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Environmental and economic analysis of industrial waste heat recovery with hybrid heat pump application

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ABSTRACT

Today, increasing energy demands and environmental concerns have made energy efficiency a necessity from both economic and ecological perspectives. High energy consumption in industrial facilities increases costs and raises CO_2 emissions. Therefore, waste heat recovery and the use of renewable energy are among the fundamental goals of sustainable production. Energy efficiency is important not only for reducing consumption but also for lowering greenhouse gas emissions, protecting the environment, and strengthening the economics of the business. In this context, heat pump technologies, which extract energy from low-temperature sources and make it reusable, stand out as effective, environmentally friendly, and efficient systems in both heating and cooling applications. In this study, waste heat from a cooling tower generated during the production process in an industrial facility was recovered through a water-source heat pump and integrated into the facility's heating system. The heat pump increased the heat energy by using low-temperature water and reused it in the process. During periods when the waste heat was insufficient, the system was supported by natural gas boilers, thus creating a hybrid operating model between the heat pump and the boiler. As a result of the implementation, natural gas consumption and electricity usage were significantly reduced, leading to lower energy costs and a substantial decrease in CO_2 emissions, thereby providing notable environmental benefits. The findings indicate that the proposed system achieves an annual natural gas saving of 6,788,251 kWh and a net financial gain of 5,703,864 TL. Additionally, the payback period of the investment is calculated as 2.41 years, demonstrating the economic feasibility of the system. Overall, this case study highlights that the widespread adoption of hybrid heat pump systems in the industrial sector can make significant contributions to Türkiye's energy transition and carbon emission goals.

I. INTRODUCTION

As the world's population increases, so does the need for energy. Currently, energy demand is largely met by fossil fuels such as oil, natural gas, and coal. However, research indicates that the reserves of these resources are at risk of depletion in the near future. This situation has made the use of renewable and alternative energy sources mandatory on a global scale [1]. Efforts to increase energy efficiency and reduce the carbon footprint of production facilities are now central to sustainable development goals [2]. In this context, heat pump technologies, which can provide high-efficiency heat production via low-temperature environmental energy (air, water, or soil resources), stand out as a significant alternative to traditional systems [3,4].

Heat pumps are systems that transfer heat from a low-temperature source to a high-temperature environment via an electrically powered compressor and can be used for both heating and cooling. In this process, which occurs through the circulation of the refrigerant in a closed loop, heat is transferred to the water distribution system via heat exchangers. Owing to their ability to offer two different functions in a single cycle, heat pumps stand out as a more efficient and economical solution than traditional heating and cooling systems do [5-8]. These systems, which include different types, including air, water, and ground sources, have performances that vary depending on the environmental conditions, heat source, and system design [1]. To ensure high efficiency, especially in cold

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climates, system designs are optimized by drawing inspiration from applications developed in regions with challenging climates [8-10].

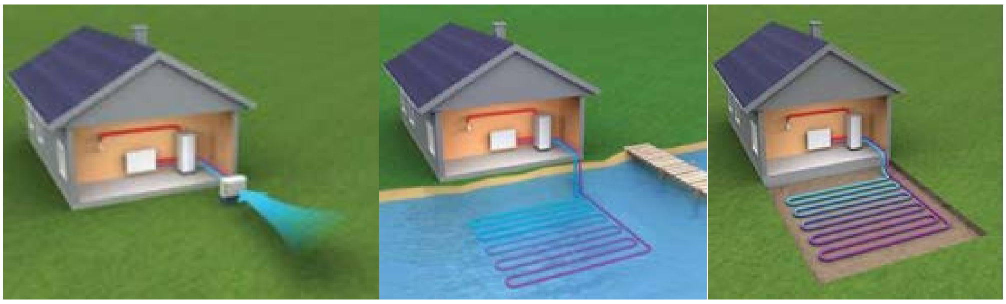

Figure 1. Types of heat pumps

This thermodynamic cycle, which takes place between the basic components consisting of a compressor, condenser, expansion valve, and evaporator, is based on similar principles in all types of heat pumps. The heat pump cycle shown in Figure 2 illustrates the heat transfer process that occurs within a closed system on the basis of the phase changes of the refrigerant. The cycle begins with the evaporation of the refrigerant, which is at a low temperature in the evaporator, by absorbing heat from the environment. The resulting vapor is compressed by the compressor, increasing its pressure and temperature, and is directed to the condenser. In the condenser, the fluid condenses, releasing heat to its surroundings, and transitions to the liquid phase. Then, the pressure and temperature of the liquid passing through the expansion valve are reduced, returning it back to the evaporator conditions. By continuously repeating this cycle, heat energy is transferred from one environment to another [8, 11,12].

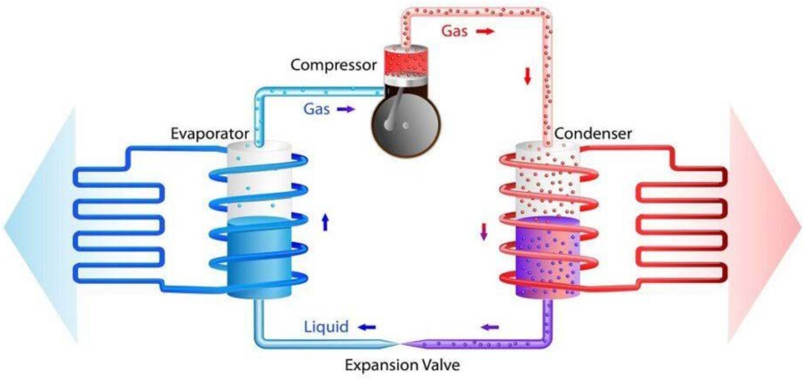

Figure 2. Heat pump working principle

The efficient and effective operation of a heat pump cycle is directly related to the properties of the refrigerant used. In this context, refrigerants are the fundamental working fluids that enable the transfer of heat from one environment to another in heat pump and refrigeration systems, and they carry out heat transfer through evaporation and condensation processes in a closed cycle. Today, refrigerant selection is evaluated not only in terms of thermodynamic performance but also in accordance with environmental sustainability criteria. While there is an increasing trend toward environmentally friendly refrigerants with low ozone depletion potential (ODP) and global warming potential (GWP), chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which were widely used in the past, have largely been phased out owing to the damage they cause to the ozone layer and their high GWP values. Hydrofluorocarbons (HFCs), hydrofluoroolefins (HFOs), and natural refrigerants such as ammonia, carbon dioxide, and propane (HC-290) have become widespread. Next-generation refrigerants offer high energy performance along with lower environmental impact [13,14]. Furthermore, international regulations such as the European F-Gas Directive encourage the development of low-GWP alternatives by gradually limiting the use of high-GWP refrigerants [15,16]. Figure 3 presents the environmental impacts of different refrigerant types and their classifications on the basis of these impacts.

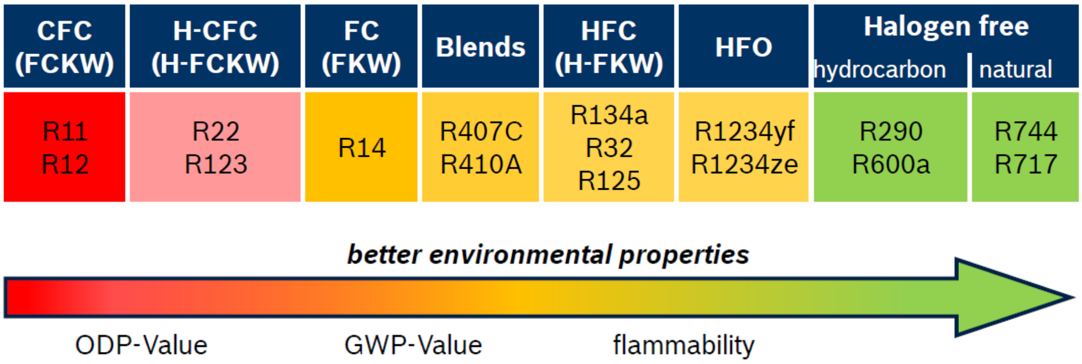

Figure 3. Coolant and properties

Energy losses and environmental emissions caused by fossil fuel-based heat sources in industrial processes have increased the need for more efficient and sustainable solutions. In this context, methods such as waste heat recovery, combustion optimization, and condensate recovery, as well as hybrid systems developed in recent years, stand out. The integration of heat pumps into industrial systems reduces fuel consumption and CO_2 emissions by preheating the feedwater or feed air while also improving the overall energy performance of the system. The use of heat pumps, which operate with high COP values at low temperatures, in conjunction with conventional heat sources that meet high-temperature requirements significantly increases overall energy efficiency [17-19].

Hybrid heat pump systems offer flexible solutions that adapt to different operating conditions by combining the high efficiency of a heat pump with an auxiliary heat generation system that is activated when needed. In these systems, the heat pump typically extracts low-temperature heat from the outside air, ground, or water to meet the primary heating needs; when ambient conditions deteriorate or high-temperature requirements arise, the auxiliary heat source is activated. This auxiliary system can be a boiler, combi boiler, electric heater, or other heat generation unit, depending on the application. Owing to the hybrid structure, the heat pump, which operates with high performance at low temperatures, is used primarily, whereas support is provided by the auxiliary heat source when the system capacity is insufficient. The generated heat is distributed to the rooms and the domestic hot water system via distribution lines; the fluid that has released its heat is directed back to the heat generation units via the return line, completing the cycle. This approach allows the system to select the most suitable energy source according to its operating conditions, increasing overall energy efficiency and reducing fuel consumption and carbon emissions.

Heat pump technology plays a significant role in the transition to sustainable energy systems within the scope of decarbonization goals and energy efficiency studies. It is estimated that approximately 1 billion Gcal of heat is produced annually worldwide through the use of various sources, such as rivers, groundwater, and industrial waste heat, highlighting the global importance of heat pumps [20]. Offering a low-carbon alternative to traditional heating systems, heat pumps have been shown to both save energy and reduce greenhouse gas emissions through integration with renewable energy sources [21-23]. In line with these advantages, the use of heat pumps is rapidly expanding worldwide. Figure 4 presents heat pump sales rates in European countries.

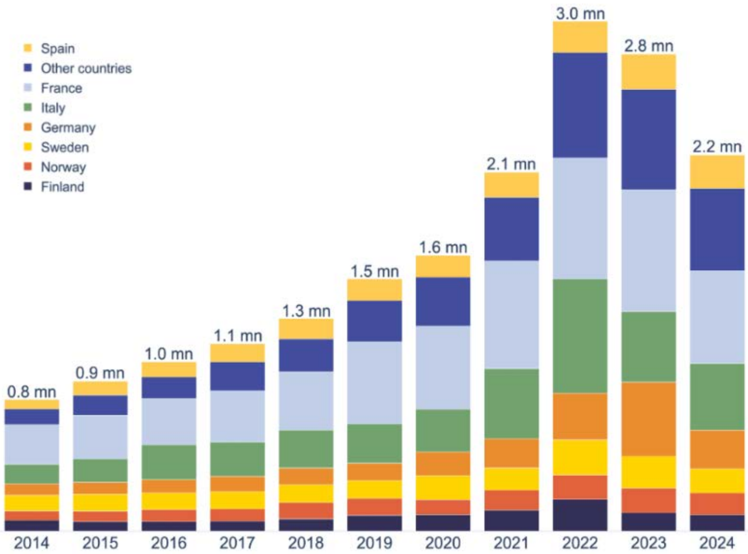

Figure 4. Heat pump sales rates in European countries from 2014—2024

The analysis in the figure shows that the heat pump market in Europe exhibited different trends by country in 2024. Sales decreased in France, Italy, Germany, Spain, and Sweden but increased in Portugal, Austria, and the United Kingdom. The main reasons for market contraction are changes in government subsidies, economic stagnation, and low natural gas prices. This has slowed Europe's decarbonization process. However, owing to their adaptability to different climate and energy policies, heat pump technologies continue to play a key role in a sustainable and low-carbon energy transition. Figure 5 shows the heat pump growth targets of European countries until 2030.

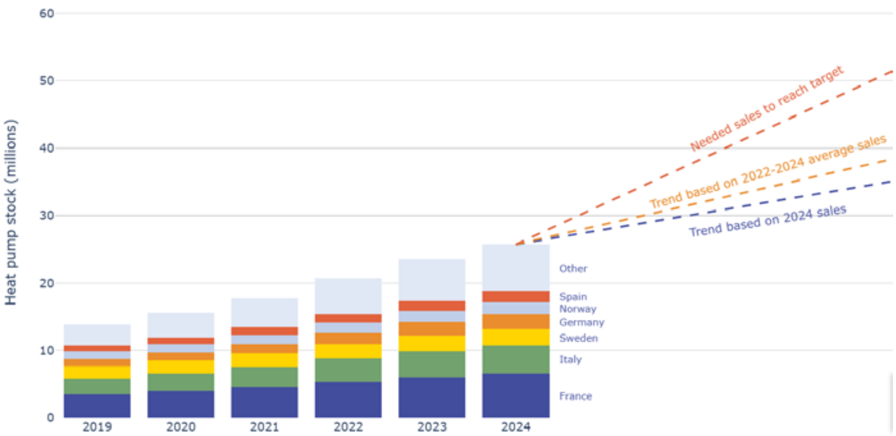

Figure 5. Current growth of heat pump stocks in Europe and a comparison with the 2030 target

Turkey has adopted low-carbon development goals within the framework of green transformation policies supporting environmental and economic sustainability and has embraced the net-zero emissions target of 2053, which is in line with the European Green Deal. This process encompasses key areas such as increasing energy efficiency, expanding renewable energy sources, engaging in circular economy practices, and decarbonizing industry. The World Bank-supported Heat Pump Market Assessment Project, which was conducted in this context, aims to reveal Turkey's heat pump potential, analyze the heating and cooling demand structure, and develop recommendations for sustainable energy policies. These studies significantly contribute to positioning heat pump technologies as strategic tools in Turkey's energy transformation process. Figure 6 shows the number of heat pumps sold in Turkey between 2015 and 2024.

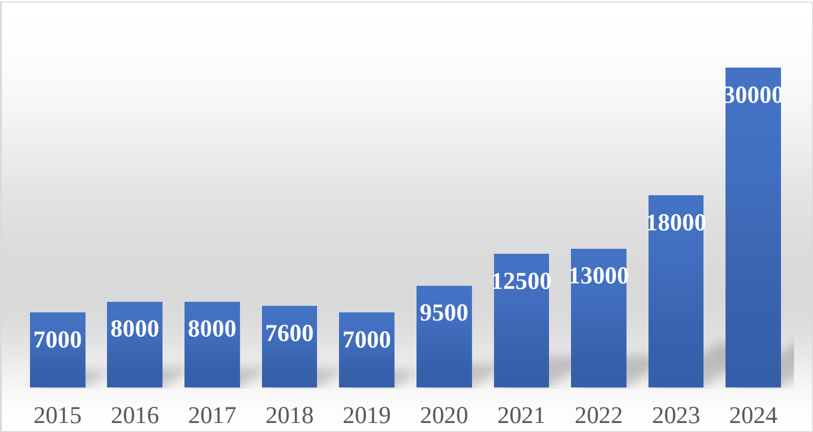

Figure 6. Number of heat pumps sold in Türkiye between 2015 and 2024

The use of heat pump technology in Turkey has increased significantly in recent years, indicating an acceleration in the evaluation of both geothermal and air-source heat potential and the transition to sustainable heating systems. This transformation is being considered, particularly in conjunction with applications aimed at increasing energy efficiency in industrial facilities. Cooling towers, which are widely used in energy-intensive sectors, are critical systems that enable the removal of excess heat generated during processes in oil refineries, power plants, thermal power plants, petrochemicals and manufacturing industries. In these towers, a portion of the water evaporates, removing it from the environment through latent heat, while the temperature of the remaining water is reduced, making it possible to reuse it. This continuous cycle is highly important in terms of process continuity and energy efficiency [24,25]. Natural draft cooling towers, especially in large-scale facilities such as thermal power plants, are fanless structures that provide airflow through a natural chimney effect owing to their hyperboloid geometries. This design offers high heat transfer efficiency and low operating costs but requires a high initial investment due to its large size. Despite their limited performance under varying load conditions, they stand out as energy-efficient and sustainable solutions [25].

Boilers, which are commonly used in industrial heat generation, are the basic equipment that converts the chemical energy of fuel into heat energy and transfers it to the fluid. However, in these systems, not all energy can be converted into useful heat because of losses from surface and flue gas sources [26]. In these systems, different types of boilers, such as steam, hot water, and hot oil boilers, improving combustion conditions, selecting appropriate capacity, good insulation, regular maintenance, and waste heat recovery, are highly important for increasing energy efficiency. These measures reduce fuel consumption and improve system performance [27]. In this context, the increasing use of heat pumps in Turkey, evaluated together with traditional systems such as cooling towers and boilers or within the scope of hybrid solutions, offers significant potential to contribute to industrial energy efficiency and decarbonization goals.

After explaining the operating principles of heat pump technology, the literature contains numerous studies focusing on system performance, application results, and energy-environmental impacts. In a comparative study conducted at the residential scale, Özçelik (2023) revealed that the use of heat pumps significantly reduces CO_2 emissions compared to natural gas and liquid fuel systems, but high electricity unit costs can limit economic performance [28]. In a study parametrically comparing different heat source types, Çokgez Kuş and Çomaklı (2015) determined that systems with higher evaporator source temperatures provide lower operating costs and higher energy efficiency; and that heat pump systems consume significantly less electricity than electric heaters [29]. Goričanec et al. (2020), who examined the integration of high-temperature heat pumps based on waste heat recovery, showed that the primary energy efficiency in boiler systems can be significantly increased and the system is economically feasible thanks to the utilization of low-temperature waste heat in the flue gas with condensing heat exchangers and high-temperature heat pump stages [30]. In a more comprehensive review, Gaur et al. (2021) emphasized that heat pumps are a critical technology in low-carbon energy systems in terms of energy efficiency and greenhouse gas emission reduction; and that they offer technical and environmental advantages through waste heat recovery, district heating networks, and renewable energy integration [31].

When these findings are considered together, it is understood that the performance of heat pump systems is strongly dependent on operating conditions, primarily heat source temperature, operating temperature levels, and waste heat integration; and that significant gains in both energy efficiency and emission reduction can be achieved with appropriate design and hybrid integration strategies.

This study examines a hybrid heating and cooling system based on the recovery of waste heat from cooling towers via a heat pump within the scope of energy audits conducted at a tire factory in Türkiye. The system is designed to meet the factory's hot water and cooling water needs, especially during the winter and transitional seasons. In the application, the low-temperature waste heat generated in the cooling towers is heated by the heat pump and transferred to the hot water circuit. When the capacity of the heat pump is insufficient, the hot water boilers are activated, and when the cooling load increases, the cooling towers are activated. Thus, the system provides automatic switching between three main energy sources (heat pump–boiler–cooling tower) dynamically according to the thermal load balance. This waste heat-based heat pump application was examined in detail, and the energy efficiency, operational efficiency, and economic return performance of the system were evaluated according to the methods described below.

II. MATERIAL and METHOD

In the system examined in this study, an integrated structure consisting of a boiler, a water-source heat pump, and cooling towers is used to meet heating and cooling loads. The system is operated with automation support to meet energy needs that vary according to seasonal conditions. An economic analysis was performed using 3 hot water boilers, 3 steam boilers, 2 open-type cooling towers, and 3 water-source heat pumps in the facility.

The facility has three steam boilers that provide the steam needed at different pressure levels in the production process. The steam obtained from these boilers is used for heating rubber in an ovens, heating oil in mixer oil tanks, heating rubber material in the textile calendar line, heating molds in baking presses and the molding area, and in repair machines in the product inspection section. The facility also has three hot water boilers that provide hot water for processing and area needs. The hot water obtained from these boilers is used to supply equipment, heat areas via fan–coil systems, and provide domestic hot water in sink hot water lines. Thus, both process support and comfort heating needs are met continuously throughout the facility.

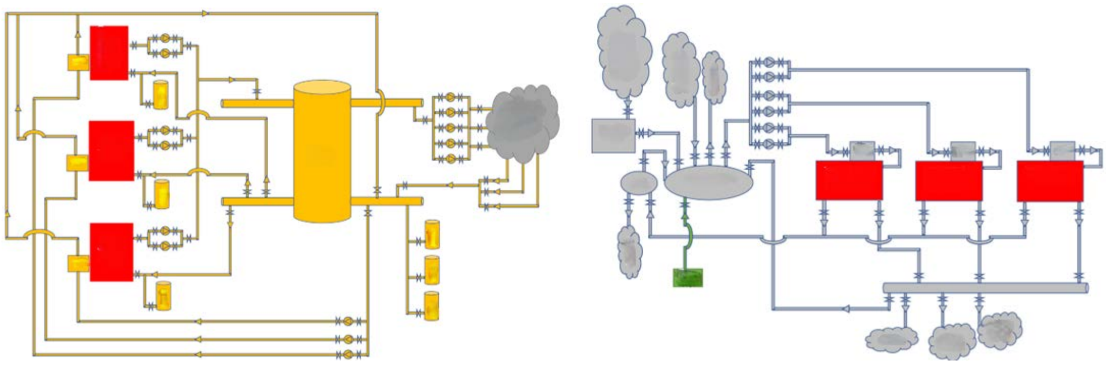

Figure 7. Boiler system diagram **a)** Hot water boiler **b)** Steam boiler system diagram

The cooling towers meet the chilled water needs of the plant and the compressors in the auxiliary facilities. The towers are open-type, and the tower fans operate on an on/off principle depending on the temperature, in a controlled manner between 18 °C and 24 °C. The figure shows a cooling tower and its connection. Two cooling towers located within the factory meet the cooling needs of different areas. To explain the interaction and operation of both cooling towers with the system, animated visuals showing the system diagrams are presented below. These visuals reveal the holistic structure of the factory's existing heating and cooling infrastructure and its integrated relationship with the heat pump in a more understandable way.

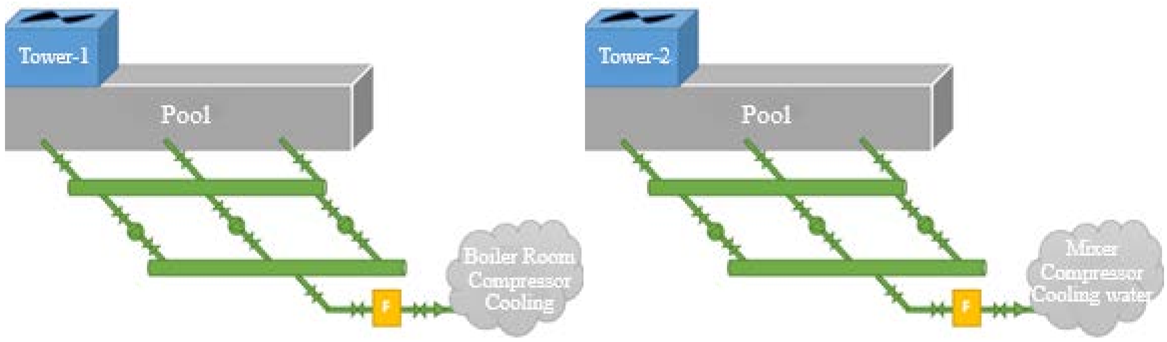

Figure 8. Flowchart of Towers 1 and 2

Tower 1 is used to cool the compressors located in the boiler room. Water taken from the pool is directed through the system to the compressor cooling line, where it is heated by heat transfer and returns to the tower. This cycle ensures that the equipment in the boiler room operates at the optimum temperature, contributing to energy efficiency. Tower 2 operates to cool the compressors and mixer systems located in the processing and raw material storage areas. The cooling water circulating through the pool absorbs the thermal load from the relevant process equipment and returns to the tower, thus ensuring a stable thermal balance in the production areas of the facility.

The aim of this project is to meet a portion of the cooling and hot water requirements during the winter and transitional seasons by implementing a heat pump system in the existing facility. This application increases the energy efficiency of the system and reduces its dependence on the conventional fuel-fired boiler system. The heat pump is planned to be activated depending on the operating time of the hot water boiler. Using factory data from

2021, energy calculations for the system's operation were performed by comparing them with energy costs from the previous two years. When the hot water demand exceeds the heat pump capacity, support is obtained from the hot water boilers; when the cooling demand exceeds the heat pump capacity, the cooling towers are activated. The cooling towers are an important part of the system, and the total power drawn by the fan motors is determined to be 8.4 kW + 11.2 kW = 19.6 kW. The boiler efficiency used in hot water production is assumed to be 95% (0.95) within the scope of the assumption. Flow rate and inlet-outlet water temperature difference data for the cooling towers were obtained from the facility automation system. At an average temperature of 21.1 °C, the physical properties of the water were density (ρ) = 997.4 kg/m³ and specific heat capacity (Cp) = 4.179 kJ/kg·°C. The monthly capacity calculations for the cooling towers were performed via the following equation:

$$Q = (V \times \rho) \times Cp \times \Delta T \quad (1)$$

Using this relationship, the heat rejection capacity of the cooling tower was determined for each month, and the obtained values were used in the operational analysis of the heat pump system. Thus, the heating–cooling load sharing and hybrid operating efficiency of the system were evaluated. The heat pump used in this study was selected in line with the objectives of high energy efficiency and environmental sustainability. The water-source heat pump uses the environmentally friendly R1234ze refrigerant and has a screw compressor structure. The technical specifications and performance values of the device are given in the table below.

This study utilized three water-source heat pump systems. The pumps employed environmentally friendly R1234ze refrigerants. The condenser circuit of each unit operates with a water temperature of 55 °C at the inlet and 65 °C at the outlet, producing a heating capacity of 652.59 kW. On the evaporator side, operating with water temperatures between 30 °C at the inlet and 25 °C at the outlet results in a cooling capacity of 502.45 kW. Each unit has an electrical power consumption of 153.97 kW, and the system as a whole has been optimized to maintain energy efficiency while producing high thermal power. Under full load conditions, the coefficient of performance (COP) of the unit was determined to be 4.29, and the energy efficiency ratio (EER) was 3.32. An increase in system performance was observed at partial loads, with a COP of 4.36 and an EER of 3.57 at 75–80% load and a COP of 4.47 and an EER of 3.89 at 50% load. These data show that the system operates with high energy efficiency even at partial loads. Furthermore, the IPLV/IP values of the devices were calculated as 4.59/5.24/6.70 at 100%, 75%, and 25% loads, respectively. The SEER (seasonal energy efficiency ratio) value, a seasonal performance indicator, is 5.63, indicating that the device operates with high efficiency throughout the year, even under varying load conditions.

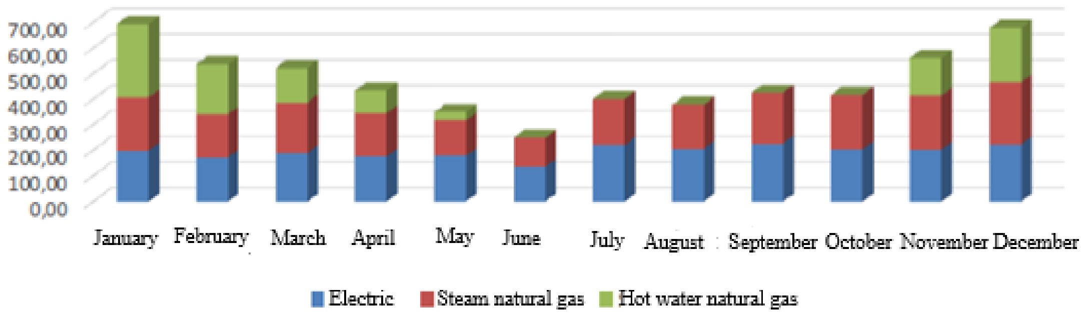

Figure 9. Energy consumption figures for 2019

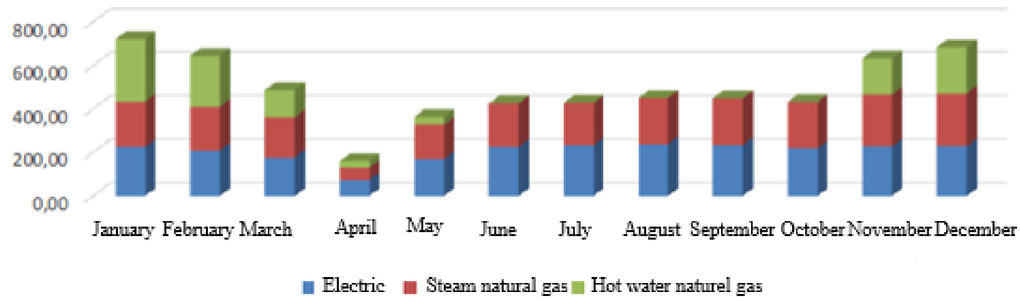

Figure 10. Energy consumption figures for 2020

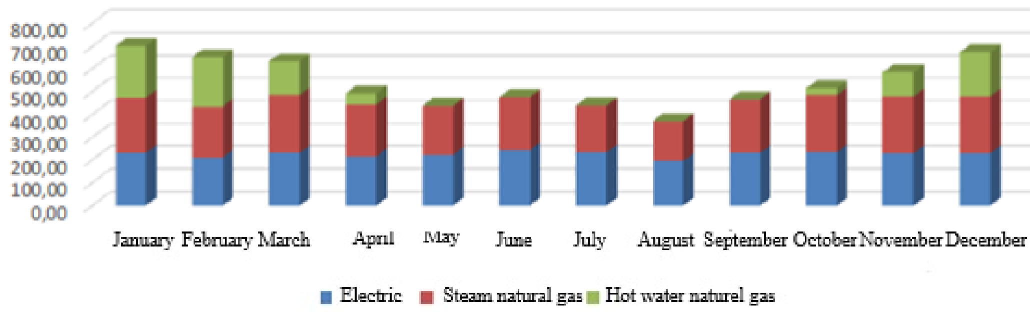

Figure 11. Energy consumption figures for 2021

Figures 12-14 show the production/energy consumption distribution graphs by month for the years 2019-2021. An analysis of the production–energy consumption graphs for 2019 and 2021 revealed that plant energy consumption is largely dependent on production volume and seasonal conditions. The fact that total energy consumption parallels production volumes indicates that energy use is predominantly based on process load. While electricity consumption and natural gas used for steam production show a consistent and stable trend in both years, the natural gas used for hot water production is significantly dependent on seasonal effects. The fact that hot water natural gas consumption increases, especially in the winter months, and almost decreases to zero in the summer months confirms that this consumption is driven primarily by heating needs. Seasonal analysis indicates that natural gas consumption increases significantly in winter months (approximately 70–90%) compared to summer periods, while electricity consumption remains relatively stable throughout the year with variations below 10–15%. This confirms that natural gas use is mainly driven by seasonal heating demand, whereas electricity consumption is largely dependent on production processes.

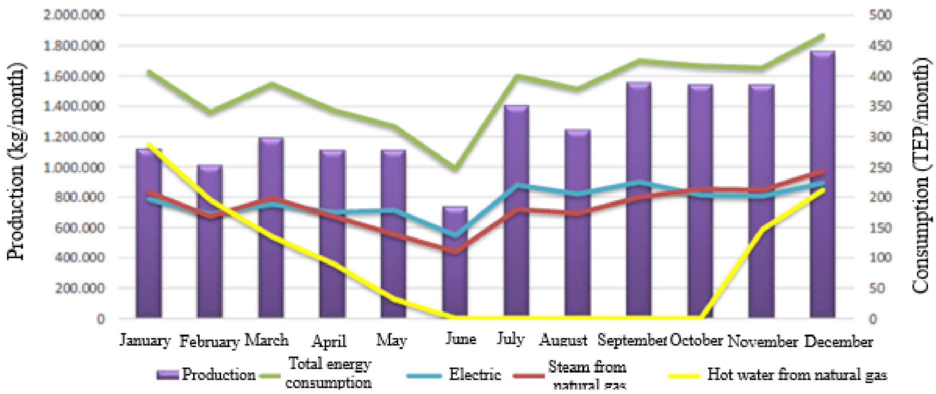

Figure 12. 2019 production/consumption graph

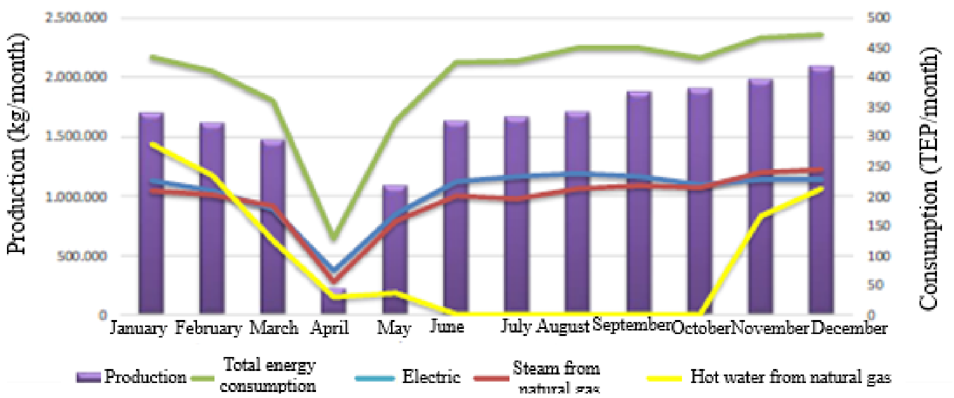

Figure 13. 2020 production/consumption graph

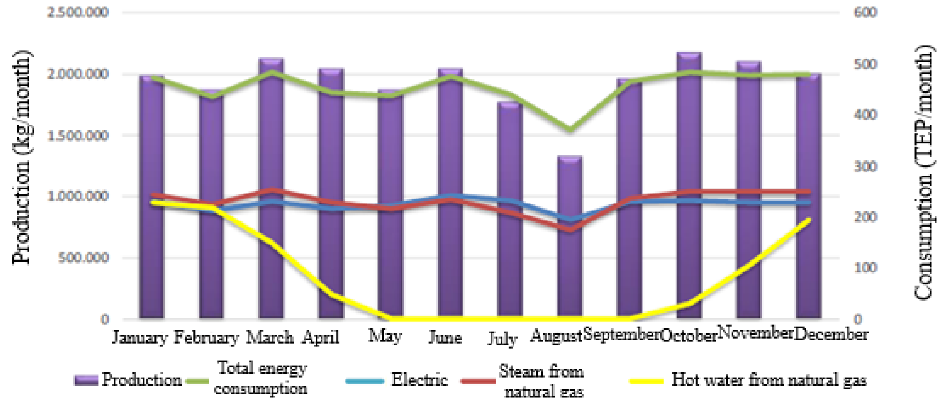

Figure 14. 2021 production/consumption graph

As a result of the measurements and calculations performed, the energy performance of the hybrid system consisting of a heat pump, boiler, and cooling towers was analyzed throughout the year. The data obtained covers the period from August 2021 to July 2022. For each month, the cooling tower flow rates, inlet-outlet water temperature differences, heat pump heating and cooling capacities, energy consumption, and gain values were determined. These results show that the heat pump system successfully achieves seasonal load sharing, reduces boiler operating times, and lightens the load on the cooling towers. When the results presented in Figures 11–14 are evaluated together, it is seen that the heat pump-assisted hybrid system provides a significant improvement in energy consumption, fuel savings, and emission reduction depending on the operating conditions. In particular, it is understood that the overall energy performance of the system improves and the boiler fuel requirement decreases in operating conditions where the waste heat recovery rate increases and the heat pump load increases. This trend is consistent with literature findings reporting that primary energy consumption decreases with reduced boiler load in waste heat-sourced or hybrid heat pump systems [30]. In addition, it is seen that the contribution of the heat pump operating with high COP at low temperature levels to the system efficiency increases in hybrid operation, and this supports the total emission reduction. These results confirm that the hybrid heat pump-boiler integration examined in the present study offers an effective solution in terms of energy efficiency and environmental performance in industrial waste heat recovery applications. The values obtained from various analyses and measurements are given in Table 1.

Table 1. Heat pump gain calculation

History	**Tower -1**		**Tower- 2**		**Working Hours**	**Cooling Capacity** (kW)	**Heating Capacity** (kW)	**Heat Pump Cooling Capacity** (kW)	**Heat Pump Heating Capacity** (kW)	**Electricity Gain** (kWh)	**Natural Gas Gain** (kWh)	**Heat Pump Energy Consumption** (kW)
	Flow (m³/h)	**Inlet-Outlet Temperature Difference** (ºC)	Flow (m³/h)	**Inlet-Outlet Temperature Difference** (ºC)								
August 21	206	4,07	198	1,78	744	1.378,80	0,00	0,00	0,00	0,00	0,00	0,00
September 21	216	3,86	205	2,05	720	1.451,91	0,00	0,00	0,00	0,00	0,00	0,00
October 21	211	3,87	221	1,81	744	1.408,57	446,94	372,45	446,94	3.855,82	350.024,59	69.275,70
November 21	203	3,79	397	0,96	720	1.332,05	1.604,64	1.332,05	1.598,46	14.112,00	1.211.464,42	239.769,00
December 21	207	3,59	360	0,96	744	1.260,55	2.895,37	1.260,55	1.512,66	14.582,40	1.184.651,62	234.462,30
January 22	206	3,47	349	1,00	720	1.231,71	3.500,96	1.231,71	1.478,05	14.112,00	1.120.207,83	221.707,80
February 22	214	3,68	342	1,01	672	1.311,74	3.588,54	1.311,74	1.574,09	13.171,20	1.113.460,14	220.372,32
March 22	214	3,77	345	1,01	744	1.337,54	2.211,54	1.337,54	1.605,05	14.582,40	1.257.006,01	248.782,44
April 22	212	3,87	339	1,09	720	1.377,74	727,59	606,33	727,59	6.210,49	551.436,63	109.138,50
May 22	194	3,69	320	1,29	744	1.306,78	0,00	0,00	0,00	0,00	0,00	0,00
June 22	162	3,83	331	1,26	720	1.201,26	0,00	0,00	0,00	0,00	0,00	0,00
July 22	194	4,20	382	2,10	744	1.872,19	0,00	0,00	0,00	0,00	0,00	0,00
								Energy Savings		80.626,32	6.788.251,25	1.343.508,06
								Financial Savings		₺255.585,42	₺9.707.199,29	₺4.258.920,55
								Total Financial Savings			₺5.703.864,16	

The performance of the heat pump system varies depending on the operating load conditions. As stated previously, the COP values of the unit were determined as 4.29 at full load (100%), 4.36 at 75–80% load, and 4.47 at 50% load.

In the monthly energy analysis presented in Table 1, these partial load performance values were dynamically integrated into the calculations. Specifically, the operating load ratio of the heat pump for each month was estimated based on the ratio of the actual heating demand to the nominal heating capacity of the system.

Accordingly, for each month, the load ratio (LR) was calculated using the following relationship:

$$LR = \frac{Q_{monthly}}{Q_{nominal}} \tag{2}$$

where $Q_{monthly}$ represents the monthly heating demand and $Q_{nominal}$ is the nominal capacity of the heat pump system. Based on the calculated load ratio, the corresponding COP value was assigned using manufacturer performance data. For load ratios close to 100%, the full-load COP (4.29) was used, whereas for partial load conditions (75–80% and around 50%), COP values of 4.36 and 4.47 were applied, respectively. For intermediate load conditions, linear interpolation between the given COP values was employed.

Thus, the electricity consumption of the heat pump for each month was calculated as:

$$W_{HP} = \frac{Q_{HP}}{COP(LR)} \tag{3}$$

where Q_{HP} is the useful heating energy provided by the heat pump and $COP(LR)$ is the load-dependent coefficient of performance. This approach ensures that the seasonal performance variations of the heat pump are realistically reflected in the monthly energy consumption calculations.

Table 2. Energy values within the scope of heat pump application.

VAP to be Implemented	**Energy Source**	**Amount saved**				**Emission Reduction**	**Estimated Implementation Fee**	**Refund Period**
		Original Unit	Amount/Year	TEP/Year	TL/Year	Tons of CO_2 e/Year	TL	Year
Heat Pump Application	Natural gas Electric	kWh	6.788.251,25 -1.262.881,74	475.18	5.703.864,16	797.89	13.750.000	2.41

According to the results shown in Table 2, when the heat pump system is implemented, annual natural gas savings of 6,788,251.25 kWh is achieved, which corresponding to approximately 475.18 TEP. However, an additional 1,262,881.74 kWh of electricity is consumed for the system to operate. Considering these two parameters together, a net annual financial gain of 5,703,864.16 TL is obtained. Furthermore, owing to the decrease in natural gas consumption, an annual reduction of 797.89 tons in CO_2-e emissions was achieved. The investment cost of the application is approximately 13,750,000 TL, and considering the net savings achieved, the payback period is calculated as 2.41 years. These results demonstrate that heat pump application is both economically advantageous and an energy efficiency measure with high environmental benefits. The values given in the table were obtained by evaluating the data.

The total investment cost of the system is approximately 13,750,000 TL and consists of several sub-components, including the main heat pump units, circulation pumps, automation system, engineering services, and installation-related expenses. In this context, approximately 33% of the total investment cost is attributed to the heat pump units, corresponding to approximately 4,537,500 TL. Auxiliary components also constitute a significant portion of the investment. The system includes 12 circulation pumps, with a total estimated cost of approximately 1,470,000 TL. In addition, the automation and control system cost was estimated at approximately 3,150,000 TL.

Furthermore, engineering and project design services were evaluated at approximately 700,000 TL. Mechanical installation works—including piping, system integration, insulation, and on-site assembly—account for approximately 25% of the total investment cost, corresponding to 3,437,500 TL. An average contractor profit margin of 20% was also included in the total investment cost.

Table 3. Energy savings achieved

Electricity Savings	80.626,32 kWh/Year
Natural Gas Savings	6.788.251,25 kWh/Year
Electricity Consumption in the New Situation	1.343.508,06 kWh/Year
Total Financial Savings	[(80.626,32*3,17)+(6.788.251,25*1,43)]–(1.343.508,06*3,17) = 5.703.864,16 TL/Year

Table 3 shows the monthly energy and cost savings obtained from heat pump application. The monthly cooling and heating capacities of the heat pump were determined on the basis of the flow rates and inlet–outlet temperature differences between the Tower-1 and Tower-2 systems. On the basis of these capacities, electricity and natural gas savings and the energy consumption of the heat pump were calculated, and its energy performance was revealed. According to the analysis results, the system achieved total annual natural gas savings of 6,788,251.25 kWh while consuming 1,343,508.06 kWh of electricity. Considering the annual electricity savings of 80,626.32 kWh, the application provides net cost savings of 5,703,864.16 TL. These findings demonstrate that heat pump application has high potential in terms of energy efficiency and is an economically viable solution. Graphs created from the obtained energy data show that heat pump consumption values increase during the winter months, whereas natural gas usage decreases significantly.

When all these gains are examined in terms of CO_2 emissions, the calculation of CO_2 emissions resulting from the application is presented in Table 4. The calculations were performed taking into account the emission factors of the relevant energy types.

Table 4. CO_2 emission calculation

Natural gas	6.788.251*0,234=1.588.450,73 kg Co_2-e
Total energy consumption of heat pump	1.343.508*0,555=745.646,94 kg Co_2-e
Electricity savings	80.626*0,555=44.747,43 kg Co_2-e

The value of 0.234 kg CO_2-e/kWh in the table is the emission factor of natural gas, meaning that 0.234 kg of CO_2 is released for every 1 kWh of natural gas burned, whereas every 1 kWh of energy taken from the electricity grid generates an average of 0.555 kg of CO_2 equivalent emissions. An evaluation of the results in Table 4 reveals that heat pump application reduces natural gas consumption and consequently significantly decreases total CO_2 emissions. Furthermore, indirect emission reduction is achieved through electricity savings, improving the environmental performance of the system. Considering that an average tree absorbs approximately 14 kg of CO_2 per year, this value corresponds to an environmental benefit equivalent to the annual carbon sequestration of approximately 58,000 trees. This result demonstrates that the system is extremely beneficial not only in terms of energy efficiency but also in terms of reducing the carbon footprint and sustainable environmental impacts.

Waste-heat-integrated WSHP hybrid systems have become increasingly common in industrial energy applications, improving energy recovery and enabling stable operation under variable thermal loads. The literature consistently reports that such systems provide significant reductions in operating costs and carbon emissions across diverse application areas, supporting their economic and environmental viability. These findings are consistent with the energy saving and emission reduction results obtained in the present study, further confirming the potential of WSHP-based waste heat recovery systems for industrial energy efficiency improvement [32-34].

III. RESULTS AND DISCUSSION

This study evaluated the energy, economic, and environmental performance of an industrial-scale WSHP system. The analyses revealed that the system operated intensively during the winter months, whereas energy consumption decreased to minimum levels during the summer months. The heat pump system achieved much greater natural gas savings than the electricity it consumed; thus, the total energy savings were largely due to the reduction in natural gas consumption. The results demonstrate that heat pumps significantly reduce fossil fuel use, increase energy efficiency and make decisive contributions to both economic and environmental aspects.

The energy and carbon performance of the industrial-scale WSHP system was evaluated. According to the analysis results, the system consumed 1,343,508 kWh of electricity; in return, it saved 6,788,251 kWh of natural gas and gained 80,626 kWh of electricity. This shows that approximately 1,588 tons of CO_2 emissions were prevented, whereas only 45 tons of CO_2 emissions were generated. These findings reveal that heat pump systems provide high energy efficiency, low emissions, and economic benefits in industrial facilities. Consequently, this hybrid system offers a sustainable solution for Turkey's energy efficiency and carbon reduction targets.

Heat pump–boiler hybrid integration significantly improves the overall energy and environmental performance of industrial heating systems. In such configurations, the heat pump preheats the boiler feedwater or supply air, thereby reducing boiler fuel consumption and associated CO_2 emissions while maintaining the high-temperature requirements of the process. This hybrid approach enables the system to benefit from the high coefficient of performance (COP) of heat pumps at low temperatures while relying on the boiler only when high-temperature demand exceeds heat pump capacity [19]. Although heat pump systems may involve relatively high initial investment costs, previous studies have demonstrated that cumulative energy savings and potential policy incentives can lead to favorable payback periods and strong economic feasibility [17,35-37]. Therefore, integrating heat pumps with existing boiler systems represents an effective pathway to maximize energy efficiency, reduce operating costs, and lower carbon emissions in industrial facilities. The findings of the present study further confirm that hybrid heat pump–boiler operation constitutes a sustainable and economically viable alternative to conventional boiler-based heating systems.

When the results obtained in this study are compared with similar studies in literature, it is seen that the system performance is competitive in both economic and environmental terms. The payback period of approximately 2.41 years obtained is higher than the amortization period of less than one year reported by Doğan [38], but it is within the range of 4.2 years determined for the ice energy storage system and 1.86 years for waste heat recovery in Sungur [39] and exhibits an economic performance consistent with the literature depending on the application conditions.

In terms of emissions, the reduction rates obtained in our study parallel Özçelik [28] finding that CO_2 emissions are 2.28 times lower in heat pump use compared to natural gas systems. Similarly, Pensini's [40] study also stated that natural gas consumption can be reduced by up to 97% in heat pump-based systems, resulting in significant emission reductions. This shows that the emission improvements obtained in the present study are consistent with the trends reported in literature. Overall, the results of this study are consistent with similar applications in literature and demonstrate that the system offers a viable and competitive solution, particularly in terms of payback period and emission reduction.

IV. CONCLUSIONS

According to the analysis results, the heat pump system saved significantly more natural gas than the electricity it consumed, and the total energy savings were largely due to the reduction in fossil fuel consumption. This demonstrates that the system offers an effective solution for increasing energy efficiency in industrial facilities.

From an environmental perspective, the system prevented a significant amount of CO_2 emissions, whereas emissions from electricity consumption remained very limited. These results show that water-source heat pump systems strongly contribute to environmental sustainability by reducing greenhouse gas emissions. In quantitative terms, the system achieved annual natural gas saving of 6,788,251 kWh, resulting in a net financial gain of 5,703,864 TL, with a payback period of 2.41 years. In addition, the reduction of approximately 797.89 tons of CO_2 emissions corresponds to an environmental benefit equivalent to nearly 58,000 trees. These results clearly demonstrate the strong economic and environmental potential of hybrid heat pump systems in industrial applications.

For future work, the widespread adoption of such hybrid systems in Turkish industry can be supported through policy incentives, energy efficiency regulations, and investment support mechanisms. Further studies focusing on different industrial sectors and varying operating conditions would contribute to the generalization and scalability of these systems.

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