International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)

Vol. 10-No.3 (2024) pp. 276-281
http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Design and Economic Analysis of a Grid-Tied Microgrid Using Homer Software

Mehmet DAYIOĞLU[1]*, Rıdvan ÜNAL[2]

[1]Afyon Kocatepe University, Electrical and Electronics Engineering Department, Afyonkarahisar, Turkiye
* **Corresponding Author Email:** mehmet.dayioglu@usr.aku.edu.tr - **ORCID:** 0000-0001-8323-0730

[2]Afyon Kocatepe University, Electrical and Electronics Engineering Department, Afyonkarahisar, Turkiye
Email: runal@aku.edu.tr - **ORCID:** 0000-0001-6842-7471

Article Info:

DOI: 10.22399/ijcesen.239
Received : 22 November 2023
Accepted : 17 July 2024

Keywords:

Microgrid
Renewable Energy Sources
Economic Analysis

Abstract:

This study focuses on the capacity optimization of Distributed Energy Resources (DERs) in Microgrids (MGs) within the Duquesne, USA region using HOMER software. Various scenarios with different grid limitations were analysed to determine the optimal configuration of wind turbines, Photovoltaic (PV) systems, diesel generators, and Energy Storage Systems (ESSs). The scenarios were evaluated based on Net Present Value (NPV), Levelized Cost of Energy (LCOE) and initial cost. In the unrestricted scenario, where MG loads can freely draw from both the macro grid and DERs, the NPV was calculated at $23.9 billion, with an LCOE of $0.122/kWh and an initial cost of $11.2 billion. The renewable energy penetration in this scenario was 62%, with a payback period of 7.4 years. The limited grid supply scenario resulted in an NPV of $40.4 billion, an LCOE of $0.199/kWh, and an initial cost of $21.7 billion. Renewable energy penetration increased to 77.9%, indicating that a significant portion of the MG's energy demand is met by Renewable Energy Sources (RESs). In the standalone scenario, where the MG operates independently of the macro grid, the NPV was $58.9 billion, with an LCOE of $0.343/kWh and an initial cost of $29.6 billion. This scenario achieved the highest renewable energy penetration at 89.47%.
The findings suggest that while higher renewable penetration offers significant environmental benefits, it comes at a higher economic cost. The optimal balance between economic viability and renewable energy integration can be achieved by implementing policies that encourage renewable energy while maintaining some level of conventional energy sources for cost-effectiveness.

1. Introduction

There has been a general increasing trend in the world's electrical energy consumption in the last 20 years, except for the effects of the 2008 economic crisis and the 2020 pandemic [1]. The main reason for this increase in electricity consumption is global population growth and the widespread use of electronic devices due to industrialization and technological development. Furthermore, the electrification of sectors that traditionally use other forms of energy, such as transportation and heating/cooling, is evident with record-breaking sales of electric vehicles and heat pumps [2]. Despite this increasing demand, according to 2022 data, 70% of global electricity production is still sourced by unsustainable energy sources. Accordingly, carbon dioxide emissions from fossil-based production have reached an all-time high [3]. Considering their effects on the environment and human health, as well as their formation processes, RESs, offered as an alternative to fossil fuels, have become one of the most widely discussed topics within the energy sector in recent years.

Another critical issue, energy independence, has become particularly urgent for European countries following the Russia-Ukraine conflict. Due to Russia's sanctions on natural gas, many countries have encountered heating problems during winter [2]. The MG concept, which facilitates seamless integration of RESs and can provide independent energy for local loads, offers a potential solution to this recent energy crisis, serving as an alternative to traditional interconnected grids. MGs can provide electrical energy to loads with their Distributed

Energy Resources (DERs), independent of the main grid, or can be operated connected to the main grid. This allows a bidirectional power flow between MG elements and the interconnected grid. Thus, power can be supplied from the macro grid when DERs, such as solar, wind, biomass, geothermal, gas turbines or diesel-oil engines which are mostly dependent on environmental conditions, cannot meet the load demand of the MG. In another case, economic benefit can be obtained by transferring the energy resulting from production exceeding the electricity demand of the MG to the macro grid. Capacity allocation of DERs in the MG should be made under optimum conditions for an economical and stable grid design. Different capacity optimization algorithms have been used in hybrid power generation systems in the literature. In [4], capacity optimization for wind, PV, diesel generator and ESSs was made with the pelican optimization algorithm. In [5] and [6], the Particle Swarm Optimisation (PSO) algorithm was used for optimal capacity allocation. In [7], annual wind speed and solar irradiance data were collected and the capacity for the hybrid power system consisting of wind, PV and pumped storage was analysed. In [8] and [9], proposed a game theory-based model to optimize distributed generation capacity allocation, considering relationships among different generators. In [10], presented an optimal allocation method for MG systems with electric vehicles, using an improved PSO algorithm to minimize costs. In [11], an enhanced artificial bee colony algorithm is proposed for optimizing power capacity in a PV-based MG, taking into account economic considerations and energy allocation factors. In [12], a method is developed for optimal allocation of energy storage capacity considering uncertainty in renewable energy generation. The approach utilizes a typical multi-day scenario set and a double-layer optimization model. In [13], consensus and diffusion methods have been applied for distributed optimization, with diffusion showing better computational performance. In [14], the equilibrium optimizer algorithm has demonstrated efficiency in solving dynamic economic dispatch for MGs with various generation sources. In [15], a two-stage capacity allocation model for PV-storage MGs is developed, considering demand response and uncertainty in PV generation. In [16], a chance-constrained stochastic optimization approach was developed to determine the optimal energy storage capacity, taking into account generation and load forecast errors. In [17], MG operation optimization was reviewed, with a focus on genetic algorithms and simulated annealing as commonly used methods. In [18], a non-cooperative game-based model was proposed for optimal MG capacity allocation, showing increased revenue potential for PV and ESSs. In [19], a multi-objective optimization model was presented for sizing battery ESSs in grid-connected MGs. This model considers economic and technical criteria, along with uncertainties in RESs. In [20], a distributed optimization algorithm for MGs is introduced, leveraging a bisection lambda iteration method to achieve efficient and resilient power allocation among DERs without relying on a centralized controller. In [21], rule-based energy management schemes optimized by nature-inspired algorithms, such as the grasshopper optimization algorithm, have shown promise in long-term capacity planning. In [22], an optimal capacity configuration model was proposed for wind-solar-hydrogen MGs using a dynamic adjustment of inertial weight PSO algorithm to enhance economic efficiency and increase renewable energy consumption. Similarly, in [23], an improved sparrow search algorithm was developed for optimizing the capacity configuration of wind-solar-storage MGs in green storage applications, with the objective of minimizing payback periods. In [24], a consensus algorithm-based distributed control strategy was introduced for power allocation, frequency, and voltage restoration in MGs under imbalanced and nonlinear load conditions. In [25], a multi-objective capacity optimization model was proposed for grid-connected wind-solar-storage MGs, utilizing an improved beluga whale optimization algorithm to enhance economic efficiency and promote renewable energy consumption. In [26], an approach is presented for optimizing the operation of MGs with a shared hybrid ESS while considering flexible ramping capacity. These studies demonstrate the effectiveness of various optimization algorithms in addressing the challenges of capacity allocation in MGs with renewable energy integration.

In this study, capacity optimization for wind turbines, PV systems, diesel generators and ESSs in the Duquesne, USA region was conducted using HOMER software across various scenarios with different grid limitations. MG scenarios with varying levels of renewable energy penetration and different investment costs were evaluated based on Net Present Value (NPV), Levelized Cost of Energy (LCOE). Thus, the environmental and economic advantages and disadvantages of each scenario were determined.

2. Material and Methods

Since energy in MGs can be supplied by many different sources, it is critical to determine these sources during the design phase. Favourable environmental conditions can be considered as a basic condition for RESs such as wind and PV [27]. Additionally, site selection based on size is another key requirement. Economic analysis is also vital: projecting the investment's future involves calculating electricity production against installation, maintenance, and operational costs specific to the region. Financial calculations guide decisions on resource investment in different regions.

2.1 Net Present Value

Net Present Value (NPV) is a financial concept frequently used in evaluating today's investment projects or business decisions. NPV is calculated by converting the estimated revenues and expenses over the project period into present value with a certain discount rate. In energy systems, the profitability of projects can be evaluated with NPV and resources can be directed to the most appropriate investment [28]. NPV can be calculated as in equation 1.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+r)^t} \quad (1)$$

where, R_t represents each year's cash flow, r represents the discount rate, t represents time and n represent the lifetime of project. R_t at t = 0, i.e., R_0, is the investment cost and takes a negative value. For t > 0, R_t is obtained by subtracting cash inflow from outflow [29]. To compute NPV in power systems, cash flow is determined by subtracting profits from items like power sales and salvage from expenses such as installation costs, replacement costs, Operation & Maintenance (O&M) costs over the project's lifespan.

2.2 Levelized Cost of Energy

Levelized Cost of Energy (LCOE) is expressed as the average total cost to produce unit energy through a system. LCOE is often used for cost comparison of alternative energy production technologies. LCOE is calculated by dividing the total cost of a system over its lifetime to the total energy production over its lifetime [30].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{(I_t + M_t + F_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (2)$$

Here, I_t is the investment cost in year t, M_t is the O&M cost in year t, F_t is the fuel cost in year t (if any), E_t is the total electrical energy produced in year t, r is the discount rate and finally n is the expected lifetime of the production facility.

2.3 Payback Time

Payback Period (PBP) refers to the time required to recover the investment. If the annual cash flow is assumed to be constant, it is calculated as in equation 3.

$$PBP = \frac{Initial\ investment}{Annual\ net\ cash\ flow} \quad (3)$$

2.3 Mathematical Model of System

In hybrid systems, the power output of each power generation unit can be modelled mathematically. This makes it possible to determine the required generation capacities for the total load. Equation 4 can be used to express the total power produced in a hybrid power system consisting of wind, PV and diesel generators.

$$P_T = N_W * P_W + N_P * P_P + N_D * P_D \quad (4)$$

Here, P_T refers to the total power produced in the system, while P_W, P_P and P_D refer to the unit power produced by wind, PV and diesel generators, respectively. N_W, N_P and N_D refer to wind, PV and diesel generator capacities, respectively. The power output for the wind turbine and PV panel is given in the following equations. Unlike wind turbines and PV panels, the power output of diesel generators is not affected by external factors such as wind speed or sunlight. Therefore, diesel generators provide a constant power output.

$$P_W = {}^{1}\!/_{2} * \rho * A * V^3 \quad (5)$$

where, ρ is effect of air density, A is swept area, V is effect of wind speed.

$$P_P = A * \eta * G \quad (6)$$

where, A is surface area of PV panels, η is efficiency of PV panels and G is solar irradiation level. The installation cost, replacement cost, O&M cost and fuel cost of MG components are given in table 1.

3. Results and Discussions

Table 2 shows the capacity analysis based on different scenarios. In the first scenario, the MG loads can freely draw from both the macro grid and

Table 1. *Unit prices of MG units*

MG units (1kW)	Installation cost ($)	Replacement cost ($)	O&M cost ($)	Fuel ($/L)
PV panel	1333.3	1333.3	10	0
Wind turbine	2000	2000	360	0
Diesel generator	600	600	0.1(H)	1.18
Battery	200	200	10	0
Converter	300	300	0	0

DERs. Here, the grid's contribution to meeting energy demands is highest because the MG relies on it when wind and PV power generation, which depend on environmental conditions, are insufficient. Diesel generators are not used extensively because the unit cost of electricity from the main grid is lower than that from diesel generators. In the second scenario, the MG's energy supply from the main grid is limited, incentivizing the MG to generate more of its own energy using predominantly renewable and independent resources. In this limited supply scenario, the total energy obtained from the grid decreases by approximately 40% compared to the unlimited scenario. In the third scenario, the MG operates in standalone mode where DERs are the sole energy providers. The capacity of RESs is significantly increased to meet energy demands independently. Diesel generators supplement energy supply during periods of reduced RESs activation due to environmental factors.

Table 2. *Capacity allocation for each component in different scenarios.*

Scenarios	PV	Wind	Grid	Diesel
Unrestricted	24.9%	37.1%	38%	-
Limited	30.9%	47%	15.8%	6.3%
Standalone	40.9%	52.2%	-	6.92%

Table 3 presents financial analyses and renewable penetration percentages for the three scenarios. The NPV values clearly indicate that the first scenario, without limitations, is the most economically viable option. This conclusion is supported by the LCOE and initial cost values. However, the renewable penetration in this scenario is lower compared to the others. Additionally, the PBP for the first scenario is calculated as 7.4 years.

Table 3. *System analysis for different scenarios.*

Scenarios	NPV ($)	LCOE ($)	Initial cost ($)	Renew. pen. ($)
Unrestricted	23.9B	0.122	11.2B	62
Limited	40.4B	0.199	21.7B	77.9
Standalone	58.9B	0.343	29.6B	89.47

4. Conclusions

As a result, although it provides many environmental and financial advantages, it may not be economically efficient to provide the energy needed for a large area, such as an entire city, solely from RESs. However, MGs renewable energy penetration can be increased with a structure that limits grid operation through policies that encourage renewable energy. Although the LCOE of RESs is decreasing year by year, using conventional energy production methods in addition to renewable resources by making optimum capacity distribution in today's conditions seems to be the most economical option.

For future works, focus can be placed on the design and optimization of energy procurement contracts between governments and energy suppliers for MGs. This could include analysing various contract structures such as Power Purchase Agreements (PPAs) and examining their impacts on the cost and reliability of energy supply. Thus, PPAs can ensure price stability and energy security for the government through fixed pricing structures, while longer-term contracts can provide stability and risk mitigation for suppliers.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

[1]Ritchie, H., Rosado, P., & Roser, M. (2020). Energy production and consumption. OurWorldInData.org.

[2]International Energy Agency. (2020). Electricity market report - December 2020. IEA.

[3]Enerdata. (2023). World energy and climate statistics-yearbook.

[4]Li, J., Chen, R., Liu, C., Xu, X., & Wang, Y. (2023). Capacity optimization of independent microgrid with electric vehicles based on improved pelican optimization algorithm. *Energies*, *16*(6), 2539. DOI:10.3390/en16062539

[5]Wang, J., & Yang, F. (2013). Optimal capacity allocation of standalone wind/solar/battery hybrid power system based on improved particle swarm optimisation algorithm. *IET Renewable Power Generation, 7*(5), 443-448. DOI:10.1049/iet-rpg.2012.0329

[6]Li, J., Zhang, Z., Shen, B., Gao, Z., Ma, D., Yue, P., & Pan, J. (2020). The capacity allocation method of photovoltaic and energy storage hybrid system considering the whole life cycle. *Journal of Cleaner Production, 275,* 122902. DOI:10.1016/j.jclepro.2020.122902

[7]Xu, Y., Lang, Y., Wen, B., & Yang, X. (2019). An innovative planning method for the optimal capacity allocation of a hybrid wind–PV–pumped storage power system. *Energies*, *12*(14), 2809. DOI:10.3390/en12142809

[8]Jin, S., & Fang, F. (2019). Optimization of microgrid capacity allocation based on game theory. In *2019 International Conference on Sensing, Diagnostics, Prognostics, and Control (SDPC)* (pp. 459-464). Beijing, China. DOI:10.1109/SDPC.2019.00089

[9]Fang, F., Zhu, Z., Jin, S., & Hu, S. (2021). Two-layer game theoretic microgrid capacity optimization considering uncertainty of renewable energy. *IEEE Systems Journal, 15*(3), 4260-4271. DOI:10.1109/JSYST.2020.3008316

[10]Lin, Y., Wang, K., Quan, M., Zhang, Z., & Dong, X. (2021). Optimal Allocation Method for Microgrid System Capacity with Electrical Vehicles. *2021 12th International Conference on Power Electronics and Renewable Energy (ICPRE)*, 1181-1185. DOI:10.1109/ICPRE52634.2021.9635343

[11]Lin, Y., Wang, K., Quan, M., Zhang, Z., & Dong, X. (2021). Optimal allocation method for microgrid system capacity with electrical vehicles. In *2021 6th International Conference on Power and Renewable Energy (ICPRE)* (pp. 1181-1185). Shanghai, China. DOI:10.1109/ICPRE52634.2021.9635343

[12]Wei, W., Ye, L., Fang, Y., Wang, Y., Chen, X., & Li, Z. (2023). Optimal allocation of energy storage capacity in microgrids considering the uncertainty of renewable energy generation. *Sustainability, 15*(12), 9544. DOI:10.3390/su15129544

[13]Ces, N.P.L., Gadelha, N.D., Almada, J.B., Leão, R.P.S., & Sampaio, R.F. (2021). Economic dispatch of a microgrid using the distributed optimization methods of consensus and diffusion. In *2021 14th IEEE International Conference on Industry Applications (INDUSCON)* (pp. 648-654). São Paulo, Brazil. DOI:10.1109/INDUSCON51756.2021.9529768

[14]Bastawy, M., Ebeed, M., Rashad, A., Alghamdi, A.S., & Kamel, S. (2020). Micro-grid dynamic economic dispatch with renewable energy resources using equilibrium optimizer. In *2020 IEEE Electric Power and Energy Conference (EPEC)* (pp. 1-5). Edmonton, AB, Canada. DOI:10.1109/EPEC48502.2020.9320054

[15]Shao, X., Ren, X., Li, Y., Song, Z., Ye, Y., & Xu, X. (2022). Capacity allocation optimization of PV-and-storage microgrid considering demand response. In *2022 Power System and Green Energy Conference (PSGEC)* (pp. 79-84). Shanghai, China. DOI:10.1109/PSGEC54663.2022.9881084

[16]Yahya Soltani, N., & Nasiri, A. (2020). Chance-constrained optimization of energy storage capacity for microgrids. *IEEE Transactions on Smart Grid, 11*(4), 2760-2770. DOI:10.1109/TSG.2020.2966620

[17]Gao, K., Wang, T., Han, C., Xie, J., Ma, Y., & Peng, R. (2021). A review of optimization of microgrid operation. *Energies*, *14*(10), 2842. DOI:10.3390/en14102842

[18]Chen, X., Ma, X., Hou, G., & Liu, Z. (2023). A non-cooperative game-based approach for optimal allocation of microgrid capacity. In *2023 3rd International Conference on Electronic Information Engineering and Computer Science (EIECS)* (pp. 629-632). DOI:10.1109/EIECS59936.2023.10435396

[19]Garmabdari, R., Moghimi, M., Yang, F., Gray, E., & Lu, J. (2020). Multi-objective energy storage capacity optimization considering microgrid generation uncertainties. *International Journal of Electrical Power & Energy Systems, 119,* 105908. DOI:10.1016/j.ijepes.2020.105908

[20]Xu, B., Guo, F., Zhang, W.-A., Xie, Z., Wang, L., & Huang, L. (2021). Distributed optimal power dispatch based on bisection lambda iteration algorithm for microgrids. In *2021 IEEE 16th Conference on Industrial Electronics and Applications (ICIEA)* (pp. 2076-2081). Chengdu, China. DOI:10.1109/ICIEA51954.2021.9516192

[21]Bukar, A. L., Tan, C., Lau, K. Y., Ayop, R., & Tan, W. S. (2020). A rule-based energy management scheme for long-term optimal capacity planning of grid-independent microgrid optimized by multi-objective grasshopper optimization algorithm. *Energy Conversion and Management*, *221*, 113161. DOI:10.1016/j.enconman.2020.113161

[22]He, G., Wang, Z., Ma, H., & Zhou, X. (2023). Optimal Capacity Configuration of Wind–Solar Hydrogen Storage Microgrid Based on IDW-PSO. *Batteries*, *9*(8), 410. DOI:10.3390/batteries9080410

[23]Zhu, N., Ma, X., Guo, Z., Shen, C., & Liu, J. (2024). Research on the optimal capacity configuration of green storage microgrid based on the improved sparrow search algorithm. *Frontiers in Energy Research*, *12*. DOI:10.3389/fenrg.2024.1383332

[24]Yang, C., Wu, X., Song, Q., Wu, H., & Zhu, Y. (2024). An Enhanced Power Allocation Strategy for Microgrids Considering Frequency and Voltage Restoration. *Electronics, 13*(10), 1966. DOI:10.3390/electronics13101966

[25]Wang, Z., Wang, T., Niu, Q., Wu, J., Li, M., & Zhu, S. (2024). Research on multiobjective capacity configuration optimization of grid- connected wind–solar–storage microgrid system based on improved BWO algorithm. *Energy Science & Engineering, 12*. DOI:10.1002/ese3.1727

[26]Pan, Y., Ju, L., Yang, S., Guo, X., & Tan, Z. (2024). A multi-objective robust optimal dispatch and cost allocation model for microgrids-shared hybrid energy storage system considering flexible ramping capacity. *Applied Energy, 369*, 123565. DOI:10.1016/j.apenergy.2024.123565

[27]Dayıoğlu, M., Oğuz, Y., & Yönetken, A. (2021). Two-Stage Three-Phase Grid-Tied Photovoltaic System with MPPT Method. *Afyon Kocatepe Üniversitesi Uluslararası Mühendislik Teknolojileri Ve Uygulamalı Bilimler Dergisi, 4*(2), 65-73. DOI:10.53448/akuumubd.992064

[28]Zore, Ž., Čuček, L., Širovnik, D., Pintarič, Z. N., & Kravanja, Z. (2018). Maximizing the sustainability net present value of renewable energy supply networks. *Chemical Engineering Research and Design, 131*, 245-265. DOI:10.1016/j.cherd.2018.01.035

[29]Zhang, R., Shimada, K., Ni, M., Shen, G. Q. P., & Wong, J. K. W. (2020). Low or no subsidy? Proposing a regional power grid-based wind power feed-in tariff benchmark price mechanism in China. *Energy Policy, 146,* 111758. DOI:10.1016/j.enpol.2020.111758

[30]Fallah, M., Sohrabi, A., & Mokarram, N. H. (2023). Proposal and energy, exergy, economic, and environmental analyses of a novel combined cooling and power (CCP) system. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 45*, 45. DOI:10.1007/s40430-023-04359-8