-objective optimization functions were implemented and validated with system advisor model software. Authors of this paper argue that this analysis might help choose the suitable RES capacities for any site worldwide. In [9], a model for a remote community off-grid PV/diesel system using dynamic modelling and artificial neural network (ANN) techniques was developed. Within a comparative analysis, authors concluded that utilising dynamic and predictive modelling techniques would enable the model to be expandable, and simple to use while still maintaining its accuracy. Using an iterative approach based on a recursive algorithm, improvements were made to a techno-economic optimal sizing technique of a hybrid off-grid microgrid system in [6]. However, a new mutation adaptive differential evolu-

tion (MADE) based on a multi-objective optimization algorithm is presented in [10] to optimise the configuration of the off-grid stand-alone photovoltaic systems. It is also worth mentioning the authors of previous publication [4] which showed how important it was to choose the right dispatch strategy for off-grid system regarding equipment sizing, and at the end how it affected the net present costs (NPC) over the project lifetime.

Table 1. Microgrid Equipment Sizing Methods and Indicators [5], [6]

Type of sizing methods	**Type of indicators**
Classical: - probabilistic - analytical - numerical - iterative	**Economic:** -levelized cost of electricity (LCOE) -life cycle cost (LCC) -annualized cost of system (ACS) -total net present value (NPV)
Software tools: - Homer Pro - RETScreen, - PVSOL - Hybrid 2 - Transys	**Reliability**: - loss of power supply probability (LPSP) - loss of load probability (LOLP) - expected energy not supplied (EENS) - deficiency of power supply probability (DPSP) - loss of load expected (LOLE), - loss of energy expected (LOEE)
Hybrid methods: - combined dynamic programming and region-elimination technique algorithm (DP-RET) - hybrid Simulated Annealing–Tabu Search - hybrid Big Bang-Big Crunch algorithm (HBB -BC) - hybrid GA-mixed integer linear programming (GA-MILP)	Environmental: - carbon emission (CE) - embodied energy (EE) - carbon footprint of energy (CFOE) - life cycle assessment (LCA)
Artificial intelligence: - genetic algorithm (GA) - particle swarm optimization (PSO) - simulated annealing (SA) - ant colony optimization (ACO) - artificial bee colony (ABC)	**Social**: - human development index (HDI) - job creation (JC) - portfolio risk (PR) - social acceptance (SA) - social cost of carbon (SCC)

In general, according to the literature review, it can be noticed that there are still difficulties in the field of equipment capacity optimization:

1. improvements in load forecasting and adoption to methods are necessary;
2. calculation time step of power output is critical for the optimization of the results; thus, it should be reduced considerably as much as possible (less than 1 hour is preferable);
3. improved sizing methods equipment could be installed in the research area to obtain real-time data and verify simulation results;
4. new evaluation indicators may be used to provide more effective and overall assessment as the microgrids are emerging solutions for sustainability policy goals;
5. artificial intelligence sizing methods have advantages in accuracy and computation speed compared to traditional methods, while, on the other hand, those significantly increase optimization complexity;
6. as good practice equipment sizing is validated and improved also with more than one optimization tool.

It can also be concluded that existing

articles mainly focus on microgrid operation state; therefore, future research might have more efforts on the planning, construction state, and microgrid servicing.

The main aim of the present research is to introduce a new multi-objective simulation tool to evaluate the performance of several off-grid cases under different dispatch approaches, which would further increase knowledge of such systems and flexibility of already existing simulation tools. The developed tool is used to justify a composition and capacities of an off-grid system equipment for the real pilot project, which currently is under implementation. It is expected that this approach can be used and easily replicated for configurations that are more complex.

2. MODEL FOR THE HOUSEHOLD OFF-GRID SIMULATION

The simulation model described in the present research was developed for the real case evaluation. At that time, the information for the sizing of the system was rather insufficient. The model determined necessary generation and storage capacities, helped assess the payback of the off-grid project and allowed visualising operating conditions.

The model has been applied to an off-grid system composed of solar PV, wind turbine, battery energy storage system (BESS or battery) and backup power generator. The model presented in this section is designed as a set of algorithms, which determine the operation of off-grid solution according to the load and supply power balances as indicated in Fig. 1 and Table 2.

Table 2. Parameter Abbreviations

Parameter	Abbr.	Parameter	Abbr.	Parameter	Abbr.
Electric load (kW)	P_l	Max amount of energy of the battery (kWh)	E_{bmax}	Power of PV modules (kW)	P_{gPV}
Generated power (kW)	P_g	Min amount of energy of the battery (kWh)	E_{bmin}	Power of wind generators (kW)	P_{gW}
Other generation capacities (kW)	P_n	State of charge of the battery (%)	SOC	Rated power of backup generator (kW)	P_r
Rated power of the battery (kW)	P_{br}	Max state of charge of the battery (%)	SOC_{max}	Minimal power of backup generator	P_{rmin}
Rated energy capacity of the battery (kWh)	E_{br}	Min state of charge of the battery (%)	SOC_{min}	Levelized costs of electricity, EUR/kWh	LCOE

The model has been developed to provide the highest (close to 100 %) electricity availability, considering that the electricity generation sources (PV, wind, etc.) connected to the off-grid are stochastic. Thus, energy storage and backup generator are needed.

For simplicity, the time interval for modelling of off-grid system is assumed to be one hour; thus, the load and at the same time the required generation capacity are defined as *Pl* in the time interval *t*. Total power generated (kW) at the time interval *i* (excluding backup generator) *Pg(i)* in Eq. (1) is defined as the sum of power capacity of solar modules, wind turbine and potentially other generation sources such as fuel cell, small-scale CHP unit, etc.

$$P_{g(t)} = P_{gPV(t)} + P_{gW(t)} + \ldots + P_{n(t)}. \quad (1)$$

As the off-grid system requires a battery energy storage system, it is necessary to determine its state of charge status at the time interval *t*:

$$\mathrm{SOC_{(t)}} = \mathrm{SOC_{(t-1)}} + \frac{\mathrm{E_{b(t)}}}{\mathrm{E_{br}}}, \quad (2)$$

where $\mathrm{SOC_{(t-1)}}$ is the state of charge of the BESS in the previous time interval, $\mathrm{E_{br}}$ is the rated energy capacity of the BESS, $\mathrm{E_{b(t)}}$ is the amount of energy BESS charged or discharged in the time interval. In addition, the model calculates the maximum possible charge and discharge capacities (kW) of the BESS (4), which at the same time gives us the amount of energy per cycle. During the first cycle $\mathrm{SOC_{(t)}}=\mathrm{SOC_{max}}$:

$$E_{bmax} = \left(SOC_{(t)} - SOC_{min}\right) \times E_{br}. \quad (3)$$

$P_{bmax}=E_{bmax}$, for time interval t = 1h. (4)

If there is a surplus or shortage of electricity (kW) at the time interval *t* in the off-grid system, Eq. (5) is used:

$$P_{(t)} = P_{g(t)} - P_{l(t)}. \quad (5)$$

In next equations (6 and 7), the model assesses whether to start-up the back-up generator and at what power:

$$\text{if } P_{bmax(t)} < P_{(t)}; \quad (6)$$

$$P_{r(t)} = P_{br} - P_{bmax(t)} - P_{(t)}. \quad (7)$$

If the BESS and other sources can cover the load, the backup generator will not be scheduled for operation. If not, the power output of the back-up generator during the time interval *t* is determined within the range P_{rmin}-P_r. The calculation is adjusted so that the back-up generator operates closer to the nominal (rated) output and charges the battery at maximum possible power during the time interval *t*.

The actual power rating (kW) of the BESS and its nature (charging / discharging) in the model is determined by Eq. (8):

$$P_{b(t)} = P_{(t)} + P_{r(t)}. \quad (8)$$

The actual charged or discharged energy rating (kWh) of the BESS $\mathrm{E_b(i)}$ at the time interval is determined by Eqs. 9–11:

$$if\, P_{b(t)} > 0, then\, k_{b(t)} = 0.9; \quad (9)$$

$$if\, P_{b(t)} < 0, then\, k_{b(t)} = 1/0.9; \quad (10)$$

$$E_{b(t)} = P_{b(t)} \times k_{b(t)} \times 1h, \quad (11)$$

where k_b is the efficiency of the BESS. The simulation cycle ends with Eq. 11) to initialize calculations for the next time interval *t*:

$$t = t + 1. \quad (12)$$

Fig. 1 shows a block scheme within the sequence of operations of the described off-grid system.

The annual costs and levelized cost of energy (LCOE) of the off-grid system are determined in a separate algorithm. Before using the algorithm, configuration of the model is necessary to set up the required dispatching strategy and input data.

The overall model optimization focuses on four aspects: off-grid system highest availability, lowest surplus generation, lowest operation hours of the backup generator, lowest LCOE.

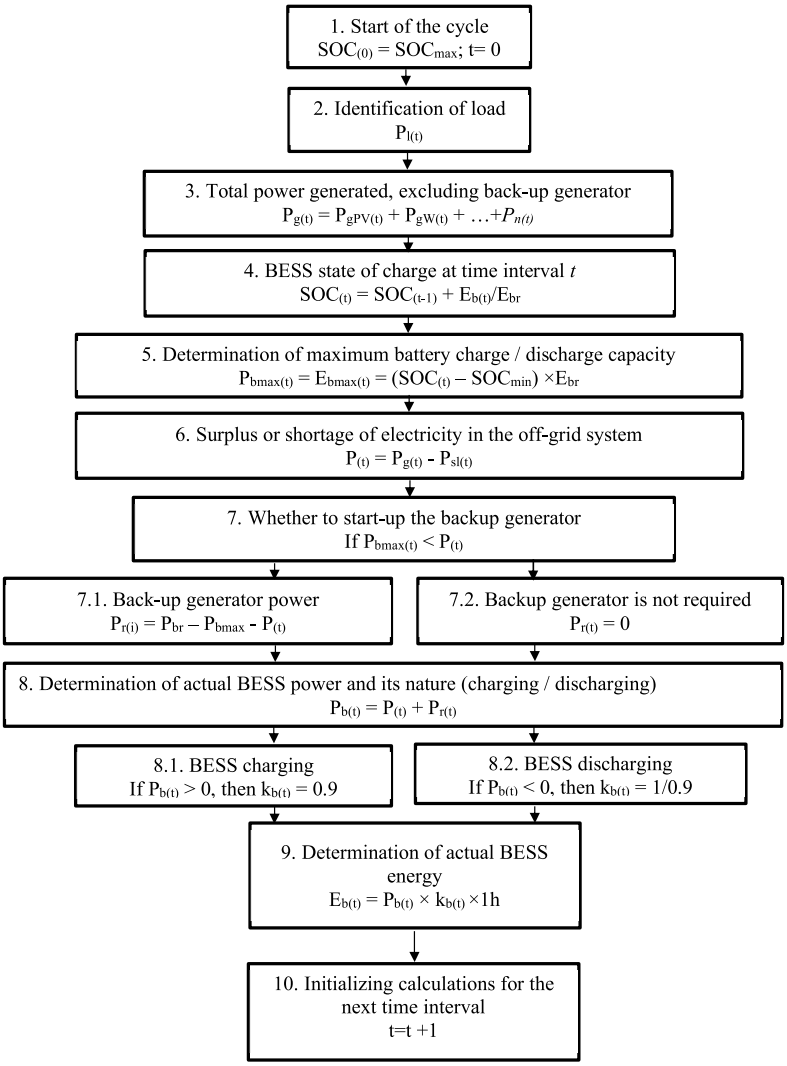


Fig. 1. Operational principles of the model of off-grid system.

3. ANNUAL COSTS OF OFF-GRID SYSTEM

The objective function in the calculations is minimization of the levelized cost of electricity (LCOE), which in this case is determined based on the method of the annual cost of system (ACS) [11].

ACS covers annual capital cost (ACC), annual operation and maintenance costs (AOM), annual replacement costs (ARC), annual fuel costs of backup generator (AFC) and annual emission cost (AEC). ACS (in EUR) is estimated as follows:

$$ACS = ACC + AOM + ARC + AFC + AEC. \quad (13)$$

Annual capital cost (in EUR) of each unit which does not need replacement during project lifetime, such as PV system, wind turbine, back-up generator and inverter, is calculated as follows:

$$ACC = C_{cap} \cdot CRF(i, y), \quad (14)$$

in which

$$CRF = \frac{i \cdot (1+i)^y}{(1+i)^y - 1}, \quad (15)$$

where C_{cap} is the capital cost of each component in EUR, but *y* is the project lifetime in years. *CRF* is capital recovery factor, a ratio to calculate the present value of a series of equal annual cash flows, and *i* is the annual real interest rate.

The annual operation and maintenance cost as a function of capital cost, reliability of components (λ) and their lifetime (y) can be determined using the following equation:

$$AOM = C_{cap} \cdot \frac{1-\lambda}{y}. \quad (16)$$

ARC is the annual cost value (in EUR) for replacing units during the project lifetime. In this study, a unit that needs replacement is only battery banks. Other units do not require replacement because their lifetime is the same as project lifetime. Economically, annual replacement cost is calculated as follows:

$$ARC = C_{rep} \cdot SFF(i, y_{rep}), \quad (17)$$

where C_{rep} is the replacement cost of battery banks in EUR, but is the lifetime of battery banks in years. In this case, the replacement cost of battery banks is like its capital cost. *SFF* is the sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. This factor is calculated as follows:

$$SFF = \frac{i}{(1+i)^y - 1}. \quad (18)$$

AFC of backup generator unit is estimated based on optimum dispatch of backup generator system. The fuel consumption (in liters) based on load characteristic of the back-up diesel generator is calculated for each time interval *t* using the following equation:

$$F(t) = 0.246 \cdot P_r(t) + 0.08415 \cdot P_r, \quad (19)$$

where is the rated power of backup generator in kW, $P_r(t)$ is the actual power generated at time interval *t* in kWh. The fuel cost (in EUR) is calculated for a year by multiplying hourly fuel consumption by fuel costs:

$$AFC = C_f \cdot \sum_{t=1}^{8760} F(t), \quad (20)$$

where C_f is the fuel cost per litre (EUR/l). To reach the maximum efficiency of operation the unit should be operated within rated power and specified maximum value.

AEC is the annual emission cost (in EUR) to capture CO_2 emission generated from backup generator system. The AEC can be expressed as follows:

$$AEC = \sum_{t=1}^{8760} E_f \cdot E_{cf} \cdot P_r(t)/1000, \quad (21)$$

where E_f is the CO_2 emission factor, kg/kWh, E_{cf} is the CO_2 emission cost in EUR/t.

By calculating the ACS it is possible to determine levelized cost of electricity (LCOE), which shows how much each kWh of electricity costs in the particular microgrid (EUR/kWh).

$$LCOE = \frac{ACS}{E_{AEC}}, \quad (22)$$

where is the annual energy consumption of a microgrid (kWh). Other parameters used in the calculations are shown in Table 3.

Table 3. The Economic Data Considered for Calculations

Parameter	Data	Parameter	Data	Parameter	Data
Project lifetime (years)	20	Reliability of PV panel (coef.)	0.98	Cost of Wind turbine (EUR/kW)	3500
Real interest rate (%)	4	Reliability of wind turbine (coef.)	0.8	Cost of battery bank (EUR/kWh)	540
PV panel lifetime (years)	25	Reliability of inverter (coef.)	0.98	Cost of battery bank (EUR/kW)	540
Wind turbine lifetime (years)	20	Reliability of battery (coef.)	0.98	Cost of inverter (EURkW)	1300
Inverter lifetime (years)	20	Reliability of backup generator (coef.)	0.9	Fuel cost (Cf) (EUR/l)	1.2
Battery lifetime (years)	10	Cost of backup generator (EUR/kW)	380	Emission factor (kg/kWh)	0.34
Backup generator lifetime (hours)	15 000	Cost of PV panel (EUR/kW)	1250	Emission cost (EUR/t)	30

The parameters shown in Table 3 can be changed as needed for other microgrids.

4. CASE STUDY

For the case study, real household hourly load data are collected, integrated in the model, and used in simulations. Household average daily electricity demand is 30.27 kWh, which reaches 11.049 MWh on an annual basis. The household consists of 2 persons. A heat pump, which is used for heat and hot water supply, and an electric vehicle for transports needs can be considered the biggest consumers of electricity in this household. This type of household matches with aims for electrification, which has a critical role to play for achieving the European Union decarbonization policy targets.

Fig. 2 shows the typical daily load curve (for 24-hour period) of this household, with a heat pump and electric vehicle charging. The largest amount of electricity is consumed at nighttime while an electrical vehicle is charging. For the case, it is highly important to choose the appropriate generation and storage solutions. When the readings were taken, the household was connected to the distribution system operator grid; thus, the energy availability were not an issue and always corresponded with the demand. Nonetheless, the connection allows the household not to consider load shifting.

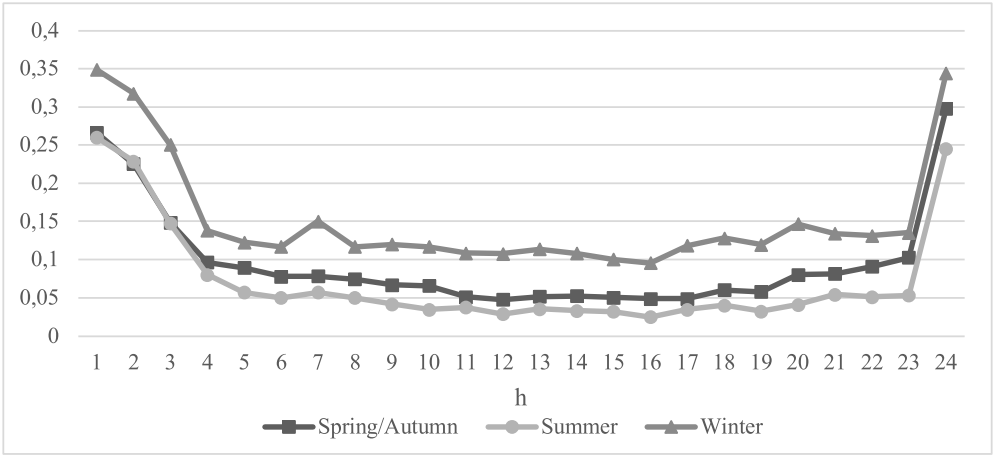


Fig. 2. Daily load curve in relative values for three seasons.

As shown in Table 4, five equipment sizing alternatives were evaluated. First three sizing alternatives are taken from the previous research on microgrid sizing with Homer software. The capacity of the back-up generator is at least 11 kW considering that system must cover the maximum daily load (which is around 9 kW), thus ensuring higher security of supply [4]. Two additional sizing options were developed to find the most sustainable and economically efficient solution.

Table 4. Average Equipment Size for All Alternatives

System equipment	1st alternative	2nd alternative	3rd alternative	4th alternative	5th alternative
BESS (kW)	4.7	5	5	8.2	8.2
BESS (kWh)	22	28.3	17.8	30	16
Solar panels (kW)	4	9.4	0	6.2	3
Wind (kW)	3	0	4	2	2
Backup generator (kW)	11	11	11	13	13

In this study, the results are displayed for the following alternatives: three dispatch strategies, different sizing options, power sources PV, wind, BESS, backup generator, the dispatch strategy is combined, and there is no capacity shortage.

5. RESULTS

Table 5 shows the results for all five equipment sizing alternatives considering three different dispatch strategies.

Table 5. Results of Simulations

Alternative	**1st**	**2nd**	**3rd**	**4th**	**5th**
Combined charging dispatch strategy (CCDS)					
Backup gen. operating hours	1277	1234	1448	778	953
Excess renewable energy, kWh	1290	3990	71	2083	1029
Excess vs. total renew. generation, %	18 %	40 %	2 %	26 %	20 %
LCOE, EUR/kWh	0.71 €	0.73 €	0.73 €	0.79 €	0.70 €
Load following strategy (LFS)					
Backup gen. hours	2249	2276	2804	1923	2333
Excess renewable energy, kWh	1073	3646	46	1870	676
Excess vs. total renew. generation, %	13 %	33 %	1 %	21 %	10 %
LCOE, EUR/kWh	0.81 €	0.83 €	0.87 €	0.91 €	0.85 €
Cycle charging strategy (CCS)					
Backup gen. hours	1406	1355	1561	949	1248
Excess renewable energy, kWh	2273	5336	293	2999	1408
Excess vs. total renew. generation, %	32 %	52 %	7 %	37 %	26 %
LCOE, EUR/kWh	0.78 €	0.80 €	0.80 €	0.87 €	0.83 €

Like Homer Pro software, while setting up the project, using a simulation tool it is possible to configure dispatch strategies to determine operating principles of how generation can provide the load.

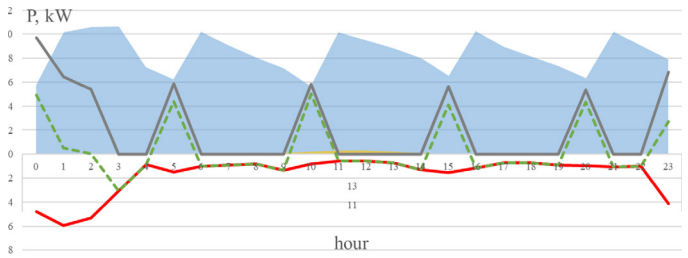
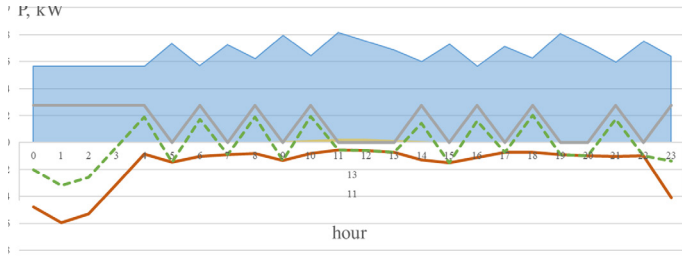
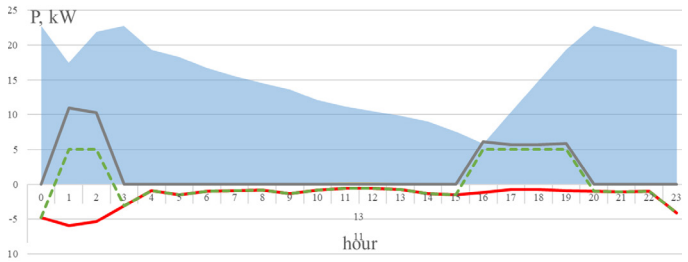
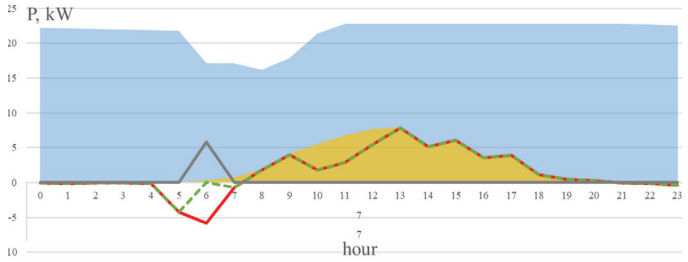
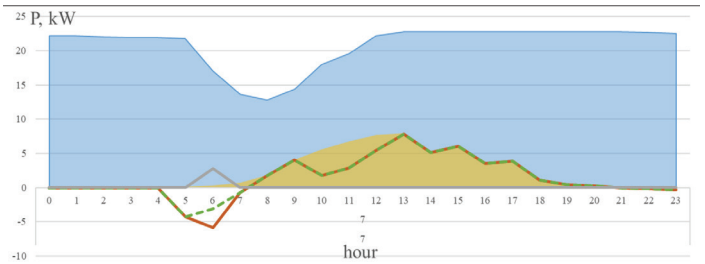
1) Combined charging dispatch strategy (CCDS) – intelligently switches between load following and cycle charging strategy. That way it can improve performance over the cycle charging and load following dispatch strategies by making more efficient use of back-up generator.

2) Load following strategy (LFS) – when a generator is needed, it produces only enough power to meet the demand. It tries not to charge battery with back-up diesel generator unless it reaches the minimum power of generator. Load following tends to be more optimal in off-grid systems with a lot of renewable power that sometimes exceeds the load.

3) Cycle charging strategy (CCS) – whenever a back-up generator is required, it operates at full capacity, and surplus power charges the battery bank. It stops charging battery at the setpoint of battery state of charge. Cycle charging tends to be more optimal in off-grid systems with little or no renewable power.

To better understand how different dispatch strategies impact the operation of generating sources and BESS charging/discharging, the visualization of off-grid operation in summer and winter day for two equipment sizing alternatives and three dispatch strategies is provided in Table 6 and 7. The graphs show the power source and amount of generation, energy storage capacity, load and its nature, battery power and its nature, backup generators power. The dates were chosen to represent the extreme situations where there was surplus or deficiency of renewable generation. During the observation period, there was low wind output on 7th July and low PV output on 13th November. By comparing the 2nd and the 5th alternatives, it is clearly visible that the microgrid benefits of diversified generation sources allow minimising the backup generators workload and maximising the share of renewables. Dispatch strategies pose the most impact on LCOE.

Table 6. Visualization of Off-Grid Operation for the 2nd Alternative and Dispatch Strategies

2nd alternative: BESS power 5 kW, capacity 28.3 kWh, solar power 9.4 kW, wind power 0 kW, diesel gen. 11 kW	
Date	13th November
Combined charging CCDS	
Load following LFS	
Cycle charging CCS	
Date	7th July
Combined charging CCDS	
Load following LFS	

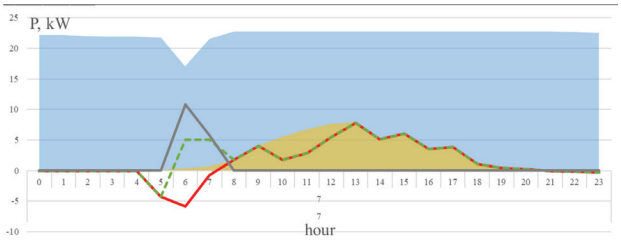
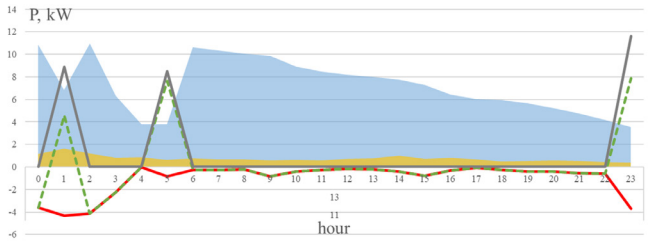
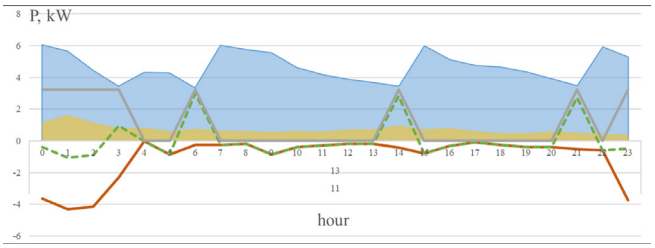
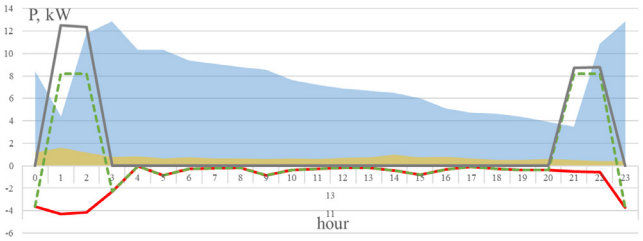
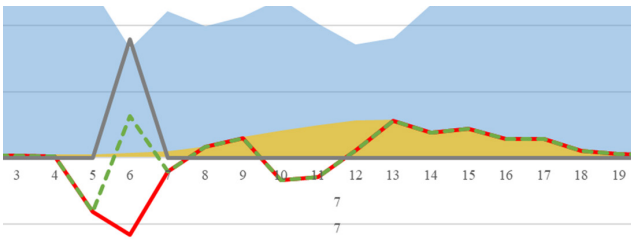
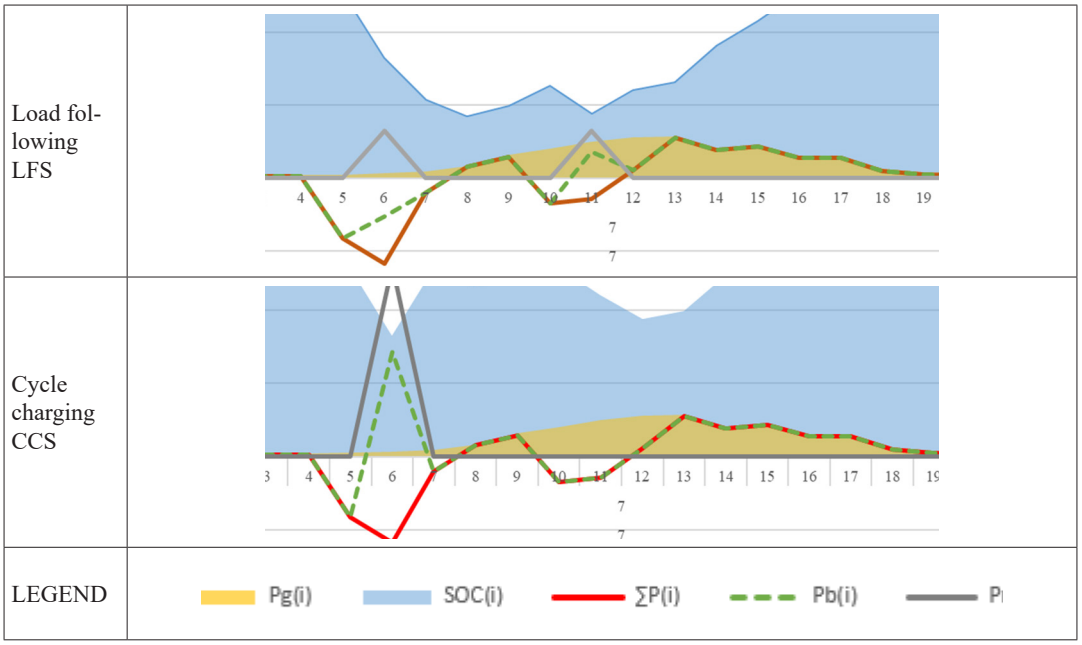
Cycle charging CCS	
LEGEND	

Table 7. Visualization of Off-Grid Operation for the 5th Alternative and Dispatch Strategies

5th alternative: BESS power 8.2kW, capacity 16kWh, solar power 3 kW, wind power 2kW, diesel gen. 13 kW	
Date	13th November
Combined charging CCDS	
Load following LFS	
Cycle charging CCS	
Date	7th July
Combined charging CCDS	



In addition to the analysis before, in the next three figures comparison of results between the new simulation tool and Homer Pro software is made.

Firstly, backup generator operating hours are analysed. As it is necessary to avoid the use of electricity produced by the backup generator when renewable energy can be used instead, it is necessary to pay attention to the operating hours of the backup generator. As shown in Fig. 3, in all alternatives and dispatching strategies, the new tool displays more backup generator hours than Homer Pro software. The largest difference is observed at load following strategy (LFS). Nevertheless, both tools show that the generator hours will be the smallest for the 1st alternative at combined charging dispatch strategy (CCDS).

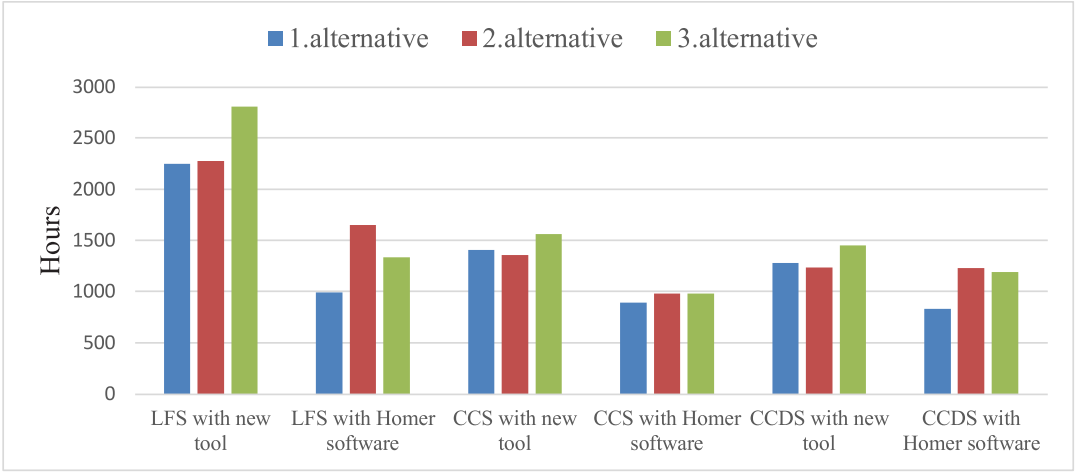


Fig. 3. Backup generator operating hours.

Secondly, "excess electricity" is analysed. Excess electricity occurs when surplus power in off-grid is produced (either by the back-up generator or by a renewable sources) and the battery or load is unable to take all electricity. Excess electricity as the percentage (%) of the total generation of three off-grid alternatives and three different dispatch strategies is shown in Fig. 4.

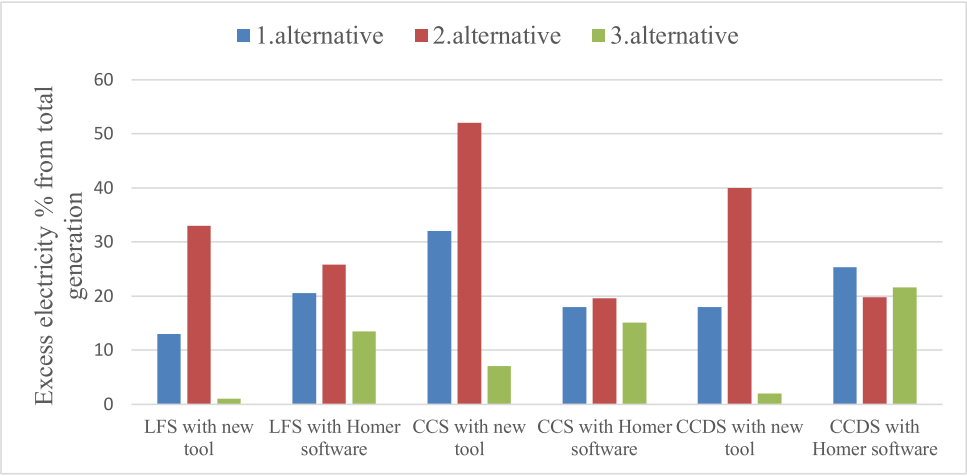


Fig. 4. Excess electricity in the all off-grid alternatives.

In average, for both tools the smallest "excess electricity" was shown by the third alternative – 10.03 %, followed by the first alternative (21.13 %) and the second alternative (31.7 %). Despite excess electricity (%) differs between the tools (especially for an alternative that includes wind), the overall trend is the same and it shows, that if the off-grid system consists of PV panels then it is crucial to correctly size its capacity and match it with adequate storage capacity.

Finally, in Fig. 5 we compare three alternatives regarding the levelized cost of electricity as the average cost per kWh of useful electrical energy produced by the system. We did not cover the LCOE in our previous publication, but we use the gained results this time.

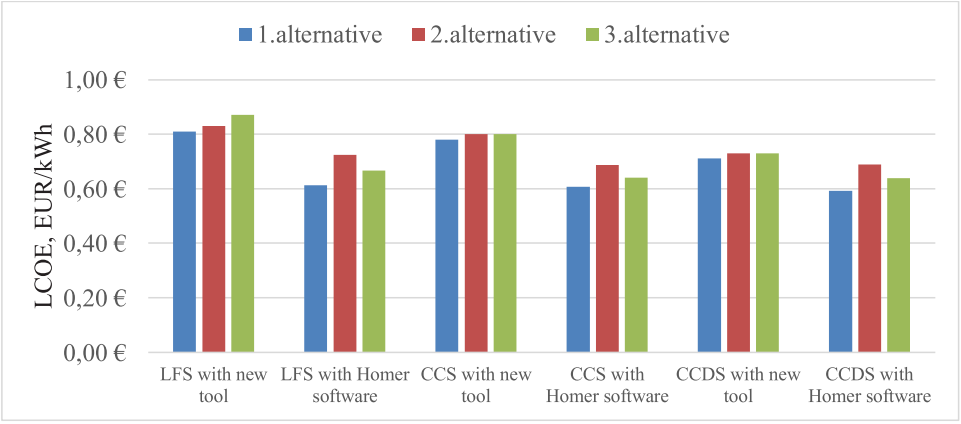


Fig. 5. Levelized cost of electricity for all off-grid alternatives.

As shown in Fig. 5, for the new tool average costs are between 0.72 EUR/kWh and 0.84 EUR/kWh, while in case of Homer Pro software they range from 0.64 EUR/kWh to 0.67 EUR/kWh. The results differ due to the emission cost implemented in the new tool and difference in models themselves. In general, both simulation tools show similar trends, which confirms and validates their accuracy.

6. DISCUSION AND CONCLUSION

The case study and comparison of results to the authors' previous publication have shown that new multi-objective simulation tool can be used as an assessment tool for microgrid equipment sizing determination. It allows analysing potential generation by source, BESS charging / discharging versus the required load, calculating annual system costs and other parameters. It gives all the necessary key values to evaluate the possibility to create a microgrid solution.

By comparing simulation results of the new multi-objective simulation tool (considered in this publication) and Homer software (from the previous publication), it can be concluded that both tools show similar trends with regard to three parameters: backup generator operating hours, excess electricity and LCOE. The differences in results might be caused by additional emission cost (30 EUR/t), and only one capacity shortage level – 0 %, which was not the case in the previous publication using Homer Pro software. Another reason for the differences may be related to approaches/algorithms themselves which differ in both tools.

Furthermore, if we compare the two additional alternatives (4th and 5th), we see that the most sustainable and economically efficient solution would be using the combined charging dispatch strategy. However, there is no solution which would correspond to "the greenest and optimal solution". On the one hand, the 4th alternative is with fewer backup generator operating hours – 778; on the other hand, the 5th alternative has an LCOE of less than 0.09 EUR/kWh comparing with the 4th alternative. Thus, the end user must decide on dilemma whether to use a "sustainable" or "economically efficient" solution.

In this publication, the results again show that the dispatch strategy has great impact on the microgrid costs. Nevertheless, like Homer Pro software, the case study revealed that the combined charging dispatch strategy (CCDS) with both solar and wind sources is the most suitable one of all the alternatives.

Practically, both tools have their advantages and disadvantages. The Homer Pro allows highly automatizing the sizing offering, thus providing a quick multi scenario approach. While our own developed simulation model gives advantage to tweak the equipment sizing for very specific cases and can be further implemented on multiple software tools taking into account users' preferences. It can be used to validate results from other software tools as well.

The battery rated power should be at least as large as the sum of non-dispatchable generation. In case there is no load and there is full generation power, it is highly significant to store every generated kWh. At the same time, it should be greater than backup generator minimal power – in case of small load and empty battery, the generator will not be used sufficiently. As there is load from electrical vehicle in consumption the amount of energy the BESS should hold

should be close to the battery capacity of the electric vehicle; otherwise, electric vehicle might be charged with diesel generator if no renewables are present.

For the further research it would be useful to compare the model against real case off-grid microgrid solution.

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