2023 14th International Conference on Electrical and Electronics Engineering (ELECO) | 979-8-3503-6049-3/23/$31.00 ©2023 IEEE | DOI: 10.1109/ELECO60389.2023.10415979

The Effect of Economic Conditions on Optimal Sizing and Feasibility of Hybrid Power System

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Abstract

Clean energy-focused hybrid power systems (HPS) can help countries with their sustainable development plans. Optimal sizing of HPS depending on the varying countries' economic conditions in a reliable and robust strategy can reduce investment risks. This study performed optimal PV-DG-ESS based HPS sizing and feasibility analyses for Antalya, considering Türkiye's last ten years' interest and inflation rates, energy purchase costs, diesel costs, HPS investment, and operating costs. Moreover, the scope of the study is extended by sensitivity analyses on solar radiation, interest, and inflation. The results show that the proposed optimal HPS can reduce electricity purchase costs by up to $143.8 thousand/year and increase the renewable fraction by up to 74%, considering the current economic and climatic conditions. According to the sensitivity analysis, the grid was preferred in scenarios where solar radiation was lower than 5.5 kWh/m^2/day. The research revealed the impact of economic conditions on HPS and is expected to guide investors and policymakers.

Keywords: Electric vehicle, diesel fuel price, grid tariff, HPS capital cost, optimization.

1. Introduction

Sustainable city and clean energy initiatives require close collaboration between energy, transportation, and storage to achieve net zero carbon emission commitments. In integration with energy storage systems (ESS), the traditional use of lead-acid batteries continues, but lithium-ion technologies with superior performance compared to their peers are often preferred. With an integrated solution, HPS are expected to be the first step in climate-neutral development. Considering the growing population of prosumers integrating renewable energy and ESS, sizing strategies and subsequent technical, economic, and environmental feasibility analyses must be managed appropriately. Optimization frameworks should be determined and realized according to many factors' sensitive and uncertain nature. The first sensitive variable affecting optimization is the fuel price of generators used as a backup energy source during power outages due to the lack of ESS. A $0.3/L increase in the price of diesel fuel reduces CO_2 by 23.4% but increases net present cost (NPC) by 39.5% [1]. Contrary to common belief, the levelized cost of energy (LCOE) does not change much as fuel prices increase [2]. Although an optimal diesel fuel price of $0.7/L is assumed to reduce LCOE to $0.11/kWh [3], fuel prices as high as $0.7-1.2/L are only economically competitive for wind speeds above 7 m/s [4]. Overall, it is emphasized that with or without a grid connection, a fuel price of $1/L and irradiance of 5.35 kWh/m^2/day would provide optimal techno-economic benefits [5]. The second sensitive variable is electricity purchase prices, or generally time-of-use (TOU), which determines the economic balance in optimal sizing by managing the revenue and cost balance. A $0.02/kWh rise in TOU increases NPC by 1.6% and reduces LCOE by 15.7% [6]. In addition, a 10% change in TOU can affect the system's total operating cost by 4% [7]. Other sensitive variables are inflation and the interest rate, which determine revenue and cost over the years and directly affect optimization economics and investment plans. Reducing inflation by 5% could decrease NPC by 13.6% and increase LCOE by 38.5% [8]. In contrast, a 2.5% increase in interest rates and an 8% fall in inflation could raise the LCOE by up to 100% [9]. An increase in nominal discount rates (DR) could raise the grid extension threshold distance by 1.3 km [10] and the system's operating costs by 15.2% [11] and reduce the NPC by up to 37.6% [12]. Accordingly, inflation and interest rates should be appropriately set based on optimization sensitivity analysis. Indeed, it is emphasized that assuming inflation and interest rates of 6% and 1% will provide the minimum LCOE [13]. On the other hand, the most crucial sensitive parameter is the variability in HPS investment costs due to technology development and market competition. For instance, a 40% reduction in PV investment cost can decrease LCOE by up to 19% [14]. In contrast, a simultaneous 50% increase in the PV and ESS investment cost raises the LCOE by up to $0.094/kWh. Since a high share of renewables in energy supply is desirable, significant increases in energy costs of up to $0.2/kWh cannot be prevented [15]. Therefore, a 30% reduction in PV, wind turbine (WT), and ESS investment can reduce LCOE by 3.3%, 10.71%, and 8.82% [16]. However, not as much as capital costs and the impact of replacement costs on the system's economy are considered mainly due to the degradation process of ESSs [17].

Other sensitivity analyses in the literature motivated this study and are categorized as fuel price, electricity purchase and sale price, inflation, and interest rate, and HPS capital cost. Although most researchers classify the sensitivity variables into several categories, none of the studies can be said to consider sensitive parameters simultaneously. Moreover, the annual data of the relevant sensitivity parameters are not dynamically evaluated, and the robustness and reliability of the optimization framework are not guaranteed.

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In this study, the dynamic data of the sensitivity variables by years and the optimization framework based on the minimum cost objective are evaluated for Antalya, considering the exchange rate differences. Interest and inflation rates, grid tariff, electricity selling and diesel fuel price and HPS's investment, replacement and operational and maintenance (O&M) costs are dynamically considered over the years and feasibility outcomes are also evaluated. Also, proposing the optimum HPS capacities for the given years. Moreover, optimal PV-DG-ESS based HPS configurations and costs were determined by interest rate, inflation, and solar radiation sensitivity analyses.

2. Methodology and System Modeling

2.1. Climatic Data and Location

This study is analyzed by considering the Antalya region of Türkiye, which has high solar radiation and temperature data. Antalya city in Türkiye is 36° 53.8' latitude and 30° 42.8' longitude. Antalya's average daily radiation is 4.54 kWh/m^2/day and average temperature is 18.23°C [18]. Average solar radiation data for each month is obtained from the National Aeronautics and Space Administration (NASA) using the software database.

2.2. Load Profiles and EVCS Visits

The electrical load profile of a building that includes an electric vehicle charging station (EVCS) and the hourly changes in the number of vehicles in this building are shown in Fig. 1.

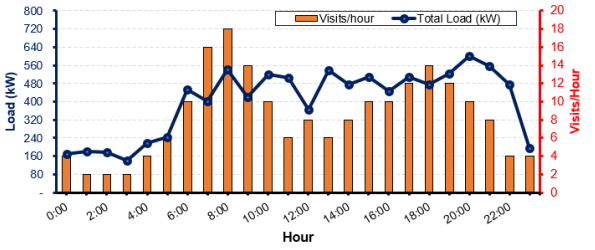


Fig. 1. Load profile and EVCS visits for hour

The EVCS accounts for 89.25% of the energy requirement of this building. The average daily profile of the primary electrical load is 1000 kWh/day, and the average daily peak power is 136.72 kW/kWp. Within the EVCS, there are slow charging stations of 3x22 kW, normal speed charging stations of 4x50 kW, and fast charging stations of 3x100 kW. The average daily profile of the EVCS is 8302 kWh/day, and the average number of customers is 400 sessions/day. The highest number of customers is between 07.00-09.00, while the lowest number of customers is between 01.00-03.00. The highest electricity consumption is at 20.00 in the evening, and the lowest electricity consumption is at 03.00 at night.

2.3. HPS Models

Hybrid power systems are controllable systems that use multiple energy sources (especially renewable energy) to meet the electricity demand of the load, and these energy sources are easily integrated into the electricity grid. This system aims to meet the energy needs of the load with the least cost and the most renewable energy sources (RES) [19], [20]. Fig. 2 shows the HPS model.

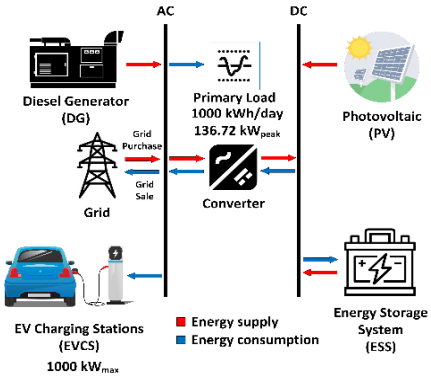


Fig. 2. HPS model

2.4. HPS Economic Parameters

The evolution of Türkiye's economic parameters between 2015 and 2023 is shown in Figure 3 [21]–[23]. In addition, Table 1 shows the investment, replacement and O&M costs, assuming an EVCS charging cost of $0.26/kWh regardless of the year [24], [25]. This, the impact of inflation and interest rate variations through the years on the optimal HPS sizing was investigated with the created scenarios.

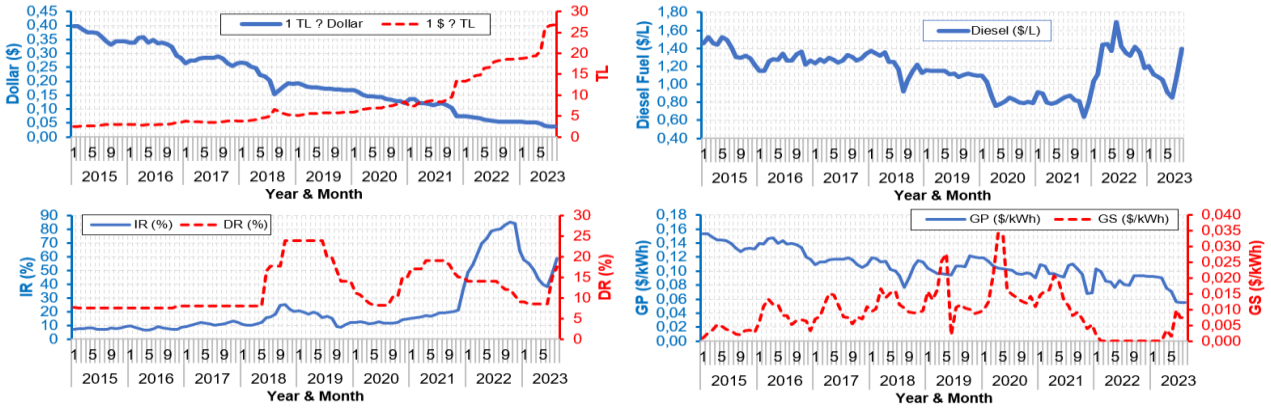


Fig. 3. Türkiye's changes in economic parameters over the years

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Table 1. HPS cost and scenarios

Scenarios	Capital				Replacement				O&M			
	PV	*DG*	*ESS*	*Converter*	*PV*	*DG*	*ESS*	*Converter*	*PV*	*DG*	*ESS*	*Converter*
Unit	$/kW	$/kW	$/kWh	$/kW	$/kW	$/kW	$/kWh	$/kW	$/kW/yr	$/kW/op.hr	$/kWh/yr	$/kW/yr
S1 (2015)	2016	750	420	650	1714	500	378	650	15.8	0.01	13	0.5
S2 (2017)	1586	900	242	550	1348	750	218	550	18	0.02	11	0.15
S3 (2019)	1120	1000	172	450	952	900	155	450	18.3	0.03	9	0.05
S4 (2021)	917	1250	141	350	779	1000	127	350	14.1	0.05	7	0.02
S5 (2023)	850	1500	140	250	500	1250	125	250	10	0.06	5	0.01

As a result of increasing inflation rates, the TL (₺) has depreciated, and the dollar ($) has appreciated significantly. This has led to increased diesel fuel costs over time and decreased electricity purchase (GP) values from the grid. This process caused fluctuations in the DR change within certain intervals. Considering these parameters, the effects of economic changes in Türkiye over the years on HPS sizing and technical, economic, and environmental changes in HPS will be analyzed.

The optimization analyses of this study were performed using Hybrid Optimization of Multiple Energy Resources (HOMER Grid) software. In this program, each analysis is hourly, and at the end of the year, this data is summed to obtain annual data. In this HPS model with a project life of 20 years, annual data are evaluated in line with DR and inflation rate (IR) changes, and real data are obtained at the end of the project [26], [27].

3. Optimization Results

As shown in Table 2, there are abnormal outputs in the HPS feasibility for 2023, considering the exchange rate differentials in recent years. However, the public opinion in favor of the consumer in electricity tariffs, the decrease in investment costs due to the development of technology and higher interest rate increases as opposed to inflation provide many advantages over only grid. For instance, it can reduce LCOE by up to 52.15% and electricity purchase costs by up to 47.84 thousand $/yr. In contrast, comparing the optimal size and feasibility outputs of the proposed HPS across scenarios, the electricity purchased from the grid and therefore carbon emissions are similar, given that electricity demand remains unchanged.

In case of blackouts, especially when there is no solar power and the ESS is fully discharged, diesel generator (DG) is used, and the reserve capacity is determined in an optimization framework based on electricity demand. In metropolitan areas, the use of diesel fuel is low due to the short duration of outages, but unnecessary DG capacity cannot be avoided in sizing.

Elaborating on the results for PV-ESS-Grid HPS, the preference of Scenario 5 over only grid reduces carbon emissions by up to 60%. It, therefore, reduces the electricity and cost from the grid by up to 2037.32 MWh/yr and 143.8 thousand $/yr. Although the self-supply rate (SSR) increases by up to 60.1% and the renewable fraction (RF) by up to 74%, the minimum cost advantage belongs to Scenario 3. In this scenario, the self-consumption rate (SCR) can increase up to 90.4%, and the curtailed energy can be maintained at a low level of 1.16%. In contrast, for the PV-DG-ESS-Grid HPS configuration, the advantage of reducing LCOE shifts to Scenario 5, where the LCOE can be reduced up to 49.3% by adding DG. It can also be noted that RF increases by up to 9.7% in that scenario. Moreover, carbon emissions are prevented by up to 3% due to the reduction of 103.89 MWh/yr of electricity purchased from the grid. Despite maintaining its advantage in SSR compared to the other scenarios, adding DG to the configuration reduces SSR by up to 3%. However, Scenario 1 can further reduce the cost of electricity purchased from the grid compared to only grid. Also, a lower NPC is guaranteed in this scenario, reducing the NPC by up to 41.4% compared to PV-ESS-Grid HPS. It is also emphasized that LCOE decreases up to 61.1% compared to PV-ESS-Grid and capital expenditure (CAPEX) increases up to 1.19M$ and payback period up to 3 years. In contrast, SCR increases up to 9.8% while CO_2 increases up to 7.65%, raising environmental concerns.

Table 2. Optimum sizes with minimum cost based on HPS configurations

Size	S1	S2	S3	S4	S5	Units
	PV-ESS-Grid HPS					
PV	756	961	641	1110	3603	kW
ESS	2	5	8	15	1959	kWh
Converter	457	544	416	575	1365	kW
	S1	**S2**	**S3**	**S4**	**S5**	
	PV-DG-ESS-Grid HPS					
PV	784	961	636	1110	2722	kW
DG	1200	1200	1200	1200	1200	kW
ESS	2	5	6	15	1959	kWh
Converter	469	544	401	575	1365	kW

4. Sensitivity Analysis Results

As shown in Fig. 4, sensitivity analyses were performed with varying irradiances. For Scenario 1, it can be easily said that up to 5.5 kWh/m^2/day irradiance, only grid HPS is preferred, while for higher irradiances, the PV-Grid HPS configuration is more attractive for economic-based optimization. In Scenario 2, DG-Grid HPS is the optimal configuration of up to 5 kWh/m^2/day irradiance, while at higher irradiances, the addition of PV reduces costs.

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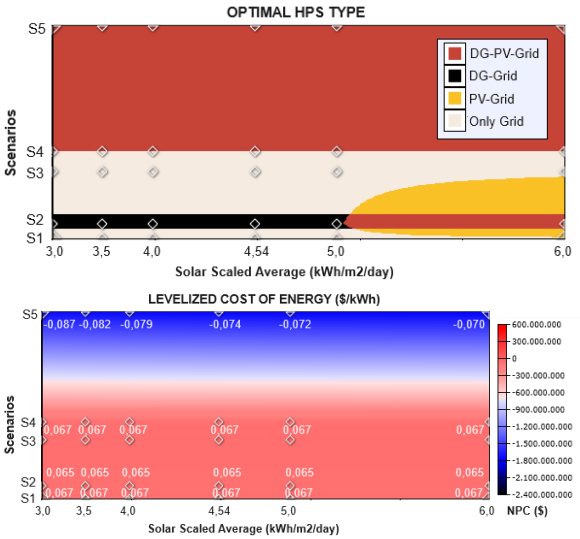


Fig. 4. Effects of solar horizontal irradiance on optimal HPS configuration and cost under scenarios evaluating economic conditions

Scenario 3 shows a similar configuration pattern to Scenario 1, but the optimum threshold irradiance is around 5 kWh/m^2/day. However, the probability of PV-Grid HPS utilization is higher compared to Scenario 1. In Scenario 4, only grid HPS is slightly preferred regardless of irradiance, but primarily PV-DG-Grid HPS is relied on. For Scenario 5, PV-DG-Grid HPS is the most favorable configuration in any irradiance. In contrast, analyzing the LCOE and NPC sensitivities, a reduction of irradiance by 3 kWh/m^2/day does not affect the costs except for Scenario 5, while for Scenario 5, it increases the costs by up to 24.3%.

The effect of IRs and DRs on PV capacity and optimal HPS configurations is discussed in Fig. 5. IRs above 30% ensure that PV-DG-Grid HPS configurations are preferred regardless of the DRs. Moreover, DRs and IRs above 21% and 24% recommend PV-Grid HPS configurations to investors. On the other hand, an abnormal increase in IR (up to 40%) at lower DRs raises PV capacity up to 1652 kW. In contrast, at higher IRs of 60% and 48%, a 25% increase in DRs reduces PV capacity by 18.2% and 45%. This effect can be increased at lower IRs from 27.15% to 72.15%. However, the impact of the DR on PV capacity is higher. In contrast, rising IR by 20% and the DR by 18%, i.e., a hybrid increase, can only raise PV capacity by up to 5.3%. At this point, increasing IR and DR by 12% and 3% would raise PV capacity by up to 87.8%.

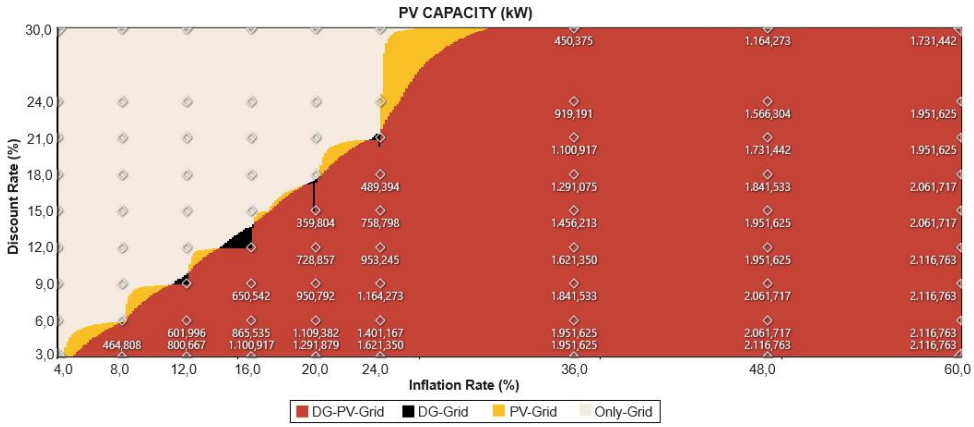


Fig. 5. Effects of inflation and interest rates on optimal HPS configuration and PV capacity

5. Conclusions

This study investigates the effects of economic conditions on the optimal HPS sizing considering solar radiation potential. Technical and environmental performance achieved the best results in 2019, with the self-consumption rate (SCR) increasing to 90.4% and curtailed energy decreasing to 1.16%. On the other hand, the most economical results were obtained in 2023, when RF reached 60.1% and carbon emissions were reduced by up to 60%. Sensitivity analyses showed that optimal results were only achieved in grid scenarios where the solar energy potential was below 5 kWh/m^2/day before 2019. An inflation rate of more than 30% ensures that PV-DG-based HPS configurations are preferred regardless of the DRs. Considering that economic conditions highly influence the optimization framework, in the future, the outputs of this study could be extended to consider tax and incentives.

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