Afyon Kocatepe Üniversitesi Uluslararası Mühendislik Teknolojileri ve Uygulamalı Bilimler Dergisi

Afyon Kocatepe University International Journal of Engineering Technology and Applied Sciences

AKÜ IJETAS Cilt **7(1)** (2024) Aralık (1-8 s)
AKU IJETAS **Vol 7(1)** (2024) June (1-8 pp)

DOI:10.53448/akuumubd.1411727

Araştırma Makalesi / Research Article

Kırıkkale İli İçin Hava Kaynaklı Bir Isı Pompasının Termodinamik İncelenmesi

Hüsamettin Tan[1], Zühtü Onur Pehlivanlı[2]

[1,2] *Kırıkkale Üniversitesi, Mühendislik ve Doğa Bilimleri Fakültesi, Makine Mühendisliği Bölümü, Yahşihan/Kırıkkale*
e-posta: husamettintan@hotmail.com[1], ORCID: 0000-0003-2576-8166 pehlivanli@kku.edu.tr[2] ORCID: 0000-0002-3094-5174

Geliş Tarihi: 29.12.2023 ; Kabul Tarihi: 14.02.2024

Öz

Bu çalışmada, R32 soğutucu akışkanlı hava kaynaklı bir ısı pompasının, Kırıkkale ili sınırları içerisinde bulunan bir konutun, kış aylarında ısı ihtiyacını karşılamak için kullanılabilirliği araştırılarak sistemin termodinamik analizi yapılmıştır. Çalışmada Kırıkkale ilinde son on yıl içerisinde görülmüş olan en düşük hava sıcaklığı Meteoroloji Genel Müdürlüğünden temin edilmiştir. Hesaplamalar, 2022-2023 yılları arasındaki Ekim – Nisan arasındaki ısıtma sezonunu örnek alınarak yapılmıştır. Çalışmada, dış ortamdan çekilen ısı, kompresörün enerji tüketimi, sistemin performans katsayısı ve ikinci yasa verimi parametreleri açısından incelenmiştir. Dış hava sıcaklığı azaldıkça çekilen ısı miktarı yaklaşık olarak %9 değerinde azalmaktadır. Bu doğrultuda ısıtma ihtiyacını karşılamak için kompresörün enerji tüketimi yaklaşık olarak %40 artmıştır. Elde edilen sonuçlar sistem performansı Ekim ve Ocak aylarında sırasıyla 5,545 ve 3,957 olarak hesaplanmıştır. Buna karşın ikinci yasa verimi Ocak ayı için 0,3266, Ekim ayı için 0,2103 olarak gerçekleştiği görülmüştür. Bulgular, hava kaynaklı ısı pompalarının iklimsel koşullara bağlı olarak değişen performansını vurgulamaktadır.

Anahtar kelimeler
Isı pompası; COP; Termodinamik analiz, II. yasa

Thermodynamic Analysis of an Air Source Heat Pump for Kırıkkale Province

Abstract

This study conducted a thermodynamic analysis of an air-source heat pump using R32 refrigerant to assess its effectiveness in meeting the heating needs of a residence in Kırıkkale province during winter. The air temperature in Kırıkkale was obtained from the Turkish State Meteorological Service according to the average of last ten years. Calculations were based on the heating season between October and April for the years 2022-2023. In the study, parameters such as heat gained from the environment, compressor energy consumption, the system's performance coefficient, and second-law efficiency have been examined. As the external air temperature decreases, the amount of gained heat decreases by approximately 9%. In this regard, the energy consumption of the compressor to meet heating demand has increased by approximately 40%. The results showed that the system performance was calculated as 5.545 and 3.957 for October and January, respectively. However, the second-law efficiency was observed to be 0.3266 for January and 0.2103 for October. The findings emphasize the varying performance of air-source heat pumps depending on climatic conditions.

Keywords
Heat pump; COP; Thermodynamic analysis, II. law.

1. Introduction

Climate change is a significant issue threatening all living beings worldwide. It is primarily caused by the emission gases arising from technological devices used for various purposes. Air-source heat pumps serve as an excellent electrical alternative to fossil fuel-based heating systems to reduce greenhouse gas emissions in residential areas. However, common temperate climate systems experience significant performance losses in regions with cold climates due to low external air temperatures. In this regard, evaluating the usage and efficiencies of air-source heat pumps for different climatic regions is crucial.

In this scope, various studies in the literature have been investigated. Congedo et al. (Congedo et al., 2023) conducted a modeling study emphasizing the comprehensiveness and robustness of the results through a multi-parameter approach to understand the climatic effects on air-source heat pumps. The study represented all Koppen climate regions for two climate systems with low and moderate operating temperatures, covering a broad spatial region worldwide. They detailedly analyzed the behavior of air-source heat pumps through seasonal performance and operating hour calculations. Naldi et al. (Naldi et al., 2015) investigated the seasonal performance of air-source heat pumps in heating of various buildings using a mathematical model in Italy. The study highlighted that there is an optimal external temperature value related to the selection of the heat pump size based on the building to increase the system's seasonal efficiency. (Yang et al., 2016) developed a simulation model for an Air Cycle Heat Pump Water Heater (ACHPWH) that considers the non-design performance of components. Then, they compared this model with experimental data in the literature. The study concluded that implementing a more efficient compressor and expander in the ACHPWH system would lead to a significant improvement in annual performance. Additionally, despite a decrease in the COP for reheating, the ACHPWH system provided substantial savings in heating time when operating at low ambient temperatures. Kazjonovs et al. Kazjonovs et al. (2014) conducted a study on residential buildings in Latvia, considering local climate conditions. The study aimed to characterize the efficiency of the heat pump by investigating the Seasonal Performance Factor (SPF) values of an air-to-water heat pump. The research focused on different types of heating systems during the winter season. The study concluded that air-to-water heat pumps could operate with an SPF ranging from 2.93 to 3.2 in the cold months of Latvia's climate. It emphasized that the operational costs of air-to-water heat pumps are lower compared to heating systems powered by natural gas, liquefied gas, diesel, and electricity. Zhang et al. (Zhang et al., 2017) proposed and implemented an air-source heat pump heating system to meet the demand for clean heating in cold regions of Northern China. In the study, a mathematical model was made to compare the primary energy consumption, emission rates, initial investment, and annual operating costs of different heating systems. They reported that air-source heat pumps could reliably and steadily meet space heating demands in residential buildings even when the external air temperature was -15 °C. Congedo et al. (Congedo et al., 2020) applied a numerical model in TRNSYS to investigate the use of an air-source heat pump (ASHP) system in conjunction with a horizontal ground heat exchanger (EAHX) to reduce energy consumption in buildings in extreme cold and hot climate regions such as Italy, Norway, and Algeria. The study reported that the ASHP-EAHX system outperformed the traditional ASHP in every season. Çoşkun et al. (Coşkun et al., 2023) conducted an economic analysis of the use of air-source heat pumps in İzmir province, investigating the hourly outdoor temperature data and electricity costs. They reported that, in the case of energy consumption being priced with a multi-tariff system, the energy cost would decrease by 20%. Konrad (Konrad & MacDonald, 2023) conducted an analysis of existing air-source heat pumps in the market, presenting their shortcomings. Regarding cold climate heat pumps, the study also highlighted additional design concepts and innovations that have not yet been implemented by the industry but could further enhance the performance and adoption of heat pumps. Jesper et al. (Jesper et al., 2021) have developed an accurate understanding and model regarding the performance of heat pumps in terms of economics, energy, and the environment in large-scale applications. Their study focuses on examining the impact of system design and operating conditions on the coefficient of performance (COP) of large-scale (>50 kWth) electrically-driven mechanical compression heat pumps. Baglivo et al. (Baglivo et al., 2023) have conducted a predictive analysis of the short, medium, and long-term behavior of air-source heat pumps in two cities with extremely cold and hot climates. They emphasized that, considering the impact of climate change, heat pumps could be used in geographic regions where they are currently not employed due to extremely low winter temperatures.

The studies conducted in the literature indicate that the usability and efficiency of air-source heat pumps vary by region, emphasizing the need for region-specific evaluations. In light of this information, this study investigates the usability and efficiency of an air-source heat pump system for residential heating in Kırıkkale province, located in the Inner Anatolia region of Turkey and characterized by a temperate climate zone. This study provides a significant contribution by evaluating the use of air-source heat pumps specific to regional climatic conditions. A selected air-source heat pump was implemented in a residence within the region, and thermodynamic analyses were conducted through modeling for the heating season (October-April).

2. Material and Method

2.1 System design

The schematic representation of the heat pump used in the study is given in Figure 1. The selected system is an air-source heat pump, widely utilized due to its commonality and ease of use. The general operating principle of the system is gaining heat from the external air ($\dot{Q}_L$) and pumping it to the high-temperature element through the compressor. The system consists of two regions: the low-pressure region and the high-pressure region. The heat required for the evaporator in the low-pressure region ($\dot{Q}_L$) is absorbed from the air, and the refrigerant circulating within the system is vaporized and sent to the compressor (#1). The temperature and pressure of the refrigerant entering the compressor are increased, and then sent to the condenser in the high-pressure region (#2). The heat load ($\dot{Q}_H$) required for heating the environment is released from the refrigerant in the condenser, and the refrigerants exits the condenser as saturated liquid (#3). To allow the cycle to repeat, the refrigerant is sent to the evaporator by providing pressure drop through the expansion valve (#4).

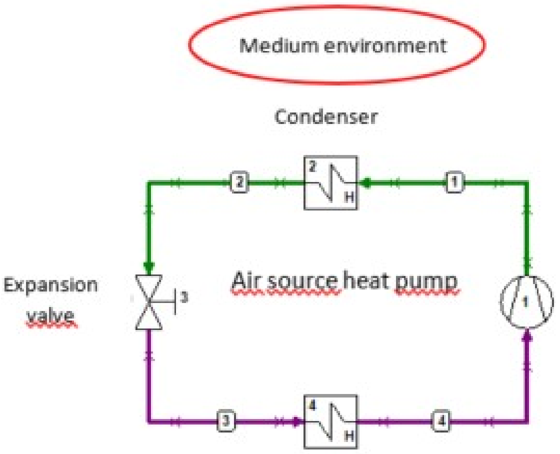

Figure 1. The schematic of the heat pump

2.2 The modelling of system and basic assumptions

During the system modeling, design values and assumptions were made for the environment and the system. Primarily, the ambient air will be utilized as the heat source. In this context, the average ambient temperature values for Kırıkkale province, where the study is conducted, are provided in Figure 2 for the October, November, December, January, February, March, and April (MGM, 2023). Heating is required for Kırıkkale province during the considered months. Additionally, the ambient air temperatures determine the design values for the evaporator temperatures.

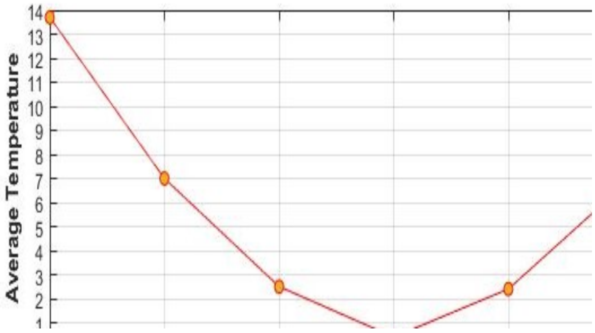

Figure 2. The average temperature of months

Energy analyses for the system were conducted based on the design conditions and assumptions provided below.

- ✓ Steady flow; changes in kinetic and potential energies have been neglected in all control volumes.
- ✓ The pressure losses in heat exchangers and pipes have been neglected.
- ✓ The throttling process is assumed to be isentropic.
- ✓ The condenser exit is assumed to be saturated liquid, and the evaporator exit is assumed to be saturated vapor.
- ✓ The compressor and expansion device are assumed to be adiabatic.
- ✓ The isentropic efficiency of the compressor is assumed to be 0.7.
- ✓ The temperature difference between the evaporator operating temperature and the ambient temperature is assumed to be 3°C, and the condenser operating temperature is assumed to be 45°C.
- ✓ The ambient pressure is assumed to be 1 bar, and the room temperature is assumed to be 298 K.
- ✓ The heating capacity of the heat pump is determined to be 20 kW.
- ✓ The working refrigerant is R32.

Design conditions, in accordance with the determined and assumed parameters, have been utilized to conduct thermodynamic analyses for the heat pump. The analyses were performed using energy equations for the system elements. Energy analyses for each system element were conducted based on Equations 2.1 and 2.2. The energy equations for system elements are given sequentially.

$$\text{Mass Balance} \longrightarrow \sum \dot{m}_i - \sum \dot{m}_o = 0 \qquad 0.1$$

$$\text{Energy Balance} \longrightarrow \sum \dot{E}_i - \sum \dot{E}_o = 0 \qquad 0.2$$

Compressor;

Neglecting kinetic and potential energy changes, the isentropic efficiency and energy equation for the adiabatic condition can be expressed as Equations 2.3 and 2.4.

$$\eta_c = \frac{h_{1s} - h_4}{h_1 - h_4} \qquad 0.3$$

$$\dot{W}_c = \dot{m}_{hp} * (h_1 - h_4) \qquad 0.4$$

Condenser;

Neglecting kinetic and potential energy changes, the energy equation for the adiabatic process (heat supplied to the indoor environment for heating) and the isobaric process can be expressed as Equation 2.5.

$$\dot{Q}_H = \dot{m}_{hp} * (h_1 - h_2) \qquad 0.5$$

Expansion valve;

Neglecting kinetic and potential energy changes, the energy equation for the adiabatic process and the isenthalpic process can be expressed using Equation 2.6.

$$h_2 = h_3 \qquad 0.6$$

Evaporator;

Neglecting changes in kinetic and potential energy, Equation 2.7 expresses the energy equation for the adiabatic and isobaric processes.

$$\dot{Q}_L = \dot{m}_{\iota p} * (h_4 - h_3) \qquad 0.7$$

The coefficient of performance (COP) of the system can be expressed as Equation 2.8.

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_c} \qquad 0.8$$

The II. law efficiency of the system can be expressed as Equation 2.9.

$$\eta_{II} = \frac{COP_{HP}}{COP_{REV}} \qquad 0.9$$

Here, COP_{REV} represents the performance coefficient of the reverse heat pump and can be expressed as Equation 2.10.

$$COP_{REV} = \frac{1}{1 - \frac{T_L}{T_H}} \tag{0.10}$$

2.3 Validation Study

The experimental study conducted by Dikici et al. (Dikici et al., 2006) was referenced for the analytical validation of the work. The study pertains to the experimental investigation of an air-source heat pump. In the study, the operating temperatures of the evaporator and condenser were determined as 0°C and 28°C, respectively. The isentropic efficiency of the compressor was assumed to be 0.25, and the exit of the evaporator and condenser was considered to be saturated vapor and saturated lıquid, respectively. According to the design criteria, it was calculated by the analytical equations The results obtained in the study are compared with the analytical results in Figure 3.

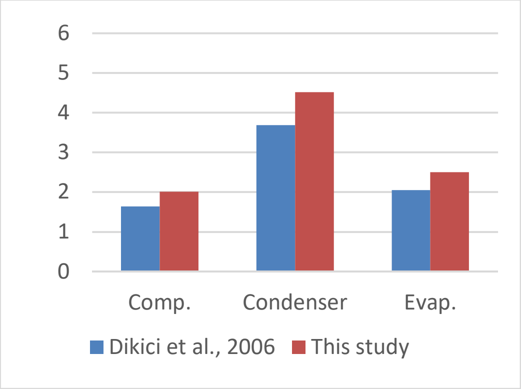

Figure 3. The model validation study

3. Results and Discussions

Energy analysis of the air source heat pump in the months when heating is needed for Kırıkkale province was made in line with the determined design values and assumptions. The energy equations were solved analytically in this situation. The results were compared in terms of the system's COP and reversible COP value, heat absorbed from the ambient environment ($\dot{Q}_L$), energy consumption of the compressor and second law efficiency parameters.

The distribution of heat absorbed from the ambient environment and compressor energy consumption for different months is given in Figure 4. It is observed that as the external ambient temperature decreases, the heat absorbed by the evaporator decreases. Similarly, with the heating capacity of the system being constant, it increases the energy consumption of the compressor. The lowest heat absorbed and energy consumption were calculated as 14.95 kW and 5.055 kW for the January, respectively. The highest heat absorbed and energy consumption were calculated as 15.17 kW and 4.836 kW for the December and February, respectively.

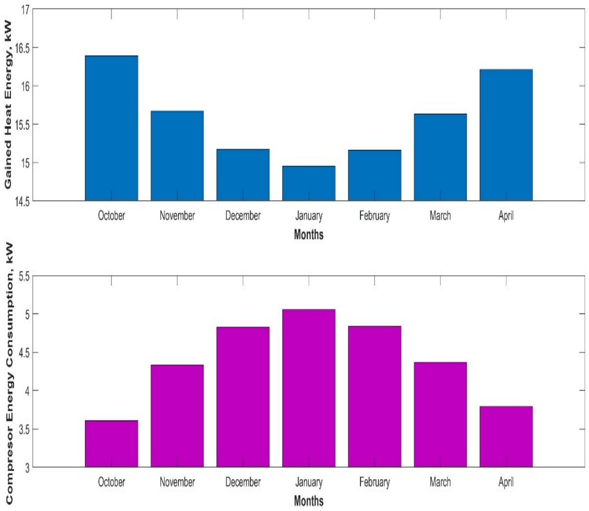

Figure 4. Gained heat energy and compressor energy consumption

The distribution of the system's Coefficient of Performance (COP) for different months is given in Figure 5. It is observed that the COP of the system decreases with a decrease in the external ambient temperature. The lowest COP value is calculated for the January, which has the lowest external ambient temperature. The highest COP value is calculated for October, which has the highest external ambient temperature. The variation in COP between the highest and lowest external ambient temperatures is approximately 28%.

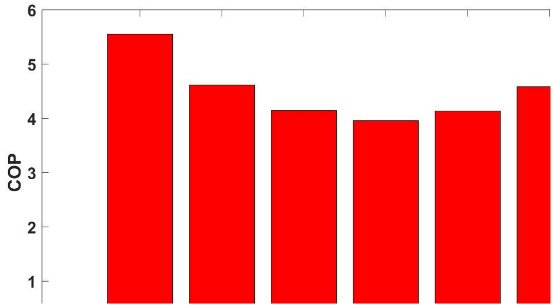

Figure 5. System COP values for different months

The reversible COP values, representing the maximum performance the system can achieve based on ambient temperatures, and the results for the second law efficiency are shown in Figure 6. As seen in Figure 6a, the reversible COP values are the lowest and highest in January and October, respectively. Accordingly, in Figure 6b, the months with the lowest and highest second law efficiency are October and January, respectively. In terms of the second law efficiency, the variation between the lowest and highest values is approximately 53%. This situation similarly valid to the reversible COP values.

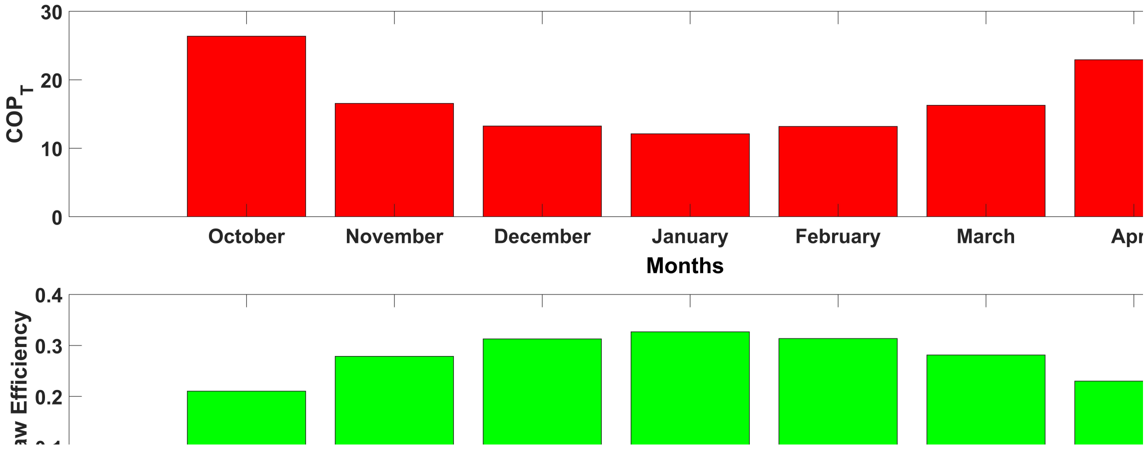

Figure 6. Reversible COP (Coefficient of Performance) and second law efficiency for different months

4. Conclusion

The use of a heat pump for heating needs in the Kırıkkale province has been investigated within the scope of the study. In this context, a basic air-source heat pump system was selected, considering the reference external air conditions. Parameters such as the heat gained from the environment, consumed energy, COP (Coefficient of Performance), and second law efficiency were taken into account for the comparison between different months. Results obtained by solving analytical equations based on specific design values and assumptions are summarized below.

- ✓ The heat gained decreases, and the consumed energy increases as the external ambient temperature decreases.
- ✓ The decrease in the heat gained is a result of the decrease in the ambient temperature, leading to a reduction in the enthalpy of evaporation and an increase in the compressor discharge temperature, which, in turn, causes a decrease in the mass flow rate circulating in the system.
- ✓ As the external ambient temperature decreases, the increase in the pressure difference between the evaporator and condenser leads to an increase in the compressor discharge temperature. This condition not only increases compressor energy consumption but also reduces the system COP value.

- ✓ From the perspective of the second law, the highest value is observed to be 0.3266 for January, while the lowest value is 0.2103 for October. This situation arises due to the highest reversible COP value that can be achieved in October and the lowest reversible COP value that can be achieved in January.

In the analyses conducted for all months, the heating capacity has been assumed to be constant. In future studies, analyses can be conducted in terms of energy and exergy considering heating capacities determined based on the average external ambient temperatures for each month in the selected climatic region.

Abbreviations and symbols

TRSSP: Transient Systems Simulation Program

ACHPWH: Air Cycle Heat Pump Water Heater

SPF: Seasonal Performance Factor

$\dot{\mathrm{Q}}_{\mathrm{L}}$: Gained heat

$\dot{\mathrm{W}}_{\mathrm{C}}$: Energy consumption

$\dot{\mathrm{E}}_{\mathrm{i}}$: Energy input

$\dot{\mathrm{E}}_{o}$: Energy output

$\dot{\mathrm{m}}_{\mathrm{hp}}$: Mass flow rate of heat pump

$\mathrm{COP}_{\mathrm{HP}}$: Coefficient of the performance

η_{II}: Second law

$\mathrm{COP}_{\mathrm{REV}}$: Reversible coefficient of the performance

η_c: Isentropic efficiency of the compressor

T_L: low environment temperature

T_H: High environment temperature

h: Entalpy

5. References

Baglivo, C., Mazzeo, D., Matera, N., & Congedo, P. M. (2023). Air-source Heat Pump Under Very Climate Change Scenarios: A Numerical Analysis. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *11*(3), 1–12. https://doi.org/10.13044/j.sdewes.d11.0458

Congedo, P. M., Baglivo, C., Bonuso, S., & D'Agostino, D. (2020). Numerical and experimental analysis of the energy performance of an air-source heat pump (ASHP) coupled with a horizontal earth-to-air heat exchanger (EAHX) in different climates. *Geothermics*, *87*(January 2019), 101845. https://doi.org/10.1016/j.geothermics.2020.101845

Congedo, P. M., Baglivo, C., D'Agostino, D., & Mazzeo, D. (2023). The impact of climate change on air source heat pumps. *Energy Conversion and Management*, *276*(August 2022), 116554. https://doi.org/10.1016/j.enconman.2022.116554

Coşkun, C., Oktay, Z., & Birecikli, B. (2023). *International Journal of Energy Applications and Technologies Investigation of the economic aspects of air source heat pump usage for Izmir province*. *10*(1), 26–33. https://doi.org/10.31593/ijeat.1249609

Dikici, A., Akbulut, A., & Gülçimen, F. (2006). Güneş, Hava Ve Toprak Enerjisi Kaynaklı Isı Pompalarının Elazığ Şartlarında Kullanımının Deneysel Olarak Araştırılması Ve Enerji Ve Ekserji Analizleri. *J. of Thermal Science and Technology*, *25*, 49–61.

Jesper, M., Schlosser, F., Pag, F., Walmsley, T. G., Schmitt, B., & Vajen, K. (2021). Large-scale heat pumps: Uptake and performance modelling of market-available devices. *Renewable and Sustainable Energy Reviews*, *137*(September 2020), 110646. https://doi.org/10.1016/j.rser.2020.110646

Kazjonovs, J., Sipkevics, A., Jakovics, A., Dancigs, A., Bajare, D., & Dancigs, L. (2014). Performance analysis of air-to-water heat pump in Latvian climate conditions. *Environmental and Climate Technologies*, *14*(1), 18–22. https://doi.org/10.1515/rtuect-2014-0009

Konrad, M. E., & MacDonald, B. D. (2023). Cold climate air source heat pumps: Industry progress and thermodynamic analysis of market-available residential units. *Renewable and Sustainable Energy Reviews*, *188*(May), 113739. https://doi.org/10.1016/j.rser.2023.113739

Müdürlüğü, M. G. (2023). *Seasonal norms for the provinces*. https://Mgm.Gov.Tr/Veridegerlendirme/Il-ve-Ilceler-Istatistik.Aspx?Ysclid=lqqame0z3d363539405.

Naldi, C., Dongellini, M., & Morini, G. L. (2015). Climate influence on seasonal performances of air-to-water heat pumps for heating. *Energy Procedia*, *81*, 100–107. https://doi.org/10.1016/j.egypro.2015.12.064

Yang, L., Yuan, H., Peng, J. W., & Zhang, C. L. (2016). Performance modeling of air cycle heat pump water heater in cold climate. *Renewable Energy*, *87*, 1067–1075. https://doi.org/10.1016/j.renene.2015.08.055

Zhang, Q., Zhang, L., Nie, J., & Li, Y. (2017). Techno-economic analysis of air source heat pump applied for space heating in northern China. *Applied Energy*, *207*, 533–542. https://doi.org/10.1016/j.apenergy.2017.06.083