

Article

Driving Urban Energy Sustainability: A Techno-Economic Perspective on Nanogrid Solutions

Onur Turan ^{1,*}, Ali Durusu ^{1,2}  and Recep Yumurtaci ¹ 

¹ Department of Electrical Engineering, Yıldız Technical University, 34220 Istanbul, Türkiye; adurusu@yildiz.edu.tr (A.D.); ryumur@yildiz.edu.tr (R.Y.)

² Clean Energy Technologies Institute, Yıldız Technical University, 34220 Istanbul, Türkiye

* Correspondence: onur.turan@std.yildiz.edu.tr or onrtrna@hotmail.com

Abstract: In response to technological advances, environmental concerns, and the depletion of conventional energy sources, the world is increasingly focusing on renewable energy sources (RES) as a means of generating electricity in a more sustainable and environmentally friendly manner. Türkiye, with its advantageous geographical location, long hours of sunshine, and favourable climatic conditions, has a high potential for the use of solar energy. The objective of this study was to identify an energy system that minimizes investment costs while optimizing the levelized cost of energy (LCOE) and minimizing greenhouse-gas (GHG) and carbon dioxide emissions. To achieve this, the study used the concept of nanogrids (NGs) and carried out different evaluations for electric vehicle charging stations (EVCS) at different energy levels connected to the grid. The research focused on classic apartment buildings and multistory condominium-style buildings in Istanbul, Türkiye. Using HOMER Grid 1.11.1 version software, the study identified two optimal configurations: a PV–GRID system with 7 kW photovoltaic capacity and a PV–WT–GRID system with 90 kW PV capacity and 6 kW wind-turbine capacity. These configurations had a significantly lower LCOE compared to the cost of electricity from the conventional grid. When examining the sensitivity to economic factors, it was observed that the net present cost (NPC) and LCOE values fluctuated with electricity prices, inflation rates, and equipment costs. In particular, the two optimal configurations did not include a battery energy-storage system (BESS) due to the low energy demand in the PV–GRID system and the efficiency of the wind turbines in the PV–WT–GRID system. This highlights the need to tailor energy solutions to specific consumption patterns and resource types. In conclusion, the adoption of PV–GRID and PV–WT–GRID systems in Istanbul’s urban buildings demonstrates economic viability and environmental benefits, highlighting the importance of renewable energy sources, particularly solar PV, in mitigating energy-related environmental challenges, such as reducing CO₂ emissions and reducing dependence on conventional grid electricity.

Keywords: nanogrid; renewable energy; hybrid power system; technoeconomic analysis



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1. Introduction

Electricity is a key enabler in the developing world, affecting several critical areas—economic growth, job creation, access to education and healthcare, agricultural productivity, infrastructure development, technological advancement, and environmental sustainability. It improves industrial efficiency, encourages business expansion, and opens up new opportunities. Essential services, such as educational institutions, health facilities, and agricultural irrigation, systems rely heavily on electricity for their operations. Generating electricity from sustainable sources is essential for protecting the environment and combating climate change, making electricity a cornerstone for the development of countries like Türkiye.

Projections show a steady increase in global demand for electricity due to population growth, access to technology, and increasing prosperity [1–3]. Meeting this increase with

renewable energy sources is essential; these sources are clean, cost effective, and with minimal environmental impact. The Turkish National Energy Plan [4] predicts that electricity consumption will grow at a rate of 3.5% to reach 510.5 TWh by 2035. Renewables are expected to increase from 52.0 to 64.7% of installed capacity by 2035. In addition, the number of electric vehicles in Türkiye is estimated to reach 32,777 by July 2023, a significant increase of 225% year on year [5]. To meet the escalating demand for electrical energy and to support its production, NGs are emerging as a promising solution. These systems, which use a single renewable energy source such as solar power, are capable of producing kilowatts of electrical energy. Particularly in sun-rich regions such as Türkiye, NGs offer a favourable contribution. Solar power, which is rapidly gaining ground as a primary renewable energy source, provides locally generated, clean energy, which is crucial in an era of stringent sustainability targets.

One of the main objectives of Türkiye's energy policy is to increase the share of domestic and renewable energy in electricity generation, as nearly 75% of Türkiye's energy needs are currently met by imports. The demand for fossil fuels is increasing rapidly as a result of the increased use of energy resources [6]. Studies have been conducted worldwide to promote the use of alternative energy sources, as the use of fossil fuels, such as oil, natural gas and coal, has increased carbon emissions and contributed to global warming [7,8]. The importance of renewable energy as an alternative energy source has been emphasized not only globally but also within Türkiye. Türkiye signed the Paris Climate Agreement in 2015, which entered into force in 2016. This international agreement emphasizes key concepts such as "net zero CO₂ emissions" and "greenhouse gas (GHG) neutrality" [9]. This commitment reflects the growing importance of RES in addressing climate change and achieving sustainable environmental goals and is in line with the global community's efforts to reduce carbon emissions and combat climate change. Although Türkiye has made considerable progress in the use of RES in the electricity sector, it remains a country that is still heavily dependent on fossil fuels. To achieve a net-zero emissions target, Türkiye, like other nations that have set a net-zero target, will need to make significant progress, particularly in the electricity sector [10]. It is evident that the construction of an electrical infrastructure in line with the above-mentioned goals and the utilization of the capacity of renewable energy sources (RES) will be made possible through the widespread use of grid-connected, single- or multienergy power systems. Considering the growing population of Türkiye and the increasing interest in EVs, the installation of NGs in the range of 5–10 kW per building will make a significant contribution to reducing the impact of EV charging loads on the grid.

According to the Turkish Statistical Institute [11], there are approximately 10 million buildings in Türkiye. Even if only a quarter of this number is considered as potential NGs, the contribution to the grid will be incredibly significant. In a country such as Türkiye, which is heavily dependent on energy imports, natural gas composed of renewable energy sources (RES) will have a synergistic effect and contribute significantly to the goal of net-zero emissions and the production of electricity from clean sources. According to a study by the International Energy Agency (IEA) in 2021 [11], Türkiye's renewable energy capacity has increased by 50% in the last five years. Türkiye had the 5th-highest level of new renewable capacity additions in Europe in 2019 and the 15th highest globally. Given its significant resource endowment, Türkiye can achieve even faster development in renewables, particularly solar, wind, and geothermal. The country's huge potential for renewable energy growth extends beyond electricity generation to the heating sector. In particular, Türkiye has only exploited 3% of its solar potential and 15% of its onshore wind potential. Advances in technology, the rebuilding of supply chains after the COVID crisis, and Türkiye's efforts to produce domestic solar panels are all contributing to the realization and utilization of renewable energy potential. In NG studies, researchers often only use solar RES, but extending these systems with the addition of small wind turbines (WT) can create a hybrid renewable energy system (HRES). This approach ensures continuous energy generation, especially during the night hours when solar systems are not producing

electricity, thereby increasing the importance of HRES for sustainability. Considering a 24 h period, the ability to generate energy from HRES when there is no sunlight is critical to the sustainability and reliability of the system [12]. The literature suggests that HRESs with battery energy storage (BESS) are the most suitable systems in terms of sustainability and reliability [7,13–15]. By adding components such as biomass, diesel generators, and others at the microgrid level, a larger and more powerful system can be obtained, providing an autonomous power supply for all the electrical needs of a region, whether connected to the grid or operating independently [16,17]. HRES systems can be installed in areas without access to the grid, operating in island mode in rural areas, facilitating access to electricity for places such as villages through the use of biofuels, and providing flexibility, continuity and reliability. Furthermore, when compared to power plants that produce an equivalent amount of electricity regardless of their grid connection or independence, it is suggested that HRES systems will contribute to the reduction of greenhouse-gas emissions and move towards the goal of net-zero emissions. In addition, it is mentioned that these systems will support the energy sector in Türkiye, which is currently dependent on external sources, from a technoeconomic perspective. In order for energy from renewable energy (RE) sources to provide reliable energy output in line with sustainability and flexibility criteria, it is necessary to use HRES in conjunction with battery energy-storage systems (BESS). A support mechanism for storage systems equal to the central power of large WT and PV plants has been introduced in Türkiye in 2022 [18]. This will enable greater benefits from storage systems, especially in places with high energy demand such as industrial areas.

In Türkiye, incentives such as FIT (feed-in tariff), NEM (net metering) and tax exemptions are available for rooftop PV systems that are only 10 kW solar PV systems [19]. In order to strengthen these incentives and speed up the bureaucratic processes, the limit for grid-connected rooftop solar energy systems (rooftop pv) without a license requirement was increased from 10 to 25 kW [20]. Consequently, with the PV–BESS structure, small but powerful nanogrids can be established to meet the self-consumption needs of a household or building, while also generating financial gains and contributing to the country's electricity grid [21]. Türkiye's significant solar and wind energy potential, together with its favourable climate zone, make it ideal for the proper exploitation of these resources. To reap the full benefits, Türkiye must continue to invest in infrastructure, incentivize renewable energy projects, and provide supportive rules and regulations for the growth of the sector. The development of wind turbines has made it possible to generate electricity from wind power. The amount of wind energy that can be generated is affected by wind speed, turbine size, and blade length [22,23]. According to the International Renewable Energy Agency (IRENA) [24], the installed capacity of wind energy, both onshore and offshore, has increased by 23.4% among other renewables worldwide in 2022. In addition to the growing global interest in renewable energy technologies, the use of renewable energy systems in Türkiye has also increased due to locally developed support mechanisms. In 2022, the share of wind power in the total installed capacity is around 11%. The Ministry of Energy and Natural Resources of Türkiye presented the National Energy Plan [4] for 2020–2035, which targets a total installed electricity capacity of 189.7 GW. Solar, wind, and nuclear power are expected to reach 52.9 GW, 29.6 GW, and 7.2 GW, respectively. Solar capacity growth will come from new land-based and rooftop systems, as well as the deployment of hybrid power plants with storage technologies. Balancing supply and demand margins, especially during periods of low solar capacity, remains crucial.

On the other hand, recent data reflect significant developments in the energy transition process across Europe. While the majority of energy in member states still originates from imported fossil fuels, there has been a substantial boost in local generation since 2020. Specifically, 41% of the EU's energy production came from renewable sources, and one-third was generated by nuclear power plants in that year. In 2021, renewables continued to dominate EU primary energy production, accounting for 41% of the total. Notably, Malta relied entirely on renewable energy production, while Latvia, Portugal, and Cyprus had renewable energy as their primary source, each exceeding a 95% share. Conversely,

Slovakia, Belgium, and France heavily depended on nuclear power, constituting 60%, 70%, and 76% of their national production, respectively [25]. In 2020, China introduced the “dual carbon” goals as part of its strategy to mitigate the risks associated with climate change. The nation pledged to reach the peak of its CO₂ emissions by 2030 and attain carbon neutrality by 2060. Notably, the power-generation sector, primarily reliant on coal, stands out as the leading contributor to CO₂ emissions in China, representing 48% of the total carbon emissions [26,27]. Despite China’s dense population and high urbanization rate, the distributed photovoltaic (PV) resources on building rooftops have been largely overlooked. This oversight is particularly evident in the adoption of household PV systems in China, accounting for only about 1%, despite the numerous advantages, feasibilities, and government encouragement [28]. Global concerns over environmental pollution and climate change have spurred widespread attention toward solving these issues through the use of renewable energy. In [29], a two-stage model to analyse the impact of uncertainty on the developing renewable energy industry, specifically comparing the effectiveness of the feed-in tariff and the renewable portfolio standard (RPS). Findings indicate that FIT leads to higher expected output and profit but lower market prices, with associated risks in production and gains being more pronounced. On the other hand, RPS results in relatively stable production and profit, with increasing incentive effects as the cost of renewable energy decreases. According to [30], Australia’s buildings account for approximately 26% of the country’s energy consumption and contribute to a daily emission of 280,000 tons of CO₂. Addressing the reduction of emissions and energy usage in the residential sector is compounded by the considerable number of new dwellings expected to be integrated into the housing stock in the coming years. To illustrate, Australia is projected to witness the construction of at least two million new dwellings between 2018 and 2050, posing a significant challenge in achieving sustainability goals. As of 2021, Australia has surpassed three million households equipped with rooftop solar systems. Current estimates suggest that this number has likely risen to approximately 3.4 million. In 2022, rooftop solar made a substantial contribution, constituting 25.8% of renewable generation and 9.3% of the total energy generation—up from 8.1% in the previous year. Insights from the Australian Energy Market Operator (AEMO) regarding minimum operational demand, which represents the lowest level of demand met by grid-based generation and is often influenced by consumer-owned sources like rooftop solar, indicate a noteworthy impact of renewables on the conventional energy mix [31]. The rapid growth of solar PV deployment in the U.S., encompassing both field and rooftop installations, is a positive trend in the context of nanogrids. The increase from 4 to 44% of new electric capacity represented by PV from 2010 to 2021 indicates a significant shift towards renewable energy adoption. However, despite this progress, solar energy, including all sources, constitutes only 3.9% of total U.S. electricity generation [32]. Europe’s notable increase in local energy generation aligns with nanogrid principles, promoting community-based, renewable energy sources. The varied energy profiles of EU member states underscore the potential for nanogrids to tailor solutions to diverse needs, particularly in regions heavily reliant on nuclear power. China’s commitment to carbon neutrality and the challenges within its power-generation sector accentuates the urgency for distributed solutions, such as NGs, to facilitate a transition away from coal dependence. The overlooked distributed PV resources in China, despite government encouragement, present a key opportunity for NG implementation, particularly in residential areas. Shifting the focus to Australia, the growing adoption of rooftop solar systems aligns with NG objectives, showcasing the impact of consumer-owned (prosumer) sources on the conventional energy mix. As the country faces challenges in reducing emissions from the residential sector, integrating NGs into new dwellings could offer sustainable solutions. Therefore, assuming a nanogrid-oriented approach could be used to explore how NGs can address the specific challenges and opportunities presented in each region, fostering a more resilient and sustainable energy future.

The main motives for this research are as follows:

- In the context of NGs, to carry out the feasibility study of a rooftop PV–GRID and PV–WT–GRID system using HOMER Grid 1.11.1 version software to achieve optimal solutions;
- To assess whether the proposed system has substantial environmental offsets and a fair payback period by comparing the system performance of on-grid NG combinations with a minimum net present cost and cost of energy value;
- First study in the Türkiye market that assesses building-type nanogrids;
- Sensitivity analysis according to levelized cost of energy (LCOE) was applied;
- Unlock the NG potential of a building type with an on-grid rooftop solar system;
- Determination of an optimal NG system using an electric vehicle charging station (EVCS) for different configurations.

The present work is carried out primarily to fulfil the following objectives. The main objective of this study is to determine the optimal grid-connected NG capacity for the specified region as a renewable energy system. The second objective is to select the best renewable energy system to supply building loads and EVCS. The final objective is to find out how the uncertainty of the important factors influences the ideal HRES configuration. The rest of this study is organized as follows. Section 2 summarizes the existing HRES studies in the literature and shows the proposed system. Section 3 presents the method, parameters, and background of the study. Section 4 gives the mathematical background and optimization methodology of the study. The results and discussion are presented in Section 5. Finally, concluding remarks are presented in Section 6.

2. Proposed System and Existing HRES Studies

2.1. Proposed System

Buildings now account for almost 40% of carbon emissions, and any solution to the energy problem must address the issue of energy use in buildings. Recent developments in smart building technologies clearly show that future buildings have the potential to be active and energy self-sufficient entities, capable of trading energy when connected to other active buildings or the upstream electrical grid [33,34].

In the present study, two buildings located in different districts of Türkiye/Istanbul are investigated. For one of these buildings, the main focus is on assessing the residential and EV load requirements within the NG concept. The aim is to determine their optimal operation while remaining on the grid, with the aim of identifying the NG potential of a standard building. For the other type of building, which includes both residential loads and additional requirements such as lifts, EV charging, water pumps, and common-area lighting, an NG system is designed to provide the necessary power. The aim here is to determine the optimum technical and economic operating conditions for this NG system. Figure 1 shows the locations of these NG buildings where technoeconomic analyses and optimization studies have been carried out.

The structure identified as NG_1 is a NG installed on an 80 m² roof, consisting of PV–GRID components, without any shading effects. On the other hand, NG_2 identified as such, represents a multienergy NG installed on the roof of 800 m² building, constructed with a PV–WT–GRID structure. Several studies have been carried out using the HOMER (Hybrid Optimization Model for Electric Renewables) program for the Türkiye site. However, none of these studies have integrated EV loads into the system. Table 1 provides a summary of recent studies conducted in Türkiye and other regions. These studies include a variety of electrical loads, such as residential buildings, a university campus building, factories, and even a town. Although these studies can be classified as HRES and RES, they have not been evaluated in the context of NG.

The research in Table 1 has primarily prioritized options with the lowest unit energy costs and net present costs. However, there is a lack of technoeconomic analyses for RES or HRES systems in NG structures. This study aims to fill this gap by analyzing recent work for MG structures. Using HOMER Grid, a widely recognized simulation and optimization

tool, this study benefits from its accuracy and different optimization algorithms for RES, nanogrids, and microgrids.



Figure 1. Proposed NG placement.

Table 1. Single- and multienergy studies with HOMER.

References	Year	Mode	Composition	Load	Load Demand (kWh/Year)	NPC (USD)	COE (USD/kWh)	Sensitivity Analysis
[35]	2022	On grid	PV-GRID	Apartment Building	6546	5974	0.034	No
[36]	2023	On grid	PV-WT-BESS-GRID	Industry Area	8,760,000	9.46 M	0.073	No
[37]	2019	On grid	PV-WT-DG-BESS-GRID	Industry Area	8,773,505	135 M	0.119	No
[38]	2021	Off grid	PV-WT-BESS	Household District	54,750,000	176 M	0.182	Yes
[39]	2020	Off grid	PV-WT-DG-BESS	Household District	116,800 (electric) 52,001 (thermal)	598,958	0.164	Yes
[40]	2022	Off grid	PV-BESS	A Textile Factory	25,721,412	151.654 M	0.012	No
[41]	2022	Off grid	PV-WT-DG-BESS	A Vineyard	3832.5	12,458	0.264	No
[42]	2021	On grid Off grid	PV-GRID PV-DG-BESS	Family House	1,514,591	1367 9159	0.058 0.438	No
[43]	2021	On grid	PV-DG-BESS-GRID	A Factory	365,000	7.81 M	0.0457	Yes
[44]	2021	On grid Off grid	PV-GRID PV-WT-DG-BESS	A University Building	730,000	1.68 M 4.29 M	0.176 0.455	Yes
[45]	2019	On grid	PV-WT-BESS-GRID	A High School	44,453	42,837	-	No
[46]	2021	Off grid	PV-WT-BESS	Irrigation	27,466	99,768	0.172	No
[47]	2023	Off grid	PV-DG	Rural House	2920	16,157	0.4280	No
[48]	2022	Off grid	PV-HFC-BESS	Rural Communities	257,284.85	7.01 M	0.244	Yes
[49]	2020	Off grid	WT-FC-BESS	Residential House	3650	59,611	1.278	No
[50]	2022	On grid	PV-FC-GRID	Family House	3759.5	10,166	0.23	No
[51]	2020	On grid	WT-BG-BESS	Family House	1679	14,507	0.588	No

Table 1. Cont.

References	Year	Mode	Composition	Load	Load Demand (kWh/Year)	NPC (USD)	COE (USD/kWh)	Sensitivity Analysis
[52]	2023	On grid	PV-WT-GRID	Rural Load	253,440	6.92 M	0.0715	No
[53]	2023	Off grid	PV-WT-DG-BESS	Telecom Station	31,025	85,673	0.214	No
[54]	2023	On grid	PV-WT-GRID	Urban House	15,695	36,457	0.153	No
[55]	2022	Off grid	PV-WT-FC PV-WT-BESS PV-WT-FC-BESS	A port Town	301,876 (GWh)	2.1 B 1.3 B 1.5 B	0.436 0.273 0.322	No

2.2. Existing HRES Studies

Renewable energy sources have the significant advantage of enabling the creation of hybrid energy systems, where multiple energy-generation units work together to provide electrical power. These hybrid systems can operate independently or be connected to the grid. The combination of wind and solar energy is often favoured to increase efficiency and reliability. This approach helps to overcome the intermittent nature of fully renewable energy systems that struggle to provide consistent power [56,57]. An analysis using HOMER for a rural HRES showed a 64% reduction in greenhouse-gas emissions and significant cost savings compared to diesel generators [58]. Another study highlighted the scalability, adaptability, and potential to improve the resilience and performance of a university microgrid through energy storage and demand-side strategies, suggesting its applicability to different systems [59]. In India, shared photovoltaic nanogrids demonstrated reduced LCOE when households had longer daily occupancy and reduced load variability, LCOE of shared NGs ranging from USD 0.151/kWh to USD 0.195/kWh [60]. In addition, a rooftop PV system in Türkiye, while not meeting all energy needs, reduced annual bills and emissions, demonstrating the positive impact of small-scale solar applications. Other recommended improvements include the integration of wind turbines and energy-storage systems to increase efficiency [61]. In Ref. [62], the study examines the reduction of grid dependency in the Saudi Arabian city of Neom through rooftop PV systems in various residential buildings. The study uses a techno-economic model using HOMER Pro to determine optimal PV-system sizes and battery capacities for different building types. The results highlight the different ideal PV-system sizes for different buildings, promoting sustainable energy solutions for Neom. In Ref. [63], researchers optimize a grid-connected HRES for a tourist hotel by integrating PV, wind turbines, and biogas generators. The most cost-effective configuration significantly lowers NPC and electricity prices, reducing grid dependency and contributing to the fight against climate change. In a study for a tsunami-affected university campus [64], HOMER was used to select solar PV and wind turbines that contributed 62% and 20%, respectively, to the energy mix, reducing energy costs. In Ref. [65], a peer-to-peer (P2P) trading strategy for NGs with renewable energy sources (RESs) and energy-storage systems (ESSs) optimizes grid power consumption, electricity costs, and delays in appliance use. It uses a battery ageing model to extend ESS lifetime and improves NG profitability by 2.86% in cost reduction and 32.75% in ESS degradation costs. The authors in Ref. [66] explore the integration of an NG concept into solar street-lighting systems using LED technology and solar energy, evaluating the power quality in both stand-alone and grid-connected modes through experimental tests. In Ref. [67] an HRES for a ship that sailed between Egypt and China incorporated solar PV, battery storage, and a diesel generator for year-round reliability. The optimal system significantly reduces greenhouse-gas emissions and fuel consumption compared to standalone diesel generators. The findings highlight the potential for increased solar installation capacity in offshore oil operations. The article also briefly compares HRES applications on land and offshore oil platforms. In Ref. [68], the authors explore the development and optimization of an HRES for domestic and telecommunication loads across India, emphasizing the importance of

considering technical, economic, environmental, and social factors (TEES). Various dispatch strategies are compared to enhance the reliability, cost effectiveness, and environmental friendliness of the HRES. Utilizing HOMER for design optimization and comparative analysis, the research reveals that the Pondicherry HRES exhibits the lowest energy cost for both loads, but other TEES parameters are optimal at different locations. Notably, an HRES with a predictive dispatch strategy outperforms other strategies in terms of economic, technical, environmental, and social factors. Sensitivity analyses for various variables contribute to achieving a more feasible configuration. The study validates HOMER results by comparing them to particle swarm optimization (PSO) and social spider algorithm (SSA) outcomes, while also providing a comprehensive comparison with the recent literature on HRESs. In Bofan et al. [69], a novel optimization method is applied to enhance HRES, incorporating fuel cells, photovoltaic cells, and windmills. In this study, the improved AI-Biruni algorithm is introduced with the aim of efficiently exploring solution spaces and enhancing solution accuracy. The HRES model is tested in a case study in Dunhuang City, China, considering supply, demand, and energy-storage constraints. The Modified AI-Biruni Earth radius (MBER) algorithm emerges as the most efficient and reliable, resulting in a system cost of 4.23 million units of currency. When compared to other optimization approaches, MBER demonstrates superior performance in terms of total cost, loss of power supply probability (LPSP), and system reliability. The research suggests that the improved AI-Biruni algorithm can effectively optimize HRES, reduce costs, and enhance load supply, contributing to the advancement of renewable energy sources and the application of advanced metaheuristic techniques in complex energy systems.

In Türkiye, there is a significant lack of scientific studies focusing on the integration of nanogrid structures. This study, which analyses the technical and economic impacts of nanogrid integration in two residential structures in Istanbul, aims to fill this research gap. By providing tailored solutions to the energy needs and sustainability goals of Türkiye, the results of these case studies can serve as important references for improving energy efficiency and sustainability throughout the country.

3. Homer Parameters and Background of the System

3.1. General Description

In this study, the authors used HOMER Grid 1.11.1 version software as the optimization tool. HOMER Grid software is critical to the design and optimization of energy systems, providing a comprehensive platform for modelling and evaluating renewable and conventional energy sources, storage systems, and grid-integration options. Its importance lies in its ability to help users minimize costs, improve energy efficiency, and reduce environmental impact while meeting energy demand and reliability requirements, making it an invaluable tool for businesses, researchers, and policymakers in the pursuit of sustainable and cost-effective energy solutions [70–74]. Figure 2 shows the proposed framework for the optimal configuration and design of NG systems. The input section, which feeds the optimization part, includes the case study's electricity consumption demand, meteorological data, selected technologies and their associated technical constraints, and some pricing information, such as capital costs, maintenance and operating costs, and replacement costs for each technology.

During the optimization phase, HOMER carefully examines a range of power-system components and configurations to determine the most economically efficient and environmentally sustainable solution. Through an iterative process, HOMER fine-tunes the system parameters to ensure that the final design meets specific criteria, such as minimizing cost, maximizing reliability, and reducing environmental impact. This iterative approach allows users to explore a wide range of possibilities and ultimately discover the energy system that seamlessly meets their unique needs and constraints. In the optimization stage, HOMER uses the HOMER Optimizer, an exclusive "derivative-free" optimization algorithm crafted specifically for seamless integration within the HOMER platform, enhancing precision in optimization processes.

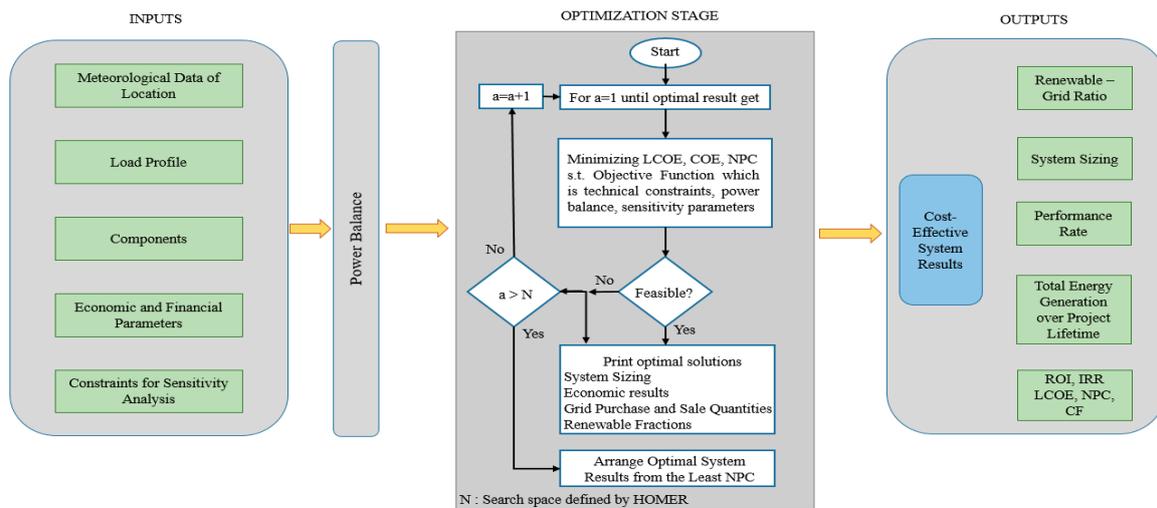


Figure 2. Schematic of the optimization process.

This study focuses on the optimization of an energy system where the key decision variables include the number of wind turbines, the dimensions of the PV panels and converters, and the number of batteries. The primary objective is to minimize a given objective function, while respecting the technical constraints imposed by the system components and maintaining a balanced power supply, all aimed at achieving the minimum power deficit in the supply.

3.2. Temperature, Wind, and Irradiation Data

The study aims to determine the optimal size and configuration of RES and HRES for an NG. The primary focus is on achieving a balanced nanogrid design, considering factors such as a reasonable NPC, long-term operational and maintenance costs, and a reduced LCOE to enhance competitiveness. The research covers sizing and capacity planning for components like solar panels and wind turbines, explores various system configurations with different energy sources and storage technologies, and conducts economic analyses to weigh costs against benefits. Additionally, accurate energy-production calculations rely on understanding site-specific wind, radiation, and temperature characteristics for rooftop solar PV and HRES systems. The use of solar-radiation data from NASA’s Prediction of Worldwide Energy Resource (POWER) database is a valuable aspect of this study. At the specified location, both NG_1 and NG_2 record an annual average daily solar irradiance of $3.94 \text{ kWh/m}^2/\text{day}$. Figure 3 provides information on the solar irradiance and clearness index received throughout the year.

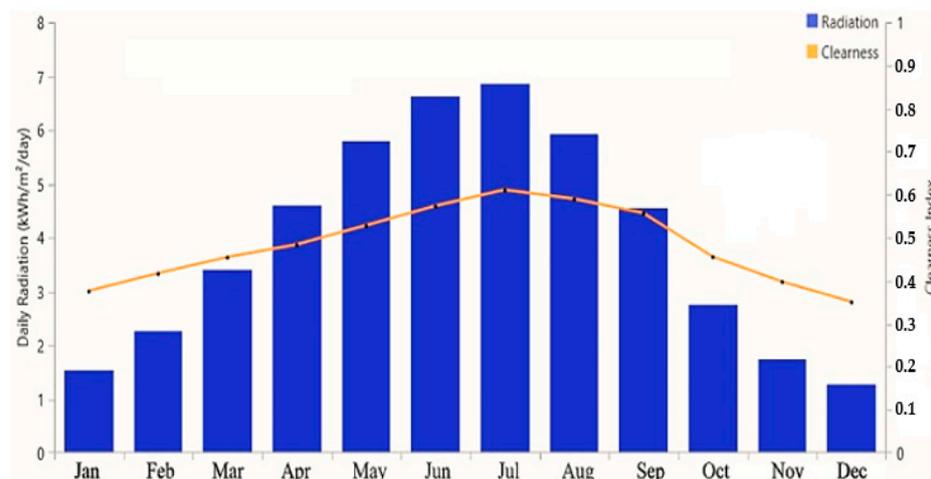


Figure 3. Solar irradiation values for both locations.

The clearness index represents atmospheric clarity, and it is known that, when it is high, the weather is sunny. Regions with a clearness index between 0.3 and 0.8 are considered to have sunny and clear skies [75]. It is observed that the period with the lowest clearness index falls in December and January. During these months, it can be said that the weather is cloudy or overcast. Similarly, it can be said that the weather is clear and sunny in June and July.

The current study uses wind-speed data from the NASA POWER database. Figure 4 shows how wind speeds vary over different months of the year. This data helps to optimize the design and operation of wind turbines in NG systems. At the site in question, the scaled annual mean wind speed was recorded at 6.33 m per second (m/s), with the highest wind speeds typically occurring during the winter months. Figure 5 shows the daily sunshine hours for the location where the study was conducted. It can be seen that the region receives the highest solar irradiance during the summer months. Similarly, the region receives the least solar irradiance during the winter months, with 2.96 and 3.46 h in December and January, respectively [76]. In this study, for NG_1 , separate cases, namely PV-GRID, PV-BESS-GRID, PV-WT-GRID, and PV-WT-BESS-GRID, are evaluated with only residential loads and EV loads, and optimal results are investigated. For NG_2 , the PV-GRID, PV-BESS-GRID, PV-WT-GRID, and PV-WT-BESS-GRID configurations were created and sensitivity analyses were conducted to examine the system operation in detail, including loads for the pool, irrigation motors, ambient lighting, and EV charging stations. Figure 6 illustrates the NG structures to be evaluated in this study. Eight different NG structures were evaluated, each installed on relevant rooftops, considering different scenarios.

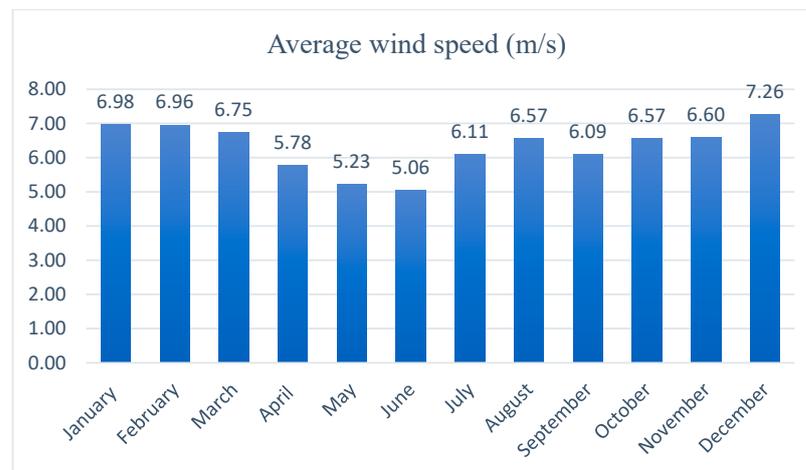


Figure 4. Average wind-speed values for both locations.

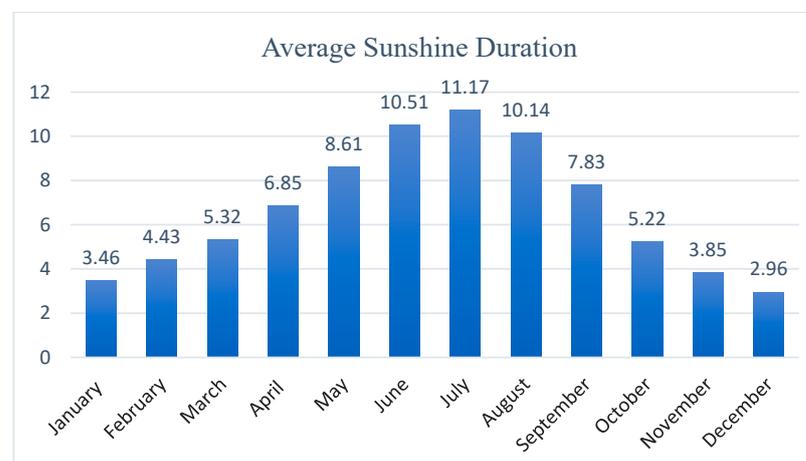


Figure 5. Monthly average sunlight duration (hours/day).

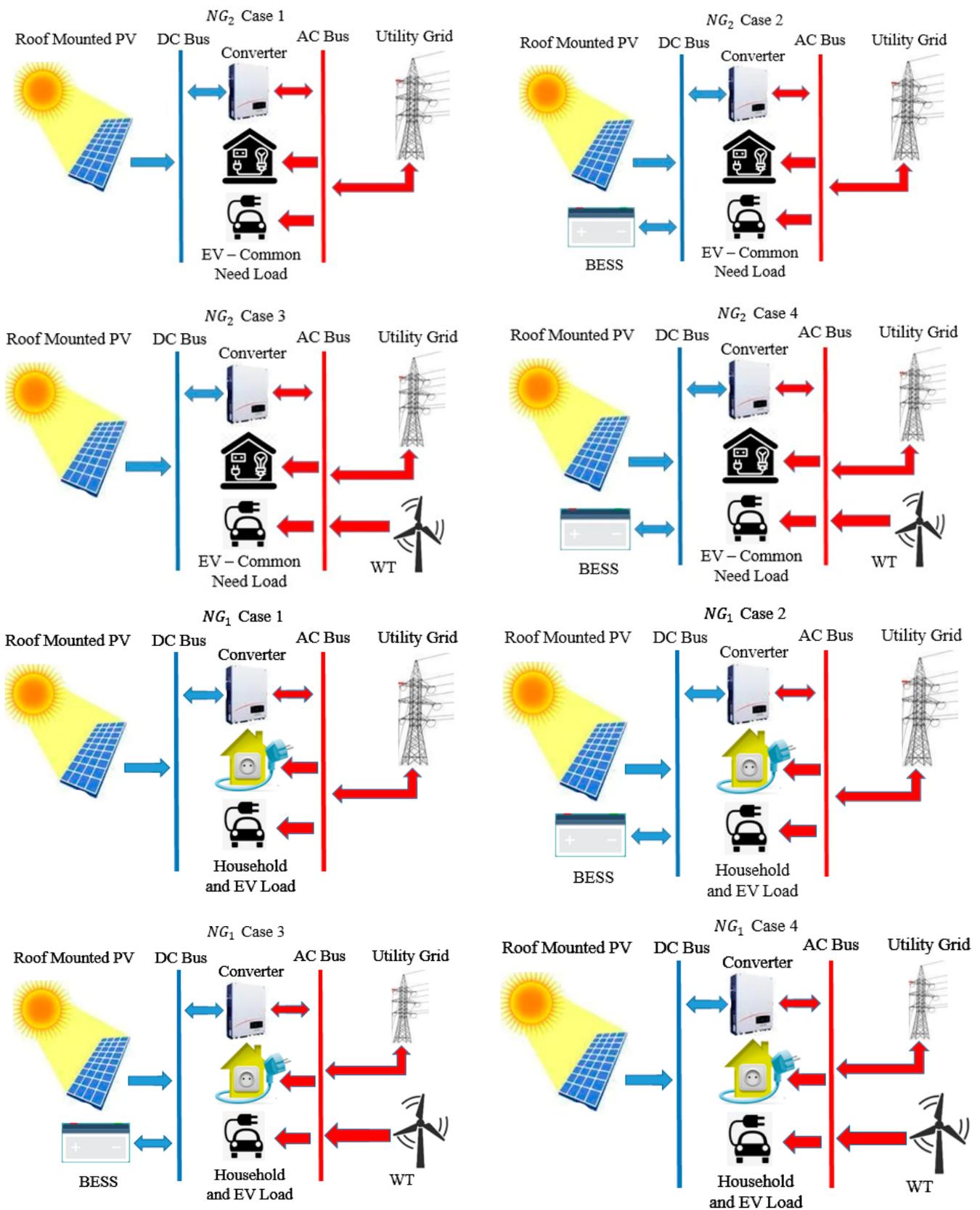


Figure 6. Proposed NG configurations.

4. Mathematical Background and Optimization Methodology

4.1. Modeling of NG

The mathematical model of solar PV, wind, battery storage, converter, and utility grid is covered in this section. In addition, economic indices, such as NPC, LCOE and optimization methodology, are explained in this section.

4.2. Solar Panels

Photovoltaic (PV) panels harness solar radiation and convert it into electrical energy. The power output of PV panels depends on several variables, including the incoming global solar radiation, the temperature of the PV panel, and the PV derating factor. The latter, a scalar factor, is used to account for and quantify various sources of loss that attenuate the electrical output of the PV module from its theoretically expected ideal performance [56,77]. In HOMER, the calculation of the photovoltaic (PV) power is based on a specific equation, referred to as Equation (1) [78].

$$P_{pv} = Y_{pv} D_f \left\{ \frac{G_T}{G_{T,STC}} \right\} [1 + \alpha_p (T_c - T_{c,STC})] \quad (1)$$

where, Y_{pv} is the output power of the PV array under standard test conditions D_f is the derating factor. G_T and $G_{T,STC}$ are the incident solar radiation in kW/m^2 at nominal and STC conditions, respectively. α_p is the temperature coefficient. T_c and $T_{c,STC}$ represent the PV-cell temperature under nominal and STC conditions, respectively. In this study, monocrystalline 17.49% efficient 340 W Canadian Solar CS6U-340M flat plate panels with 45°C nominal cell temperature and $1960 \times 992 \times 40$ mm PV panel dimensions were used in all designed NG systems. The unit price for each kW of PV was assumed to be 12,500 TL, but studies predict that this price will decrease significantly with new advances in PV systems [79]. In addition, the derating factor, which takes into account losses due to soiling, shading, snow cover, wire loss, ageing, etc., is set at 88%, and the lifetime of the PV panels is 25 years.

4.3. Wind Turbine

The wind turbines (WT) used in the proposed NG models have special blades designed to capture kinetic energy. When exposed to the wind at an optimum height, these blades provide additional lift, causing the turbine blades to rotate. These turbine blades are connected to a drive shaft which drives the generator, resulting in the production of electrical energy. In the current study, we used small 1 kW Aeolos turbines with an 8 m^2 swept area and a 3.2 m rotor diameter. The main reason for selecting small but powerful wind turbines is their suitability for the NG studies presented and their lower maintenance requirements. The unit price of this WT was 116,000 TL. The lifetime of this WT was assumed to be 20 years, and its generator efficiency was 0.96. The mechanical wind power P_{mec} is expressed as Equation (2) [80].

$$P_{mec} = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V_w^3 \quad (2)$$

4.4. Battery Energy-Storage Systems

BESS has a significant role to play in nanogrids for several compelling reasons. First, a BESS acts as a critical energy-storage solution, enabling nanogrids to capture excess energy generated by renewable sources, such as solar panels and wind turbines, ensuring a continuous and reliable supply of electricity. In addition, BESSs enhance grid stability by acting as a buffer against fluctuations in energy supply and demand, which is particularly important for stand-alone nanogrids. It supports peak shaving, reducing demand charges by releasing stored energy at peak times, thereby reducing costs. A BESS also integrates seamlessly with energy-management systems, optimizing the use of renewable resources and promoting cost-effective energy practices. Its ability to provide emergency backup power increases

the resilience of the nanogrid, and by facilitating the integration of renewables, a BESS supports environmental sustainability while contributing to long-term cost savings. The BESS charging and discharging process is described below, and the electrical energy stored in a BESS is denoted by Equation (3).

If $P_{NG} > P_{Load}$ and $BESS_{chr} < BESS_{chr,max}$ then BESS charging mode on,
 If $P_{NG} < P_{Load}$ and $BESS_{chr} > BESS_{chr,min}$ then BESS discharging mode on,

$$P_{BESS} = \eta P_{bess,chr} \tau_{bess,chr} \quad (3)$$

where $P_{bess,chr}$ is the BESS's charging power, η is the charging efficiency, and $\tau_{bess,chr}$ is the BESS's charging time in hours. In this study, a rack-mounted 1 kW Li-On battery energy-storage system is considered. The rack-mounted design has the advantage of being easy to add to the system when additional BESSs are required and simplifies maintenance and repair. Its unit price for one unit is 14,200 TL, its lifetime is 7 years and the minimum state of charge taken is 20%.

4.5. Converters

In an NG system, converters are the key components that enable three basic energy conversions. The first conversion is to convert the direct current (DC) power generated by photovoltaic panels into alternating current (AC) for the AC bus, making it compatible with the grid and loads. The second conversion occurs when the power generated by the WT is converted from AC to DC on the DC bus. This DC power is then used to charge the BESS after meeting the energy needs of the load. Finally, the third conversion occurs when the BESS is required to supply power to the load. In this scenario, the stored DC energy is efficiently converted back to AC, ensuring a seamless and reliable power supply [81]. These three key conversions illustrate the critical role of converters in managing the flow of energy within a nanogrid system. The capacity of a converter is given by Equation (4) [82].

$$C_{conv} = \frac{L_{AC,DC}}{\eta} \sigma_s \quad (4)$$

where $L_{AC,DC}$ represents the peak AC or DC load, η is the efficiency of the converter and, σ_s is the safety factor. In this study, a 1 kW generic converter was chosen, with a capital cost of 6700 TL for one unit. Its lifetime is 15 years, and its efficiency is 95%.

4.6. Utility Grid

In this study, an NG is connected to the grid all the time. After supplying energy to the loads in the NG, any excess energy is exported to the grid. Similarly, if the energy generated within the NG is insufficient to meet the load demand, energy will be imported from the grid. According to the Energy Market Regulatory Authority of Türkiye, the prices for energy import and export are given as 2 Turkish Liras (TL) and 0.737 TL per unit of energy, respectively.

4.7. Economic Indices

Net present cost (NPC) and levelized cost of energy (LCOE) are the economic metrics used in this article for grid-connected nanogrids. The net present cost (or life-cycle cost) of a component is the present value of all costs to install and operate the component over the life of the project minus the present value of all revenues generated over the life of the project. HOMER calculates the net present value of each system component and the system as a whole [83]. The net present value can be calculated using Equation (5) [84,85].

$$C_{NPC} = \frac{[i(i+1)^N - 1] C_{annual,total}}{1 - (i+1)^N} \quad (5)$$

where N is the number of years in the project's lifecycle, i is the real discount rate, and $C_{annual,total}$ is the total annualized cost of all the system components, which is expressed as below Equation (6).

$$C_{annual,total} = CRF(i, R_{prj-lifetime}) \cdot C_{NPC} \quad (6)$$

where $R_{prj-lifetime}$ denotes the project's economic lifetime, and the capital recovery factor (CRF) is defined in [86] as related to both project lifetime (N) and inflation rate (i) as given below in Equation (7).

$$CRF_{i,N} = \frac{i(i+1)^N}{(i+1)^N - 1} \quad (7)$$

The levelised cost of energy generation (LCOE) is computed by equating the cost and generation across the system's life span [33], as indicated in Equation (8).

$$LCOE = \frac{\sum_{t=1}^N \frac{I_t + M_t + F_t}{(r+1)^t}}{\sum_{t=1}^N \frac{E_t}{(r+1)^t}} \quad (8)$$

where I_t is investment costs, M_t is operations and maintenance cost, F_t is fuel costs, E_t is total electricity generation, and r is the discount rate [87].

4.8. Other Economic-Input Variables

According to the Central Bank of Türkiye [88], the average annual inflation rate over the past two decades has been 14.98%. In the context of this study, which has a projected life of 25 years, we have chosen to assume an average inflation rate of 15% for Türkiye over the next quarter century. If we look closely at the average discount rate for Türkiye over the last 12 years, we find an average of 12.31%. However, for the purposes of our current study, which covers a projected life of 25 years, we have deliberately chosen to project a more conservative average discount rate of 9.5% for Türkiye over the next quarter century.

4.9. Optimization Methodology

To optimize the NGs, we used the HOMER Grid 1.11.1 version software, which uses advanced mathematical optimization algorithms. These algorithms aim to minimize the objective function while respecting defined constraints. HOMER Grid offers two optimization options: the grid search algorithm, which systematically evaluates all possible system configurations within the search space and the innovative HOMER Optimizer, which uses a proprietary derivative-free algorithm to identify cost-effective solutions. The optimization process includes system configuration, setting optimization objectives, defining constraints, selecting the appropriate algorithm, execution, and generation of a ranked list of configurations by net present cost and least energy cost [63,89]. For the current study, the objective function is given by Equation (9).

$$\min F = \sum_{t=1}^N C_{NPC} \quad \text{st. min (LCOE)} \quad (9)$$

In the NG_1 optimization process, P_{PV}^{NG1} is PV-panel capacity as kW, P_{BESS}^{NG1} is converter capacity as kW, and P_{WT}^{NG1} is the number of WT as decision variables. These decision variables represent the key elements that we optimize in the design of the NG. The determination of the lower and upper limits for these decision variables is particularly influenced by factors such as the available installation area, solar irradiance, wind speed and the economic indices of the components used, especially when considering this small-scale NG system.

The upper and lower limit taken for PV and WT are as follow in NG_1 and NG_2 , respectively.

$$NG_1 \text{ can use 21 pcs PV panel, meaning that } 0 < P_{PV}^{NG1} \leq 7$$

$$NG_1 \text{ can use 2 kW WT separately, meaning that } 0 < P_{WT}^{NG1} \leq 2$$

In addition, the optimization constraints are set to include the requirement to minimize the maximum annual electricity capacity shortfall, while the minimum renewable share is set as a baseline, effectively taking a zero-tolerance approach.

In the NG_2 optimization process, P_{PV}^{NG2} is PV panel capacity as kW, P_{BESS}^{NG2} is converter capacity as kW, and P_{WT}^{NG2} is number of WT as decision variables.

The upper and lower limit taken for PV and WT are as follow in NG_2 :

$$NG_2 \text{ can use 270 pcs PV panel, meaning that } 0 < P_{PV}^{NG2} \leq 90$$

$$NG_2 \text{ can use 6 kW WT separately, meaning that } 0 < P_{WT}^{NG2} \leq 6$$

4.10. Load Profile

In the context of a nanogrid, household electrical load refers to the combined power consumption of various appliances and devices. It includes peak demand (high power consumption) and base load (continuous, lower power consumption). Efficient management of this load is critical to the operation of the nanogrid. Techniques, such as load-scheduling, energy-efficient appliances, and renewable energy integration, help to balance supply and demand. Battery storage and demand response (DR) programs can ensure reliability, but we did not consider DR programs in this study. Electric load design was an important part of this study. The daily electrical load profile for a five-story building with five households in NG_1 is provided to the HOMER model. Table 2 shows the estimated electrical loads of the considered buildings. The main energy-consuming household appliances include lighting, TV, air conditioning, refrigerator, stove, dryer, dishwasher, washing machine, and small powered appliances.

Table 2. Electrical loads for the considered buildings in NG_1 .

Component	Device Piece	Power Consumption (W)	Used Time (h)	Daily Average Usage for a Single House (W/s)	Daily Total Usage for Building (kW/Day)
Lightning Fixture	5	15	1.5	112.5	0.5625
Lightning Fixture	2	20	2	80	0.4
TV	1	160	3	480	2.4
Owen	1	2200	0.5	1100	5.5
Air Conditioner	1	1400	1.2	1680	8.4
Washing Machine	1	840	1.5	1260	6.3
Dryer	1	1800	1	1800	9
Vacuum Cleaner	1	600	0.5	300	1.5
Refrigerator	1	150	24	3600	18
Cattle	1	1600	0.5	800	4
Dishwasher	1	1200	1	1200	6
Small powered devices	2	30	3	180	0.9
EV Charging Socket	1	7000	4	1	28

In the residential environment analyzed, the cumulative average electrical load is 12.59 kW/day. If we extend our scope to the entire five-story building, the total electrical consumption reaches 62.96 kW/day. The determination of the load demand for this particular building is guided by Equation (10), as specified in references [90,91].

$$P_{LOAD} = \sum_{k=1}^{N_{house}} \left[\sum_{i=1}^{N_{component}} D_p P_c U_t \right] \quad (10)$$

where, D_p , P_c , and U_t are the number of appliances, the power consumption of the appliance in use in W, and the time of use in hours, respectively. According to the Regulation on Electricity Installations in Türkiye, it is imperative to consider simultaneity (demand) coefficients when constructing residential load profiles, as specified in reference [7]. In order to ensure that the load data generated by the HOMER Grid 1.11.1 version software is as close as possible to real-life scenarios, specific parameters have been introduced. These parameters include a 14% variation in daily load and a 21% variation in time-of-use load, as documented in Refs. [92,93]. By incorporating these variations, we aim to create more realistic and representative load profiles, thus aligning our simulations with the actual dynamics of electricity consumption in residential environments. This approach improves the accuracy of our analyses and facilitates more informed decision making regarding energy management and infrastructure planning in the context of the electricity regulations in Türkiye. The NG_1 study focused on an EVCS designed to meet the daily charging needs of homeowners' EVs. The combined load profile resulting from this configuration is shown visually in Figure 7. In particular, it is clear from the load profile that there is a significant increase in electricity consumption during the night hours, primarily due to the charging requirements of the EVs.

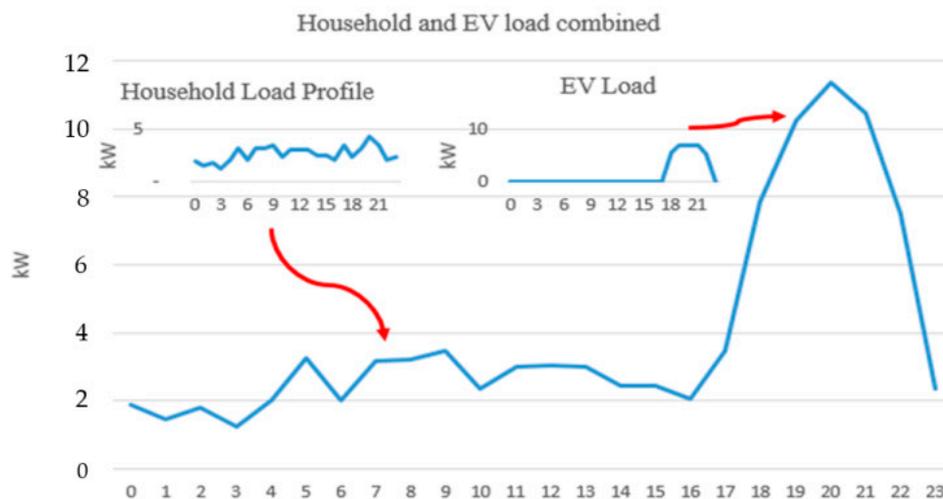


Figure 7. Combined load profile for NG_1 .

To improve the fidelity of the EV charging data within the HOMER Grid software, we have carefully introduced specific parameters to incorporate variability into the modelling process. This includes a 30% charge duration variability factor, recognizing that real-world EV charging times can vary due to various factors, such as battery capacity and individual preferences.

In addition, a 10% time step variability factor has been introduced to capture the dynamic nature of EV charging loads even over short time intervals, accounting for intermittent plug ins and real-time adjustments. By incorporating these variability parameters, our aim is to generate EV charging data that closely mimic the unpredictability of real-world charging behaviour. This nuanced representation is critical for accurate load modelling and robust system design when integrating the EV charging infrastructure into the broader context of a nanogrid.

As part of the NG_2 study, we developed a daily electrical load profile for a residential building. This load profile includes a wide range of electrical loads, including but not limited to lifts, irrigation systems, lighting, and various other household- and building-related electrical demands. This comprehensive load profile was fed into the HOMER model for

analysis and simulation. By including different types of electrical loads, we aim to gain a holistic understanding of the energy requirements and consumption patterns within this residential-style building. This information is essential for optimizing energy management strategies and exploring potential improvements in energy efficiency and sustainability within such residential environments. Table 3 provides an overview of the estimated electrical loads associated with the analyzed building. Notably, the most significant contributors to energy consumption in this context are the EVCS and the building's lifts. These two loads in particular have a significant impact on the overall electricity consumption of the building. The EVCS, as a vital component of modern urban living, plays a key role in meeting the charging needs of electric vehicles, while the lifts are essential for vertical transport within multistory buildings.

Table 3. Electrical loads for the considered buildings in NG_2 .

Component	Piece	Power Consumption (W)	Used Time (h)	Daily Average Usage for Single House (W/s)	Daily Total Usage for Housing Estate (kW/day)
Environmental Lighting	50	20	8	8000	8
Cameras	25	15	24	9000	9
Elevators	3	6200	4	74,400	74.4
Irrigation	8	600	1	4800	4.8
Car-Park Lighting	180	20	4	14,400	14.4
General Dwelling Floor	1	780	8	6240	6.24
Sports Center General	1	3000	12	36,000	36
Swimming Pool	1	1100	6	6600	6.6
EV Charging Area	8	7000	6	336,000	336
Barriers	3	120	1	360	0.36

Within the housing estate building under analysis in the context of NG_2 , the total average electrical load is 495.80 kW/day. This cumulative electrical load represents the total power consumption arising from various building systems and appliances, including but not limited to elevators, irrigation systems, lighting, EVCSs, and other electrical loads. Accurately quantifying this average load is fundamental for understanding the building's energy demands, optimizing energy-management strategies, and ensuring the reliable provision of electrical power to meet the diverse needs of the building's residents and other needs. In NG_2 , charge duration and day-to-day and timestep variability were taken at 30%, 20%, and 10% respectively. By incorporating these parameters, our aim is to create simulations that closely emulate the diversity and unpredictability of actual EV charging behaviours, thereby enhancing the accuracy of our analyses for informed decision making, load management, and infrastructure planning. The combined load profile, as a result of the configuration within NG_2 , is visually depicted in Figure 8. What stands out prominently in this load profile is a pronounced surge in electrical power consumption. This increase is predominantly attributed to the substantial charging demands imposed by the EV being integrated into the system.

In the proposed NG systems, the costs of components and technical parameters will be determined through a process involving either bilateral negotiations or competitive bidding. It is important to note that all the components required for these NG systems are readily available in the Turkish market. This approach ensures that cost estimates and technical specifications are based on the realities of the local market, thereby enhancing the practicality and feasibility of implementing these NG systems in Türkiye.

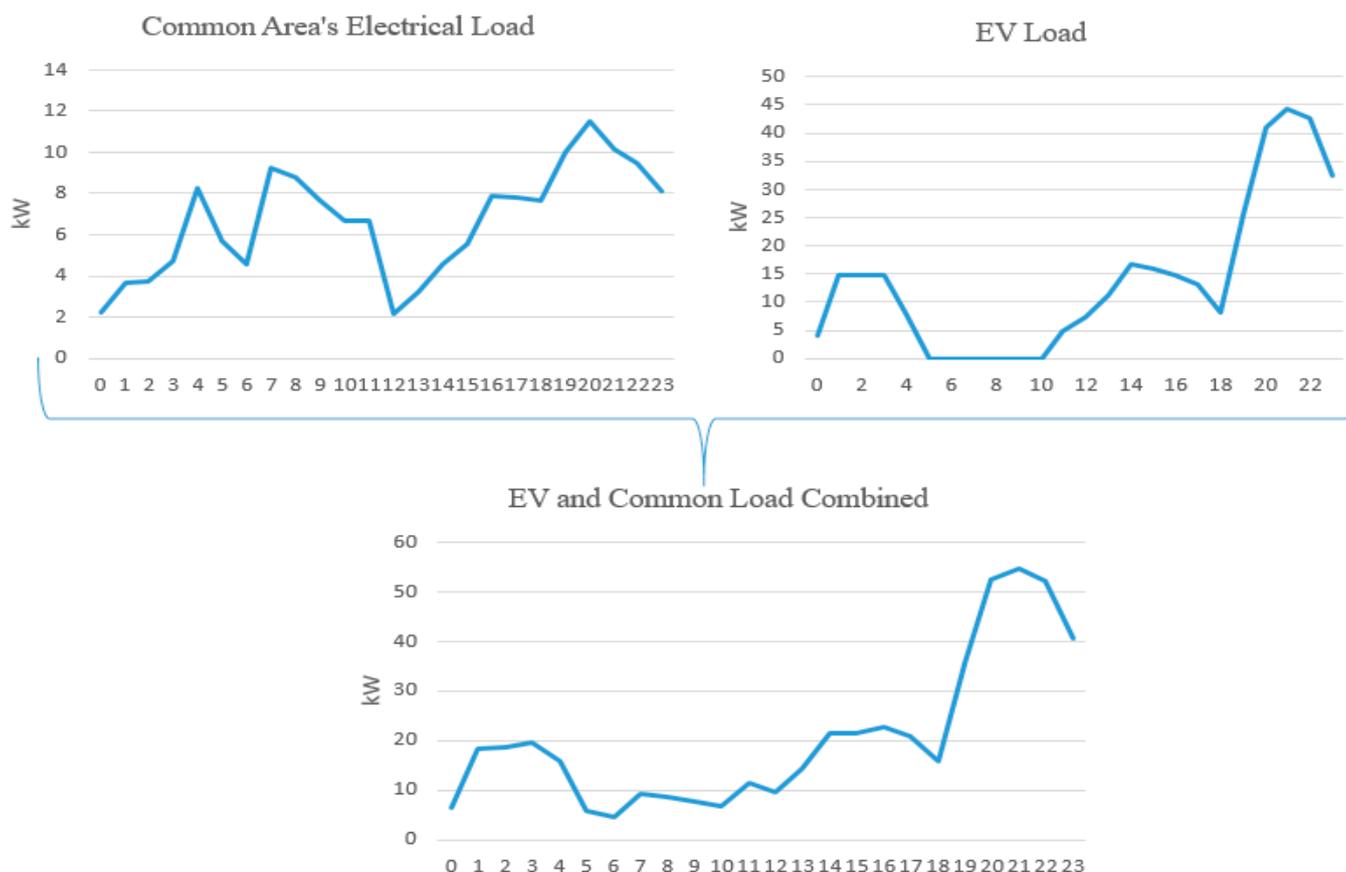


Figure 8. Combined load profile for NG_2 .

5. Results and Discussion

In the current study, we focused on various NG configurations. Our goal is to optimize the utilization of on-site renewable energy to meet total electric demand, including electric vehicles (EVs), while reducing reliance on the utility grid. We also assess the economic benefits, such as revenue from selling surplus electricity to the grid and environmental advantages by comparing life cycle CO_2 emissions with the base energy system. Our analysis relies on HOMER Grid simulations, which consider factors like grid purchases, grid sales, renewable fraction, inflation rate, and operational costs. These simulations provide critical insights into the performance of NG case studies under current conditions. HOMER Grid simulation results for NG_1 's case studies under current conditions are presented in Table 4.

Table 4. Optimal results for NG_1 considering all cases.

Scenario	Architecture				Costs			Systems			Payback	Emission
	PV	BESS	WT	CONV	NPC M	LCOE TL	OC year TL	Ren. Fr. %	IRR %	ROI %	Discounted Payback Year	CO_2 Kg/Year
Base Case	-	-	-	-	1.73	2	32,424	0	-	-	-	10,246
NG1-CASE1	7	-	-	4.5	1.36	1.2	24,656	38.6	3.8	2.3	10.71	8863
NG1-CASE2	7	1	-	4.88	1.38	1.22	24,772	39	4.2	2.5	11.55	8700
NG1-CASE3	7	1	1	4.57	1.54	1.25	25,453	49	2.3	1.2	12.02	8055
NG1-CASE4	7	-	1	4.5	1.49	1.2	24,907	48.4	2.3	1.3	12.09	8055

All values in Table 4 represent PV, BESS, and WT in kilowatts. The economic analysis of the proposed system is based on two key economic parameters, NPC and LCOE. HOMER identifies the most feasible configurations using these criteria and presents only the optimal

feasible configurations, resulting in 384 different configurations. The optimal configuration is detailed in Table 4. By considering the NPC and LCOE values for different system configurations, we identify the optimal NG system as CASE1, with an NPC of 1.36 million Turkish liras (MTL) and an LCOE of 1.20 Turkish liras per kilowatt-hour (TL/kWh). Table 4 presents the optimization results for the proposed NGs and compares them with the baseline system, which relies primarily on the utility grid to meet load demand. Notably, the proposed optimized system proves to be superior and less costly than the associated base system. The electricity price for the proposed NG, at 1.20 TL/kWh, is 40% lower than the existing retail grid price.

The monthly averages of electricity purchases and sales in NG are shown in Figure 9. The blue bars represent energy purchased from the grid and the orange bars represent electricity sold to the grid.

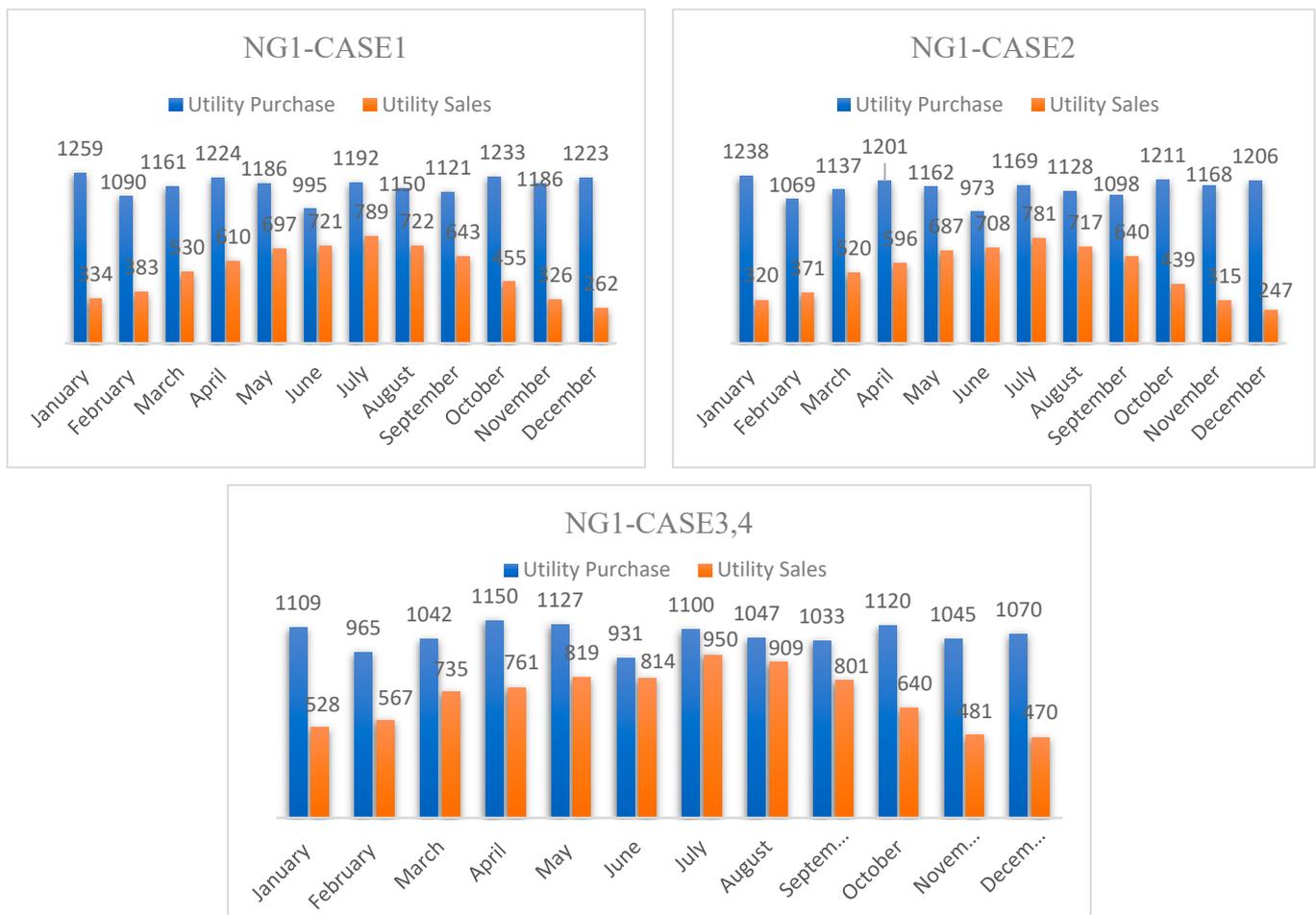


Figure 9. Monthly electricity sales and purchases in the NG_1 for each case.

As shown in Figure 10, there is a noticeable contrast between the annual electricity sales and purchases within NG_1 's Case 3 and Case 4. It is worth noting that, although Case 4 and Case 3 have the lowest delta value, indicating an efficient energy exchange, it ultimately proves infeasible. In stark contrast, Case 1 emerges as the optimal configuration, highlighting the importance of selecting the most appropriate NG configuration for improved performance and economics. This observation underlines the critical role of careful planning and system optimization when implementing NG.

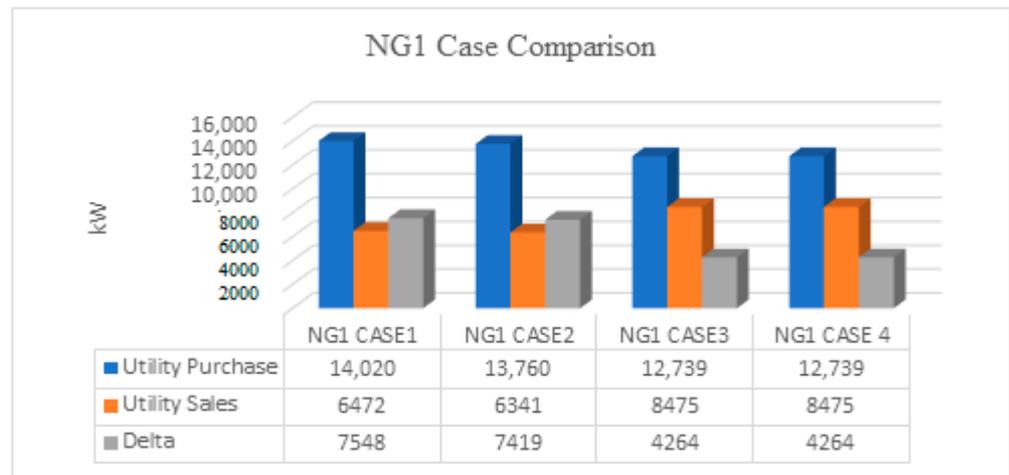


Figure 10. Annual electricity sales and purchase difference in the NG₁ for each case.

5.1. Sensitivity Analysis for NG₁ Case1

Sensitivity analysis in HOMER plays a key role in the planning and design of energy systems. It involves evaluating how variations in key input parameters or assumptions affect the results of the designed simulation. By selecting and varying parameters, such as equipment costs, load profiles or the availability of renewable resources, the economic parameters in the sensitivity analysis allow a comprehensive understanding of the robustness and reliability of a system. Through a series of simulations, HOMER calculates and records the results as these parameters are varied, providing insight into the influence of each variable on metrics such as NPC and LCOE. This analysis helps to identify trends and inform decisions about system design and component selection, ultimately guiding the optimization of energy systems to meet performance and economic objectives. In the current study regarding NG₁ for Case 1, which is the feasible outcome, we conducted future-oriented projections and assessed the impact of changing inflation rates, grid tariffs, and equipment capital costs. Specifically, we explored scenarios involving inflation, grid tariff increases, and reductions/increases in capital costs for PV and converter technologies.

In Figures 11 and 12, an analysis has been carried out to assess the impact of inflation and grid tariff increases on a feasible natural gas system. An increase in inflation is associated with an increase in the NPC, while it is observed that the LCOE decreases. Similarly, when the price of electricity purchased from the grid increases, both NPC and LCOE costs increase. Understanding these results provides valuable insights into the influence of economic analysis on the viability of energy projects such as this NG study.

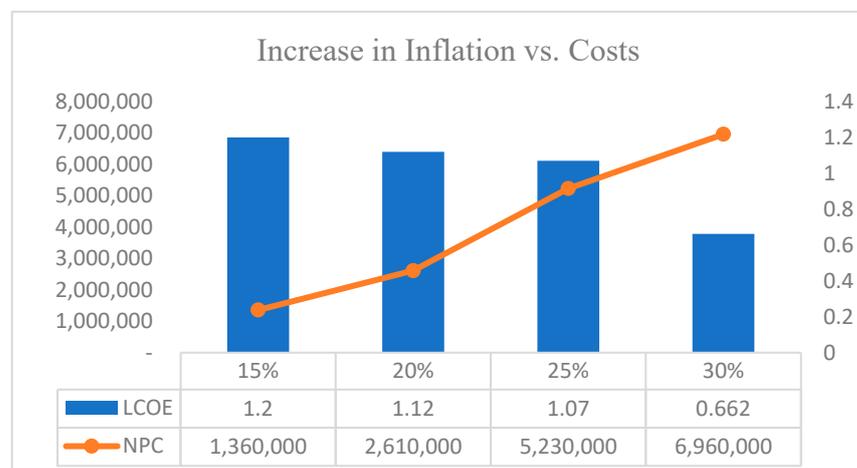


Figure 11. Inflation rate increase effect on Costs.

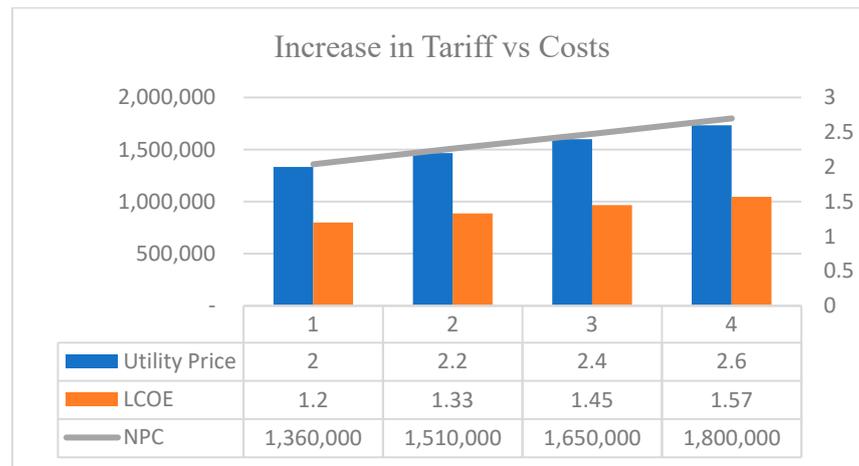


Figure 12. Grid tariff increase effect on costs.

As shown in Figure 13, the impact of fluctuations in the capital cost of PV systems and converters on NPC and LCOE is an important factor to consider. An increase in the capital cost of PV systems and converters tends to result in an increase in both NPC and LCOE. Conversely, a reduction in capital costs can lead to a reduction in NPC and LCOE.

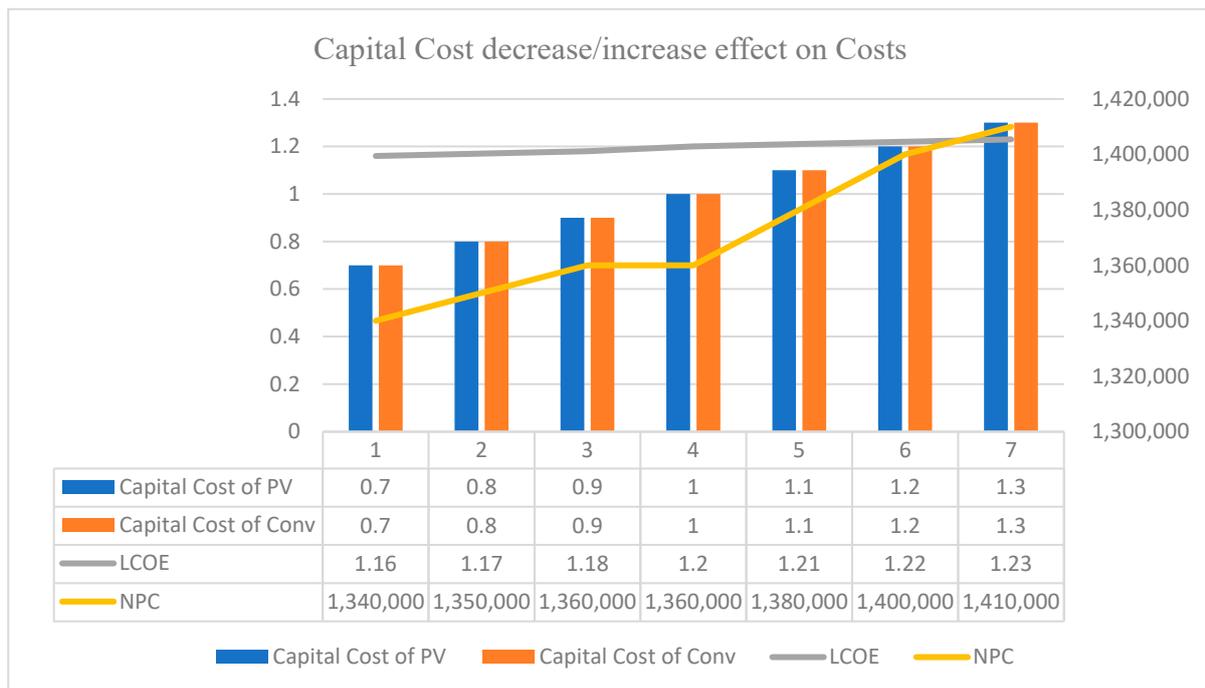


Figure 13. Capital cost increase/decrease in PV and converter’s effect on NPC and LCOE.

5.2. Analysis for NG₂ Cases

In our second study, we considered the installation of different types of NGs on the roof of a multistory building with a useful area of 800 m². The load profile of this building consists mainly of EVCS and other general building needs. The average daily load is 495.80 kW/day. Our analysis is based on HOMER Grid modelling, which takes into account variables such as grid purchases and sales, renewable content, inflation, and operating costs. These models provide critical insights into how the NG case studies operate under current conditions. Table 5 shows the results of the HOMER Grid simulations for the NG₂ case studies.

Table 5. Optimal results for NG_2 considering all cases.

Scenario	Architecture				Costs			Systems			Payback	Emission
	PV	BESS	WT	CONV	NPC M	LCOE TL	OC Year TL	Ren. Fr.%	IRR %	ROI %	Year	CO ₂ Kg/Year
Base Case	-	-	-	-	17.6	2	362,048	0	-	-	-	114,407
NG2-CASE1	90	-	-	51.8	13.5	1.15	248,678	44.2	5.6	3.5	8.94	85,308
NG2-CASE2	90	16	-	51.8	14.1	1.22	255,780	44.8	5.6	3.5	8.65	82,818
NG2-CASE3	90	-	6	52.6	12.9	1.06	220,972	51	3.5	2.1	12.17	77,878
NG2-CASE4	90	16	6	52.1	13.6	1.14	230,596	51.7	3.4	2	13.11	75,180

All values in Table 5 represent PV, BESS, and WT in kilowatts. The economic analysis of the proposed system is based on two key economic parameters, LCOE and NPC, as NG_1 . According to the results, the winning system architecture is NG_2 Case 3. In the search for optimal nanogrid results, 799 optimization runs were performed with the HOMER Grid 1.11.1 version software. However, 106 of these were excluded due to infeasibility. The results show that, when examining the system results, Case 3 appears to achieve a lower NPC and LCOE compared to the base system. The unit energy cost is about 45% lower than the base system and the annual CO₂ emissions are expected to be about 30% lower.

The monthly average of electricity purchases, sales, and production figures for NG_2 are shown in Figure 14. In the figure, all numbers are expressed in kW.

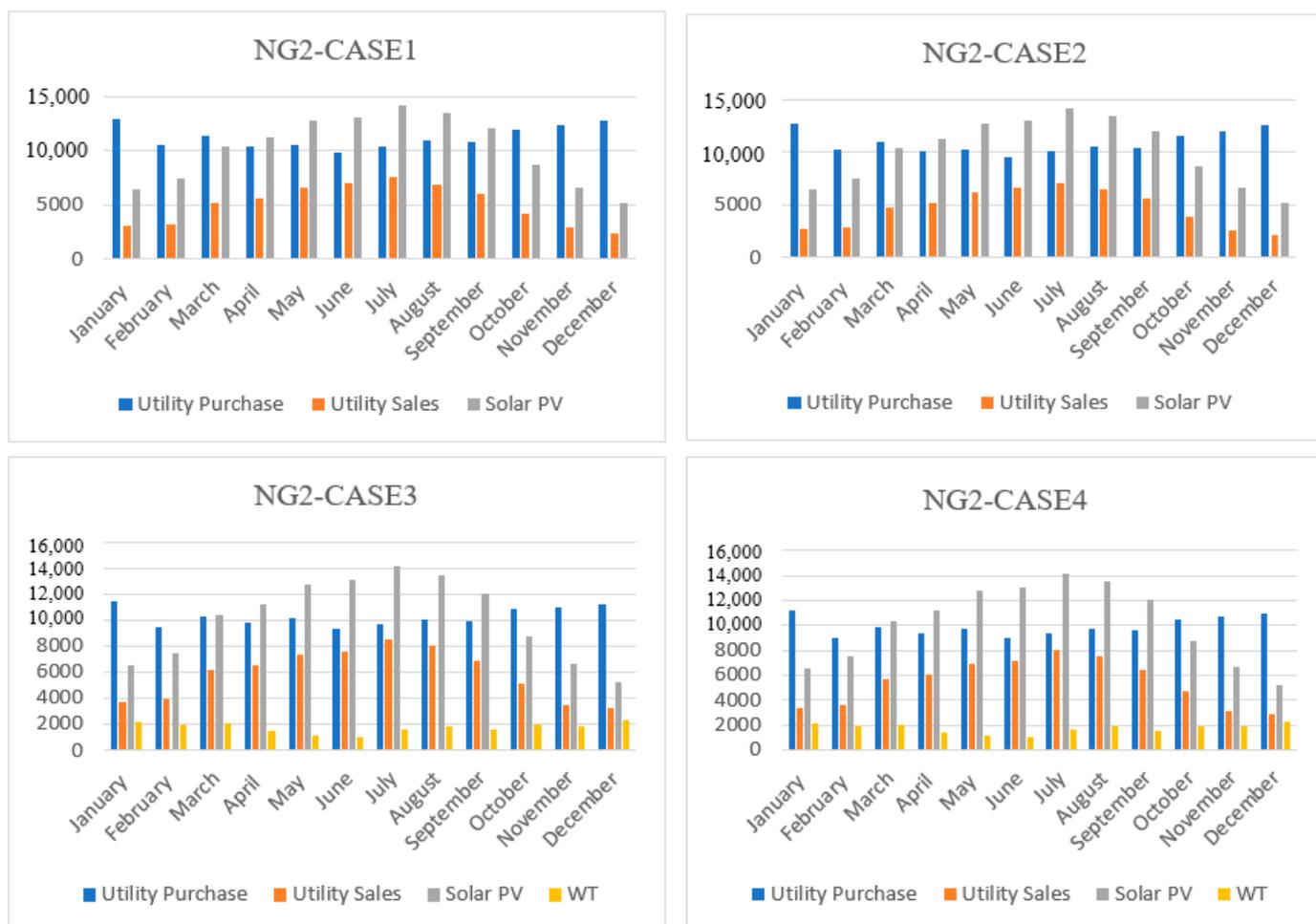


Figure 14. Monthly electricity sales, purchase and production figure in NG_2 for each case.

5.3. Sensitivity Analysis for NG₂ Case3

Effective analysis is crucial when assessing the feasibility and performance of nanogrids using the HOMER Grid. In this context, incorporating sensitivity analysis for key variables such as inflation, capital costs, and tariff rates is critical. Inflation has a direct impact on cost estimates and financial projections, so it is essential to consider its impact on the long-term viability of the project. Through sensitivity analysis, we can assess how different inflation scenarios affect the overall economics of the project, allowing for more robust financial planning. Similarly, capital costs are critical to the budgeting, financing, and technology selection of nanogrid projects. By performing capital-cost sensitivity analysis, we can gain insight into the impacts of cost overruns or savings, allowing us to make informed decisions for successful implementation. Tariff rates are equally critical, as they underpin revenue projections and market risk assessments. Rate-sensitivity analysis helps optimize revenue generation, negotiate advantageous contracts, and adapt to market dynamics. Ultimately, this integrated approach to sensitivity analysis facilitates data-driven decision making, effective risk management and long-term sustainability.

In Figures 15 and 16, an analysis has been carried out to assess the impact of inflation and network tariff adjustments on the viability of the natural gas system. It was observed that an increase in inflation leads to a corresponding increase in the NPC, reflecting the higher costs associated with project development and operation over time. Surprisingly, the LCOE showed a decrease under these conditions, possibly due to the relatively fixed nature of the system’s operating costs. Conversely, an increase in the price of electricity purchased from the grid leads to an upward shift in both the NPC and the LCOE. The increase in the cost of grid tariffs contributes to higher overall costs for the NG system, which affects its economic viability. These findings underline the delicate balance between inflation, grid tariff adjustments, and the financial performance of the NG system and highlight the need for informed decision making and effective cost management in the planning and operation of such systems.

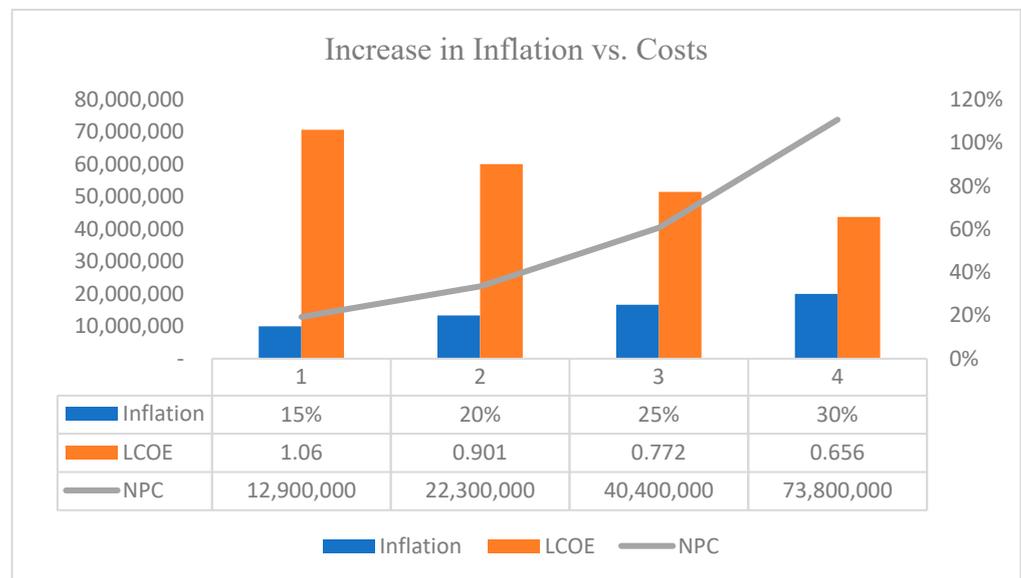


Figure 15. Inflation rate increase effect on costs for NG₂ Case3.

The capital costs associated with key components, such as photovoltaic panels, wind turbines, and converters, have a profound impact on the economic viability and competitiveness of a nanogrid. An increase in the capital cost of these components has a direct impact on the NPC and LCOE of the nanogrid, as shown in Figure 17. Rising capital costs require a larger initial investment, resulting in a higher NPC. Correspondingly, the LCOE increases as the increased capital cost is spread over the energy output, making electricity

production more expensive. Conversely, a reduction in the capital cost leads to a reduction in the NPC, making the nanogrid more financially attractive due to its lower upfront cost. In addition, the LCOE decreases, making the nanogrid more cost effective and competitive with alternative energy sources.

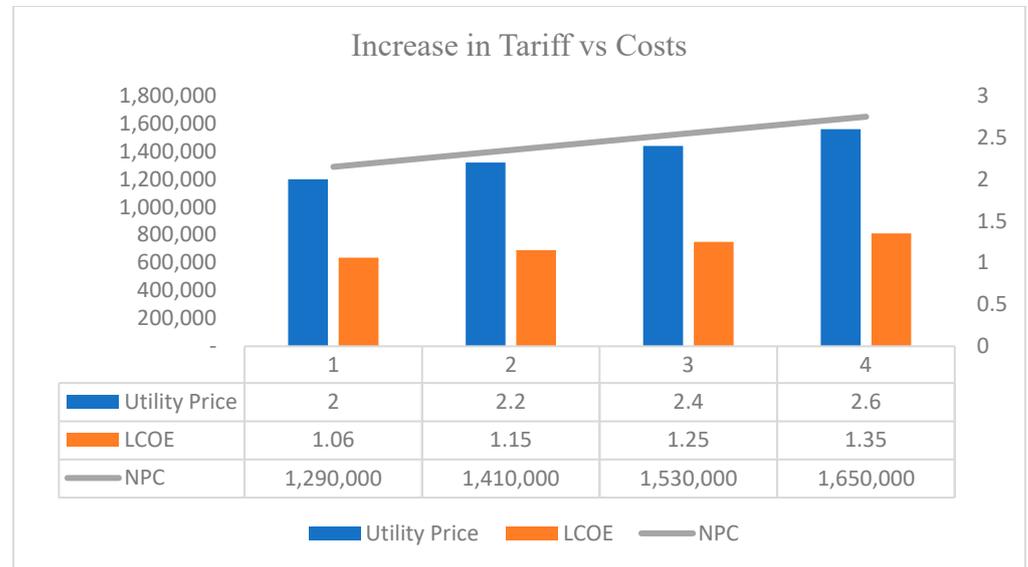


Figure 16. Grid tariff increase effect on costs for NG₂ Case3.

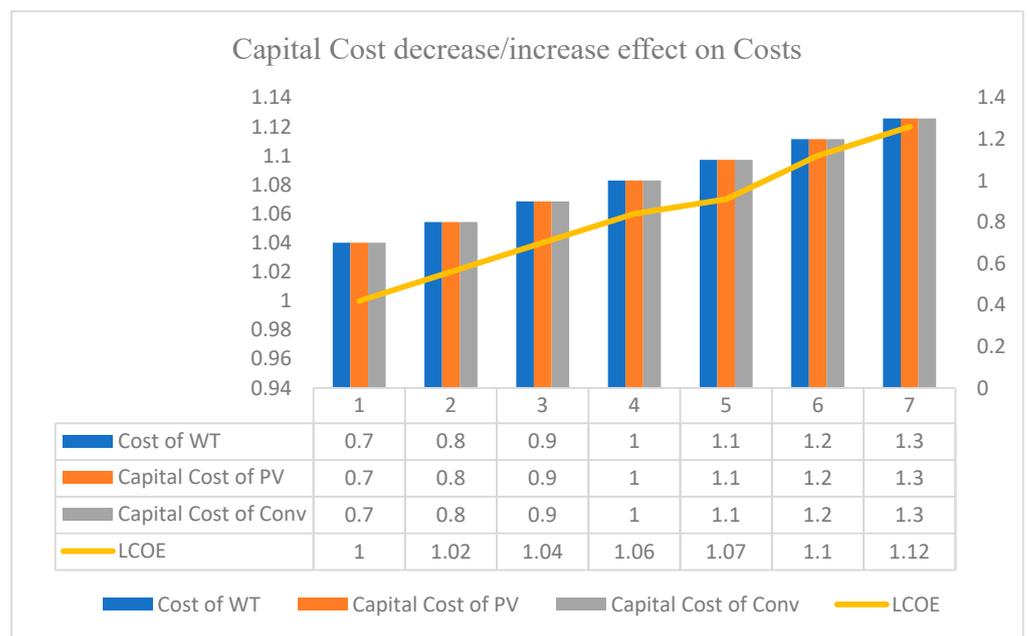


Figure 17. Capital cost increase/decrease in PV, WT, and converter’s effect on NPC and LCOE.

6. Conclusions

The objective of this study was to find a sustainable solution to reduce the consumption of grid-supplied electricity in classical apartment buildings and multistory residential buildings in Istanbul, Türkiye. The research used HOMER Grid version 1.11.1 software to perform an economic evaluation of different nanogrid configurations, ultimately identifying two optimal setups. The first is a PV-GRID system with 7 kW of photovoltaic capacity, and the second is a PV-WT-GRID system with 90 kW of PV capacity and 6 kW of wind-turbine capacity.

These NG configurations showed an LCOE of 1.20 TL and 1.06 TL, respectively, representing a significant cost advantage over the current conventional grid rate of 2 TL. The PV–GRID system contributed 38.6% of the renewable energy, while the PV–WT–GRID system contributed an even more substantial 51%. This reduction in reliance on non-renewable grid electricity resulted in a significant reduction in greenhouse-gas emissions, with a 15% reduction for the PV–GRID system and a substantial 30% reduction for the PV–WT–GRID system. This highlights the important role of solar PV and wind power in mitigating energy-related environmental problems, particularly in terms of CO₂ emissions.

The study also examined the sensitivity of NPC and LCOE values to variations in economic factors. For the PV–GRID system, the NPC increased as utility prices increased, while the LCOE values decreased as inflation rates increased. For the PV–WT–GRID system, both NPC and LCOE values increased as utility prices and equipment capital costs increased but decreased as equipment prices decreased. It is worth noting that, contrary to common practice, BESS was not used in either of the optimal configurations. We attribute this to the low energy demand of the PV–GRID configuration, while, in the case of the PV–WT–GRID system, the use of WTs obviated the need for BESS. This observation suggests that, for systems with low energy demand, such as PV–GRID, the cost effectiveness of implementing an energy-storage solution such as BESS may not be justified. Similarly, the presence of wind turbines, which can utilize energy efficiently, may obviate the need for additional storage. This highlights the importance of tailoring energy solutions to specific consumption patterns and the type of energy resources used. In light of the recognized environmental concerns associated with large-scale battery energy-storage systems, our study has taken a proactive approach toward mitigating such impacts. The optimal configurations proposed in this research exclude BESS, aligning with the growing awareness of the environmental implications tied to extensive battery usage. The introduced NG configurations have a notable impact on local grid stability, reinforced by the integration of distributed energy resources. This enhancement is particularly advantageous during outages, as NG can provide backup power to critical loads, contributing to overall grid resilience. However, the broader integration of multiple NGs into the existing grid infrastructure poses challenges, requiring careful management of bidirectional power flow and synchronization with the main grid demand.

In conclusion, this study shows that the implementation of PV–GRID and PV–WT–GRID systems in Istanbul’s apartment and multistory buildings can be both economically viable and environmentally beneficial. These findings emphasize the pivotal role of renewable energy sources, with a particular focus on solar PV and WT, in addressing energy-related environmental challenges, such as reducing CO₂ emissions and reducing dependence on conventional grid electricity.

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