Hybrid Renewable Energy to Greener and Smarter Cities: A Case Study of Kayseri Province

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Abstract. In this study, a hybrid energy system was implemented to fulfill the electricity requirements of the trams operating in Kayseri province. The tram's annual electricity consumption data was acquired on a monthly basis from the local electricity company in Kayseri. Utilizing the obtained data, energy and cost simulations were conducted employing the Homer-Pro program. The primary objective of this investigation is to enhance sustainability while satisfying electricity demands with minimal carbon emissions. Consequently, the established hybrid energy system incorporates renewable energy sources, specifically wind, solar, and biomass energy, with the inclusion of batteries for energy storage. Furthermore, generators and converters are integrated for energy conversion purposes. The study encompasses a detailed cost analysis to identify the most economically efficient hybrid energy system, determined through optimization studies. Through this research, it is anticipated that the implementation of such a system will significantly diminish carbon emissions in Kayseri, contributing to a substantial increase in sustainability.

Keywords: Homer Pro · Smart City · Sustainability · Hybrid Energy · Kayseri

1 Introduction

The foundation of societal prosperity and the impetus behind its advancement is energy. Future sources of energy must be both cost-effective and sustainable while maintaining environmental friendliness. Over time, renewable energy sources are anticipated to supplant conventional fossil fuels [1]. The persistent reliance on fossil fuel-based energy sources, such as coal, oil, and gas, to meet the escalating global energy demands and population growth has given rise to various issues. These include the depletion of fossil fuel reserves, the emission of greenhouse gases, and other environmental challenges [2]. Escalating concerns related to climate change and sustainability are exerting pressure to embrace more renewable resources and technologies [3]. Renewable energy sources possess the advantages of being limitless, environmentally friendly, and amenable to decentralized utilization. An additional benefit lies in their complementary nature and

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seamless integration, allowing for efficient collaboration. For instance, on days characterized by sunshine, cool temperatures, wind, and intermittent cloud cover, solar photovoltaic energy can generate electricity. On such occasions, strategically positioned wind turbines contribute additional electricity for both stand-alone and grid-connected applications [4]. Configurations of hybrid renewable energy systems are imperative for ensuring a secure and sustainable electricity supply. The intermittent nature of renewable resources can be addressed through the incorporation of hybrid sources and efficient storage solutions [5]. The deployment of hybrid solar-wind renewable energy systems is experiencing daily growth and has witnessed substantial expansion in the past few decades, contributing significantly to global electricity production [6]. The burgeoning popularity of Hybrid Renewable Energy Systems (HRES) for meeting specific energy demands is evident in the existing literature on HRES modelling. HRESs find extensive application in remote region power setups and are increasingly becoming economically viable in scenarios where expanding the grid supply would be cost-prohibitive [7]. The optimization of hybrid renewable energy systems involves the meticulous selection of components, determining their sizes, and formulating an effective operational strategy. This optimization aims to produce alternative energy solutions that are not only inexpensive but also reliable, efficient, and cost-effective.

Despite being endowed with abundant energy resources, Turkey relies on energy imports due to the limited availability of these resources. Currently, imports constitute more than half of the nation's primary energy consumption, and this percentage continues to escalate annually. Therefore, it becomes imperative for the country to realize renewable energy sources within a reasonable timeframe to meet its energy demands using domestic resources, including natural gas, oil, lignite, and hard coal [8]. Kayseri, ranking as the fifteenth most populous city in Turkey, experiences an increase in energy consumption commensurate with its urban size. In the conducted study, hybrid renewable energy systems were conceptualized and subjected to techno-economic analysis to fulfill the electrical energy requirements of trams in the city of Kayseri through entirely renewable methods. The tram system holds a pivotal role in public transportation for Kayseri, exhibiting substantial energy consumption, approximately 65,000 kWh/day. The project's objective is to establish a hybrid and renewable energy system to cater to the energy needs of public transportation. The environmental impact of the proposed project is minimal, and optimal costs have been assessed using the Homer Pro program.

2 Methodology

2.1 HOMER Simulation and Optimization

The hybrid renewable energy system in this research is developed using the HOMER-Pro Programming, a software tool developed by the National Renewable Energy Laboratory in the United States. This tool facilitates simulation and design under ideal circumstances with predetermined limitations. A novel programming technique known as HOMER is employed to generate sophisticated models for grid-integrated and hybrid energy system planning [9]. HOMER Pro incorporates a range of energy plant components, including wind turbines (WT), photovoltaic arrays (PV), fuel cells, small hydropower, biomass, converters, batteries, and traditional generators [10].

The Homer program requires various datasets, encompassing information related to the types of renewable energy sources, electric load data, and cost data. Homer serves not only as an energy analysis tool but also as software capable of conducting cost analysis [11]. Initially, understanding the electricity load to be addressed was imperative. To obtain this information, communication was established with the city's electricity company, and the daily and monthly electricity consumption by all trams was meticulously calculated. The determined electric consumption data were then input into Homer, enabling the generation of an electric charge profile. The average daily electrical load was computed to be 64,341 kWh (Fig. 1).

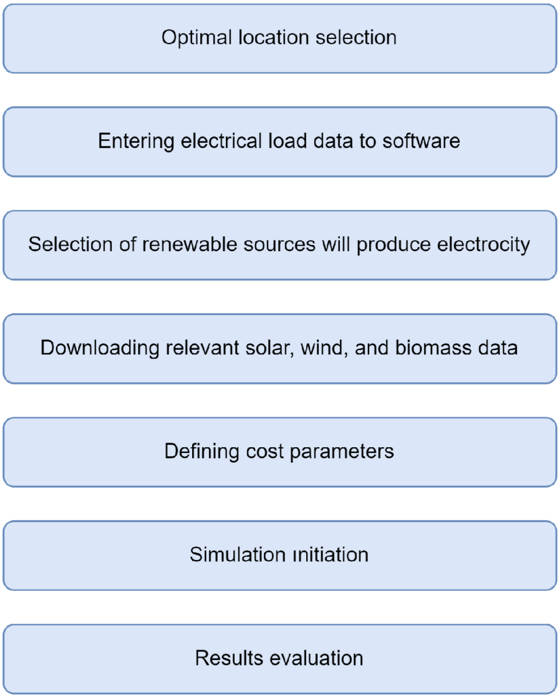


Fig. 1. Methodology flowchart.

In this study, three distinct types of renewable energy resources were employed as follows: biomass, wind, and solar. This selection was driven by the favourable conditions for these energy systems in the geographical location of Kayseri province. The specific location chosen for implementation is illustrated in Fig. 2.

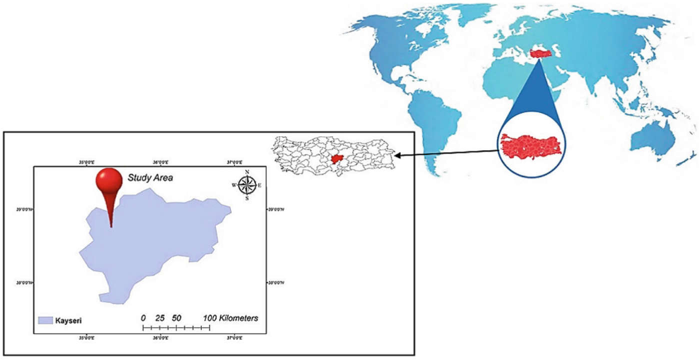


Fig. 2. Geographical location of the study area.

Simulations were conducted to assess the costs and energy returns associated with different combinations of biomass, wind, and solar energy resources. Through comparisons, the option with the lowest cost was identified. The study presents costs in terms of net present cost (NPC). The system was conceptualized as a 25-year project, encompassing replacement costs and operating expenses incurred over this duration in the calculations. Following the determination of the electrical load, the next critical step involved obtaining the necessary data for the selected renewable energy systems. For the Photovoltaic Module (PV), clarity and daily radiation values specific to the chosen location were essential. These data were sourced from the internet using the Homer Pro software.

The maximum clearness and radiation occur in July, with values of 7.35 kWh/m^2 for radiation and a clearness index of 0.651. The subsequent step involves defining wind energy data, wherein the selection of the optimal wind turbine (WT) becomes crucial. Initial considerations involve importing and evaluating wind speed values at the chosen location based on meteorological data. The maximum average wind speed, observed in February, is 5.46 m/s, while the yearly average for the selected location stands at 4.79 m/s. The subsequent phase involves the integration of the biomass renewable energy system into the hybrid system. The critical aspect here is the availability of data. The daily average biomass mass required for the biomass system, measured in tons, was obtained from the literature. Based on the annual data, the average daily biomass mass was determined to be 25,640 tons [12].

Generic 100 kWh Li-on batteries were used for storage in the study. In addition, a biogas generator and converter were used to provide energy conversion. Cost calculations in the project are calculated according to the default cost values of the program. System Structure in the established system, the hybrid operation of 3 different renewable energy systems was examined. In the study, the operating and cost efficiency of different energy system combinations were also examined. Figure 3 shows the structure of the optimally selected hybrid system.

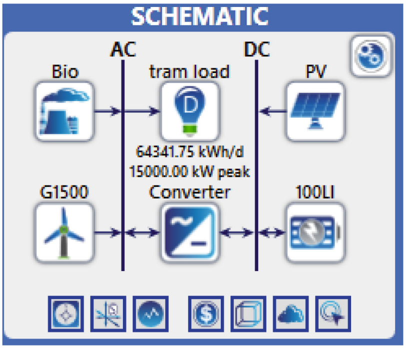


Fig. 3. Schematic of designed structure.

To enhance the visual comprehensibility of the conducted work, a symbolic design was created using the SolidWorks 3D design program. The 3D design of the renewable energy system is depicted in Fig. 4.

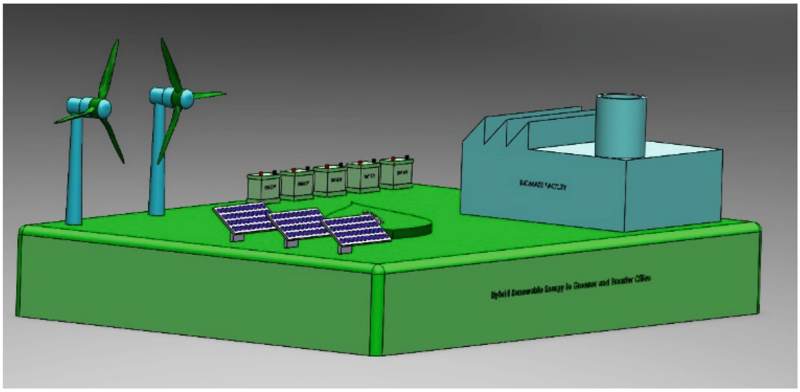
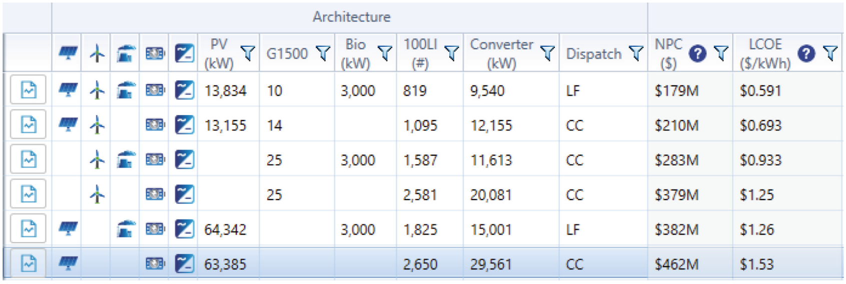


Fig. 4. Visual representation of hybrid energy system.

3 Results

The outcome of the simulations revealed that the minimum cost required to fulfil the necessary electricity demand amounted to 179 million dollars (M$). The categorized costs are presented in Fig. 5. The following are the costs resulting from various hybrid systems and simulations.



	Architecture											NPC ($)	LCOE ($/kWh)
						PV (kW)	G1500	Bio (kW)	100LI (#)	Converter (kW)	Dispatch	NPC ($)	LCOE ($/kWh)
						13,834	10	3,000	819	9,540	LF	$179M	$0.591
						13,155	14		1,095	12,155	CC	$210M	$0.693
							25	3,000	1,587	11,613	CC	$283M	$0.933
							25		2,581	20,081	CC	$379M	$1.25
						64,342		3,000	1,825	15,001	LF	$382M	$1.26
						63,385			2,650	29,561	CC	$462M	$1.53

Fig. 5. Cost analyses results of different structures.

In light of the optimization results, it was observed that opting not to install a hybrid system but relying solely on a renewable energy system had a significantly adverse impact on costs. Additionally, it was noted that forgoing the establishment of a biomass facility resulted in a cost impact of $41 million.

In the research, Fig. 6 illustrates the contribution of each renewable energy source to the overall energy production. This figure delineates the electric production values of three distinct renewable energy systems, namely biomass, wind turbines, and solar panels. Given that the maximum radiation and clearness values occur in July, it is evident that higher electric production is observed during that month.

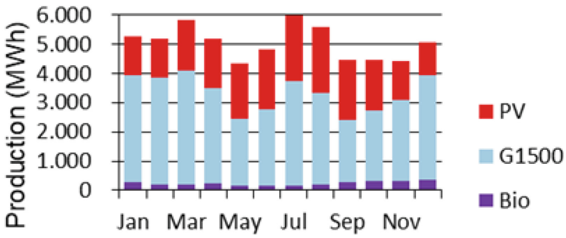


Fig. 6. Electrical production values of 3 different renewable energy systems.

3.1 Cost Analysis

The cost analysis in the study utilized the Homer-Pro program to determine the minimum monetary outlay for the desired energy output. This research encompassed a 25-year period, including installation costs, maintenance costs, and operating costs. The optimization results are detailed in Table 1. The cost analysis revealed that, over the 25-year duration of the project, the installation cost of renewable energy surpassed the operating cost. Furthermore, Fig. 7 provides a classification of the costs associated with different renewable energies in hybrid systems. According to the obtained data, it was observed that battery installation incurred relatively higher costs compared to other systems.

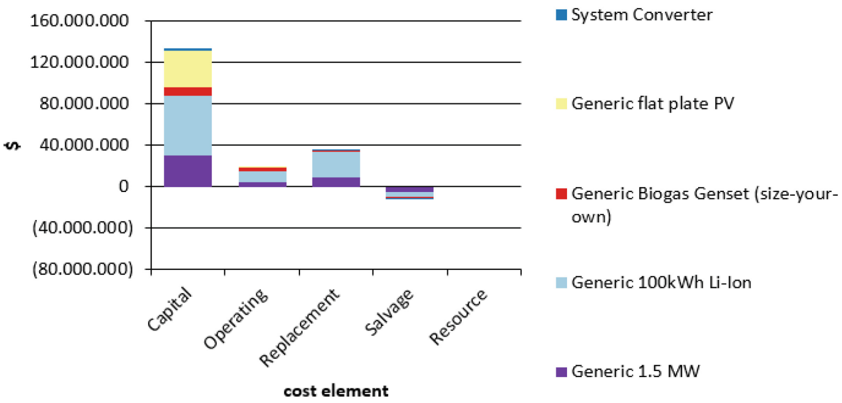


Fig. 7. Cost values of optimized hybrid design.

Table 1. Cost values during the project time.

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1.5 MW	\$30.0M	\$3.88M	\$9.56M	−\$5.39M	\$0.00M	\$38.1M
Generic 100 kWh Li-Ion	\$57.3M	\$10.6M	\$24.3M	−\$4.58M	\$0.00M	\$87.7M
Generic Biogas Genset	\$9.00M	\$3.64M	\$1.11M	−\$743,378M	\$0.00M	\$13.0M
Generic flat plate PV	\$34.6M	\$1.79M	\$0.00M	\$0.00M	\$0.00M	\$34.6M
System Converter	\$2.86M	\$0.00M	\$1.21M	−\$228,537M	\$0.00M	\$3.85M
System	\$134M	\$19.9M	\$36.2M	−\$10.9M	\$0.00M	\$179M

3.2 Engineering Analysis

The Generic PV system boasts a nominal capacity of 13,834 kW, with an annual production reaching 20,720,428 kWh/yr. Figure 8 illustrates the electrical production of the PV system by the day of the year, with the y-axis representing hours of the day. As depicted in this illustration, the production during midday is notably higher compared to the morning and night hours.

The power output from the Generic wind turbine system, with a rating of 15,000 kW, reaches 37,096,044 kWh/yr. Figure 9 visually represents the electrical production of the wind turbine by the day of the year, with the y-axis denoting hours of the day. As indicated in this illustration, the production on different days of the year is not constant, reflecting the proportional influence of wind resource data. Production tends to increase with higher

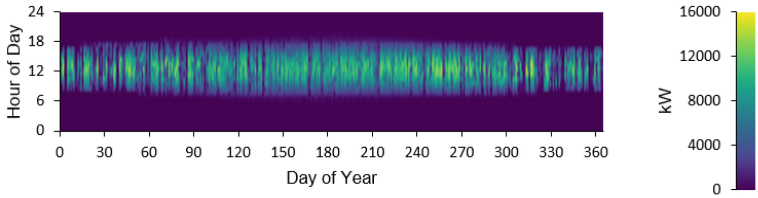


Fig. 8. Daily electrical production of PV.

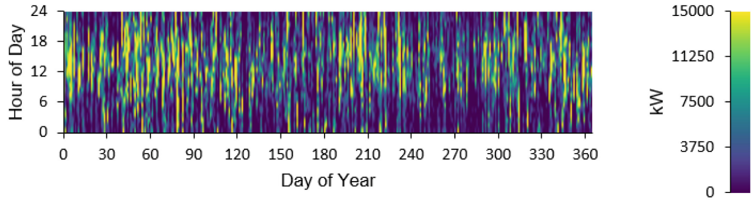


Fig. 9. Electrical production of wind turbines.

wind speeds. Additionally, the power output from the Generic generator system, with a 3,000-kW rating and utilizing Biogas as fuel, amounts to 2,805,703 kWh/yr.

3.3 Electrical Summary

The total amount of electricity obtained is calculated as 60,622,174 kWh/year. This quantity of electricity significantly exceeds the electrical load required for the tram system. If the surplus electricity is connected to the grid, it has the potential to meet the electricity needs of thousands of households.

4 Conclusions

The outcomes of our research underscore the positive impacts of widespread adoption of hybrid energy systems in large cities. While the use of renewable energy is progressively aligning with sustainable development goals (SDGs) in Turkey, the research aims to further enhance this integration through hybrid systems. The combination of diverse energy sources has notably reduced costs. To mitigate climate change, the global implementation of such systems must be intensified. The overarching objectives of the research are summarized as follows:

- Reducing carbon emission;
- Increasing awareness related to sustainability;
- Representing advantages of hybrid energy;
- Providing renewable energy for public transportation;
- Optimizing energy plants with minimum cost and maximum efficiency.

It is imperative to prioritize the United Nations' sustainable development goals and undertake projects aligned with these objectives. One of the key findings of the conducted research is that hybrid systems entail high installation costs, which could be mitigated through advancements in technology and production methods. The study suggests that future research endeavours should concentrate on reducing the production cost of renewable energy systems. The optimization results presented in this research underscore the significance of prolonging the lifespan of materials used in the market, as this would contribute to the widespread adoption of hybrid systems. According to the optimization results, the cost of meeting the energy consumption of trams in Kayseri entirely with renewable energy sources was determined to be 179M$. The established plant incorporates wind energy, solar energy, biomass energy, and batteries, with 95% of the required energy obtained from solar and wind sources. The total energy yield was found to be 60,622,174 kWh per year, significantly surpassing the tram's energy requirements. Consequently, the surplus energy can be fed into the grid, potentially yielding profits. The lithium-ion battery cost constitutes 50% of the overall project cost. The project, designed to fulfil a 25-year need, entails an installation cost of 133M$, with the remaining costs attributed to replacement and operation. The reduction of these costs can be achieved through advancements in technology and ongoing research.

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