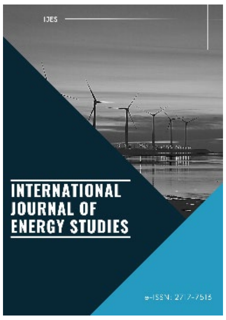
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article
Int J Energy Studies 2024; 9(2): 331-346
DOI: 10.58559/ijes.1407064

Received : 23 Dec 2023
Revised : 20 Apr 2024
Accepted : 22 Apr 2024

Assessment of small-scale wind turbines for domestic use in different situations

Abdallah Albast[a], Nezihe Yıldıran[b*]

[a]*Bahçeşehir University, Energy Systems Engineering Department, ORCID: 0009-0009-2938-5091*
[b]*Bahçeşehir University, Energy Systems Engineering Department, ORCID: 0000-0002-5902-1397*
*(*Corresponding Author: nezihe.kucukyildiran@bau.edu.tr)*

Highlights

- Assessed the effectiveness of small-scale wind turbines in three different countries.
- Inflation rates of different years were used as input for the system.
- It was determined that Germany was the most suitable country for installing the turbine.

You can cite this article as: Albast A, Yıldıran N. Assessment of small-scale wind turbines for domestic use in different situations. Int J Energy Studies 2024; 9(2): 331-346.

ABSTRACT

This study focuses on the potential of wind energy systems installed at residential premises in particular locations from three different countries that are climatically diverse and economically viable for achieving self-sufficient electricity production. The three selected locations were Lebanon, Turkey, and Germany. At each location different simulations were tested using HOMER Pro software starting from wind turbines to combining them with grid that could aid in case of shortage of electricity generated by the turbine and adding batteries for energy storage. The most cost-efficient configuration was determined by simulation and optimization. The outcomes showed that the whole system had been successfully implemented and it fulfilled its purpose of providing electricity for the average household with an LCOE of \$0.07334/kWh, -\$0.01705/kWh, and \$0.2044/kWh at each of Oldenburg, Foça and Hamat respectively. The wind turbine yearly total production was the maximum in Germany with 10,657 kWh, Turkey came second not far from Germany with 10,223 kWh while Lebanon had the lowest production with 7,527 kWh. Lebanon's NPC of the system was most expensive with \$22,381.13 while Turkey had the least expensive one with \$-14,200.34 and Germany in between with \$13,638.7 for the system. Economically, some systems were meant to witness failure due to the high rates of inflation in some of the countries. This finding suggests that not only climate potential could affect the success and failure of system, but other parameters could also have huge effect on whether it is feasible or not to implement such systems.

Keywords: Wind turbines, Electricity, Lebanon, Turkey, Germany

1. INTRODUCTION

There have been a few changes on the world stage in recent decades, most notably in energy. The world's energy landscape has undergone a dramatic shift due to factors such as climate change, fossil fuels as a finite energy source, and rising electricity prices. As a means of reducing the challenges arising from reliance on traditional energy sources, countries invest in renewable energy. According to the International Energy Agency (IEA) report, it depends on the country, location, and policy, but in most countries renewable energy is competitive with conventional energy generation [1].

One of the resources that countries are trying to take advantage of is wind energy. Wind power is one of the most significant potential new energy sources available today. It can be produced from the kinetic energy of wind to generate electricity and has been applied in a variety of applications such as power generation for homes, business, or industry [2]. Compared to traditional fossil fuels, such as carbon dioxide (CO_2) reduction, improved air quality and enhanced energy security, wind power offers many advantages.

The wind energy industry is on a rapid growth path. The total number of wind energy installations worldwide is now 837 gigawatts, which could bring down CO_2 emissions by around 1.2 billion tons per year. As far as greenhouse gas (GHG) emissions are concerned, wind energy is a good alternative source [3]. Wind energy has become a significant contributor to the world's electricity generation, accounting for 7% of global electricity production in 2020, with some countries such as Denmark and Portugal achieving even higher levels of wind energy penetration.

Cost-effectiveness is a further benefit of wind energy. Wind energy costs have declined substantially over recent decades, and this form of renewable energy is one of the best options for competition. Advances in wind turbine technology have driven the decline in costs, economies of scale, and improved manufacturing processes [4].

Wind power, which can contribute to reducing dependency on imported fossil fuels, enhancing energy security, and promoting industry growth, is also a domestic free energy source. Investments in wind power to provide electricity demand were being made by many countries with a high degree of wind energy, while reducing their dependence on imported fuels.

Wind energy has some challenges that need to be addressed for the industry to continue to grow. The intermittent nature of wind energy is one of the major obstacles. Wind speeds can be highly variable, which makes it challenging to maintain a stable power supply from wind energy. However, advancements in energy storage technology and smart grid systems can help address this challenge by storing excess energy during times of high wind speeds and releasing it when needed.

Another challenge for wind energy is the impact on local wildlife and ecosystems. Wind turbines can pose a threat to birds and bats, and their construction can have adverse impacts on local ecosystems [5]. However, careful site selection, environmental impact assessments, and the use of mitigation measures can help minimize these impacts [6].

Additionally, there are several studies focusing on efficiency improvements, such as using advanced control and hybrid power systems, optimization algorithms, and flow control technologies. Recent studies about passive flow control methods for airfoils and wind turbine blades also propose modifications to improve performance. An advanced bent winglet is proposed to maximize power gain of 14.5% [7]. Integrating vortex generator pairs increased the annual energy production of a 2.3 MW wind turbine by 1.87% [8]. Modifying the leading edge of the wind turbine with tubercles increased maximum power production by 30% [9].

In China, Li et al. by collecting data from two wind measurement towers, was able to compare between onshore and offshore wind farms with monthly and hourly data according to some criteria such as wind speed, air density and potential. The data included wind power density and variations of mean wind speed. Finally, economic comparison was done based on operating probability and annual energy production to find out which farm is more feasible [10].

Many studies have been done to test and find if it is feasible or a good idea to install small-scale wind turbines. The objective of this study was to examine the potential of small-scale wind turbines in meeting the electrical demands of a typical household. Three different turbines were tested in an area called Incek, it was found out that two of the three turbines could generate electricity for an average household throughout the year, while the remaining wind turbine can cover a huge amount of the energy needed [11]. A study was aimed to investigate the economic viability of implementing small-scale wind turbines. The study incorporated the participation of numerous

European nations, particularly Italy, France, Germany, Spain, and The Netherlands. 10 industrial wind turbines were utilized in the study, with power capacities ranging from 2.5 kW to 200 kW. The study assessed many aspects that exert significant influence on the performance of wind turbines. Subsequently, projections of the annual cash flow during the anticipated lifespan of the wind turbine were computed, considering factors such as geographical location and turbine specifications. The data obtained from the study are analyzed using a parametric approach that relies on a net present value capital budgeting method [12]. Another study was conducted to evaluate which is the best renewable energy system to be integrated for households. The research revealed that a mono-system featuring a 2.4 kW micro-wind turbine was identified as the most advantageous solution. However, it was determined that this system lacks financial feasibility due to its negative net present value throughout the duration of the project [13].

A study was conducted about how Germany could achieve its goal of having 40% of its generated electricity coming from wind energy. The generated electricity would be around 250 TWh per year and it would be achieved by 2030. About 36000 wind turbines of capacity 100 GW would be sufficient to reach the goal of 250 TWh per year [14]. The examination of wind power in the Çanakkale region was conducted using the Weibull distribution and seasonal average power density analysis, resulting in the acquisition of the following data. The power densities recorded during the seasons were as follows: 49.11 W/m2 in spring, 51.12 W/m2 in summer, 50.16 W/m2 in autumn, and the highest value of 81.68 W/m2 in winter [15]. In Lebanon, by using Weibull distribution a study was conducted for evaluating wind energy potential at various sites. Wind speed data are taken from NASA (1983-2020) period. The results of the study show that wind speeds vary from 3,695 m per second to 4.457 m per second at 10 m height. It recommended that small-scale wind turbines are used to generate electricity in selected areas, based on the results of this study [16].

This study aims the evaluation of the use of wind turbines particularly small-scale micro turbines to provide homes with clean and low-cost energy sourced from wind at three different locations: Lebanon, Germany and Turkey. Concerning the criteria of choosing these three countries, these countries were chosen due to the difference in economic conditions, electricity prices, weather, and wind speed conditions to analyze the situation from all angles.

Germany, a country from the European Union with huge industrial power has been trying for the past years to cut its dependence on fossil fuels and non-renewables such as nuclear energy and replace it with renewables. In fact, Germany was one of the main countries that stopped using nuclear power and the European country with the most investments in the wind energy sector [17]. However, this situation has raised some concerns on Germany's energy market because of Russia's invasion of Ukraine and the increase in global energy prices because of gas price increases.

Turkey, with recent economic development, urban use and the increased need for electricity is facing some problems in the energy sector due to its dependence on the import of expensive energy resources. It has been investing heavily in the renewable energy sector to produce and secure its own electricity without having to depend on the import of energy resources [18]. In fact, Turkey reached the maximum capacity for the hydropower sector. With a huge potential for wind energy, onshore and offshore, the Turkish government has been focusing on this renewable source also to mitigate the problems of depending on other countries.

Although Lebanon is a small country in the middle east, electricity is a problem for a long time. The economic crisis, import of expensive energy resources and many other factors lead to electricity cut outs in most hours of the day. For this purpose, people of this country were trying to find the best substitute for fossil fuels as energy sources. According to IRENA, Lebanon has a potential capacity of 6,233 MW from wind energy and 182 GW from solar energy.

2. MATERIAL AND METHOD

In this study, a comparison between three countries is made to assess the feasibility of installing domestic wind turbines. Each of these countries has its own economic and resource conditions to help make this study wide and unique. The same system components will be installed in the three areas to make the study related to real-life conditions. The components used for this study were wind turbine from AWS manufacturer model HC5100, converter and battery. The specifications of the wind turbine are given in Table 1. The project lifetime will be 20 years. Most of the chosen parts are from HOMER Pro software. The selection of components was based on their respective requirements and suitability for each of the three countries, aiming to strike a balance between cost-effectiveness and high quality.

Table 1. Selected wind turbine technical data

Data	Wind turbine
Manufacturer	AWS
Model	HC5100
Rated Power	5100W
Rotor Diameter	5.24m
Swept Area	21.4m^2
Hub Height	16m
Cut In Wind Speed	2.7m/s
Cut Out Wind Speed	23m/s

Each of the three countries had an average annual residential electricity load. For Lebanon, Turkey and Germany, the following loads were used 3,346 kWh, 3,114 kWh, and 3,340 kWh respectively. The residential load module was used in HOMER.

Monthly average wind speed data were introduced into the software for wind turbine calculations. Regarding wind speed data, it was collected from three different websites and an average of these data was obtained [19-21]. Figure 1 shows the data of wind speed at each site. Wind speed varies in the same way in all the three countries except during October, Oldenburg witnessed a high increase in wind speed unlike the other two countries the wind speed kept declining.

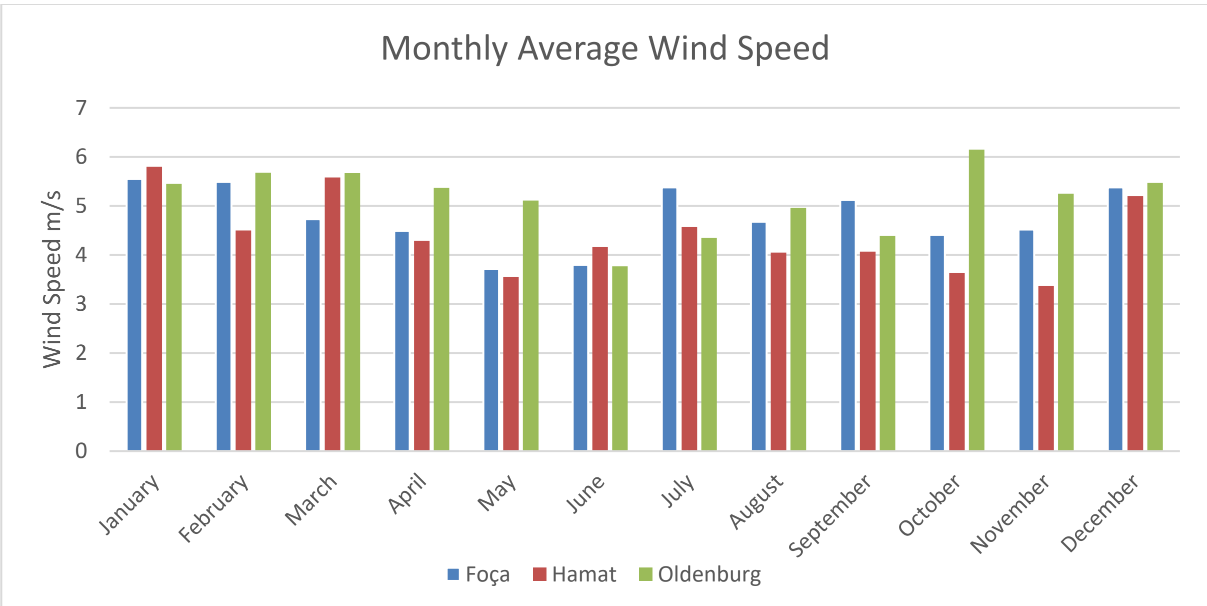


Figure 1. Monthly average wind speed at selected areas

In addition to the monthly average wind speed, other inputs were introduced into the software, such as electricity load, grid power price, grid sellback price, discount rate, inflation rate and project lifetime. Input parameters are shown in Table 2.

Table 2. Inputs introduced to Homer pro software

Country	Project lifetime (years)	Electric load (kWh/day)	Grid power price ($/kWh)	Grid sellback price ($/kWh)	Discounted rate 1	Discounted rate 2	Inflation rate 1	Inflation rate 2
Germany	20	9.15	0.4	0.095	1.86	0.14	-1.88	7.2
Turkey	20	8.53	0.088	0.073	0.64	-24.5	12.28	43.7
Lebanon	20	9.17	0.345	0.05	7.29	-57.71	3	154.8

2.1. Germany Analysis

In the first case study, a discount rate of 1.86% and an inflation rate of 0.14% will be employed by implementing the system in Oldenburg, Germany for 2020. In Germany, the average daily energy consumption of a typical household is approximately 9.15 kilowatt-hours per day. The monthly average production in Oldenburg, Germany is illustrated in Figure 2. Based on the information depicted in Figure 2, it is apparent that the wind turbine constituted around 95% of the household's electricity use during the entire year, with the remaining electrical requirements being covered by the grid.

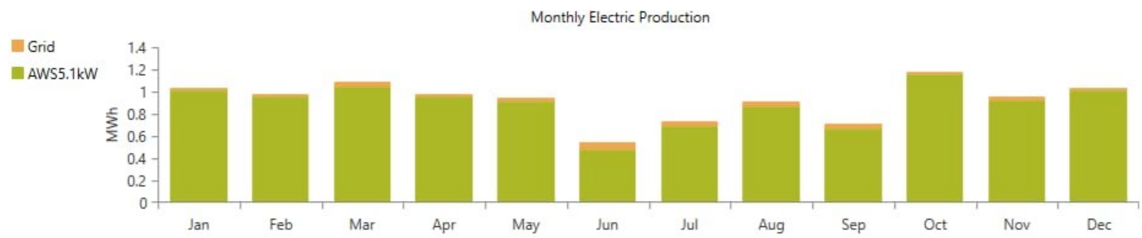


Figure 2. Monthly electric production at Oldenburg

Furthermore, the most current rates to be utilized for the discount rate and inflation rate are determined as -1.88% and 7.2%, respectively to simulate the calendar year of 2023. The outcomes derived from utilizing different rates in 2020 and 2023 are depicted in Table 3.

Table 3. Energy and cost summary at Oldenburg, Germany for 2020 and 2023

Data	2020	2023
Quantity WT	1	1
WT Mean Output (kW)	1.22	1.22
WT Total Production (kWh/yr)	10,657	10,657
Quantity Batt	1	1
System Total Production (kWh/yr)	11,106	11,077
NPC of System ($)	13,638.7	-5,220
LCOE ($/kWh)	0.07334	-0.008227
Return on Investment ROI (%)	3.4	3.4
Internal Rate of Return IRR (%)	5.6	5.6
Simple Payback (yr)	11.83	11.93
Discounted Payback (yr)	13.44	7.9
Coverage Ratio	100.36	100.4

Upon examining the data shown in Tables 3 about Germany, it becomes evident that the findings exhibit a high degree of similarity, except for the discrepancy observed in the net present cost (NPC) amounting to around $8,418.7, and a slight variation in the simple payback period, which stands at approximately 0.1 years. Also, when comparing discounted payback, there is a difference of around five years in advantage of the second system. However, the eye-catching part is having NPC and LCOE in negative in the second system. This is due to the increase in inflation, which makes the components of the system and earnings more and more profitable at the end of the project's lifetime.

2.2. Turkey Analysis

Foça is selected for Turkey analysis. In Turkey, the average daily energy consumption of a typical household is approximately 8.53 kilowatt-hours (kWh) per day. Monthly average production in Foça, Turkey is illustrated in Figure 3. In the case of Turkey, the wind turbine has shown a capacity to fulfill a significant portion of the country's electricity requirements, generating almost 90% of the total demand over the course of the entire year. During May and June, the turbine experienced a decrease in its operational capacity, ranging between 80 and 85%. This decline can be attributed to the low wind speed observed during this period.

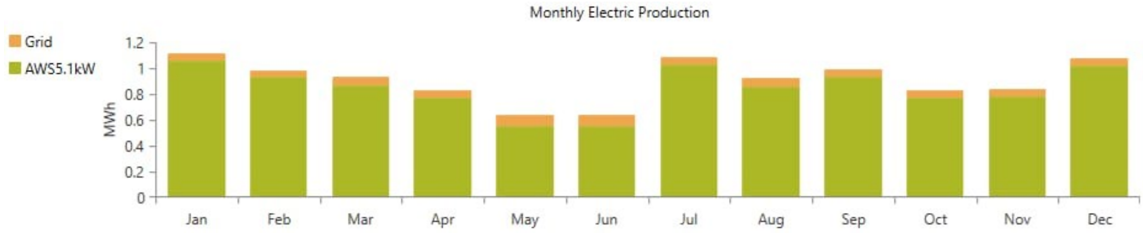


Figure 3. Monthly electric production at Foça

The discount rate of 0.64% and an inflation rate of 12.28% will be employed for the preceding numerical values pertaining to the calendar year 2020. Furthermore, the discount rate of -24.5% and the inflation rate of 43.7% will be employed as the most up-to-date rates for 2023. Analyzing the results of 2020 and 2023, it becomes evident that the rates of inflation and discount significantly impact the feasibility of the system. Also, the low price of electricity in Turkey and the high feed-in tariffs provided by the country contributed significantly to the results we got here. Electricity production is the same in both cases, but again due to the high inflation rates that Turkey is experiencing, this led to the over feasibility of the system in both cases. In the case of Turkey, for the goal of demonstrating the effect of prices and inflation on the system, a third scenario has been created with the following parameters changed in comparison with Turkey's first case study. Grid power price is to be changed from \$0.088/kWh to \$0.35/kWh and grid sellback price is changed from \$0.073/kWh to \$0.05/kWh. The purpose of adding a 3rd case is to show the effect of prices on such systems. Table 4 demonstrates the results of the analysis.

Table 4. Energy and cost summary at Foça, Turkey

Data	2020	2023	3rd scenario
Quantity WT	1	1	1
WT Mean Output (kW)	1.17	1.15	1.17
WT Total Production (kWh/yr)	10223	10115	10223
Quantity Batt	0	1	1
System Total Production (kWh/yr)	10872	10872	10623
NPC of System (\$)	-14200.34	-1.01B	8545.55
LCOE (\$/kWh)	-0.01705	-0.1188	0.01056

Return on Investment ROI (%)	-1.5	-2.2	0.1
Internal Rate of Return IRR (%)	n/a	n/a	0.3
Simple Payback (yr)	n/a	n/a	19.54
Discounted Payback (yr)	12.55	4.3	10.12
Coverage Ratio	100	100	100.37

When comparing the 2020 result and the third scenario of the Turkey study from an economic point of view, it is obvious the effect of changing grid power price and grid sellback price on the system economics, where in the last case the numbers came to be more logical and applicable in real-life systems.

2.3. Lebanon Analysis

Lebanon analysis was performed based on the village of Hamat. In Lebanon, the average daily energy consumption of a typical household is approximately 9.17 kilowatt-hours per day. A load parameter of 9.17 kilowatt-hours per day will be utilized. In relation to Lebanon, the proportion of power generation has decreased to approximately 90% of the required amount as compared to the other two nations. Monthly average production in Hamat, Lebanon is illustrated in Figure 4. Only during October and November, grid is needed to cover more of electricity generation due to the decrease of wind turbine generation to around 80% of the needed electricity. However, in general, the turbine has the capacity to generate a significant portion of the required electrical power.

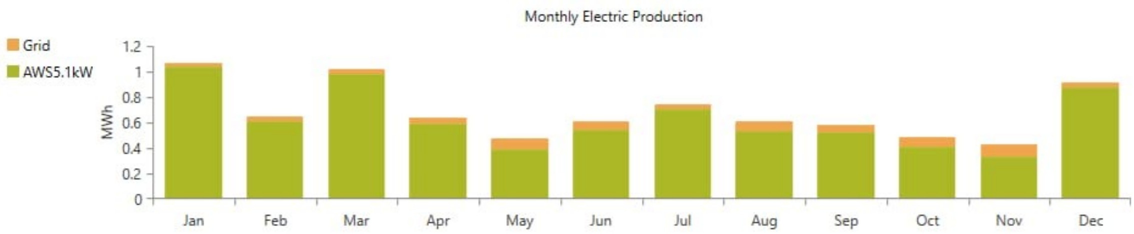


Figure 4. Monthly electric production at Hamat

In the first case study, a discount rate of 7.29% and an inflation rate of 3% will be employed for the preceding numerical values pertaining to the calendar year 2019. In the second scenario, the prevailing rates will be employed, with a discount rate of -57.71% and an inflation rate of 154.8%. The previously mentioned rates pertain to the calendar year 2021. The findings of the Lebanon computations are demonstrated in Table 5.

Table 5. Energy and cost summary at Hamat, Lebanon

Data	2019	2021
Quantity WT	1	1
WT Mean Output (kWh/yr)	0.859	0.859
WT Total Production(kWh/yr)	7527	7527
Quantity Batt	1	8180
System Total Production (kWh/yr)	8214	-
NPC of System ($)	22381.13	7.55E+018
LCOE ($/kWh)	0.2044	-0.1948
Return on Investment ROI (%)	0.0	-0.7
Internal Rate of Return IRR (%)	0.0	n/a
Simple Payback (yr)	19.91	n/a
Discounted Payback (yr)	n/a	1.42
Coverage Ratio	100.49	100.54

According to the results of the Lebanon analysis, it becomes evident that the system findings exhibit greater logical coherence and practical applicability in real-life scenarios when the rates of discount and inflation align closely with normal or rational rates. In such instances, the net present cost (NPC) amounts to $22,381.3, the return on investment (ROI) stands at 0.0% as the payback period is nearly the same period of project lifetime. These outcomes are deemed feasible and justifiable for investment purposes. Conversely, when these rates deviate significantly from the global normal rates, the results diverge considerably from real-life situations. Consequently, installing such a system with these rates is deemed unsuccessful, as the outcomes lack logical coherence and practical feasibility.

3. DISCUSSION

A more sophisticated knowledge of how inflation levels affect the viability and feasibility of energy systems is shown by the results, especially when considering the examples of Lebanon, Turkey, and Oldenburg, Germany. These comparison analyses provide insight into the intricate interactions that shape the performance results of energy systems, involving macroeconomic variables, technology configurations, and regional settings.

It is clear from looking at the statistics in Table 6 that the Oldenburg, Germany system is the most technically sound and economically feasible of the situations that were examined. The system's capacity to attain the lowest Levelized Cost of Electricity (LCOE) at $0.07334 per kilowatt-hour and a Net Present Cost (NPC) of $13,638 is the main factor that led to this result. Both of Oldenburg's systems are viewed as wise investments in the context of Germany's energy environment, which is marked by significant government subsidies and incentives for the development of renewable energy. On the other hand, the appearance of negative figures, such as the second system's negative NPC of $-5,220 and the negative LCOE of $-0.008227 per kilowatt-hour, highlights how susceptible energy systems are to inflationary pressures. In spite of their apparent economic feasibility, these investments are neither practicable nor sustainable in the long run due to rising inflation rates.

Table 6. Optimization results of configurations at selected areas

Data	Oldenburg	Foça	Hamat
Quantity WT	1	1	1
WT Mean Output (kWh/yr)	1.22	1.17	0.859
WT Total Production (kWh/yr)	10657	10223	7527
Quantity Batt	1	0	1
System Total Production	11106	10872	8214
NPC of System	13638.7	-14200.34	22381.13
LCOE ($/kWh)	0.07334	-0.01705	0.2044

On the other hand, Lebanon offers an extremely different picture, with the highest NPC and LCOE values among the systems under study, coming in at about $22,381 and $0.2044 per kilowatt-hour, respectively. This illustrates the difficulties in implementing and running energy systems in areas characterized by unstable economies, volatile currencies, and weak investment policies. In addition, the fact that Lebanon produces just 8,214 kilowatt-hours of power yearly highlights the structural inefficiencies and infrastructural limitations that beset the nation's energy industry.

Turkey's data also paint a worrisome picture, with both systems producing negative values for LCOE and NPC. Even if these results seem advantageous from an economic perspective, high rates of inflation and low energy costs make them unfeasible and unachievable in real-world situations. This emphasizes how important it is for stakeholders, investors, and governments to approach energy planning and investment holistically, taking into consideration sociopolitical factors, technology breakthroughs, and macroeconomic variables.

To sum up, the comparative examination of the energy systems in Germany, Turkey, and Lebanon highlights how complex energy transition and sustainability are. The performance results of energy systems are significantly shaped by policy interventions and technology improvements, but macroeconomic factors—especially inflation—have a greater overall impact. Societies must take a forward-thinking stance that incorporates inclusive governance structures, technological innovation, and economic resilience as they manage the challenges of the energy transition and work toward sustainable development goals. We can only create the conditions for a more resilient, egalitarian, and sustainable energy future for all by working together and putting in concerted effort.

4. CONCLUSION

This study delves extensively into the electricity generation potential of household wind turbines across three distinct geographical locations: Oldenburg, Germany; Foça, Turkey; and Hamat, Lebanon. HOMER Pro enables analyzing various sectors as microgrid or hybrid grid integrating different resources to simulate and evaluate economic feasibility. Through rigorous analysis utilizing the HOMER Pro program, an in-depth exploration of energy systems was conducted to identify the most optimal solution for domestic electricity generation through the utilization of wind turbines. To ensure a fair and robust comparison, standardized components were employed across all regions, and the optimization process was meticulously tailored to address technological, economic, and environmental considerations.

The research findings illuminate the remarkable capacity of wind turbines and accompanying battery systems to meet the entirety of national electricity demand within the three regions of interest. However, it is noteworthy that during periods of low wind speed, supplementary electricity from the grid was required to maintain uninterrupted power supply, emphasizing the need for hybrid energy solutions.

A particularly intriguing observation arises from the case of Lebanon, where despite the apparent economic advantage of purchasing electricity from the grid, the implemented wind turbine system showcased feasibility and promising cost recovery within the project's lifespan. This underscores the potential of decentralized renewable energy systems to not only meet energy needs but also offer economic viability and sustainability, even in regions with established grid infrastructure.

Nevertheless, the study also unveils a significant challenge posed by the disproportionately high inflation rates observed in Lebanon and Turkey. These inflationary pressures cast a shadow over the logical coherence and long-term viability of energy solutions in these regions, necessitating strategic interventions to mitigate their adverse effects.

In conclusion, this comprehensive investigation underscores the transformative potential of household wind turbines in advancing sustainable energy practices and fostering energy independence across diverse geographical and socio-economic landscapes. While the findings present promising opportunities, they also highlight the imperative of addressing systemic challenges such as inflation to ensure the robustness and longevity of renewable energy initiatives. Moving forward, concerted efforts in research, policy formulation, and technological innovation will be essential in harnessing the full benefits of renewable energy adoption and realizing a more resilient and sustainable energy future for all.

NOMENCLATURE

CO_2	Carbon dioxide
NPC	Net present cost
LCOE	Levelized cost of energy
GIS	Geographic information system
WT	Wind Turbine
ROI	Return on investment
IRR	Internal Rate of Return

ACKNOWLEDGMENT

This research did not receive any specific grant from funding agencies in public or not-for-profit sectors.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Abdallah Albast: Methodology, experimental investigations, analysis of the results and wrote the manuscript.

Nezihe Yıldıran: Methodology, edited the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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