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Research Article

Energy and Economical Analysis of Drying Process of Domestic Wastewater Treatment Sludge with Heat Pump

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ABSTRACT

In this study, a heat pump was designed to dry the sludge produced by a wastewater treatment plant. The purpose of drying the sludge is to convert it into raw material as fuel pellets, which can provide some or all of the energy needed by the treatment plant. The design of the heat pump considered the plant's production capacity and sludge generation rate. All thermal analyses were carried out according to the First Law of Thermodynamics. The heat pump system performances are investigated by using Danfoss Coolselector 2.0 program. The capacities of the heat pump components were calculated for different refrigerants and performance coefficients. The highest coefficient of performance (CoP) was found to be 5.99 for R1234zeE in summer, while the lowest was 2.33 for R134a. If the sludge is burned as biofuel, theoretically it was estimated that the energy production could range from 723,000 kWh/month to 744,000 kWh/month for the R407c and R1234zeE refrigerants respectively. The economic analysis showed that the system's payback period could range from 1.9 to 6.5 years.

Keywords: *Sludge, drying, heat pump, refrigerant, energy calculation*

Evsel Atıksu Arıtma Çamurunun Isı Pompası Yardımıyla Kurutulması Prosesinin Enerji ve Ekonomik Analizi

Öz

Bu çalışmada, bir atık su arıtma tesisi tarafından üretilen çamuru kurutmak için bir ısı pompası tasarlanmıştır. Çamurun kurutulmasının amacı, arıtma tesisin ihtiyaç duyduğu enerjinin bir kısmını veya tamamını sağlayabilecek yakıt peletleri olarak hammaddeye dönüştürmektir. Isı pompasının tasarımında tesisin üretim kapasitesi ve çamur üretim oranı dikkate alınmıştır. Tüm termal analizler Termodinamiğin Birinci Yasasına göre gerçekleştirilmiştir. Isı pompası sistem performansları Danfoss Coolselector 2.0 programı kullanılarak incelenmiştir. Isı pompası bileşenlerinin kapasiteleri farklı soğutucu akışkanlar ve performans katsayıları için hesaplanmıştır. En yüksek performans katsayısı (CoP) yaz aylarında R1234zeE için 5,99 olarak bulunurken, en düşük performans katsayısı R134a için 2,33 olarak bulunmuştur. Çamurun biyoyakıt olarak yakılması halinde, teorik olarak enerji üretiminin R407c ve R1234zeE soğutucu akışkanları için sırasıyla 723.000 kWh/ay ile 744.000 kWh/ay arasında değişebileceği tahmin edilmiştir. Ekonomik analiz, sistemin geri ödeme süresinin 1,9 ila 6,5 yıl arasında değişebileceğini göstermiştir.

Anahtar Kelimeler: *Arıtma çamuru, kurutma, ısı pompası, soğutucu akışkan, enerji hesabı*

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I. INTRODUCTION

The misuse of existing water resources due to technological innovations, industrialization, and increased population causes various environmental problems. Wastewater treatment plants are the facilities where both domestic and industrial wastewater are collected and treated to solve this problem. After the wastewater is treated, it leaves the site in two forms: solid and liquid. While the liquid part is discharged to the receiving environment, the solid part, i.e. treatment sludge, is accumulated in the facility or stored in a suitable area. Since sludge cannot be released into the environment without any treatment, there is a search for a sustainable solution for the sludge generated in wastewater treatment plants [1]. There are some methods for converting sludge into a useful input. Biological methods such as anaerobic fermentation, composting, thermal methods such as incineration, pyrolysis, and gasification, as well as energy production, soil applications, use as an auxiliary by-product in other sectors or as a building material are among the current existing applications [2-4]. On the other hand, according to subparagraph "k" of Article 13 of the Regulation on Soil Pollution and Control of the Ministry of Environment and Urbanization and Climate Change, the sludge generated in facilities with a capacity of over one million equivalent population must be dried to at least 90% dry matter (DM) value [5].

Since the moisture content of the sludge is high when it exits the process at the end of the process, the moisture must be removed from the sludge. Moisture removal requires energy, so sludge drying is an energy-intensive and therefore a costly process. The use of sludge as a by-product or input depends on solving the energy source required for drying at a low cost. Incineration of sewage sludge in the incineration process is not technically feasible due to the high moisture content of the sludge. Additional fuel supplementation is required as the calorific value of sewage sludge is low. The high moisture content sludge will have a longer ignition time compared to other fuels (coal, sawdust, wood, natural gas, etc.) during incineration. The sewage sludge should enter the drying process so that the moisture content is reduced, and the calorific value is increased just before entering the incineration process [2]. The amount of the sludge production rate is 10-15 kg (27-41 g DM/person/day) as dry matter (DM) in EU countries while it is 36 g DM/person/day in Turkey [2, 5]. According to 2018 TURKSTAT data, 3.8 billion m^3 of the 4.5 billion m^3 of urban wastewater collected by municipalities through the sewerage network was treated in urban wastewater treatment plants, resulting in approximately 319,000 tons of sludge on a dry matter basis [4].

It will be easier to store, transport, or use the low moisture content sludge compared to high moisture content one. In addition, the calorific value of the sludge will increase after drying, so it can be used alone as an input in the energy production process. Conveying dryers, where hot air is directly applied to the sludge for drying, are available in the market as rotary or drum, fluidized bed, or belt dryers. These systems transfer the heat with conduction so the heat transfer of the sludge with the hot fluid takes place indirectly without contacting each other. Heating efficiency is lower than direct/conductive systems. There are different methods such as conveyor belt, drum dryer, thin film type, disk type, and fluidized bed drying systems [6-7]. The cost of the selected drying method is also important for the operation of the system and its sustainability. When looking at the costs, the investment cost for thermal drying is 350 Euro/ton.DM, while the operating cost is 50 Euro/ton.DM. On the other hand, the solar energy drying system is 400 Euro/ton.DM and 45 Euro/ton.DM respectively [3, 8]. The investment cost for the treatment of sludge in a wastewater treatment plant is between 20-30% of the wastewater treatment plant cost. The operating cost of the sludge treatment plant is 50-70% of the operating cost of the wastewater treatment plant [9, 10].

Sıkı [6] dried sewage sludge to reduce the moisture content from 82% to 9% and the total amount of wet sludge entering the system decreased by 19% at the outlet with a paddle type dryer. Salihoğlu [1], on the other hand, loaded 1,600 kg of sewage sludge containing 14-19% DM into solar drying system with a flow rate of 400 kg per day for 4 days and reached 93-98% DM at the end of the 4^{th} day. Sapmaz [11] determined that 13 m^3 of natural gas per ton can be saved if the sludge is burned auto thermally at 50% DM by applying partial drying. Sayılgan et al. [12] dewatered the sludge with a closed solar system and determined that the sludge reached 90% dry matter value within 15-20 days in the winter season and 5 days in the summer season. In addition, Ameri [13] tried to dry sludge with 85% moisture content with solar energy through natural convection. They recommended this method for plants where the capacity of the wastewater treatment plant is lower (20-30 tons/day) in regions with high solar radiation by focusing on the thermodynamic parameters of the system. There is an indoor area needed for this process that can directly receive the sun for drying.

Kocbek et al. [10] studied sludge drying using microwaves. They performed an energy analysis of the sludge drying process by generating microwaves at different energy levels and found that this method requires more energy than conventional drying methods. Finally, Schmitt et al. [14] stated that when the wastewater treatment sludge was dried with thermal drying, the moisture content reached 80%, its calorific value (1,800-2,500 kcal/kg) was close to half the value of lignite. Tunckal and Doymaz [15] studied the effect of the incoming air temperature of the banana slices drying with a heat pump system. They suggested that the drying rate exhibited an upward tendency with increasing temperature of the incoming air temperature of the drying cabinet, while both the coefficient of performance (CoP) and specific moisture extraction rate gradually rose. Zheng et al. [16] investigated the change and distribution laws of circulating air in sludge heat pump drying equipment. The results showed that the adverse effect of increasing sludge thickness was greater than the beneficial effect of extending drying time. Liu et al. [17] studied the effects of temperature, relative humidity, and sludge thickness on sludge drying characteristics to provide an energy-saving working condition for heat pump drying. They stated that under the conditions of 2–6 mm thickness, 40–60 ºC temperature, and 30–60% relative humidity, drying time decreased by 15–25% for a 10 ºC increase in temperature when thickness and relative humidity were fixed. Additionally, relative humidity decreased from 60% to 30% and drying time decreased by about 50%. Hu et al. [18] established a model for a closed low-temperature heat pump sludge drying system. The effects of incoming air temperatures of the drying cabinet, circulating air volume, and ambient temperature on both drying rate and system performance were investigated. The findings revealed that the drying rate and specific moisture extraction rate rose with higher incoming air temperatures of the drying cabinet and circulating air volume, while the coefficient of performance (CoP) exhibited a contrasting trend. In addition, the CoP increased as the ambient temperature rose, while the drying rate decreased gradually.

Sludge drying and subsequent treatment require energy with low investment and operating costs. Therefore, renewable energy sources can be a solution for sludge drying. There are many studies on solar-powered systems. However, the disadvantages of solar sludge drying are the need for either large areas or long waiting times and the short period of solar availability [19]. On the other hand, sludge drying by heat pumps is also another renewable energy source. Moreover, when compared to other renewable sources, the availability of a heat pump system is much higher than, for example, a solar system. While conveyor belts are used for transportation purposes, it has been determined that they also provide benefits for sludge drying depending on the ambient temperature. In the study, it was determined that when hot air or gas is given to the sludge from an appropriate distance, it provides drying. The conveyor system is also used in pyrolysis, gasification, coal-fired thermal power plants, and waste incineration plants, but they also drew attention to the fact that the sludge can easily move on the conveyor belt without sticking and easily leave the conveyor at the point of end use [20].

There are many methods and studies on sludge drying in the literature. It is observed that each method has its limitations. In this study, a sustainable and low operating cost system, that can be a good alternative to similar drying applications in the literature, is proposed for wastewater treatment plants. This study aims to increase the dry matter content of the domestic wastewater treatment sludge. A heat pump system is analytically designed to supply the necessary heat in reducing the water content of the sludge. When compared with other studies in the literature, it can be stated that the proposed system provides advantages to waste water treatment plants in terms of lower operating cost, availability, and energy consumption. This study aims to transform sludge, which is a residual product for domestic wastewater treatment plants, into a useful product with a sustainable method. The treatment sludge (44% moisture + 56% dry matter) from the decanter is transported out of the plant by conveyor belt. While being transported by a conveyor belt, the belt is covered, and the amount of moisture is reduced by drying with hot air. The hot air is supplied from an air source heat pump. The system consists of a compressor and a fan. The performance of the refrigerants used in the compressor, the amount of energy required for the system, and energy costs were examined within the scope of this study.

II. MATERIAL AND METHODS

A. SYSTEM DESCRIPTION

In this study, an air source heat pump drying system is designed to convert the sludge of a treatment plant operating in the Marmara region and utilized as pellets for biomass fuel. In this way, the 90% DM target required by the Ministry of Environment and Urbanization and Climate Change will be achieved [5].

The facility considered in this study is the largest wastewater treatment plant in Yalova. Domestic sewage from pumping stations in Yalova and surrounding areas is treated using biological methods. At the end of the treatment process, sludge cakes are produced. The disposal of these dewatered solid sludge cakes represents a significant cost and workload for the facility due to the need for storage and transportation. Therefore, this study analytically investigates the drying of the sludge and its conversion into fuel pellets to create a value-added product.

The wet sludge process subject to the study is stored in ponds at the wastewater treatment plant. This stored sludge is directed to the dewatering unit. The sludge is conveyed to decanter units as illustrated in Figure 1, where it is separated into two phases: solid and liquid.

Figure 1. *The decanter unit considered in this study*
1&2 Decanter units (main and spare one), 3&4 Sludge feeding, 5 Decanter electric motor 6-Separated liquid output 7-Separated solid output

There is a conveyor belt 4.9 meters long and 0.5 meters wide that takes the sludge to the storage area located at the outside of the building like the one shown in Figure 2. Afterward, the sludge is transported to the landfill or suitable dumping areas.

Figure 2. *Sample sludge conveyor unit*
1-Conveyor belt feeding from decanter, 2-Conveyor belt sludge transfer, 3-Sludge sampling point

Sludge samples were taken from the conveyor belt and analyzed within the on-site laboratory and the results are given in Figure 2.

Table 1. *Sampling results of the sludge*

Sludge dry matter content (DM) *(%)*	56
Sludge moisture content *(%)*	44
Sludge density *(kg/m^3)*	567.6

The sludge production rate was measured and found that the volumetric flow rate was 5 m^3/hour (this was calculated while the sludge was poured onto an open trailer), and the mass flow rate was 2,837.9 kg/hour (0.79 kg/second) (The gravimetric method was used to calculate the dry matter and water content of sludge within the on-site laboratory). These values are given in Table 2.

Table 2. *Output flow data*

Volumetric Flow *(m^3/hour)*	5
Mass Flow Rate *(kg/hour)*	2.837,9
Mass Flow Rate *(kg/second)*	0.79
Mass Moisture Flow Rate *(kg/moisture.s)*	0.27
Inlet Moisture *(%)*	44
Final Moisture *(%)*	10

The drying characteristics in Table 2 represent the characteristics of the sludge flowing on the conveyor belt after the decanter unit in Figure 2. Therefore, the system is designed to remove 0.27 kg/second of moisture from the sludge at a flow rate of 5 m^3/hour after the decanter, thus reducing the moisture content of the sludge from 44% to 10%.

B. SLUDGE DRYING SYSTEM DESIGN

It is planned to cover the conveyor belt and blow the hot air that comes from the air source heat pump to the sludge with the help of a fan while the dewatered sludge flows over the belt after the decanter. The designed heat pump air dryer system is illustrated in Figure 3.

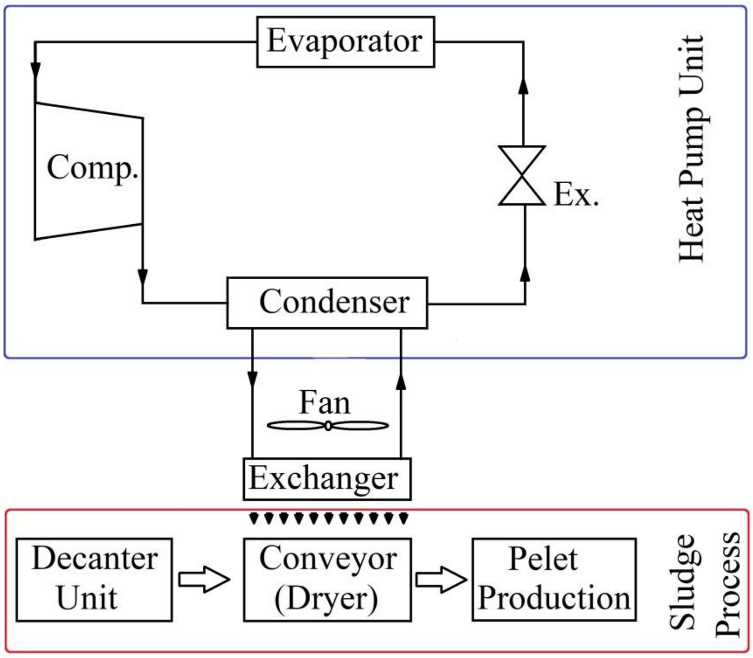

Figure 3. *Sludge drying system*

The sludge is sent away from the plant by a conveyor belt after the decanter unit (Figure 3). The hot air blowing system is installed on the conveyor belt. It is shown as a heat exchanger. In this hot air-blowing system, a heat exchanger is designed to be placed on top of the conveyor belt. The hot air will be blown to the conveyor line using a fan and the moisture of the sludge will dry. The heat exchanger is positioned perpendicularly over the conveyor belt, and it is designed to transfer the entire effect of the blown air to the sludge on the belt by splitting to the right and left. At this stage, the calculations related to the system design are given respectively.
The mass flow rate of the sludge is calculated as follows.

$$\dot{m}_t = m \times \rho \tag{1}$$

The following calculation was used to remove a 34% moisture difference (44% initial moisture content and 10% target value) from the sludge to reduce the moisture content of the sludge.

$$M = (y_{in} - y_{out}) \times m_t \tag{2}$$

The thermal power required to evaporate the targeted moisture from the sludge ($\dot{E}$) was obtained by the following calculation.

$$\dot{E} = M \times (h_g - h_f) \tag{3}$$

The amount of heat needed is determined by the following equation with the assumption of η = 95% heat exchanger efficiency.

$$\dot{Q}_{net} = \frac{\dot{E}}{\eta} \tag{4}$$

The results are presented in Table 3.

***Table 3**. Calculation results*

Parameter	Abbreviation	Value	Unit
Active Operating Period	t_m	8	*h/day*
Number of Working Days	d	30	*day/month*
Hourly Sludge Flow	m	5.0	*m^3/h*
Sludge Density	ρ	567.6	*kg/m^3*
Sludge Mass Flow	$\dot{m}$	2,837.9	*kg/h*
		0.79	*kg/s*
Moisture Percentage in Sludge	y_{in}	0.44	*%*
Target Moisture Percentage of Sludge	y_{out}	0.10	*%*
Moisture to be Evaporated	M	0.27	*kg.moisture/h*
		268.0	*g.moisture/h*
Hf Value for Water @35 ºC	h_f	146.6	*kj/kg*
Hg Value for Water @35 ºC	h_g	2,564.5	*kj/kg*
Enthalpy Difference	Δh	2,417.9	*kj/kg*
Required Energy	$\dot{E}$	648.0	*kj/s*
Heat Exchanger Efficiency	η	0.95	*%*
Net Heat	$\dot{Q}_{net}$net	682.1	*kWt*

The electricity consumption of the compressor is determined by the following calculation.

$$E_{comp} = \frac{\dot{Q}_{net}}{CoP} x\ t\ x 30 \quad (5)$$

here CoP is the coefficient of performance The capacity calculation of the fan that blows the hot air below is calculated by Eq. (6).

$$\dot{Q}_{fan} = \frac{\dot{E} x 3.600}{4,184} \quad (6)$$

60 ºC maximum condenser outlet temperature was taken for each refrigerant. Monthly average temperature values were used on the evaporator side. The CoP is calculated with Equation 7 by using monthly outdoor temperatures and 60 ºC constant outlet temperature data.

***Table 4.** Average monthly atmospheric temperatures of Yalova*

Month	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**August**	**Sep**	**Oct**	**Nov**	**Dec**
Temperature *(ºC)*	6.5	7	8.4	12.2	16.8	21.1	23.4	23.5	20.1	16.1	12.1	8.7

The electricity consumption according to the nominal power of the fan was calculated considering the monthly average temperature data of the city where the plant is located (Table 4). The theoretical fan power is calculated by;

$$\dot{E}_{fan} = \frac{\dot{Q}_{net}}{Cp \times (T_{cond} - T_{ambient})} \times \Delta P \quad (7)$$

The following equation is used for the fan nominal power.

$$N_m = \frac{\dot{E}_{fan}}{t_m} \quad (8)$$

If the system operates for 30 days and 8 hours/day, the fan nominal power is calculated as 51.3 kWe (Table 5). However, the fan capacity was selected as 55 kWe, which is slightly above the calculated value. Fan efficiency was assumed to be 80% in the calculations.

Table 5. *Specifications of the hot air fan in the system*

Parameter	Abbreviation	Value	Unit
Amount of heat to be fed	$\dot{Q}_{fan}$	557,308	*kcal/h*
Specific heat of air	Cp	0.31	*kcal/m^3.C*
Pressure difference	ΔP	30	*mbar*
Fan rated power	N_m	51.3	*kWe*
Selected fan-rated power		55	*kWe*

The CoP of the system by using different refrigerants that can be used within the compressor determined per each design according to the monthly temperature variation was calculated separately. CoP's of the refrigerants are compared. Refrigerants, R290, R1234zeE, R513a, R134a, R134a, and R407c, are the preferred fluids that can be used within the compressors available in the market. Since these fluids are available within the market, they are preferred within the scope of the study. Electricity consumption for the compressor and fan was calculated monthly and the sum of these two was accepted as the total monthly electricity consumption of the system. A semi-hermetic type of compressor was selected to pressurize these fluids.

Finally, the Monthly Net Energy Gain (MNEG) that can be obtained basis monthly is the difference between the energy obtained from burning the pellets derived from the sludge and the energy consumed to operate the heat pump, calculated using the following equation.

$$MNEG = \sum E_p - \sum E_c \quad (9)$$

Here Ep is the energy production (kWh) and Ec (kWh) is the energy consumption that accounts for the energy consumed by fans and the energy consumed by compressor.

III. RESULTS AND DISCUSSION

It is planned to use the condenser of the heat pump for heating purposes. The drying system is planned to take the drying air from both the atmosphere and the heat from the condenser of the heat pump and send it to the sludge. Five different refrigerants were included in the calculations in this study. The Danfoss Coolselector 2.0 program was utilized to determine the CoP of the designed heat pump. This program has a compressor selection interface and simulates the performance of the compressors according to the chosen refrigerant, heating capacity, evaporator input temperature, and condenser output temperature. The performance simulation was carried out to enter the following values for each refrigerant evaluated in the study, and these outputs were referenced to seasonal CoP.

• Refrigerant fluid type: R290, R1234zeE, R513a, R134a, R407c
• Heating capacity of the heat pump: 682 kWt
• Condenser output temperature: 60 °C
• Evaporator input temperature: Monthly outdoor air temperatures taken from meteorology

During the hot summer months, the same CoP is observed in the systems. This is due to the maximum evaporator input temperature limits of the preferred compressors suitable for the refrigerator. All the results from the Danfoss Coolselector 2.0 software are presented in Figure 4.
The CoP value of the system varies between 3.20 and 6.00. The refrigerant with the highest CoP value is R1234zeE. The lowest CoP belongs to R407c. While the CoP value of R407c is around 3.50, the CoP value of R1234zeE rises to 3.80 in winter and 6.00 in summer. In contrast, R134a refrigerant is the most frequently and easily available refrigerant and has the lowest performance in winter. However, it has the highest CoP value after R1234zeE in summer.

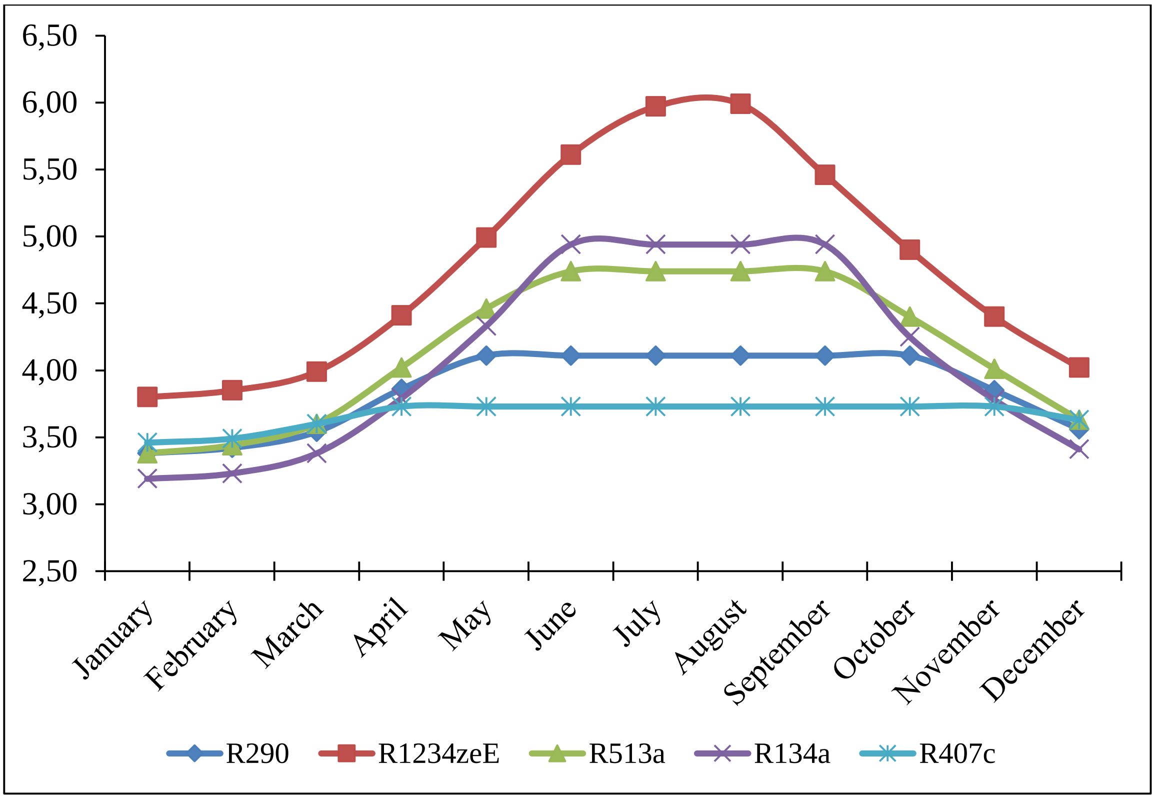

Figure 4. *Variation of CoP of the system vs. different refrigerants*

CoP is an important indicator when selecting a heat pump drying system. However, other indicators should also be considered before making an investment decision. In this study, the MNEG, another important indicator, was calculated. Figure 5 shows the MNEG calculated for different refrigerants. To calculate MNEG, the approximate energy that can be obtained from burning the sludge was theoretically calculated. In this calculation, the average calorific value of the sludge was assumed to be 4,500 kcal/kg, and the efficiency of the energy conversion system was assumed to be 30%. Thus, the thermal power that can be obtained from burning the sludge was calculated to be 3,267 kW. To calculate MNEG, the consumption of the heat pump compressor and fan, which consume electricity in the system, was subtracted from the total production.

If R1234zeE is used as the refrigerant in the heat pump, the electricity production could range between 727,000 kWh and 733,000 kWh per month. If R290 refrigerant is chosen, the monthly MNEG ranges between 724,500 kWh and 739,500 kWh. This amount is sufficient to meet the energy consumption of approximately 2,500 households.

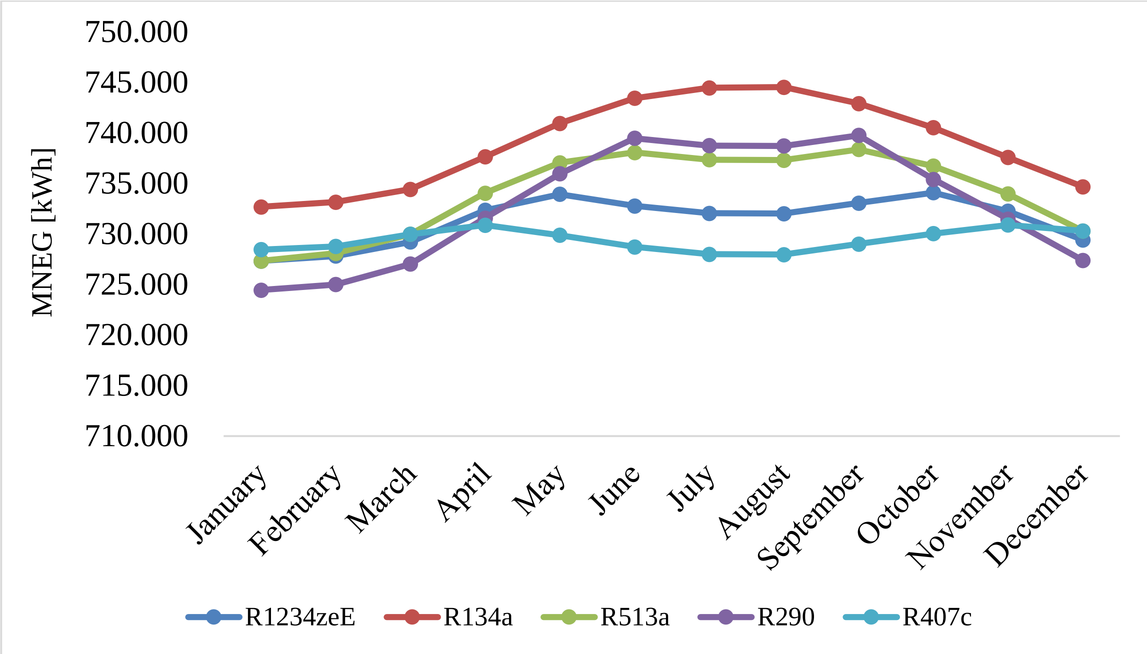

Figure 5*. Monthly net energy gain of the system according to refrigerants*

Energy conversion from pellets produced from dried sludge can be conducted at locations other than the treatment facility. In such cases, the treatment plant will only consume energy to operate the heat pump system. To analyze the scenario where the treatment plant does not gain energy or generate revenue from energy sales, the energy costs of the system using different refrigerants were calculated. In case no electricity is generated from the produced pellets, the cost of the energy for operating system is given in Figure 6.

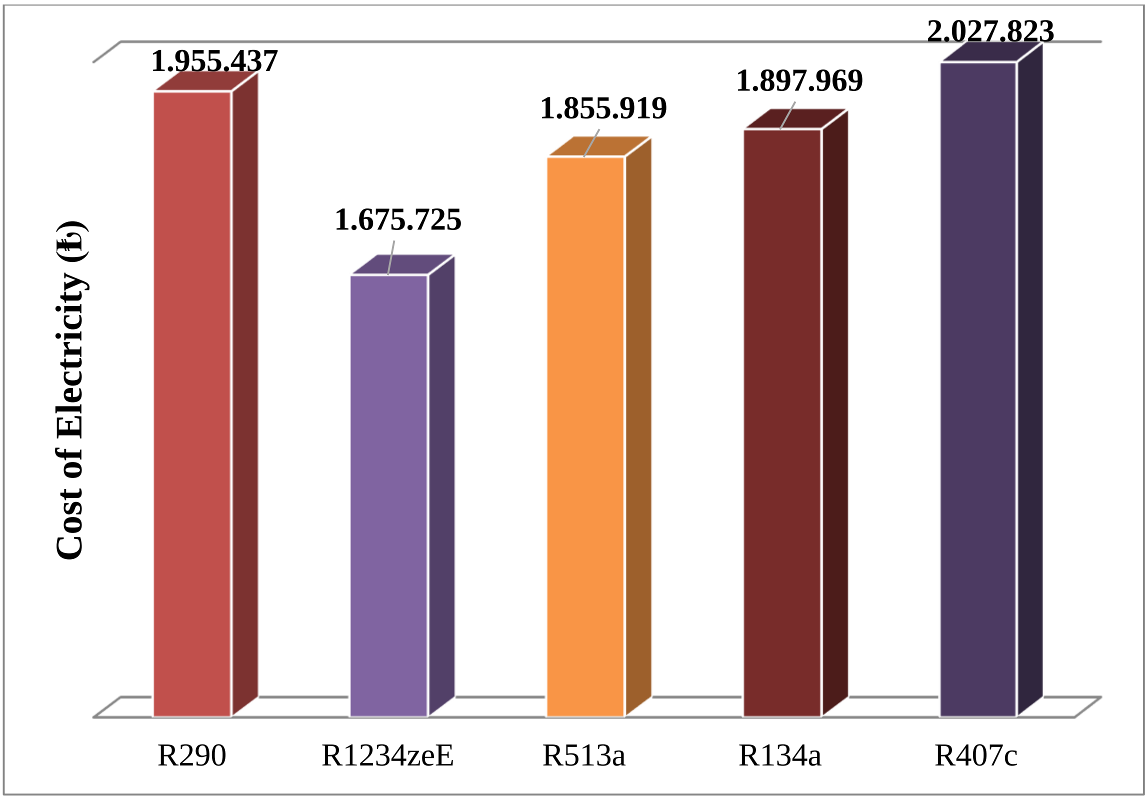

Figure 6. *Monthly electricity cost of the heat pump system*

The energy cost of the R1234zeE fluid, which is the most efficient among the analyzed refrigerants, is the lowest with 1.68 million ₺. If the R407c fluid is used, the monthly energy cost exceeds 2 million ₺. In the analysis, the unit price of electricity is taken as 3.09 ₺/kWh. All analysis is being done as the produced energy is not utilized within the plant. The cost of the sludge heating system is presented in this study. However, if the electricity is produced with 30% efficiency, then there is no energy cost for the plant.

IV. CONCLUSION

This study investigated reducing the moisture content of domestic wastewater treatment plant sludge by drying it with hot air coming from an air source heat pump. The sludge was from a domestic wastewater treatment plant and the moisture content was 44%. The moisture content was reduced to 10% with this drying system. 5 different refrigerants were analyzed and compared for the heat pump. According to the calculations, the CoP of the system varies between 3.20 and 6.00. The refrigerant with the highest CoP is R1234zeE. The lowest CoP belongs to R407c. While the CoP value of R407c is around 3.5, the CoP value of R1234zeE rises to 3.80 in winter and 6.00 in summer. In contrast, R134a refrigerant is the most frequently and easily available refrigerant and has the lowest performance in winter. However, it has the highest CoP value after R1234zeE in summer. It is calculated that the net amount of electrical energy obtained because of installing a heat pump system using R407c fluid and drying and burning the sludge will be around 730,000 kWh/month. This figure is sufficient to meet the energy consumption of 2,500 households consuming an average of 300 kWh of energy per month. Finally, in the absence of energy production, the most efficient system is the one with R1234zeE fluid, and the electricity cost of this system is 1.675 million ₺. In the case of the R407c refrigerant, the electricity cost is more than 2 million ₺. Sludge drying so that the sludge can be utilized in energy production with the help of a heat pump has been analyzed within the scope of this study. The investment cost of the system is not included in this study. Therefore, it is possible to carry out studies on topics such as investment cost analysis of the system, utilization of sludge in a better efficient energy production process, use of sludge as an input in the pyrolysis process, or research on drying with other renewable energy sources.

Nomenclature

CoP	Coefficient of Performance
Cp	Specific heat of supply air (kCal/m^3 C)
DM	Dry Matter
E_{comp}	Electricity consumption of the compressor (kWh)
$\dot{E}_{fan}$	Theoretical fan power (kW)
$\dot{E}$	Required thermal power (kW)
h_g	Enthalpy of saturated water at gas phase (kj/kg)
hf	Enthalpy of saturated water at fluid phase (kj/kg)
m	Volumetric Flow (m^3/hour)
$\dot{m}_t$	Mass flow rate of the sludge (kg/s)
M	Mass Moisture Flow Rate
MNEG	Monthly Net Energy Gain
Nm	Nominal Power
$\dot{Q}_{fan}$	Fan power (kW)
$\dot{Q}_{net}$	Net thermal power (kW)
t_m	Operation period (h/day)
y_{in}, y_{out}	Inlet and final moisture (%)
ΔP	Pressure difference supplied by fan (bar)
ρ	Density of the Sludge (kg/m^3)
η	Exchanger efficiency

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