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A Comparative Study of Waste Heat Utilization and Solar Power Plant for Sustainable Energy Production

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ABSTRACT

A comparison was conducted between a steam turbine system utilizing waste heat and a solar power plant (SPP) in the same region, focusing on energy production potential and investment evaluation. The steam turbine system enhances energy efficiency in industrial facilities by generating electricity from waste heat produced during furnace operations. Waste heat is obtained from natural gas and petroleum coke, In contrast, SPPs are sustainable and typically require lower initial investment costs. Solar energy production depends on geographical conditions, sunlight exposure, and panel efficiency. However, output can vary due to environmental factors and time of day. This variability impacts electricity production, yielding an average daily output of 7.52 MWh. Both systems were analyzed in terms of energy production capacities and payback periods. The steam turbine system provides stable production in large facilities with continuous waste heat availability, though its efficiency is influenced by the type of fuel used. SPPs, with shorter payback periods and lower initial costs, offer rapid financial returns but are more susceptible to environmental fluctuations. The study highlights that both systems have distinct advantages and disadvantages, emphasizing the importance of selecting the most suitable system based on local energy needs and environmental conditions. SPPs have a short payback period of 5.6 years, delivering quick financial returns and short-term economic benefits. Conversely, waste heat recovery systems, with a longer payback period of 10.5 years, represent a cost-effective, environmentally friendly solution for energy-intensive industries, enhancing energy efficiency and reducing long-term operational costs.

Keywords: Steam turbine system; Waste heat utilization; Solar power plant (SPP); Energy production efficiency; Investment evaluation

Sürdürülebilir Enerji Üretimi için Atık Isı Kullanımı ve Güneş Enerjisi Santralinin Karşılaştırması

ÖZ

Aynı bölgede atık ısı kullanarak elektrik üreten bir buhar türbini sistemi ile güneş enerjisi santrali (GES) arasındaki enerji üretimi karşılaştırılmıştır. Bu çalışma, iki sistemin potansiyel enerji üretimini analiz etmeyi ve yatırım değerlendirmesi yapmayı amaçlamaktadır. Buhar türbini sistemi, endüstriyel tesislerde, fırınlarda üretilen atık ısıdan elektrik üreterek enerji verimliliğini artırmaktadır. Atık ısının elde edilişinde doğal gaz ve petrokok kullanılmaktadır. Petrokok doğal gaza göre daha fazla atık ısı üretirken, doğal gaz daha temiz

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bir yakıttır. Buna karşın, güneş enerjisi santralleri sürdürülebilir olup, genellikle daha düşük başlangıç yatırımı gerektirmektedir. Güneş enerjisi üretimi, coğrafi koşullar, güneş ışığına maruz kalma süresi ve panel verimliliği gibi faktörlere bağlıdır. Üretim kapasitesi sabit olup çevresel koşullar ve günün saatine bağlı olarak değişkenlik gösterebilmektedir. Bu değişkenlik, elektrik üretimini etkilemekte ve günlük ortalama 7.52 MWh üretim sağlanmaktadır. Her iki sistemde geri ödeme süreleri ve enerji üretim kapasiteleri açısından değerlendirilmiştir. Buhar türbini sistemi, büyük tesislerde sürekli atık ısının sağlanması ile istikrarlı üretim sunarken, verimliliği yakıt türlerine bağlıdır. GES ise daha düşük başlangıç maliyetleri ve kısa geri ödeme süreleri sağlamakta, ancak çevresel faktörlerden etkilenebilmektedir. Çalışma, her iki sistemin kendi avantaj ve dezavantajlarına sahip olduğunu ve en uygun sistemin yerel enerji ihtiyaçları ve çevresel koşullara göre seçilmesi gerektiğini vurgulamaktadır. GES, 5.6 yıl gibi kısa bir geri ödeme süresiyle yatırımcılara hızlı finansal getiri ve kısa vadede ekonomik avantaj sunmaktadır. Atık ısı geri kazanım sistemleri ise 10.5 yıllık geri ödeme süresiyle başlangıçta maliyetli görünmekle birlikte, enerji yoğun endüstrilerde atık enerjiyi değerlendiren çevre dostu bir çözüm sunar. Bu sistemler, enerji verimliliğini artırarak uzun vadede işletme maliyetlerini düşürmektedir.

Anahtar Kelimeler: Buhar türbini sistemi; Atık ısı kullanımı; Güneş enerjisi santrali (GES); Enerji üretim verimliliği; Yatırım değerlendirmesi

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1. INTRODUCTION

Energy is of vital importance in terms of sustainability and efficiency in the modern world. The increasing use of renewable energy sources minimizes environmental impacts by reducing fossil fuel dependency (Olcay & Cetinkaya, 2023) Energy efficiency supports both economic growth and enables more efficient use of natural resources. In particular, the development and application of energy-saving technologies reduce energy costs and contribute to the fight against climate change by reducing greenhouse gas emissions (Olcay et al., 2024). In order to increase energy efficiency in the industrial sector and contribute to sustainable production processes, utilization of waste heat is becoming increasingly important today. Recovery of waste heat in industry offers significant potential to increase energy efficiency and reduce environmental impacts (Erbas, 2021). The use of waste heat released in processes in various sectors, especially in secondary processes such as heating, electricity generation or cooling, is becoming increasingly common (Guo et al., 2021). For example, waste heat recovery systems in the cement and steel industries reduce energy consumption, lower costs and minimize carbon emissions (Worrell et al., 2016). In recent years, systems that can convert low-temperature thermal energy, such as organic Rankine cycles (ORC), have emerged as a highly effective solution for converting waste heat into electricity (Vélez et al., 2012). These technologies promote sustainable production methods in industry and enable more efficient use of energy resources.

Although installation of waste heat recovery systems provides energy savings and environmental benefits, the initial investment cost and operating expenses can be high. In particular, the installation of high-temperature systems and the application of technologies such as ORC (Organic Rankine Cycle) require large-scale investments (Bao & Zhao, 2013). A large portion of these costs consist of the prices of components such as heat exchangers, energy conversion equipment and system integration (Forman et al., 2016). However, studies show that the payback period of such systems varies from process to process and that in some sectors, the investment cost can be covered in a short period of 3 to 5 years (Dong et al., 2020). It is emphasized that these systems, which reduce energy costs in the long term, are becoming an increasingly competitive solution.

Solar Energy Systems (SPP) stand out as one of the most important components of renewable energy sources and offer environmental and economic benefits such as increasing energy security and reducing carbon emissions (Zhao, 2020). Worldwide and up-to-date, inscriptions on solar power plants are increasing rapidly in letters. (Yolcan & Köse, 2020). The fact that solar energy is an infinite resource and its easy accessibility as a sustainable energy source has made SPPs the center of energy strategies in many countries (Jacobson et al., 2017). The use of photovoltaic panels (PV) and other solar energy technologies is of great importance, especially for countries aiming to reduce their dependence on fossil fuels (Bogdanov et al., 2021). In addition to technological advances, the reduction of costs plays an important role in the spread of SPP applications. The cost of solar energy systems, which used to be high-cost in the past, has decreased rapidly thanks to developments in production processes. The decrease in unit costs of PV panels, in particular, contributes to the preference of SPP projects as a larger-scale and low-cost option. Studies show that PV system installation costs have decreased by approximately 80% since 2010, making solar power plant investments attractive in many sectors (Feldman et al., 2021). These cost reductions have enabled more widespread use of solar power plants in commercial, industrial and residential applications and accelerated the transformation process in the energy sector (IRENA, 2020).

Although energy demand is met economically, the primary cause of greenhouse gas emissions is fossil fuels (Lehtola & Zahedi, 2019). In the studies conducted, the environmental effects of solar energy systems were discussed in detail and it was emphasized that the relevant procedures should be followed (Rabaia et al., 2021). Carbon emissions encourage studies in the field of renewable energy, and a study on the benefits of renewable energy in terms of emissions was conducted in (Shahsavari & Akbari, 2018). Although the use of fossil fuels is considered economical, it has many harmful effects on the environment (Adekanbi, 2021). However, the generation of large amounts of greenhouse gases has a negative impact on the carbon footprint (Arshian et al., 2021). It is estimated that a 1 MW capacity solar power plant (SPP) can produce approximately 1.5 million kWh of electricity annually. If this amount replaces carbon-intensive sources like coal, it can prevent the emission of an average of 1000 tons of CO_2 (Liu et al., 2019).

Investments in solar power plants (SPPs) offer significant long-term savings in energy costs due to their short payback periods (Özgür & Köse, 2012). Studies indicate that solar energy projects with shorter payback periods reduce operational costs in the long run and enhance energy security (Sharma & Jain, 2019). This contributes to greater predictability and cost savings in the energy budgets of enterprises or public institutions. Furthermore, clean energy derived from solar power reduces carbon emissions, thereby lowering the carbon footprint and contributing to environmental sustainability goals (Chaudhari et al., 2020).

Both waste heat recovery systems and solar power systems (SPPs) emerge as critical investments aimed at improving energy efficiency and providing sustainable energy solutions. However, the installation of waste heat recovery systems typically involves higher initial investment requirements and technical challenges, whereas the costs of SPPs have significantly decreased in recent years. While SPPs are becoming more attractive due to their low operating costs and short payback periods, waste heat recovery systems are more suitable for enhancing energy efficiency in larger industrial applications.

This study evaluates the electricity production data obtained through a steam turbine powered by waste heat and compares it with the production of a solar power plant designed to generate the same output. Specific flow rates and production values achieved under defined conditions for waste heat utilization were analyzed. Based on these findings, a solar power plant capable of generating 7.52 MWh of electricity per month was designed. Calculations for the required land, solar panels, and associated costs were conducted. The advantages and disadvantages of both systems were discussed, highlighting key considerations for investment decisions. The choice between these systems depends on the constraints of existing production capacities or investment plans.

This study provides significant contributions to the energy systems literature by comparing Solar Power Plants (PV systems) and waste heat recovery systems from economic and environmental perspectives. While PV systems offer a short payback period of 5.6 years, delivering rapid financial returns and low operational costs for investors, waste heat recovery systems, with a payback period of 10.5 years, contribute to sustainability and energy efficiency by utilizing waste energy in energy-intensive industries. This comparative analysis offers a comprehensive perspective on balancing economic returns with environmental benefits in energy investment decision-making processes, thereby contributing to the development of strategies for enhancing energy efficiency and reducing operational costs. Furthermore, the assessment of the complex infrastructure requirements and maintenance processes of waste heat recovery systems addresses existing gaps in the literature regarding industrial applicability and technical sustainability. Finally, the findings of this study serve as a guide for policymakers and investors in shaping energy policies and selecting appropriate energy solutions for different sectors, emphasizing the importance of a holistic evaluation of the economic and environmental performance of energy systems.

2. ENERGY GENERATION THROUGH WASTE HEAT RECOVERY

Waste heat systems are important technologies that enable the recovery and reuse of heat generated in industrial processes. In addition to increasing energy efficiency, these systems offer an effective way to reduce operating costs and minimize environmental impacts. In general, waste heat recovery covers a wide range of energy conversion methods from high-temperature processes to low-temperature heat recovery (Oyedepo & Fakeye, 2021). Organic Rankine cycles (ORC), thermophotovoltaic systems and heat exchanger technologies are the main applications that enable the integration of industrial waste heat into electrical energy or district heating-cooling systems (Smith et al., 2019). Such systems are gaining more and more importance as part of sustainable energy management strategies and contribute to the use of renewable energy sources (Wang et al., 2020). According to the operating principle of the rotary kilns in the mentioned industrial facility, instead of cooling the waste heat generated by the flue gas and discharging it, the idea of utilizing the waste heat has been realized by providing a connection between the boiler and the steam turbine (Tunca & Akbulut, 2023).

The steam turbine system is an energy generation unit designed to achieve high efficiency and reliability. The system operates with an inlet steam pressure of 21 bar and a temperature of 340°C. The outlet pressure is set at 0.2 bar, and the turbine has a nominal steam flow capacity of 8.27 tons per hour. The turbine operates at a speed of 8600 RPM, which is connected to a generator running at 1500 RPM, producing energy at 6300 V and a frequency of 50 Hz. The nominal capacity of the generator is 1540 kVA, with a total power output of 1234 kWe. The turbine is designed with five stages and a nominal shaft output power of 1285 kW. The water-cooled vacuum condenser manages a steam flow of 8.3 tons per hour and operates efficiently with cooling water at a maximum inlet temperature of 34°C. This comprehensive design supports the system's objectives of high performance, environmentally friendly energy production, and long operational life.

In steam turbine systems, flow rate and steam temperature are important factors for electricity production. The continuity of energy production should be achieved by working in harmony with the entire system. When **"Figure 1"** is examined, cumulative energy production is seen. In more than 100 measurements, it is seen that the production in the system is fluctuating. It should not be forgotten that the amount of waste heat in such systems depends on the production method and amount.

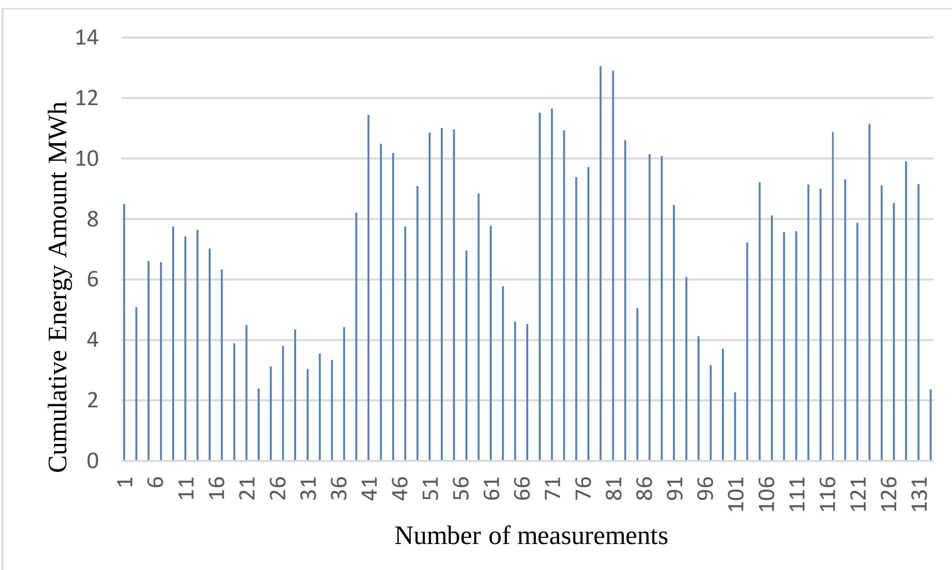

Figure 1. Cumulative energy amount

One of the important factors in energy production is the flow rate in the cycle. The measurements show that the flow rate affects electricity production (See **Figure 2**). It is seen that different energy production occurs at the same flow rates. This situation negatively affects energy production due to factors other than flow rate. It is known that there is unstable waste heat production in the system, but this does not change the fact that there are unexpected losses in the cycle. For energy production to occur healthily, system components must work in harmony with each other. The current situation shows that all components should be examined in detail.

The flow rate determines the capacity of heat energy to be transported, and as the flow rate increases, more heat energy can be taken into the system. This means that the amount of heat sent to the turbines increases, and therefore electricity production increases. In addition, high flow rate allows heat to be used more quickly and efficiently, converting it into more energy (Li, et al., 2017). However, the flow rate must remain within the physical limits of the system, in other words, excessively high flow rates can cause mechanical problems in components such as heat exchangers and turbines, as well as reduce efficiency. The flow rate must be optimized correctly, because the correct flow rate value maximizes the electricity production from waste heat while also ensuring the efficient operation of the system. The main reason for the inefficiency of energy production in waste heat systems is the incompatibility and obsolescence of system elements. Old systems may be incompatible with modern components such as new generation steam turbines and heat exchangers. This causes the waste heat not to be collected and used efficiently. Old equipment usually operates with lower efficiency and cannot fully convert heat into energy. In addition, wear and tear of components in the system or technological backwardness reduces heat transfer efficiency and leads to heat loss. This causes less energy to be obtained from the same amount of waste heat. Old systems may not be efficient enough to meet modern energy production needs, and therefore the energy production capacity decreases. As a result, the incompatibility and obsolescence of system elements in waste heat systems lead to losses in energy production, increase operating costs and make it difficult to achieve environmental sustainability goals.

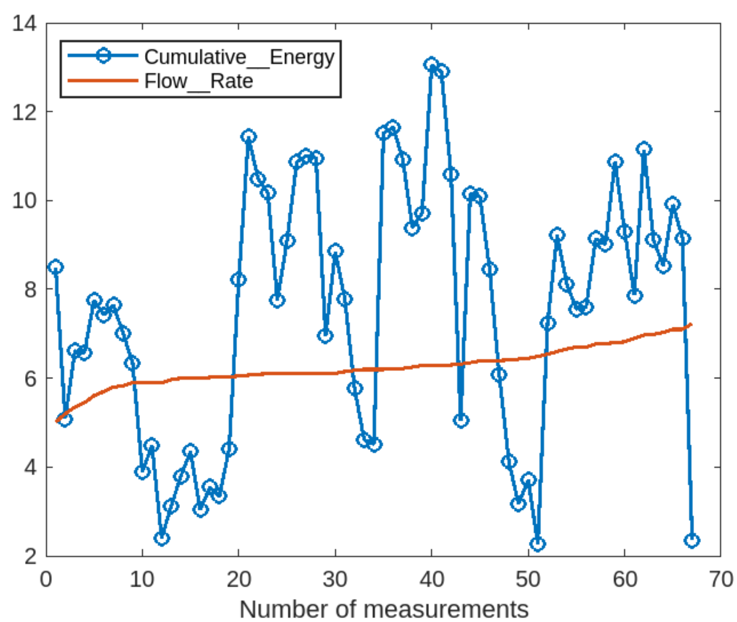

Figure 2. Cumulative energy production in proportion to flow rate

Another factor in the amount of energy production in steam turbines is the steam temperature. Steam temperature and flow rate values are effective in energy production. When looking at **"Figure 3"**, steam temperature and instantaneous production data are seen depending on the flow rate. As seen in other figures, it is seen that a fluctuating production occurs in Fig. 3. At steam temperature values between 250-350 ^{0}C, real-time production occurs in a wide range such as 200-600 kWh.

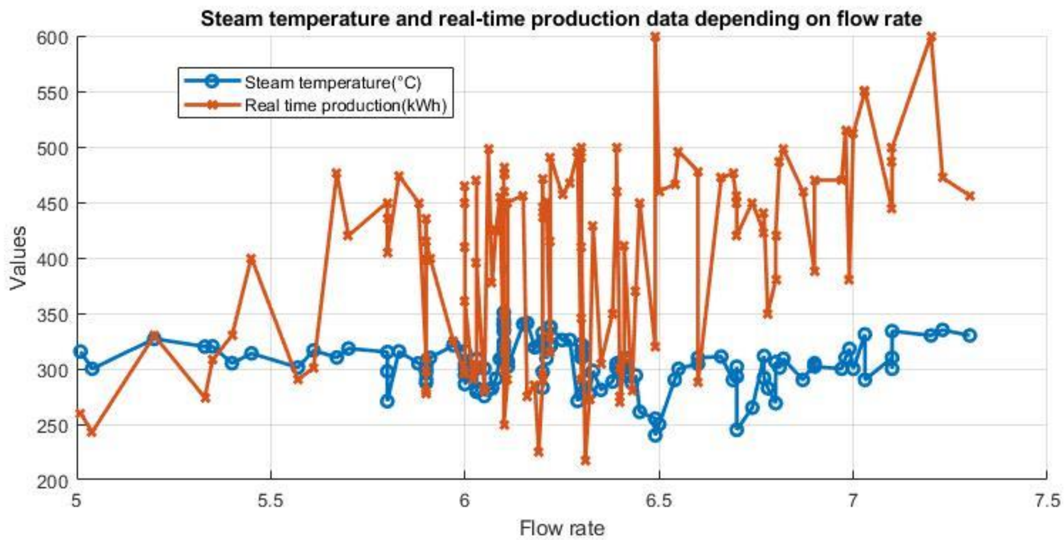

Figure 3. Steam temperature and real-time production data depending on flow rate.

The flow rate, which was thought to be constant at 8 tons/h during the installation phase of the system, was found to be in the range of 5-7 tons/h. With this operation of the system, 7.52 MWh of electricity is produced per day. It should be noted that there are differences between the preliminary study data made before the system was installed and the actual data. This situation can be seen as the reason why the expected energy production cannot be met in terms of investment planning.

3. ELECTRICITY GENERATION THROUGH SOLAR POWER PLANTS

Reducing dependency on fossil fuels is accelerating the transition to renewable energy technologies (Harsito et al., 2022). In order to prevent a future climate crisis, the 2015 Paris Agreement set a goal to limit global temperature rise to 1.5 to 2 degrees Celsius above pre-industrial levels (Lamb et al., 2021). As a result, minimizing the use of fossil fuels and increasing the use of energy derived from clean sources should become a priority (Eshiemogie et al., 2023). By 2040, it is estimated that more than one-third of the energy produced from renewable sources will come from solar and wind energy, with solar energy production reaching 7200 TWh (Ghosh, 2020). The sun has the capacity to provide 1.7×10^{22} J of energy in just 1.5 days, which is equivalent to the total energy that could be provided by 3 trillion barrels of oil (Hayat et al., 2019) (Kabir et al., 2018).

The ideal size of a solar energy system to be installed in different regions is specified with the lowest system cost. Technical research on the areas has shown that there is a direct relationship between the system's efficiency and climate parameters (Panayiotou, 2012).

The solar panel is a critical component of the solar energy system. PV technology uses semiconductor-based solar cells (panels) to capture solar radiation and convert it into electrical energy (Jordan et al., 2012). These panels perform better when there are no environmental issues and when they are oriented and tilted at ideal angles (Toth, 2019). The instantaneous efficiency of photovoltaic panels is related to the cell temperature of the panels (Yolcan & Köse, 2023).

When the waste heat installation processes with an average daily electricity production of 7.52 MWh are evaluated, 3968-580-watt panels will be needed for the solar power plant to be installed for the same value of electricity production. The placement of the panels on the land in the same region is as seen in **"Figure 4"**. The surface area of the 3968 solar panels in the solar power plant covers an area of 10250.3 m^2.

Figure 4. The land arrangement of solar panels

There are 22 inverters in the solar power plant (SPP). It is necessary to convert the direct current (DC) produced by solar panels into alternating current (AC) in the electrical grid. This conversion ensures that the energy obtained from the sun can be used. Inverters also optimize the energy flow and regulate voltage and frequency, which contributes to the provision of a safe and compatible energy with the grid (Tunca et al., 2023). Inverter systems can also undertake functions such as monitoring energy production and detecting faults, which increases the efficiency of the SPP system. It has been calculated that the planned solar power plant prevents a significant amount of CO^2 emissions in terms of emissions. In the study conducted by Parida et al. (2018), it was emphasized that with the installation of SPPs, not only electricity production but also CO^2 emissions from energy used in industry and public institutions can be significantly reduced (Parida et al., 2018). Similarly, Owusu and Asumadu-Sarkodie (2016) stated that the use of renewable energy sources such as solar energy reduces the carbon footprint of countries by reducing greenhouse gas emissions and reduces dependence on fossil fuel consumption (Owusu & Asumadu-Sarkodie, 2016).

Table 1: Solar panel data.

Parameters	Values
Maxsimum Power (P_{max})	550 W
Module Efficiency (%)	20.98
Maximum Power Point Current (I_{mmp} (A))	12.96
Short Circuit Current (Isc(A))	13.70
Maximum Power Point Voltage (V_{mpp}(V))	42.13
Open Circuit Voltage (V_{oc}(V)	49.33
Nominal Cell Operating Temperature	41.2 °C + 2 °C
Temperature Coefficient P_{mpp}	0.311 % / °C
Temperature Coefficient Isc	+0.040 % / °C
Temperature Coefficient Voc	-0.237 % / °C

Alternatively, the solar panels used in the planned SPP have an efficiency of 21.17%. The efficiency of these panels is the panels with Tunnel Oxide Passivated Contact (TOPCon) cell technology, which has recently started to be used in the current energy sector. With this technology, solar panels work more efficiently. It is thought that SPP is installed on a land near the field in question with these panels. The installed power of this plant planned with 550 W panels is calculated as 2305.6 kWp. It is thought that the plant will sell energy to the grid and generate income from this, and it is designed as a ten-grid. Solar panel data is shown in **"Table 1"**.

Table 2: Inverter data.

Parameters	Values
Maximum Input Voltage(V)	1.110 V
Maximum Current per MPPT	30 A
Max. Short Circuit Current per MPPT	40 A
Start Voltage	200 V
MPPT Operating Voltage Range	200 V – 1000 V
Nominal Input Voltage	600 V (at 400 V AC)
Number of MPP trackers	10
Maximum Input number per MPPtracker	2

The plant incorporates 18 inverters, each designed with a nominal active power output of 100 kW, to achieve AC energy integration with the grid. Inverters data is shown in **“Table 2”**.

The inverter used has the Maximum Power Point Tracking (MPPT) feature. Each solar panel has a maximum power point (MPP). This point is the moment when both the voltage and current of the panel produce the highest power together. This point changes continuously depending on sunlight and environmental conditions. That is, during the day, in cloudy weather, morning and evening hours, the maximum power point (MPP) of the panel also varies. MPPT technology constantly tracks the maximum power point and adjusts the voltage and current to operate at this point. In this way, system efficiency is increased because each panel operates at its highest power point. Even when different panels operate in different light conditions, the inverter ensures that each panel operates at maximum efficiency. Energy loss is minimized, especially in partial shading or changes in light levels. The number of MPP trackers for the selected inverter is 10. In the configuration of the modules, 233 panels have been connected to each of the 17 inverters. The panels are connected to the inverter MPP inputs in series as groups of 13, 11, and 16 modules. For the final inverter, a total of 231 panel connections have been designed. Therefore, 1.8 MWe active power is output to the grid.

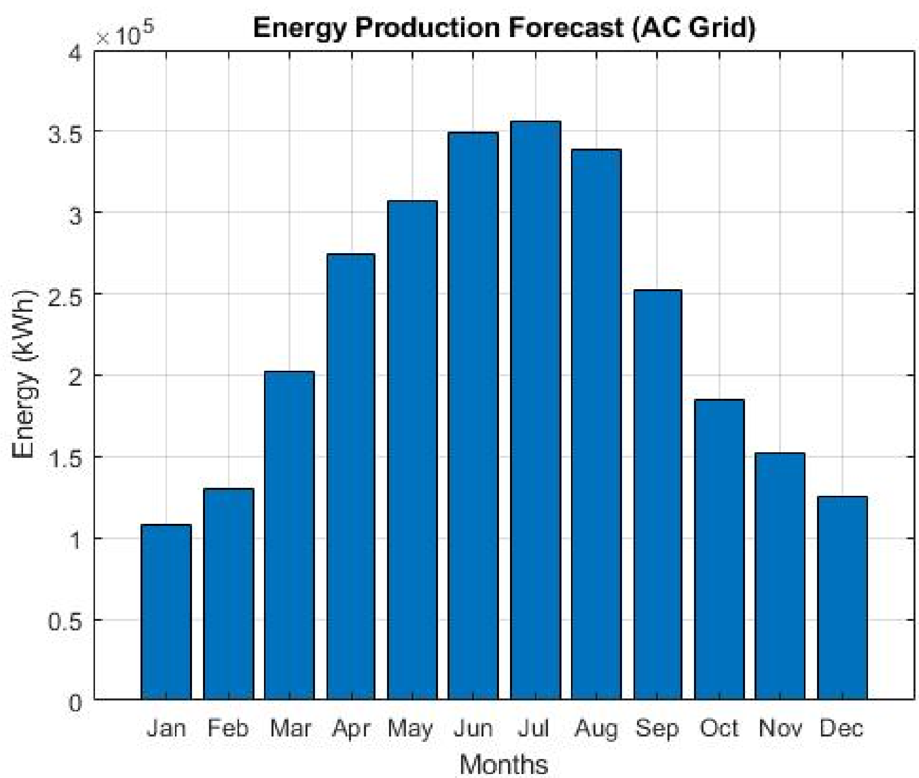

Figure 5. Energy production forecast

As a result of the calculations and simulations made for SPP energy production, it is found that 2,736,703 kWh of annual energy production is made. Energy production varies in different months according to the changing energy radiation and temperature amounts. Annual energy production is shown in **“Figure 5”**.

All shading elements and meteorological changes are taken into account when making energy production calculations. Meteorological databases are used to make energy production estimates for solar power plants, to optimize system performance and to assist in the selection of the right location. In this way, energy production estimates that are very close to reality can be made.

4. RESULTS

Based on this data, the projected solar power plant's annual prevention of 1,306,947 kg of CO^2 emissions represents a significant contribution to environmental sustainability and the global effort to mitigate climate change. Such renewable energy investments not only reduce environmental pollution but also increase energy security by paving the way for a transition to cleaner and more sustainable energy sources in the long term. Since solar energy provides energy production with zero carbon emissions compared to fossil fuels, the installation of solar power plants significantly reduces the negative impacts on the environment. The reduction of CO^2 emissions prevents the release of this gas, which accumulates in the atmosphere and causes greenhouse gas effects and global warming, into the environment.

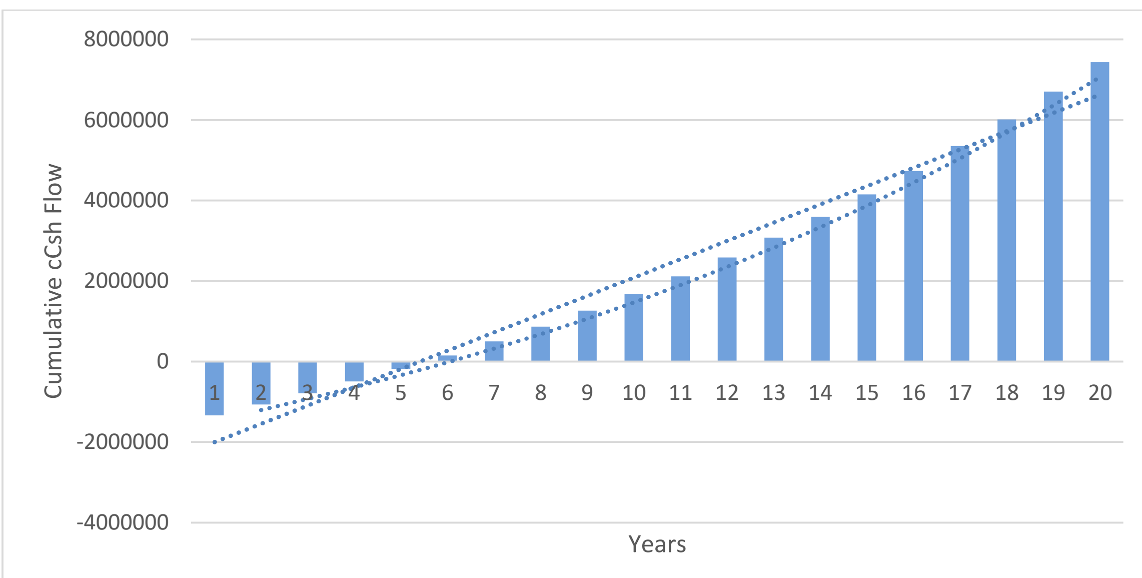

Figure 6. Yearly cumulative cash flow obtained from solar power plant utilization

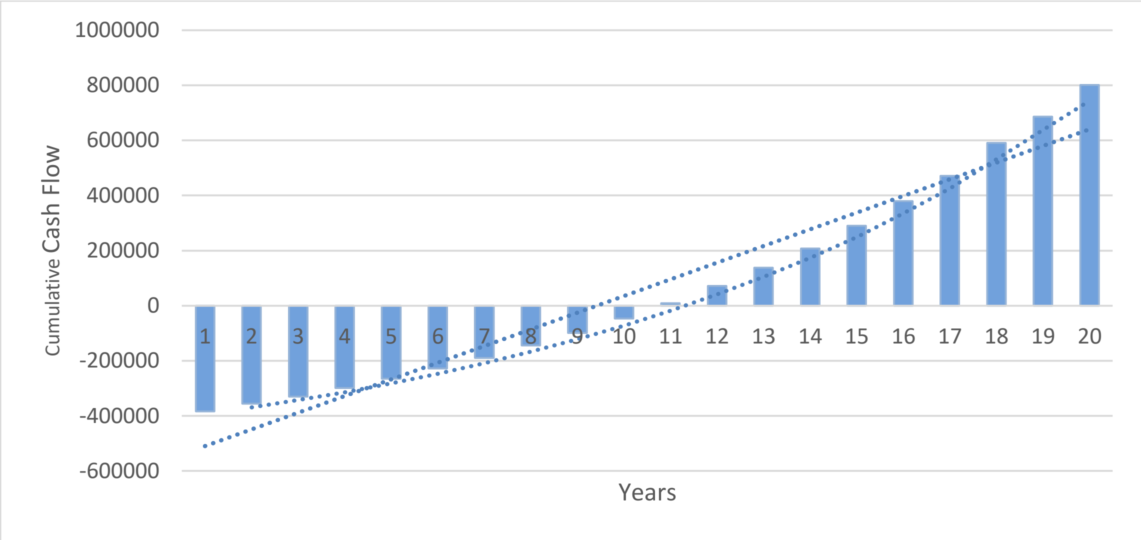

Figure 7. Yearly cumulative cash flow obtained from waste heat recovery

A solar power plant (SPP) investment with a payback period of 5.6 years offers a highly advantageous payback period in financial terms (See **Figure 6**). Amortization periods, which usually vary between 5-10 years, are considered a critical indicator in determining the cost-effectiveness of solar energy projects. Recovering costs in a relatively short period of 5.6 years offers an attractive opportunity for investors and ensures that the investment quickly turns into profit. Especially in today's world where energy production costs are constantly changing and efforts are being made to reduce dependence on fossil fuels, this amortization period contributes to the sustainability of the investment both economically and environmentally. A steam turbine system that utilizes waste heat with a payback period of 10.5 years can be considered a meaningful investment in terms of energy efficiency (See **Figure 7**). Such systems enable the utilization of waste heat in industrial processes and at the same time offer businesses significant savings in energy costs through electricity generation. 10.5 years is generally an acceptable payback period for waste heat recovery systems, as these systems provide energy production while minimizing operating costs for many years after installation.

Waste heat recovery offers a sustainable solution both environmentally and economically. The payback period of such a system is usually an important indicator of the return on investment, reducing the energy consumption of the enterprise and minimizing the use of fossil fuels.

In addition, steam turbine systems that utilize waste heat increase energy supply security and reduce external dependency. Such systems reduce operating costs in industrial facilities with high energy consumption while also contributing to the sustainability goals of the facilities. Therefore, a payback period of 10.5 years indicates a period in which the investment will be profitable in the medium term and provide energy efficiency and environmental benefits in the long term.

4. CONCLUSION

Solar power plants (SPP) and waste heat recovery systems offer different advantages and disadvantages in terms of investment payback periods, areas of use and environmental benefits, despite having the same amount of energy production. While the payback period of SPP is calculated as 5.6 years, this period is 10.5 years for the waste heat recovery system. With a shorter payback period, SPP offers investors a quick financial return and offers an economic advantage in the short term. This can make SPP more attractive, especially for businesses that expect a quick return on their energy investments. In addition, the installation and maintenance processes of SPPs are generally simpler and can be managed with lower operational costs. On the other hand, waste heat recovery systems offer an environmentally friendly solution, especially in energy-intensive industries, by using waste energy from existing processes. Although the longer payback period of these systems may seem costly at first, they provide continuous energy savings by increasing the energy efficiency of industrial processes and reduce operating costs in the long term. In addition, waste heat recovery systems contribute to the enterprise's sustainability goals by increasing its energy efficiency. However, it requires a more complex infrastructure compared to GES and since it is suitable for industrial facilities, it may be difficult to implement in every business. In the current system, the fact that the furnaces where waste heat is obtained undergo maintenance for 45 days per year can be seen as a disadvantage for the steam turbine system. As a result, while GES seems more advantageous for investments seeking short-term gain and quick return, waste heat recovery systems may be a more suitable choice in terms of energy efficiency and industrial compliance in the long term.

CONFLICT OF INTEREST STATEMENT

There is no conflict of interest among the authors.

CONTRIBUTIONS OF AUTHORS

S.G.T.: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, writing—original draft preparation.

K.O.: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, writing—original draft preparation.

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