JEE Journal of Ecological Engineering

*Journal of Ecological Engineering* 2024, 25(8), 317–324
https://doi.org/10.12911/22998993/190286
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.06.03
Accepted: 2024.06.24
Published: 2024.07.01

# The Influence of Atmospheric Air Temperature on the Consumption of Natural Gas in Terms of Heating Costs of a Single-Family Building – A Case Study

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## ABSTRACT

The aim of this study was to determine the costs of heating a single-family detached home with natural gas during the heating season, considering the variability of atmospheric air temperature. In addition, this study composes a forecast of monthly costs incurred for heating a single-family detached home as an operational guideline for potential users of this type of residential building. The research was conducted during 7 heating seasons covering the years 2015–2022. Daily gas consumption was measured using an automatic gas consumption recorder. The ambient air temperature was gauged using the Nautilus 85 electronic sensor produced by the company ACR with a margin of error of 0.2 °C. As a result of this analysis, it was calculated that the average number of days in the heating season is 232 days per year. The average consumption of natural gas for heating purposes is 1.438.1 $m^3$/season. The average expense of heating a building during the heating season is 696 €. Due to determining a high correlation between the daily ambient air temperature and the amount of gas used for heating purposes, it is possible to predict the costs associated with heating the building in the upcoming heating season.

**Keywords:** heating expenses, natural gas, heating season, ambient air temperature.

## INTRODUCTION

In the last two years, all-time high energy prices (electricity, natural gas, coal) have been documented in Europe, which in general is caused by the armed conflict in Ukraine. Increasing prices of energy sources, such as hard coal, lignite, wood, or natural gas, prompt many residents to replace the heating system of their buildings with alternative sources, such as heat pumps or electricity acquired from photovoltaic panels and geothermal energy (Bugajski et al., 2017, Herbut et al., 2019, Schreurs et al., 2021, Operacz et al., 2024). Nevertheless, the usage of natural gas as a heating medium is and will be in the forthcoming years one of the most common methods of heating single-family detached homes in Poland (Kulesza and Maludziński, 2021). This is indicated by the growing consumption of natural gas in Poland, where in 2016 the usage amounted to 16 billion $m^3$, and in 2021 it amounted to 19.5 billion $m^3$. In 2022, the annual usage of natural gas decreased to 16 billion $m^3$, but, as mentioned before, this was due to a substantial upsurge in the prices of this raw material. In the coming years, natural gas consumption is expected to increase again in Poland and Europe (Paliński, 2021). For the current and future users of residential buildings, the maintenance expenses, including the costs of water consumption, sewage disposal, electricity consumption, and heating are immensely important. If the building's source of heating is the combustion of non-renewable resources, such as coal, natural gas, or heating oil, the cost of heating will comprise approximately 50% of all utility expenses. The costs of heating buildings depend, of course, on many factors, such as the geographical location of the building, the type of building technology, the type of building insulation, and the programmed internal temperature during the heating season (Eguiartea et al., 2022, Bugajski, 2017). Considering the $CO_2$ emissions from burning natural gas compared to burning hard coal and lignite, natural gas is an environmentally friendly fuel. In the case of burning hard coal, about 2.86 kg of $CO_2$ is emitted per kW/h of energy produced. In the case of lignite, this figure is about 3.11 kg of $CO_2$ per kW/h of energy produced, while in the case of natural gas, about 1.93 kg of $CO_2$ is emitted per kW/h of energy produced (Ściążko, 2009).

The research aimed to determine the costs of heating with natural gas during the heating seasons of a single-family building in terms of the influence of atmospheric air temperature variability. In addition, the work presents a prognosis of monthly costs incurred for heating a single-family detached home as an operational guideline for potential users of this type of residential building.

## MATERIALS AND METHODS

### Description of a residential building

The residential building in which gas consumption measurements were made is located in the Wieliczka County, Lesser Poland Voivodeship, Poland (50°1'21.498" N; 20°6'7.345" E).

The building has a usable area of approximately 140 m$^2$ and is constructed with MAX U-220 ceramic block material. The walls are insulated with 12 cm thick polystyrene, while the attic is insulated with 20 cm thick fiberglass. There are five draw-off points in the building where hot water is delivered, located in two bathrooms (on the ground floor and in the attic) and the kitchen. To heat utility water and process water, a dual-function boiler with a sealed combustion chamber and a power of 14 kW and a utility water tank with a volume of 60 dm$^3$ is utilized. The heating system is controlled by an automatic controller (thermostat) which is programmed to maintain a minimum temperature of 21.5 °C during the heating season. The building is home to three permanent residents who are all adults. The building is heated with natural gas via a gas conduit with a diameter of DN = 40 mm.

### Analytical and statistical methods

The research was conducted over seven heating seasons from 2015 to 2022. The daily gas consumption was measured using an automatic gas consumption recorder that is programmed to read at 23:59 every day.

The Nautilus 85 electronic sensor, provided by the company ACR, was used to measure the ambient air temperature. It has a margin of error of 0.2 °C. The sensor, along with the data recorder, were placed at a height of 2 meters in a weather cage located on the building owner's property. To determine the average daily air temperature, 24 measurements were taken at an interval of 1 hour, and the arithmetic average of these measurements was calculated.

When analyzing the frequency of occurrence of characteristic amounts of daily natural gas consumption, the number and range of class intervals were determined based on the guidelines provided by Jóźwiak and Podgórski in 2001.

$$k \leq 5 \log n \tag{1}$$

where: $k$ – number of class intervals ($5 < k < 20$);
$n$ – number of the study samples

Carefully selecting the class intervals achieves a distribution series that provides a highly detailed and transparent view of the statistical set's structure.

Statistical analysis regarding Pearson's linear correlation was performed using the „STATISTICA 8" (StatSoft, Inc., USA). The significance of the studied connection was checked with the Student's t-test at the significance level α = 0.05.

## RESULTS AND DISCUSSION

The analysis conducted on the consumption of natural gas for heating purposes did not include the consumption of gas for heating domestic water. The usage of gas for heating domestic water amounts to 0.4 m$^3$ per day. The daily consumption of natural gas for heating domestic water was determined based on the average consumption during the non-heating period from 2015 to 2022.

The heating season for each calendar year begins when the temperature inside the building drops to 21.5 °C and ends at the same temperature. The temperature in living rooms set at 21.5 °C was considered optimal for the functioning of residents according to the recommendations of Nakagami et al. (2022), Seri et al. (2021), and Sellaro et al. (2015). The heating period, during which a temperature of 21.5 °C inside the building was maintained, in the 7 analyzed periods lasted on average 232 days, which constituted 63.3% of the time in each analyzed year. In individual heating seasons, the beginning of the heating season usually started around the end of September or the beginning of October and ended during a period of time starting in the last 10 days of April (2017/18 season) to the first 10 days of June (2020/21 season). The average consumption of natural gas during the heating season was 1,438.1 m$^3$ per season. In individual heating seasons, the amount of natural gas used for building heating ranged from 1,120.6 to 1,729.0 m$^3$ per season.

According to the guidelines currently in force in Poland, the costs of natural gas consumption for heating purposes in a single-family house are defined as the unit of measurement in kWh. According to the W-3.6 tariff group, to which the analyzed residential building is classified, the amount of kWh is calculated as the product of the amount of gas consumed in m$^3$ and the conversion factor of Wk = 11,359 kWh/m$^3$. According to the current unit price of kWh = PLN 0.20,017/kWh, the price of 1 m$^3$ of gas is approximately PLN 2.27/m$^3$. Assuming the exchange rate of 1 € = 4.69 PLN (rate of January 10, 2023), the price of 1 m$^3$ of gas is approximately 0.48 €/m$^3$.

The highest building heating costs were recorded during the 2016/2017 season, which amounted to 837 € per season. However, the lowest costs were for the 2021/2022 season, which amounted to 542 € per season. The average heating costs in the 7 heating seasons studied amounted to 696 € per m$^3$ (Fig. 1). The number of days in the analyzed heating season and the amount and costs of gas consumption in individual heating periods are presented in Table 1. The following data presents the cost of heating a building during the heating season, including the cost in individual months. The data is illustrated using histograms in Figure 2 (A, B, C, D, E, and F) to show the imbalance of the daily amount of gas consumed for heating purposes in individual heating seasons. Each histogram contains 7 class intervals with a class rang of 3 m$^3$/d.

During the 2015/2016 season, which lasted 221 days, the average daily gas consumption was mostly in the range of 3 to 6 m$^3$/d in 40.3% of the cases, while in 33.5% of the cases it was in the range of 6 to 9 m$^3$/d. Gas consumption above 15 m$^3$/d was considered incidental.

In the following season, 2016/2017, the distribution of daily gas consumption was slightly different, with 29.3% of the cases recording daily gas consumption in the range of 3 to 6 m$^3$/d, 25.3% in the range of 6 to 9 m$^3$/d, and 23.6% in the range of 9 to 12 m$^3$/d. As in the previous season, gas consumption above 15 m$_3$/d was incidental.

The 2017/2018 season saw a different distribution of average daily gas consumption than previous seasons, with 31.5% of the cases recording gas consumption in the range of 6 to 9 m$^3$/d, and 25.8% in the range of 9 to 12 m$^3$/d. Gas consumption above 15 m$^3$/d was recorded in only 2.8% of the cases.

In the 2018/2019 season, the dominant daily gas consumption was in the range of 3 to 6 m$^3$/d (31.4 cases), 1 to 3 m$^3$/d (28.0% of the cases), and 6 to 9 m$^3$/d (25.8% of the cases).

This season, there were no days when gas consumption exceeded 15 m$^3$/d. The 2019/2020 heating season was exceptional in terms of the structure of the daily amount of gas consumed since approximately 31% of the cases were recorded in three class intervals, i.e., from 1 to 3 m$^3$/d, from 3 to 6 m$^3$/d, and from 6 to 9 m$^3$/d. No daily gas consumption exceeding 15 m$^3$/d was recorded this season.

Similarly to the previous season, in the 2020/2021 season, the range of variability of average daily gas consumption was at a similar level in three ranges. Approximately 28% of the cases were recorded in the range of 1 to 3 m$^3$/d, 3 to 6 m$^3$/d, and 6 to 9 m$^3$/d. No daily gas consumption exceeding 15 m$^3$/d was recorded this season. In the last research season, 2021/2022, as many

**Table 1.** Number of days, amount of used natural gas, and the costs of heating in specific heating seasons

| Parameter | Unit | Heating season | | | | | | | Average |
|---|---|---|---|---|---|---|---|---|---|
| | | 2015/2016 | 2016/2017 | 2017/2018 | 2018/2019 | 2019/2020 | 2020/2021 | 2021/2022 | 2015–2022 |
| The days of the heating season | Number of days | 221 | 225 | 213 | 236 | 253 | 248 | 225 | 232 |
| The amount of gas used | m$^3$/season | 1488.0 | 1729.0 | 1624.0 | 1394.3 | 1298.7 | 1412.2 | 1120.6 | 1438.1 |
| The cost of gas consumption | zł/season (€/season) | 3378 (720) | 3925 (837) | 3686 (786) | 3164 (675) | 2946 (628) | 3205 (683) | 2542 (542) | 3264 (696) |

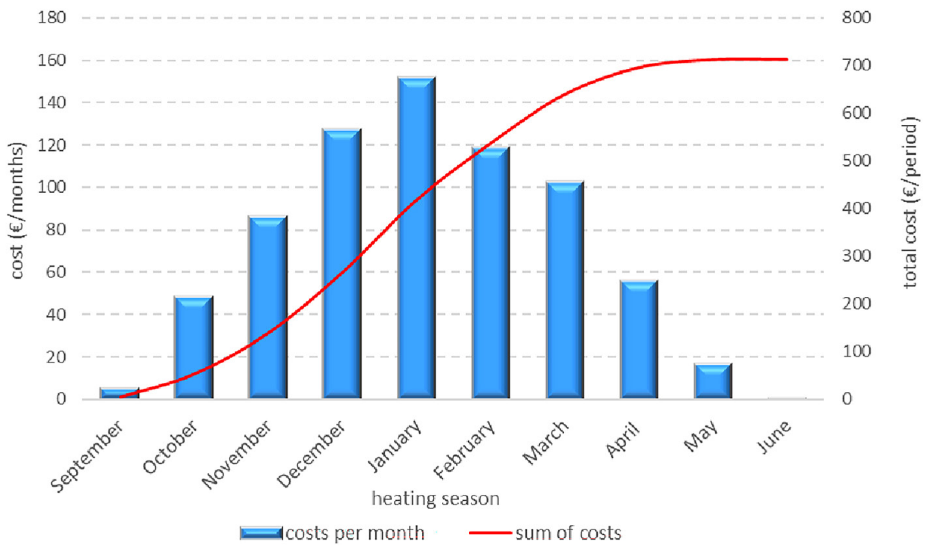


**Figure 1.** Cost in respective months and the total cost of heating the building during the heating season

as 36% of the cases were most often recorded in the range between 6 and 9 $m^3/d$. Gas consumption most often ranged from 3 to 6 $m^3/d$. No daily gas consumption exceeding 15 $m^3/d$ was recorded this season.

Over the course of a 7-year measurement period, it was discovered that the average daily gas consumption varied by month. In September, it was 1.9 $m^3/d$, in October it was 3.3 $m^3/d$, in November it was 6.0 $m^3/d$, in December it was 8.6 $m^3/d$), in January it was 10.2 $m^3/d$, in February it was 8.8 $m^3/d$, in March it was 6.9 $m^3/d$, in April it was 4.1 $m^3/d$, in May it was 2.4 $m^3/d$, and in June it was 0.9 $m^3/d$. The greatest fluctuation in gas consumption occurred in January, ranging from 2.2 to 20.0 $m^3/d$, while the smallest fluctuation was recorded in May, with changes ranging from 0.6 to 3.2 $m^3/d$. The analysis did not include the month of June due to the limited number of measurements obtained. Figure 3 shows the characteristic daily amounts of gas consumed during the 7 seasons of research. Moving forward with the static analysis, the next step involves refining the daily gas consumption distribution to establish an empirical model for variable gas usage in heating. To ensure the empirical distribution of daily gas consumption aligns with the theoretical logarithmic-normal distribution, we conducted a null hypothesis verification using both the non-parametric Kolmogorov-Smirnov test and the chi-square test. Figure 4 provides a visual representation of the theoretical distribution's fit to the empirical distribution, which accurately depicts the frequency of specific daily gas consumption. The results of the verification analysis indicate that, at a significance level of $\alpha = 0.05$, there is no evidence to reject the null hypothesis for the daily gas consumption data. This implies that the empirical distribution of daily gas consumption for heating purposes in the analyzed residential building can be modeled using a log-normal distribution. In the subsequent stage of the analysis, the effect of external air temperature on the amount of gas consumed for heating purposes in a residential building was examined for seven research periods from 2015 to 2022. Pearson's linear correlation coefficient was used to determine the association between the amount of gas consumed (dependent variable) and the atmospheric air temperature (independent variable). The correlation coefficient ($r_{xy}$) was utilized to provide a quantitative measure of the linear relationship between the variables. The significance of the calculated regression coefficient was assessed by applying Student's t-test at a significance level of $\alpha = 0.05$. The findings suggested that the intercept term in the regression equation describing the above relation was not significant. The mutual dependence of natural gas consumption on atmospheric air temperature was evaluated, and it was discovered that the correlation between these variables is $r_{xy} = 0.86$, indicating a very high level of correlation according to the scale proposed by Czaja and Prewed (2000). From the equation describing the regression line presented in Figure 4, it can be inferred that a 1 °C increase in atmospheric air temperature results in a 0.52 $m^3/d$ increase in gas consumption. An informative scatterplot has been generated,

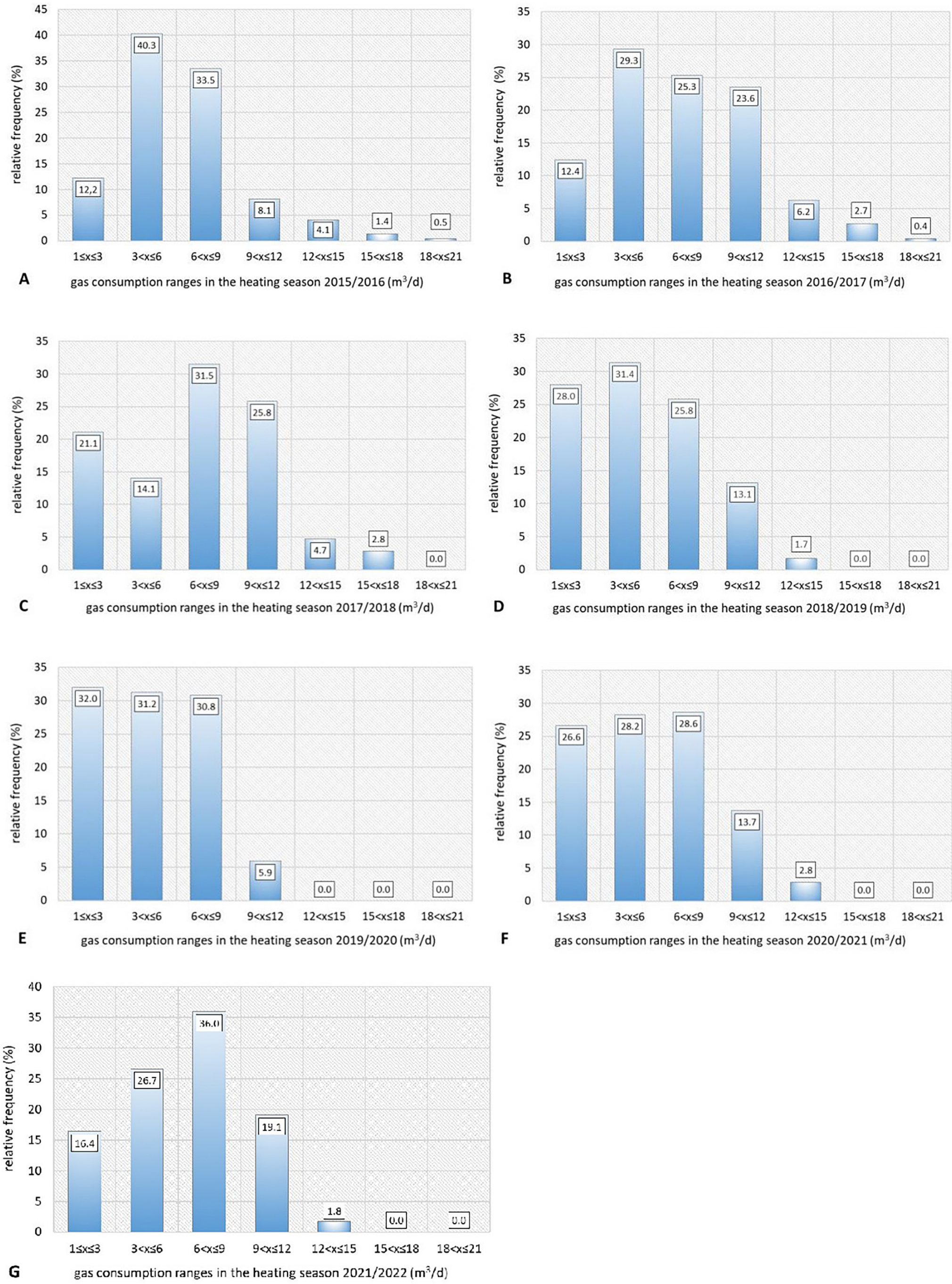


**Figure 2.** The histogram of the frequency of dependence of the typical daily consumption of natural gas during individual heating seasons

displaying a regression line and 95% confidence level, which highlights the correlation between atmospheric air temperature and gas consumption for heating purposes. This visual representation provides valuable insights into the influence of temperature on energy usage, and can be used to inform future decision-making regarding resource allocation and energy conservation. It is imperative for building operators to take into account long-term projections of ambient air temperature in order to develop a forecast of gas consumption and associated costs. Through the use of a developed regression line, as illustrated in Figure 5, a forecast of the daily amount and costs of gas consumption can be presented in Table 2, based on variations in atmospheric air temperature. This approach allows for a more informed decision-making process, thereby contributing to the efficient management of the building's resources.

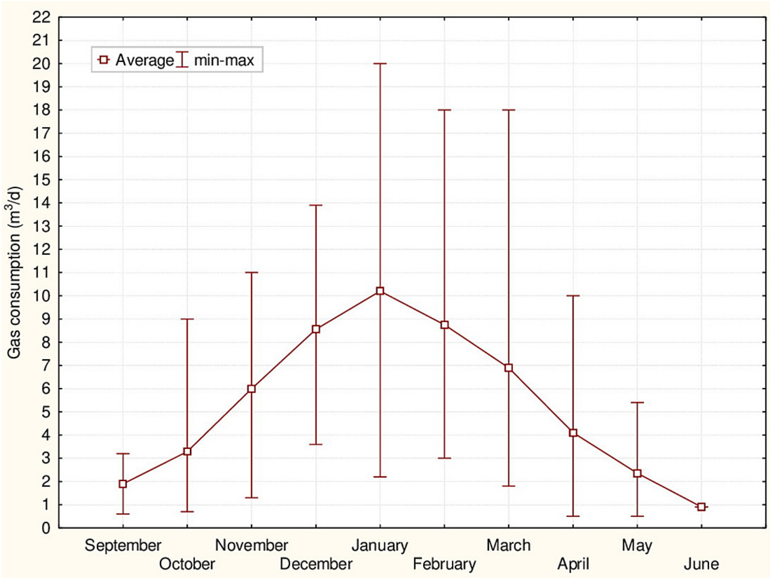


**Figure 3.** Variability of gas consumption in individual months in the research period

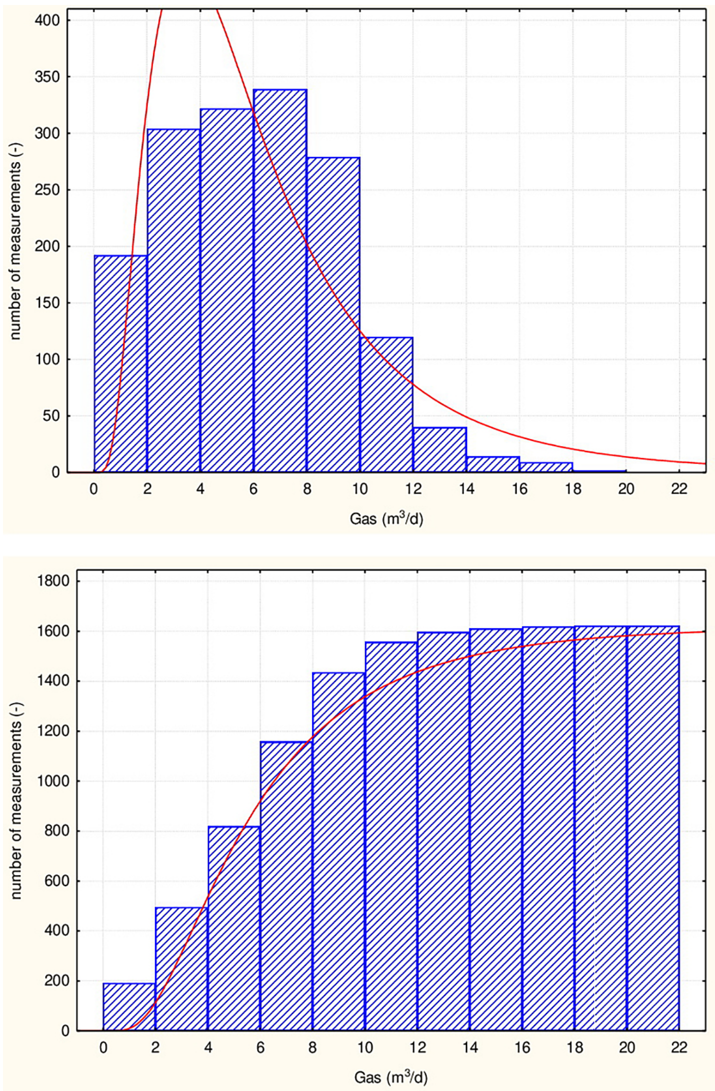


**Figure 4.** Histogram with density function and empirical and theoretical distribution function showing the fit of the log-normal distribution to the empirical distribution of the daily amount of gas consumed.

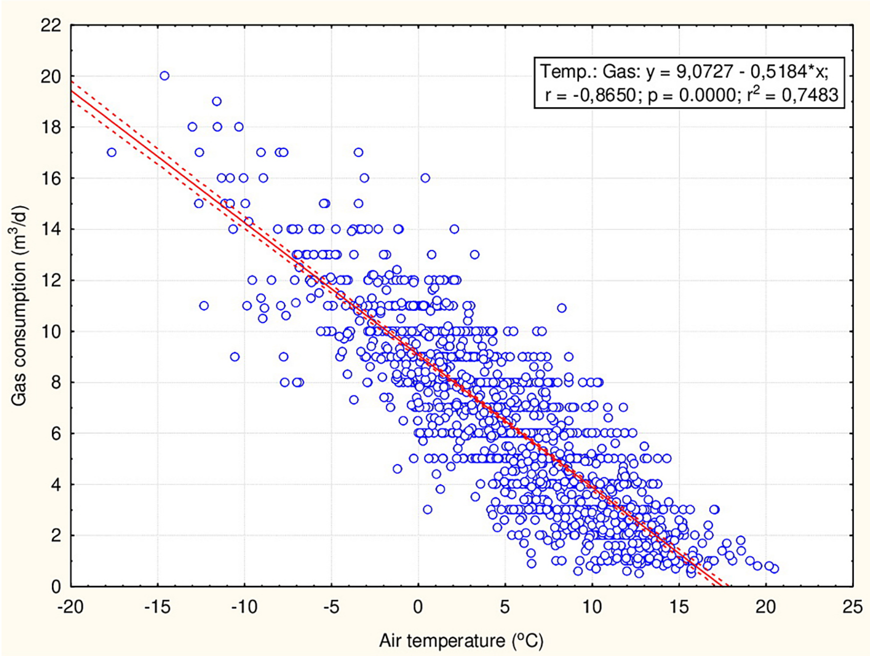


**Figure 5.** Scatter graphs with regression lines and 95% confidence levels for correlations between atmospheric air temperature and gas consumption for heating purposes

**Table 2.** Prognosis of daily consumption and prices of natural gas for heating purposes

| Consumption and cost | Air temperature (°C) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | -20 | -15 | -10 | -5 | 0 | 5 | 10 | 15 | 20 |
| ($m^3$/d) | 19.5 | 16.8 | 14.0 | 12.2 | 9.0 | 6.3 | 4.0 | 0.8 | 0.4 |
| (€/d) | 9.4 | 8.1 | 6.7 | 5.9 | 4.3 | 3.0 | 1.9 | 0.4 | 0.2 |

## CONCLUSIONS

Through a thorough analysis, it has been determined that the cost of natural gas consumption for heating a residential building with an area of 140 m² during the heating season amounts to roughly 700 €. Accurately estimating monthly heating costs is a crucial factor for residents to effectively plan their home budget. The information gathered on the costs of heating a building with natural gas serves as a valuable resource for individuals who wish to install or upgrade their heating system, as it allows for a comparison between different heat sources such as coal, wood, heat pump, and others. Despite the professional insulation of the building, it was discovered that in the climatic conditions of southern Poland, the atmospheric air temperature significantly affects the amount of natural gas consumed for heating purposes. The highest gas consumption is observed during the months of December, January, and February, while minimal gas usage for heating purposes occurs in the months of September, May, and June. In general, the research results can be dedicated to buildings in which the range and duration of air temperature is similar to the climatic conditions occurring in the Małopolska region. It is also important that the research results refer to buildings made of ceramic bricks and the building is insulated with a 12 cm layer of polystyrene.

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