COMPARATIVE ANALYSIS OF HEATING ENERGY SOURCES IN ALCOHOL DISTILLATION: EFFICIENCY, COST, AND CARBON FOOTPRINT

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Abstract
The use of different energy sources in technological processes, specifically the distillation process, has its specific economic and ecological aspects. Natural gas is economically efficient, has high efficiency, but generates significant amounts of greenhouse gases. Electricity is convenient and precisely controllable but tends to be more costly in terms of economics. Traditional wood is often cost-effective when locally available, but its combustion is less efficient and produces local pollution. Wood pellets provide high efficiency and a low carbon footprint when managed properly and are a more sustainable alternative to fossil fuels. In the paper presented, the different energy sources will be evaluated from an economic and sustainable point of view

Key words: *distillation process; energy source; sustainable; economic.*

INTRODUCTION

Distillation is a process that requires a reliable and efficient heat source to separate components based on their different boiling points. In distillation, different types of energy can be used as heat sources, most commonly gas, electricity, wood and wood pellets. Each of these sources has advantages and disadvantages that affect the efficiency, cost and environmental impact of the process *(Bulii et al., 2022)*. Natural gas as a heat source brings high efficiency and easy temperature control, which is important for precise distillation control. The main advantages of using natural gas include high energy efficiency and clean combustion compared to other fossil fuels, resulting in lower CO_2 emissions and minimal production of pollutants such as nitrogen oxides or sulphur dioxide. The disadvantages of natural gas are that it is a non-renewable energy source with limited reserves and, more recently, its price has been volatile and subject to significant fluctuations *(Cenker, 2017)*. Electricity allows a clean heating process without direct fuel combustion and easy integration into distillation systems. Heating the boiler with electricity is economically uninteresting. This energy source makes sense in the distillation industry if the company has a photovoltaic system *(Früh et al., 2021)*. Wood as a traditional heat source is available and cost-effective but requires more storage space and can produce higher particulate matter and CO_2 emissions when burned incorrectly. However, the operator must be experienced enough to know how much wood to add at a given stage of distillation *(Mydlarz & Wieruszewski, 2024)*. Wood pellets are a greener alternative to traditional wood. Pellets have a higher calorific value and more homogeneous combustion. The combustion of wood pellets produces a low amount of CO_2 emissions *(Ritmantho, 2024)*. The aim of this study is to compare, from an economic and ecological point of view, the energy sources used for heating in distillation.

MATERIALS AND METHODS

The article is based on data recorded during 5 years *(1400 measurements)* in 4 distilleries in the Slovak Republic. These data were processed for the needs of The Slovak Distillers Association for The Production of Distillates. Prices for individual energy sources were obtained from Slovak suppliers.

Fig. 1 Distillation column KK 350

Distillation column KK 350 with a nominal volume of 350 litres were chosen for comparison *(see Fig. 1)*. Technical parameters of the distillation column KK350 for selected energy sources used for heating are presented in Tab. 1. The following values were used to calculate carbon footprints natural gas 0.2 kg · CO2e · kWh^{-1} *(Yanan et al., 2018)*, electrical energy 0.066 kg · CO2e · kWh^{-1} *(Giambattista & Violante & Iuliis, 2023)*, wood 1.6 kg · CO2e · kWh^{-1} *(Solli et al., 2009)*, wood pellets 0.29 kg · CO2e · kWh^{-1} *(Jovcevski & Lakovic & Jovčevski, 2018)*.

Tab.1 Technical parameters of the distillation column KK350 *(Distillation column, 2025)*

Distillation column KK 350			
Type of heating	Natural gas	Electrical energy	Wood/Wood pellets
Heating power	60kW	28.5 kW	60kW
Price	34 500 €	54 700 €	33 250 €

RESULTS AND DISCUSSION

The results of 5 annual measurements of the consumption of different energy sources are presented in Tab. 2. From tab. 2 is clear, that the lowest costs are for heating with wood, ranging from 3.55€ per 100 liters to 5.71 € per 900 liters of processed mash. By heating with wood pellets, the costs are from 5.10 € to 9.28€. In the case of heating with natural gas or electrical energy, we can conclude that for volumes up to 500 liters, heating with electricity is more cost-effective. When processing 900 liters of mash, the difference between electricity and natural gas is 3.94€. This represents a 24.5% lower cost for gas.

Tab. 2 Results of consumption measurements

Volume of mash	Natural gas	Price	Electrical energy	Price	Wood	Price	Wood pellets	Price
l	kWh	€	kWh	€	m^3	€	m^3	€
100	131	6.42	22.34	4.02	0.037	3.55	0.028	5.10
150	144	7.06	26.12	4.70	0.042	3.94	0.032	5.82
200	157	7.69	29.97	5.39	0.044	4.20	0.034	6.19
250	168	8.23	33.87	6.10	0.047	4.42	0.039	7.10
300	178	8.72	37.82	6.81	0.049	4.61	0.041	7.46
500	207	10.14	54.11	9.74	0.054	5.15	0.045	8.19
900	247	12.10	89.12	16.04	0.060	5.71	0.051	9.28

Tab. 3 Annual consumptions and annual carbon footprints

	Natural gas	Electrical energy	Wood	Wood pellets
Consumption, kWh	86626.67	18405.73	93440	19953.33
Carbon footprint, tCO_2e	17.33	0.22	149.50	5.79

On average, a distillery in Slovakia processes 146 000 liters of mash. For this amount of mash, were calculated annual consumptions and annual carbon footprints *(see Tab. 2)*. The highest annual combustion has the wood, specifically 93 440 kWh. Wood also has the highest annual carbon footprint. The lowest annual consumption has the electrical energy 18 405.73 kWh. At electrical energy was identified lowest annual carbon footprint with value 0.22 tCO_2e. Natural gas has the second highest annual consumption and carbon footprint.

According to Haile and Didwania *(2015)*, the implementation of secondary preheating of the mash using wastewater from the condenser can enhance heating efficiency by more than 20%. This approach contributes to a substantial reduction in the energy demand for primary heating of the distillation apparatus. This approach aligns with modern principles of energy optimization and waste heat recovery, which are increasingly applied in the food and beverage sector *(Früh et al., 2021)*

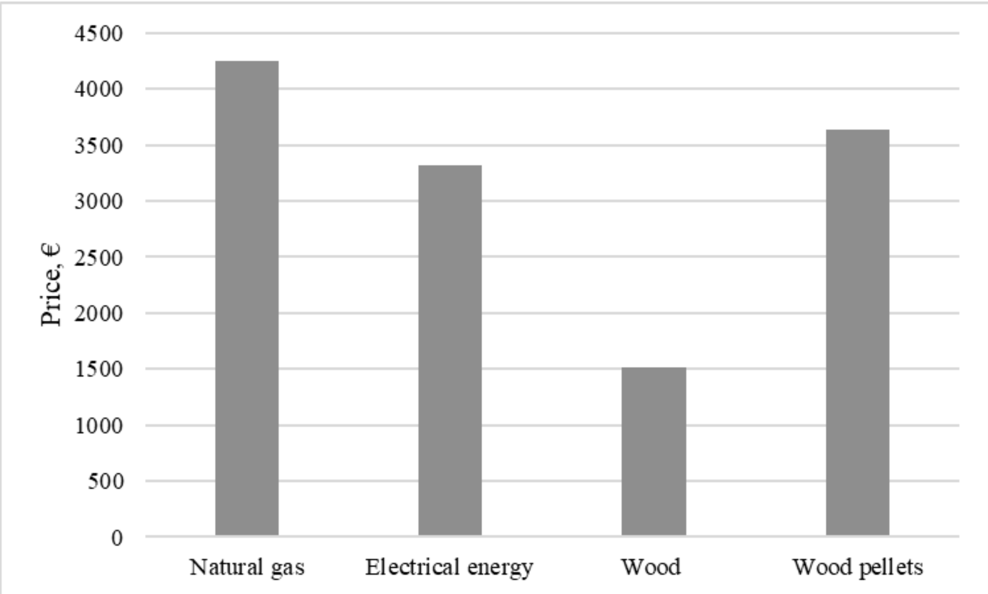

Fig. 2 Annual costs for individual energy sources

The individual energy sources annual costs for 146 000 liters of mash are shown on Fig. 2. From the Fig. 2 is clear, that wood heating has the lowest costs. The highest costs are for heating with natural gas, specifically 4244.71 €. Annual costs for heating with electrical energy are 3313 €. In the case of wood pellets, it is 3631.51 €.

Moreover, integrating thermal energy storage systems could further reduce energy waste, as demonstrated in renewable distillation models *(Liu et al., 2018)*. Mydlarz & Wieruszewski *(2024)* note that by-products of wood processing can enhance energy circularity, which aligns with the circular economy principles emphasized by Rimantho *(2024)*. Adopting a hybrid system that combines renewable electricity with waste heat recovery could lead to the most sustainable and cost-efficient operation.

CONCLUSIONS

The comparative analysis of different energy sources used in the distillation process highlights a clear trade-off between economic efficiency and environmental sustainability. The results show that while natural gas and electricity offer advantages in terms of efficiency and controllability, they come with higher operational costs and, in the case of gas, a higher carbon footprint. Wood, although the most cost-effective option, results in the highest carbon emissions, making it the least environmentally friendly. Wood pellets present a balanced alternative, offering relatively low emissions and moderate costs. Overall, the most sustainable option from an environmental perspective is electricity, especially when supported by renewable sources. However, it is necessary to take into account the 37% higher cost of purchasing a distillation column. These findings can support distillery operators in making informed decisions based on both ecological responsibility and economic feasibility. The inclusion of environmental performance indicators, such as CO_2e per liter of mash processed, can support future regulatory compliance and reporting. Ultimately, modern distillation systems should be reconfigured not only for efficiency but also to reduce emissions in line with European Green Deal objectives. As energy costs and carbon taxes continue to rise, the implementation of low-carbon and energy-saving technologies becomes essential for economic resilience and environmental responsibility. Thus, applying integrated energy management strategies based on the synergy of renewable energy, waste heat recovery, and fuel optimization is a key path forward for sustainable alcohol production.

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