algorithms

*Article*

# European Efficiency Schemes for Domestic Gas Boilers: Estimation of Savings in Heating of Settlements

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## Abstract

This article aims to evaluate the seasonal efficiency of natural gas boilers used in European households, highlighting the cost effectiveness, environmental benefits, and user comfort associated with higher-efficiency models, particularly those based on condensing technology. The study applies a standardized algorithm used in European energy labeling schemes to calculate the seasonal efficiency of household gas boilers. It further includes a comparative analysis of selected boiler models available on the Serbian market and outlines a step-by-step method for estimating gas savings when replacing older, less efficient boilers with modern units. Condensing boilers demonstrate significantly higher seasonal efficiency than standard models by recovering additional heat from exhaust gases. These improved boilers produce lower greenhouse gas emissions and offer annual fuel savings of approximately 10% to 30%, depending on the boiler's age, system design, and usage patterns. The results also confirm the direct correlation between seasonal efficiency and annual fuel consumption, validating the use of efficiency-based cost comparisons. The analysis focuses on residential gas boilers available in the Serbian market, although the models examined are commonly distributed across Europe. The findings highlight the important role of energy efficiency labels—based on a standardized algorithm—in guiding boiler selection, helping consumers and policymakers make informed decisions that promote energy savings and reduce environmental impact. This article contributes to the theoretical and practical understanding of gas boiler efficiency by integrating algorithm-based evaluation with market data and user-centered considerations. It offers actionable insights for consumers, energy advisors, and policymakers in the context of Europe's energy transition. Verifying the efficiency calculations of gas boilers requires a careful combination of theoretical methods, measured data, and adherence to standards.

**Keywords:** gas boilers; heating systems; natural gas; condensation technology; energy-related products; seasonal efficiency; efficiency labels

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## 1. Introduction

Gas boilers [1] remain integral components of modern heating systems, delivering reliable and efficient heat and domestic hot water in residential and commercial applications [2]. By converting a significant proportion of fuel into usable thermal energy, these systems help reduce energy costs and limit greenhouse gas emissions [3]. The ability to maintain a stable and comfortable indoor climate is not only essential for physical well-being but also linked to cognitive performance and emotional stability. Even minor temperature variations can impact productivity and comfort, underscoring the continued importance of efficient heating solutions.

In recent years, condensing boiler technologies have advanced substantially increasing efficiency of gas boilers significantly [4,5], particularly in heating systems powered by natural gas. Additional advancements include high-performance heat exchangers, smart control systems with remote access, and hydrogen-ready models capable of operating on natural gas–hydrogen blends [6]. Such innovations improve energy efficiency, enhance user convenience, and contribute to environmental sustainability.

The heating landscape is evolving in response to climate change. Rising global temperatures are projected to reduce heating demand in many regions, potentially lowering overall energy consumption. Nevertheless, the need for high-efficiency boilers remains critical. Extreme weather events still demand reliable heating, and improved efficiency supports household energy savings while advancing the European Union's climate and energy goals [7,8].

As the building sector transitions toward low-carbon heating technologies [9,10], efficient natural gas boilers are expected to play a key transitional role. Their performance under realistic seasonal conditions is increasingly important for informed policy decisions and energy planning. Among the most relevant performance metrics is seasonal efficiency, which directly determines a boiler's energy efficiency class and regulatory compliance.

This study examines the seasonal efficiency of household gas boilers through the lens of the algorithmic framework used in European energy labeling schemes. By applying a standardized algorithm for calculating seasonal efficiency, the research systematically evaluates boiler performance and cost effectiveness. Key factors influencing energy use and savings are analyzed, with a focus on how efficiency algorithms shape regulatory classifications. A comparative assessment of selected boiler models available on the Serbian market is included [11,12], offering insights relevant to both national and broader European contexts. By combining computational modeling with market data, the study contributes to the theoretical and practical understanding of gas boiler optimization within the ongoing energy transition.

The correctness of energy efficiency calculations for domestic gas boilers is verified through standardized European procedures [13]. Boilers are tested under controlled conditions following harmonized standards, measuring performance at different loads. Seasonal efficiency is calculated using a defined formula incorporating these test results. Accredited labs perform the tests, and regulatory bodies oversee compliance, ensuring results are reliable, comparable, and transparent across the market.

## 2. Gas Boilers

Efficient boilers reduce energy waste while lowering greenhouse gas emissions and operational costs, making them both cost-effective and environmentally beneficial [14]. Modern gas boilers—particularly those utilizing condensing technology—are capable of converting a large proportion of fuel into usable heat.

Section 2.1 provides a concise overview of relevant legislation. In Europe, residential gas boiler efficiency is regulated by the Energy-Related Products Directive, which requires performance to be assessed over a full heating season using seasonal efficiency—a metric that accounts for varying loads and operating conditions. As described in Section 2.2, seasonal efficiency is determined using a standardized algorithm that ensures a realistic and consistent assessment of boiler performance under typical household conditions. Based on these calculations, energy labels are assigned to guide consumers in making informed purchasing decisions. These labels, which are discussed in detail in Section 2.3, classify boilers by efficiency, ranging from A or A+++ for the most efficient models to G for the least efficient.

Figure 1 illustrates three main categories of domestic gas boilers based on their efficiency: modulating condensing boilers [15], which are the most efficient; non-condensing boilers; and on–off boilers, which are the least efficient. Historically, the heat of vaporization in exhaust gases was not recovered due to technological limitations making difference between the efficiency based on lower heating value (LHV) and higher heating value (HHV). Consequently, the lower heating value (LHV) was adopted as the reference point for efficiency calculations. As can be seen in Figure 1, under these conditions, boiler efficiency can theoretically exceed 100%—a concept known as net efficiency. This occurs because conventional efficiency standards in heating technology continue to use lower heating value (LHV) as the benchmark. However, when the higher heating value (HHV) is used as the reference, which accounts for the total energy content of the fuel including latent heat, efficiency cannot exceed 100%—this is referred to as gross efficiency.

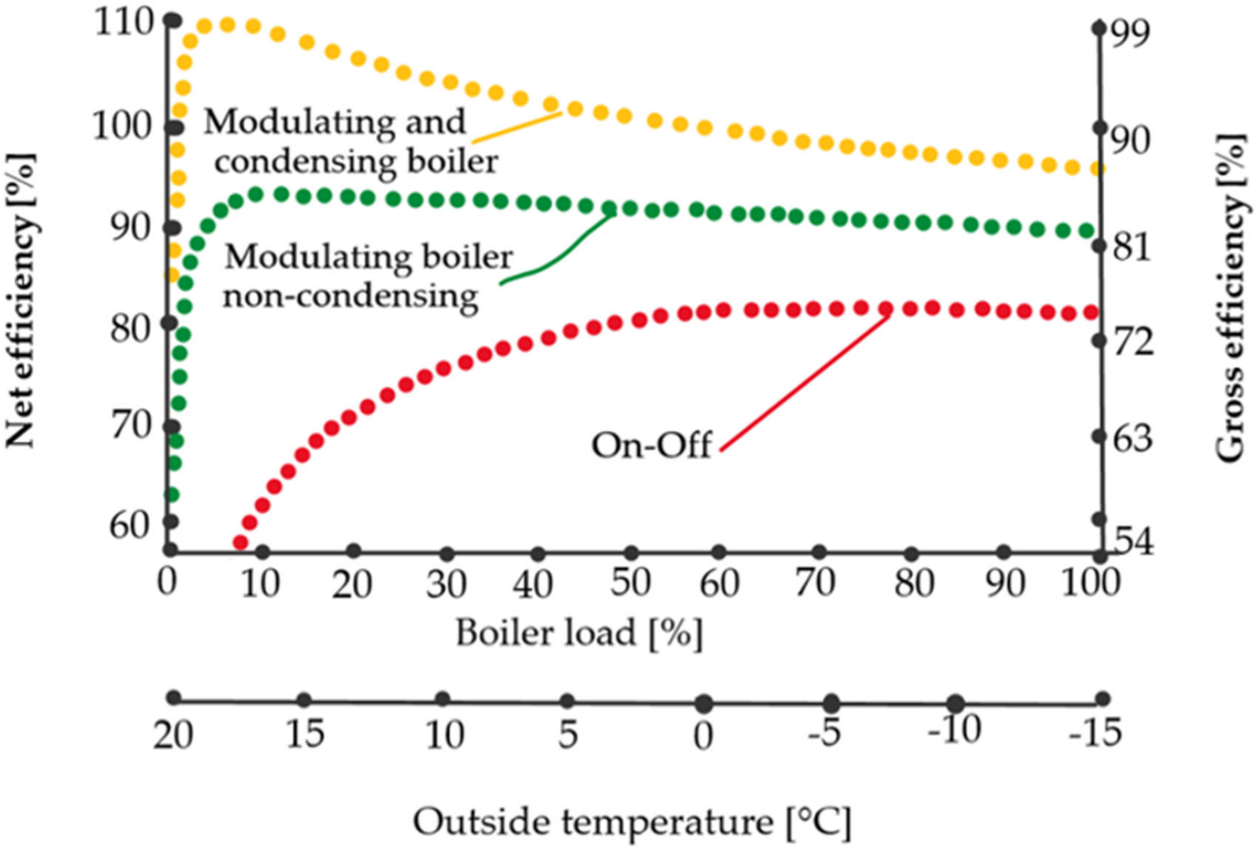


**Figure 1.** Diagram of efficiency dependence on boiler load for three different types of boilers.

Lower heating value (LHV) was primarily used before the adoption of condensing boiler technology, which recovers latent heat from water vapor in the exhaust gases. With condensing boilers, the higher heating value (HHV) becomes more relevant, as it accounts for this additional heat recovery.

As given in Table 1, the average water temperature in the boiler for standard conditions under which efficiency levels are determined is 70 °C at full power, 50 °C at partial power for standard boilers, and 40 °C for low-temperature boilers, while for condensing boilers, the important input water temperature must be 30 °C to achieve the condensing effect.

**Table 1.** Required efficiency of boilers according to Directive 92/42/EEC [1].

| Type of Boilers | At the Nominal Power of the Boiler (%) | At Partial Load of the Boiler (%) |
|---|---|---|
| Standard | $\geq 84 + 2\log P_n$ | $\geq 80 + 3\log P_n$ |
| Low-temperature | $\geq 87.5 + 1.5\log P_n$ | $\geq 87.5 + 1.5\log P_n$ |
| Condensing [2] | $\geq 91 + \log P_n$ | $\geq 97 + \log P_n$ |
| $P_n$—Power given in kW and can range from 4 to 400 kW | | |

[1] see Section 2.1.; [2] see Appendix A.

### 2.1. Legislation

In Europe [13,16], the efficiency of gas boilers is assessed using methodologies that comply with the Energy Efficiency Directive (EU/2023/1791) [17] and the Energy Performance of Buildings Directive (EU/2024/1275) [18]. Specifically, Directive 92/42/EEC addresses the efficiency requirements for new hot water boilers fired by gaseous and liquid fuels, ensuring that these appliances meet high-performance levels. These Directives establish stringent guidance for energy consumption and efficiency, aiming to reduce overall energy use and promote sustainable practices:

- EU/2023/1791—Energy Efficiency Directive: This Directive aims to enhance energy efficiency by setting binding targets for reducing energy consumption and promoting energy-efficient practices [19];
- EU/2024/1275—Energy Performance of Buildings Directive: This Directive focuses on improving the energy performance of buildings, aiming for a fully decarbonized building stock by 2050. It includes measures for renovation, better air quality, and digitalization of energy systems for buildings [20];
- Directive 92/42/EEC: It sets efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels, promoting energy efficiency and reducing energy consumption in the domestic and tertiary sectors. The Directive covers boilers operating on liquid and/or gaseous fuels with a nominal power of 4 kW to 400 kW.

The Directive 92/42/EEC has been updated few times since 1992, namely in 1993, 2004, 2005, 2008, and 2013. These updates helped to enhance the Directive's effectiveness in promoting energy efficiency and reducing energy consumption, additionally including, i.a., the following:

- Directive 2004/8/EC (2004): Focused on the promotion of cogeneration based on a useful heat demand;
- Directive 2005/32/EC (2005): Established a framework for setting eco-design requirements for energy-using products;
- Directive 2008/28/EC (2008): Made further amendments to improve energy efficiency.

These Directives collectively contribute to the European Union's strategy to enhance energy efficiency and reduce greenhouse gas emissions [21].

Barriers to the adoption the regulations include regulatory disparities across different countries, which can create trade barriers and market fragmentation. Additionally, manufacturers face significant implementation costs to comply with new eco-design requirements, and limited consumer awareness of the new energy labels can hinder their effectiveness.

The annual fuel consumption of a boiler is closely correlated with its seasonal efficiency, providing a basis for comparing the annual fuel costs of different models. To ensure consistency and comparability, the seasonal efficiency of domestic gas boilers is typically calculated using standardized methodologies. One such method is the Standard

Assessment Procedure (SAP), which is used for the energy rating of dwellings in the UK [22].

This methodology is aligned with the European Directive 92/42/EEC, which sets minimum efficiency requirements for new boilers fueled by gas or liquid fuels. The resulting efficiency values are expressed as the seasonal efficiency of a domestic boiler in the UK (SEDBUK) [23], a metric that offers a more comprehensive view of boiler performance over time than instantaneous efficiency measures.

Comparisons between the seasonal efficiency of gas boilers and ErP requirements are given in Table 2. Both systems aim to improve energy efficiency and reduce carbon emissions, but they differ in their approach to presenting information and regulatory scope.

**Table 2.** Comparisons between seasonal efficiency of gas boilers and ErP requirements.

| SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) Efficiency Classes | Energy-Related Products (ErP) Efficiency Classes |
|---|---|
| -Provides a detailed percentage rating indicating the exact proportion of fuel converted into usable heat over a typical year | -Uses a simpler A+++ to G rating system to classify boiler efficiency |
| -Primarily used in the UK for new-build homes | -Applies across Europe to all residential and commercial heating products |
| -Was the standard from 1999 to 2015, still referenced for new buildings | -Introduced in 2015, replacing SEDBUK for existing properties |
| -Offers precise efficiency percentages, allowing detailed comparison | -Provides a more straightforward, consumer-friendly label system |
| -Focuses on detailed efficiency metrics | -Includes regulations for manufacturers to meet higher energy efficiency standards before products can be sold |

### *2.2. Calculation of Seasonal Efficiency*

Understanding the efficiency of gas boilers is essential for making informed decisions regarding heating systems, as efficiency directly influences both operational costs and environmental sustainability. One of the most significant indicators of boiler performance is seasonal efficiency, which reflects how a boiler performs over a typical year, accounting for variations in operating conditions.

The Directive 92/42/EEC prescribes the efficiency levels that boilers must meet and under what conditions, which are the input data for calculating seasonal efficiency (see Table 1). Directive 92/42/EEC also specifies what is exactly meant by different types of boilers, such as low-temperature and condensing boilers.

An algorithm for calculation of seasonal efficiency is presented, including a step-by-step approach for savings by switching an obsolete boiler with a more efficient one. The classification of gas boilers is easiest to perform based on the degree of seasonal efficiency obtained through a specially prescribed procedure.

For the calculation of seasonal efficiency of household gas boilers or individual boiler models, it is necessary to have known data on the degree of utilization for the lower heating value (LHV) at full load ($E_{full}$) and at 30% load ($E_{part}$) as well as the type of boilers. Based on these input data, the calculation of seasonal efficiency can be approached according to the method prescribed by SAP (Standard Assessment Procedure) [22,24]. SAP was first published in 1993 and has since been updated periodically, in 1998, 2001, 2005, 2009, 2012, and most recently in 2022. The highest efficiency values for condensing boilers at full load can be 101.0% and at 30% load 107.0%, while for non-condensing boilers, the highest values at full load can be 92.0% and at 30% load 91.0% if it is calculated for the lower heating value (LHV). The efficiency degree is calculated for the lower heating value (LHV) so that it can exceed 100% for condensing boilers because they are designed to utilize the thermal energy released by the condensation of water vapor.

The following instructions should be followed to calculate seasonal efficiency:

1. The degrees of utilization at full load ($E_{full}$) and partial load ($E_{part}$), which serve as input data and cannot exceed the specified values, should be converted to the higher heating value (HHV) by multiplying them by a coefficient of 0.901 for gas boilers and 0.921 for liquid petroleum gas (LPG) boilers (SAP [22], Table D2.2);
2. In the further course of calculation, it is necessary to determine the type of boiler in accordance with Section D1 and Table D2.3 in SAP [22]. Based on this, select the appropriate expression for the calculation of seasonal efficiency from Table D2.4. For example, for an on–off gas boiler (on–off regular), whether condensing or not, the Expression 101 applies (Equation (1)). For the same type with a storage reservoir (on–off storage combination), the Expression 105 applies (Equation (2)), according to SAP [22]. For modulating boilers, whether condensing or not, if they do not have a storage reservoir (modulating regular), the Expression 102 applies (Equation (3)). If they have a storage reservoir (modulating storage combination), the Expression 106 applies (Equation (4)), according to SAP [22], etc. Boilers covered by Expressions 101 and 102 provide heating but not domestic hot water in general (regular boilers). Boilers covered by Expressions 105 and 106 are combination boilers, which provide heating as well as domestic hot water and have an internal reservoir of at least 15 $dm^3$ and at most 70 $dm^3$. If the reservoir is larger than 70 $dm^3$, the heating circuit must not be supplied from this reservoir. If it is supplied, then it does not fall under this class of boilers, and the seasonal efficiency is calculated by a different expression. If there is no expression number in Table D2.3 in SAP [22] that is selected from Table D2.4 in SAP [22] or if the designation X is present, the calculation cannot continue. For gas boilers and liquid petroleum gas (LPG) boilers, the parameter $p$ in expressions 105, 102, and 106 is zero if they do not have a pilot flame. If they have a permanent pilot flame, then $p = 1$. The parameter $b = 0$ if the losses from the reservoir are not included for boilers with a reservoir or if the reservoir was not connected during testing; otherwise, $b = 1$. If there is a reservoir with a volume Vcs, in $dm^3$, then the parameter L is calculated as $L = 0.0945 + 0.0055t$ if $t < 10$ mm or as $L = 0.394/t$ if $t \geq 10$ mm, where t is the thickness of the insulation in millimeters.

$$101\text{: } E = 0.5(E_{full} + E_{part}) - 2.5 - 4, \tag{1}$$

$$105\text{: } E = 0.5(E_{full} + E_{part}) - 2.8 + (0.209 \times b \times L \times V_{cs}) - 4p, \tag{2}$$

$$102\text{: } E = 0.5(E_{full} + E_{part}) - 2.0 - 4p, \tag{3}$$

$$106\text{: } E = 0.5(E_{full} + E_{part}) - 1.7 + (0.209 \times b \times L \times V_{cs}) - 4p, \tag{4}$$

where

E—seasonal efficiency (%).
$E_{full}$—efficiency under full load (%).
$E_{part}$—efficiency under 30% of full load (%).
$V_{cs}$—volume of the reservoir ($m^3$).
B—was reservoir connected during testing? Yes: b = 1; No: b = 0 (see Figure 2).
L—a parameter related to insulation of reservoir (see Figure 2).
P—is there a plot flame? Yes: p = 1; No: p = 0 (see Figure 2).
T—thickness of insulation of the reservoir (mm).

3. The obtained result, i.e., seasonal efficiency (E), should be rounded to one decimal place (seasonal efficiency = [x]%), with mandatory reference to the Notified Body

accredited for the testing of boilers by an EU National Accreditation Service, which confirms the input data and calculation method [13].

A suitable algorithm for calculation of seasonal efficiency is given in Figure 2.

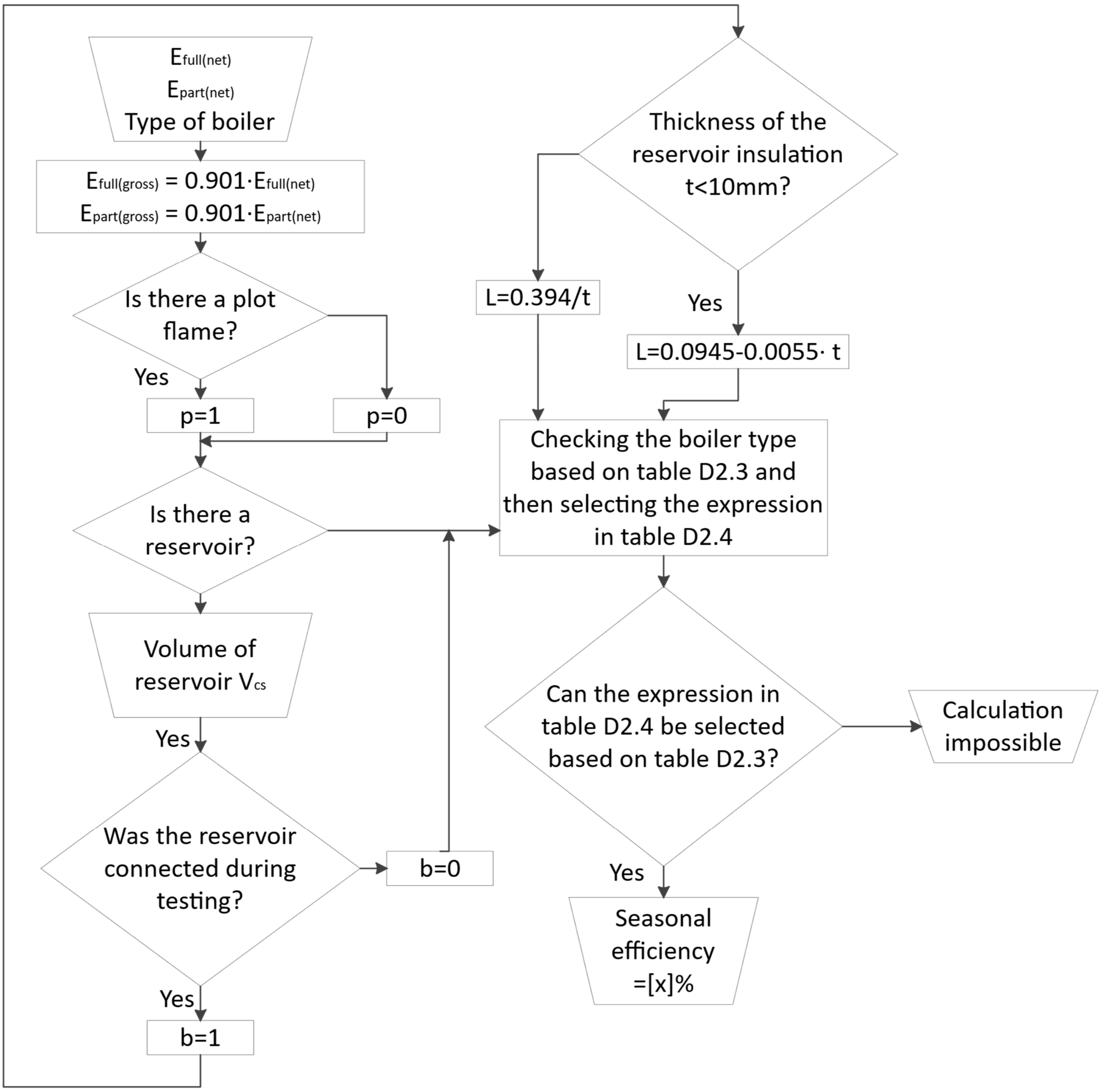


**Figure 2.** Algorithmic calculation of seasonal efficiency.

## 2.3. Energy Classes

To support consumer decision making, seasonal efficiency values are used to assign energy labels that indicate performance under standardized conditions [25]. In 2015, the Energy-related Products (ErP) Directive introduced a simplified, consumer-friendly classification system, replacing the SEDBUK scale for existing properties. This system uses an A+++ to G rating scale to classify boilers based on their energy efficiency, with a focus on reducing carbon emissions and improving overall energy use [26–29]. While SEDBUK remains in use for new-build homes, the ErP label provides a practical reference for consumers, and its ratings can be correlated with SEDBUK values, as shown in Table 3.

**Table 3.** Energy efficiency class symbols [1].

| SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) Efficiency Classes [2] | Energy-related Products (ErP) Efficiency Classes [3] |
|---|---|
| A: 90% and above<br>B: 86% to 90%<br>C: 82% to 86%<br>D: 78% to 82%<br>E: 74% to 78%<br>F: 70% to 74%<br>G: Below 70% | A+++: 98% and above<br>A++: 95% to 98%<br>A+: 92% to 95%<br>A: 90% to 92%<br>B: 82% to 90%<br>C: 77% to 82%<br>D: 70% to 77%<br>E: 65% to 70%<br>F: 60% to 65%<br>G: Below 60% |

[1] Requirements are the same for new and existing buildings; only the way that the efficiency information is shown is different under the 2015 ErP Directive. [2] SEDBUK originally used a percentage-based system to indicate the efficiency of boilers, but it is now often presented as a letter rating, similar to energy-related products (ErP). [3] Since 2021, the current energy label with energy classes from A+++ to D is gradually being replaced with a new, simpler scale from A (most efficient) to G (least efficient) [30].

Energy labels are not mandatory for manufacturers, and they may choose to use them or not. The efficiency classes are based on verified seasonal efficiency ratings, agreed upon by the boiler manufacturer or importer. Manufacturers and importers are not required to provide data for this classification or to be classified. This classification aids consumers in selecting more energy-efficient products, promoting energy savings and environmental protection.

## 3. Savings and Comparisons

Natural gas boilers sold for use in European households are assigned energy efficiency ratings primarily based on their seasonal efficiency, providing clear and practical information to consumers. The algorithm presented for calculating seasonal efficiency and estimating fuel savings offers a systematic and reproducible method to optimize boiler performance, encouraging manufacturers to improve their designs in line with evolving standards. Based on this, estimates of annual gas savings are provided when replacing a lower-efficiency boiler with an advanced model. Examples include an overview of boilers available on the market, showing their seasonal efficiency and corresponding energy labels to illustrate the potential savings.

### 3.1. Estimates of Annual Gas Savings

As energy efficiency becomes a central focus in building decarbonization strategies, upgrading household heating systems is gaining renewed importance across Europe. Natural gas boilers, still widely used in residential buildings, vary significantly in efficiency depending on their age, design, and technology [31,32]. Older boilers often operate with efficiencies as low as 55%, resulting in substantial energy losses and higher operating costs. In contrast, modern condensing boilers can achieve efficiencies exceeding 90%, offering both economic and environmental advantages.

Assessing the benefits of upgrading to a high-efficiency boiler requires a clear and quantitative understanding of fuel consumption and potential cost savings. This is particularly important for homeowners, policymakers, and energy advisors who aim to promote informed investment decisions and support climate targets. Standardized estimation procedures allow for consistent comparison of different boiler models, accounting for variables such as annual fuel use, fuel prices, and thermal efficiency.

The following example outlines a step-by-step method for calculating the annual gas and cost savings when replacing a low-efficiency boiler with a high-efficiency model. This approach not only illustrates the potential for household savings but also provides a framework for broader cost–benefit analyses in the residential heating sector. Steps to estimate gas savings include the following (example is for switching a 55% efficient boiler with a 95% efficient one):

Determine annual fuel consumption of the current boiler: Find out the annual fuel consumption of your current boiler. This can be obtained from the gas bills or estimated based on heating needs. Assume the current boiler consumes 1260 m$^3$ of natural gas per year.

Calculate the annual heating cost with the current boiler: Multiply the annual fuel consumption by the cost per cubic meter. For example, if the cost is around EUR 0.50/m$^3$ [11,12], this gives EUR 630.

1. Calculate the effective heating output of the current boiler: Multiply the annual fuel consumption by the efficiency of the current boiler (55%, i.e., 0.55): 1260 m$^3$ × 0.55 = 693 m$^3$;
2. Determine the required fuel consumption for the new boiler: Divide the effective heating output by the efficiency of the new boiler (95% i.e., 0.95): 693 m$^3$/0.95 ≈ 729.47 m$^3$.

Calculate the annual heating cost with the new boiler: Multiply the required fuel consumption by the cost per cubic meter: 729.47 m$^3$ × EUR 0.50/m$^3$ ≈ EUR 364.74.

Estimate the annual savings: Subtract the annual heating cost of the new boiler from the annual heating cost of the current boiler: EUR 630 – EUR 364.74 ≈ EUR 265.26.

If the most efficient boiler, which is no longer produced or is outdated, is taken for comparison, and the others from the corresponding group are compared, annual fuel savings of up to 39.76% are obtained if the least efficient, outdated boiler is replaced with the most efficient boiler that is no longer produced. In the class of current boilers, this saving goes up to 22.62%. Both can be seen in Figure 3.

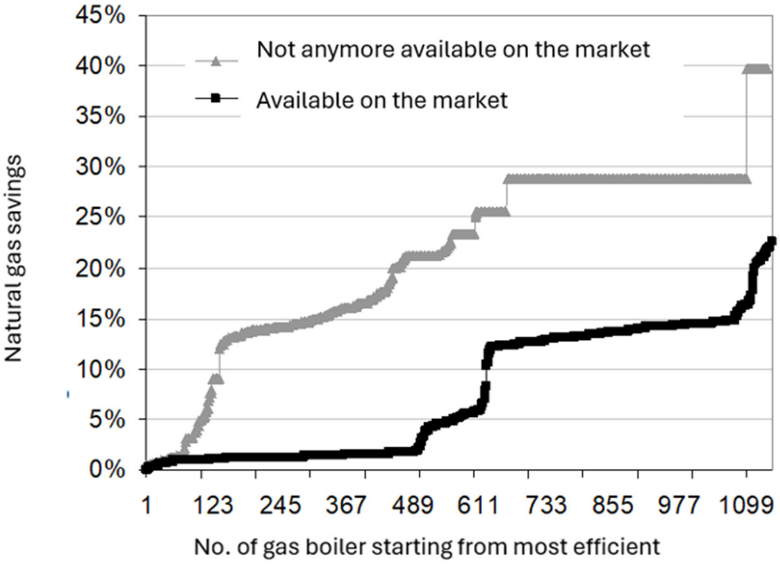


**Figure 3.** Savings of natural gas: summary of boilers from Serbian market; natural gas savings are in % of savings in gas by switching a less efficient with a more efficient boiler, where the presented boilers are listed according to their efficiency (No. 1 is the most efficient among more than 1100 listed boilers).

The fuel savings achieved by replacing the boiler with the lowest estimated seasonal efficiency of 55% with a better boiler are shown in Figure 4. However, Figure 4 does not suggest that the more efficient boilers are more likely available on the market or opposite.

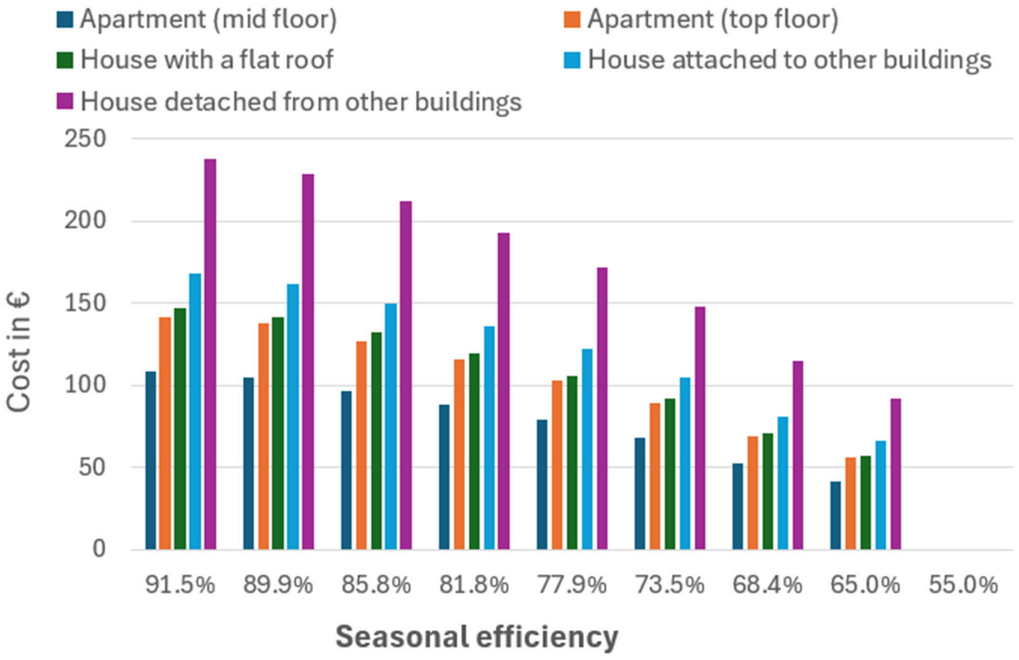


**Figure 4.** Annual savings by replacing the least efficient boiler with a more efficient one in EUR (data and methodology [33]).

As can be seen from Figure 4, upgrading from a G-rated boiler to a modern A-rated condensing boiler can result in substantial annual energy savings depending on the type of dwelling. For a house detached from other buildings, the expected savings range from approximately EUR 240 annually, while in the case of a mid-floor apartment, the annual savings are around EUR 110.

In addition to traditional natural gas, the use of biogas [34] and gas derived from waste [35] can further enhance the sustainability of gas boilers. Biogas, produced from organic materials such as agricultural waste, manure, and food waste, is a renewable energy source that can significantly reduce greenhouse gas emissions. Similarly, gas from waste, generated through the anaerobic digestion of municipal solid waste, provides a sustainable alternative to fossil fuels. By incorporating these renewable gas sources, households can further reduce their carbon footprint.

While high-efficiency boilers—particularly condensing models—offer clear energy and economic benefits, their real-world adoption depends on multiple factors, including cost, infrastructure readiness, and government support. In recent years, many European countries have introduced targeted measures to promote the uptake of such technologies as part of broader climate and energy strategies. Several European countries support the adoption of high-efficiency boilers through various measures. For example, Germany offers subsidies via the Federal Subsidy for Efficient Buildings (BEG) [36] and uses carbon pricing to discourage inefficient systems; France's MaPrimeRénov' [37] and Italy's Ecobonus [38] provide substantial financial aid for boiler replacements; Austria and the Netherlands promote condensing and hybrid systems through grants; and Central and Eastern European countries like Slovenia and Croatia utilize EU funds to co-finance boiler upgrades.

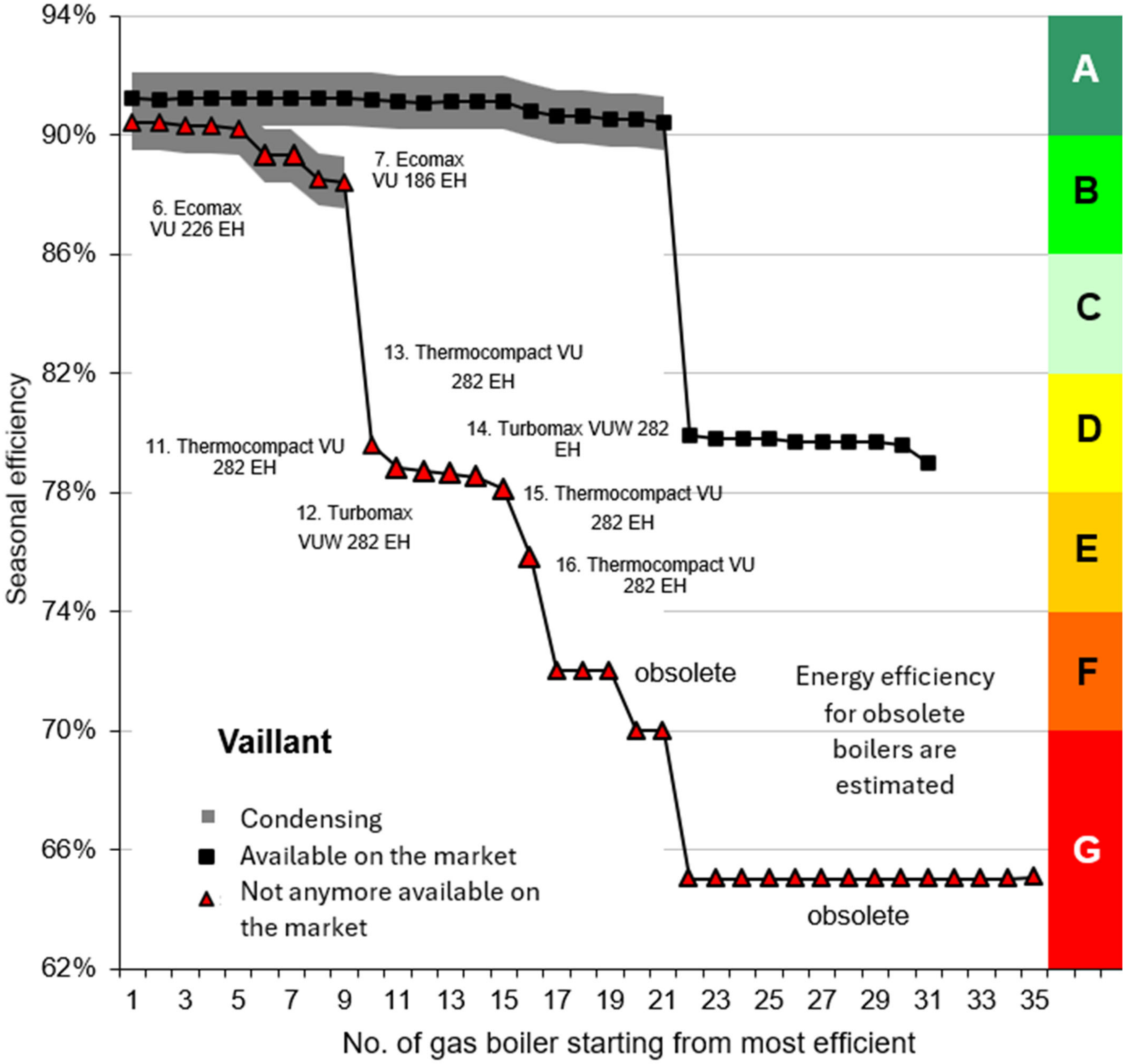
In Serbia, although incentive mechanisms are not yet as extensive as those in the European Union, meaningful steps have been taken to align with EU energy efficiency goals. The country has adopted several national energy efficiency programs and participates in regional initiatives supported by EU funding, such as the Western Balkans Investment Framework (WBIF). These programs have contributed to financing building renovation projects that often include upgrades to heating systems. Additionally, local authorities and public utilities have occasionally implemented co-financing schemes for energy efficiency improvements—though these vary by municipality and are typically coordinated through Serbia's Ministry of Mining and Energy. Given Serbia's strong trade and regulatory ties with the European Union, the boiler models available on its market closely mirror those sold across Europe. This makes Serbia's experience and policy direction highly relevant to broader regional trends. To accelerate the adoption of high-efficiency boilers and support its contribution to European climate goals, Serbia will need to continue developing financial incentives, public awareness campaigns, and enforceable minimum performance standards.

### *3.2. Comparison of Boilers*

Gas boilers used in households across Europe are often produced by large international manufacturers and sold under the same trade names in multiple countries. Due to the integration of European markets and Serbia's active participation in regional trade, many of the boiler models available in Serbia are also commonly found throughout Europe. As such, insights gained from the Serbian market can be considered representative of broader European trends in gas boiler technology. The market share and technology representation for Serbia are illustrated in Figure 5. This figure presents gross seasonal efficiency data for various boilers from different manufacturers that are or were available under the same trade names on the Serbian market and across Europe.

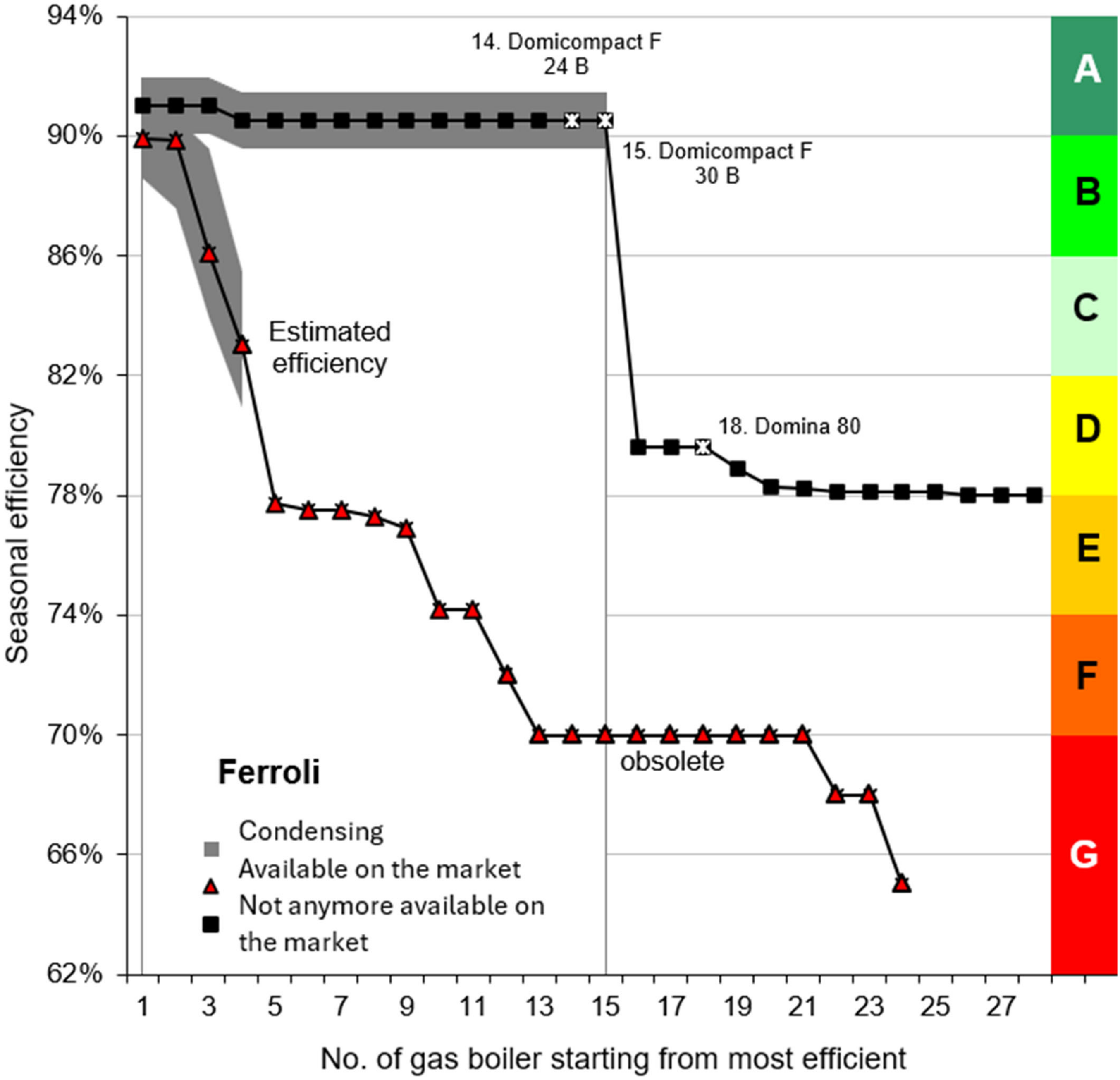
Figure 5 presents the efficiency levels of both currently produced boilers and those no longer in production for various reasons. For each manufacturer, the boilers are connected by a line indicating the range from the most to the least efficient. Condensing boilers are highlighted with a darker background in the diagram for clarity. The displayed efficiency of boilers depends on the accuracy of the input data measurements. Statistical analyses have shown that if two boilers have an efficiency calculated using the SEDBUK methodology that differs by three percentage points, then the boiler with the higher calculated efficiency value is indeed more efficient in reality with 95% certainty.

Considering the various types of boilers from all manufacturers presented in Figure 5, it can be concluded that the greatest potential for both energy and economic savings lies in the use of condensing boilers. These boilers consistently fall into energy class A due to their ability to recover latent heat from exhaust gases, significantly improving overall efficiency—often exceeding 90%. In contrast, most conventional and older non-condensing boiler models are classified in energy class D, reflecting their lower efficiency and higher fuel consumption. Condensing technology not only reduces energy bills for end users but also contributes to lower greenhouse gas emissions, aligning with European energy efficiency targets and climate goals. As such, the widespread adoption of condensing boilers is strongly encouraged, particularly in residential heating, where space and water heating account for a substantial portion of household energy use.



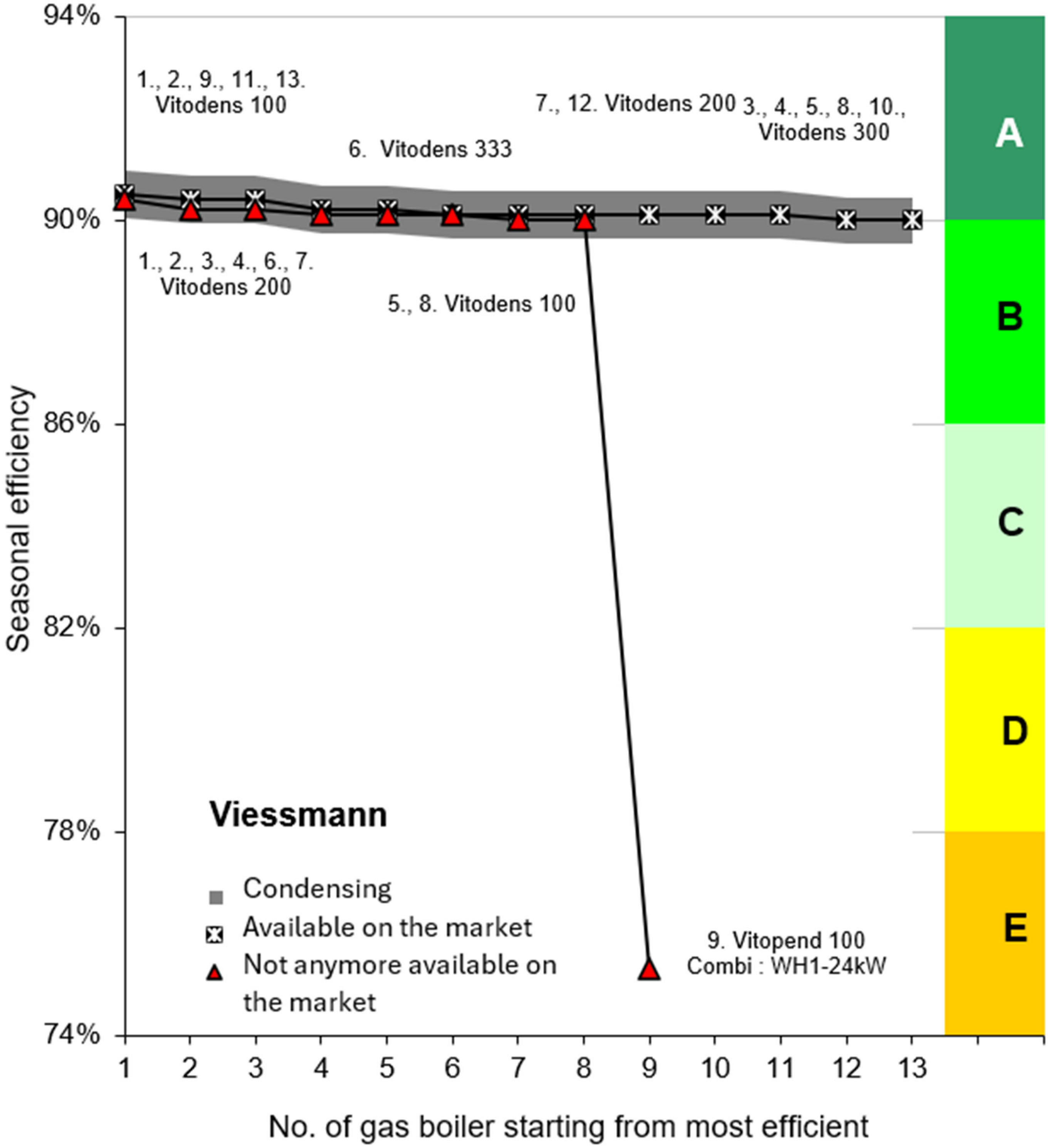
(**a**) Vaillant

**Figure 5.** *Cont.*



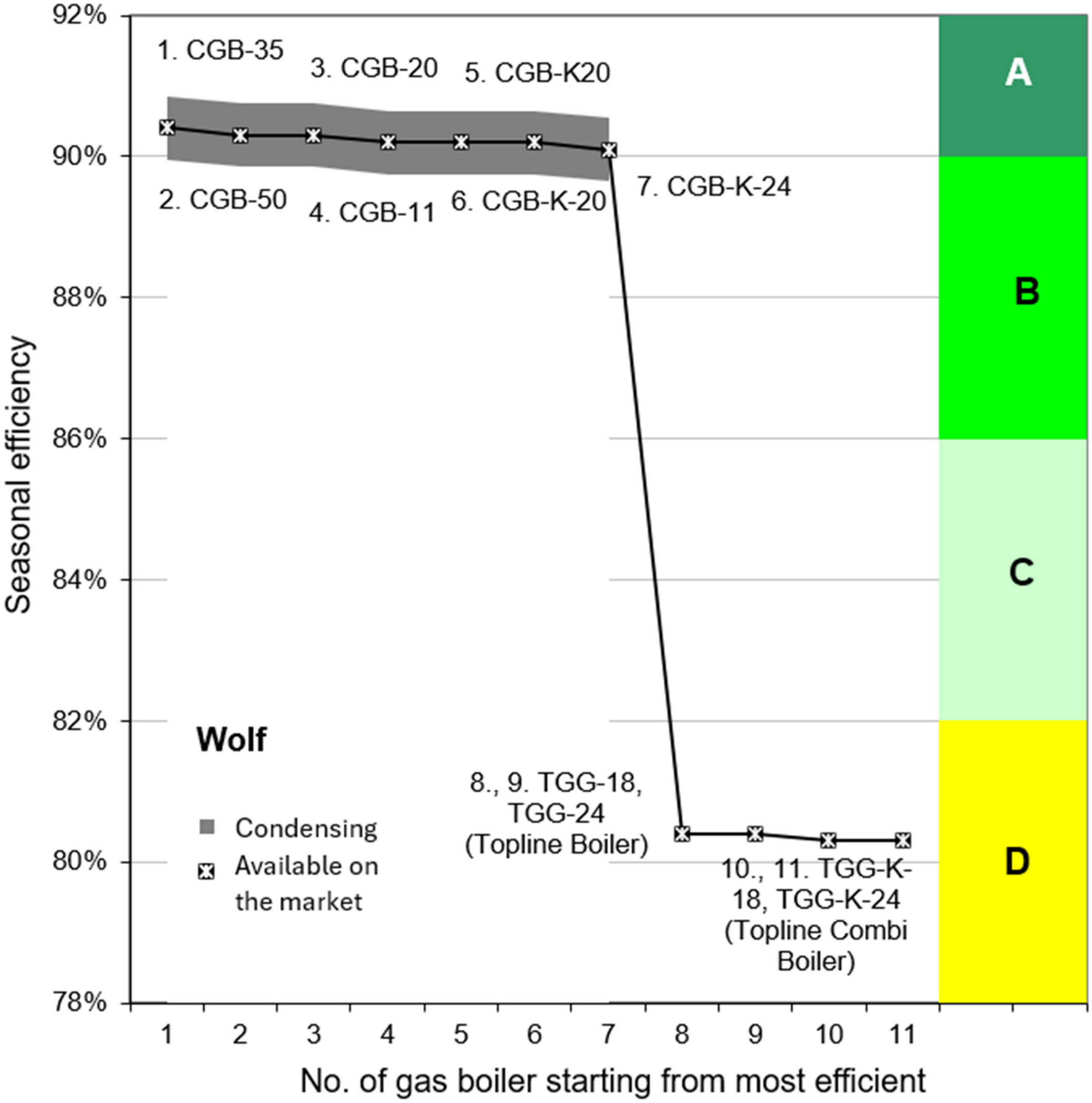
(**b**) Ferroli

**Figure 5.** *Cont*.



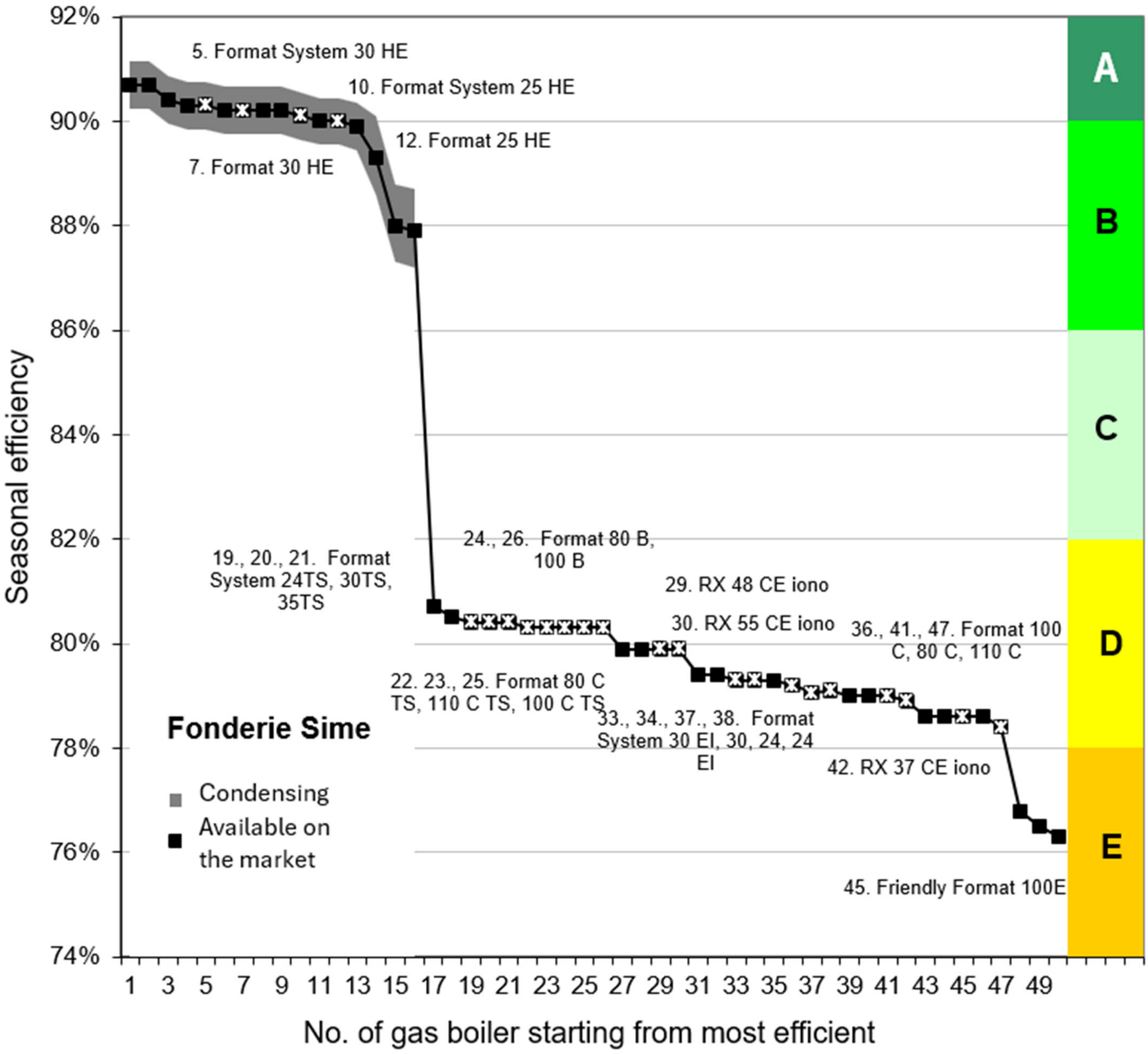
(**c**) Viessmann

**Figure 5.** *Cont.*



(**d**) Wolf

**Figure 5.** *Cont*.



(**e**) Fonderie Sime

**Figure 5.** Classification of boilers: (**a**) Vaillant, (**b**) Ferroli, (**c**) Viessmann, (**d**) Wolf, and (**e**) Fonderie Sime.

## 4. Conclusions

The seasonal efficiency of household gas boilers [39] remains a crucial and effective parameter for ranking these products, providing a transparent and comparable measure of performance over an entire heating season. Making this ranking accessible to the public empowers consumers to make informed purchasing decisions and fosters healthy competition among manufacturers, which in turn drives innovation and improvements in product design. This dynamic not only advances energy efficiency but also results in significant fuel savings and environmental benefits. Central to this process is the use of a standardized calculation methodology—one that relies on prescribed, verified input data and a uniform output format—ensuring that efficiency classifications are accurate, trustworthy, and based on voluntary compliance. Such standardization, as given in this article, underpins the credibility of energy labels and supports regulatory frameworks across Europe.

Among different boiler types, condensing boilers stand out as the most energy- and cost-efficient, consistently achieving energy class A (or A+++) ratings. This efficiency advantage stems largely from their ability to recover heat at low return water temperatures. The next generation of condensing boilers includes hydrogen-ready models, smart controls integrated with the Internet of Things, advanced heat recovery, low-$NO_x$ emissions, and hybrid heating systems that dynamically optimize energy use without compromising user comfort [40,41]. These innovations represent significant progress in reducing environmental impact and increasing operational convenience, aligning with broader decarbonization goals. This article clearly shows in an illustrative way how more efficient boilers can reduce the amount of used gas for heating significantly.

It is underlined that regulatory frameworks, financial incentives, and strategic initiatives across Europe are increasingly supporting the sustainable deployment of hydrogen-based heating technologies [42–44], signaling a clear pathway for future boiler development.

The calculation of energy efficiency for domestic gas boilers is a highly regulated and standardized process, grounded in harmonized European standards and rigorously verified through laboratory testing and market surveillance. This framework ensures that efficiency values are consistent, comparable, and reliable, making them suitable for informing policy decisions, labeling schemes, and consumer choices.

Looking ahead, updates to this research will continue to reflect changes in energy efficiency legislation, including adjustments to account for climate change impacts and the evolving heating market landscape, thereby maintaining relevance and supporting ongoing improvements in household heating efficiency.

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## Appendix A. Condensation Technology

Condensing boilers are designed to extract the latent heat of condensation from the water vapor in combustion products. By extracting latent heat, condensing boilers can achieve a high level of efficiency. A critical factor for achieving maximum efficiency of condensing boilers is the return water temperature, which is generally kept below 57 °C. The return water temperature determines whether the boiler operates in condensing mode. Due to the need to extract as much latent heat as possible and the high corrosiveness of the condensate from combustion products, condensing boilers require special materials for construction. To withstand corrosive conditions, condensing boilers must be made of stainless steel and other corrosion-resistant (and therefore more expensive) materials. They require sophisticated management and careful installation to reach their potential capabilities. Additionally, other units (radiators, convectors, spiral heat exchangers) connected to the system with a condensing boiler are more expensive due to the larger heat exchange surface required for operation at low water temperatures.

Condensation technology is an efficient method for converting natural gas and liquid fuels into useful energy through combustion [45–47]. While in low-temperature boilers, the condensation of hot gases is avoided due to the wetting of heating surfaces, condensation technology operates in a completely different manner: the condensation of gases is highly desirable and necessary to extract the latent energy contained in water vapor as well as additional sensible energy from flue gases into usable heat. At the same time, the residual heat of the flue gases is significantly reduced compared to low-temperature boilers. Acidic condensate can cause corrosion, leading to higher maintenance costs and reduced boiler lifespan [48].

Through a reaction with oxygen ($O_2$), a component from the air, the combustion of liquid fuel or natural gas, which primarily contains carbon (C) and hydrogen ($H_2$) compounds, produces carbon dioxide ($CO_2$) and water ($H_2O$). For natural gas (methane $CH_4$), the following simplified combustion formula is applied (Equation (A1)):

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 + \text{Energy} \tag{A1}$$

Condensate forms from steam in combustion products when the temperature of the walls on the hot gas side drops below the condensation point of water vapor.

The different chemical compositions of natural gas and heating oil result in different evaporation temperatures at which water vapor from combustion gases condenses. As shown in Figure A1, the dew point of water vapor for natural gas is approximately 57 °C, while for extra-light liquid fuel, it is approximately 47 °C. Theoretically, energy increases by 11% compared to low-temperature technology. For heating oil, the application of condensation technology theoretically increases energy by about 6%.

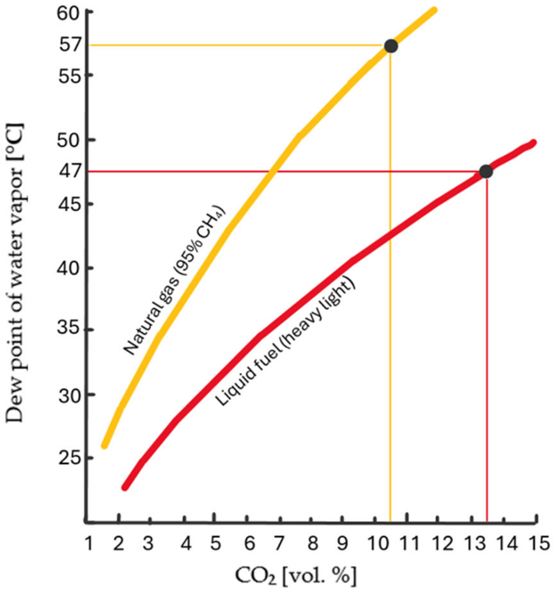

**Figure A1.** Dew point of water vapor as a function of $CO_2$ content in the combustion products.

Condensation technology is closely linked to the fuel's heating value and the state of water in combustion products, whether in vapor or liquid form. The heating value is a measure of the energy released when a fuel is completely combusted. It indicates the amount of heat produced by the combustion of a specific quantity of fuel. Heating values are essential for calculating the efficiency of heating systems and comparing the energy content of different fuels. They are typically expressed in kWh/$m^3$ or MJ/$m^3$. There are two main types of heating values:

- Lower heating value (LHV) is the energy released during complete combustion, with the water produced in the process, being separated as vapor;
- Higher heating value (HHV) determines the energy released during the complete process, including the heat of vaporization contained in the water vapor of hot gases.

Table A1 provides an overview of fuel characteristics relevant to the use of condensation technology.

**Table A1.** Heating values of some typical fuels.

| in kWh/m$^3$ | Lower Heating Value (LHV) | Higher Heating Value (HHV) |
|---|---|---|
| Natural gas | ~10 | ~11 |
| Propane | 25.8 | 28.1 |
| City gas [1] | ~4.2 | ~5.0 |
| Heating oil [2] | ~10 | ~10.6 |

[1] Obsolete—mainly produced from coal and consisted primarily of carbon monoxide and is now abandoned; [2] values given in dm$^3$.

The efficiency of condensation technology, which allows for better utilization of the fuel's primary energy compared to other heating systems, is due not only to the additional use of the heat from water vapor condensation in flue gases but also to reduced losses through cooler flue gases.

When discussing condensation technology, three key terms are regularly mentioned: efficiency, average efficiency, and nominal heat load of the boiler. These key terms are explained in the following sub-sections.

### *Appendix A.1. Efficiency of a Condensing Boiler*

The formula for determining the efficiency of a condensing boiler differs from those commonly used for standard and low-temperature boilers. It consists of two terms that encompass the effects of sensible and latent heat:

- Sensible heat refers to the heat that causes a change in the temperature of a substance without changing its state. In condensing boilers, sensible heat is the energy used to raise the temperature of the water or air being heated;
- Latent heat is the heat absorbed or released during a phase change, such as when water vapor condenses into liquid water. Condensing boilers capture this latent heat from the water vapor in the flue gases, which significantly improves their efficiency.

In the latent or condensation term, which describes the impact of latent heat from the condensation of water vapor in flue gases, an additional variable appears alongside the usual lower and higher heating values of the fuel. The condensation rate, $\alpha$, represents the ratio of the actual to the theoretically possible amount of condensate. The boiler becomes more efficient as the value of $\alpha$ increases. As the temperature of the flue gases decreases, the amount of condensate increases, leading to a higher condensation rate and thus lower flue gas losses. The equation for determining the efficiency of condensing boilers is given in Equation (A2):

$$\eta_{cc} = 1 - \frac{q_{fg} - q_{irr}}{100} + \alpha \cdot \frac{HHV - LHV}{LHV} \tag{A2}$$

where

$\eta_{cc}$—efficiency of condensing boilers (dimensionless).
$\frac{q_{fg}-q_{irr}}{100}$—dimensionless term related to sensible heat.
$\alpha \cdot \frac{HHV-LHV}{LHV}$—dimensionless term to latent heat.
$q_{fg}$—losses of flue gases (%).

$q_{irr} = \left(t_{fg} - t_{air}\right)\left(\frac{A}{CO2} - B\right)$—loss due to boiler radiation into the immediate surroundings (%).

$t_{fg}$—temperature of flue gases (°C).

$t_{air}$—temperature of air (°C).

A,B—dimensionless terms for gases provided by public gas supply, where A = 0.66, and B = 0.009.

CO2—volume content of $CO_2$ in flue gases and an indicator of combustion quality that depends on burner design (%).

$\alpha = \frac{V_{cm}}{V_{ct}}$—degree of condensation, which depends on boiler design and installation (dimensionless).

$V_{cm}$—measured amount of condensate ($kg/m^3$).

$V_{ct}$—theoretical amount of condensate ($kg/m^3$).

HHV—higher heating value ($kWh/m^3$).

LHV—lower heating value ($kWh/m^3$).

The theoretical amount of condensate $V_{ct}$ for natural gas (methane, $CH_4$) is 1.6 $kg/m^3$.

### *Appendix A.2. Average Normative Efficiency of a Condensing Boiler*

For comparing energy efficiency in modern heating boilers, the concept of average normative efficiency was introduced in DIN 4702-8. It is defined as the ratio of useful heat delivered by the heat source to the amount of heat supplied by fuel combustion based on the lower heating value (LHV) of the fuel over the course of a year. The same standard establishes the procedure for obtaining comparable data during testing.

The total heating season time can be divided into five periods with different plant load values, where each value and duration corresponds to approximately equal areas on the diagram shown in Figure A2.

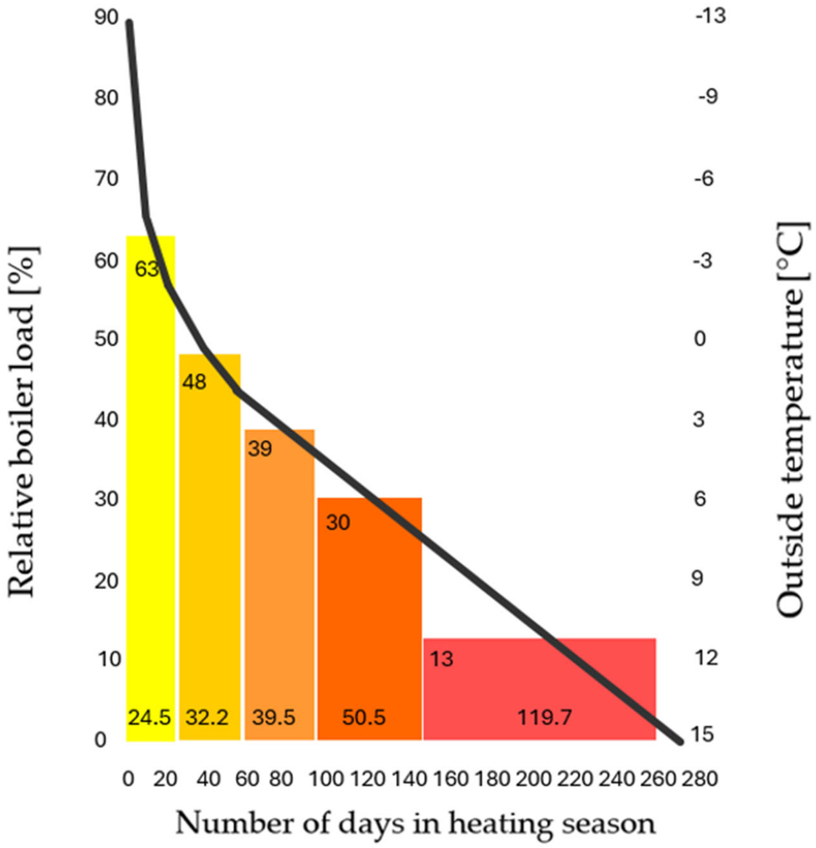

**Figure A2.** Diagram for determining the average efficiency rate according to DIN 4702-8.

According to DIN 4702-8, for these five defined periods and two pairs of temperatures (one for radiator heating based on temperatures of 75/60 °C and the other for underfloor heating based on a temperature difference of 40/30 °C according to EN 677), efficiency rates at partial loads are determined at the testing station. The average efficiency rate is then calculated as the mean value of these partial load efficiency rates.

According to DIN 4702-8, a testing procedure is available that uses standard testing programs to measure efficiency rates at partial loads with defined load levels. From the five measured partial efficiency rates, the average efficiency rate is calculated. This provides a definitive characteristic value to compare the energy efficiency of boilers of different designs.

### *Appendix A.3. Nominal Thermal Load*

The boiler is dimensioned so that its nominal thermal load can fully cover the heat requirements at the lowest external temperature values. However, such temperature values are rare, so the boiler operates at nominal power for a very short time during the year, while much less power is needed for most of the heating season. When considering the whole year, most of the heat requirements occur when temperatures range between 0 and +5 °C, as shown in Figure A3. Therefore, the average heating load of the boiler, considering the whole year, is less than 30%.

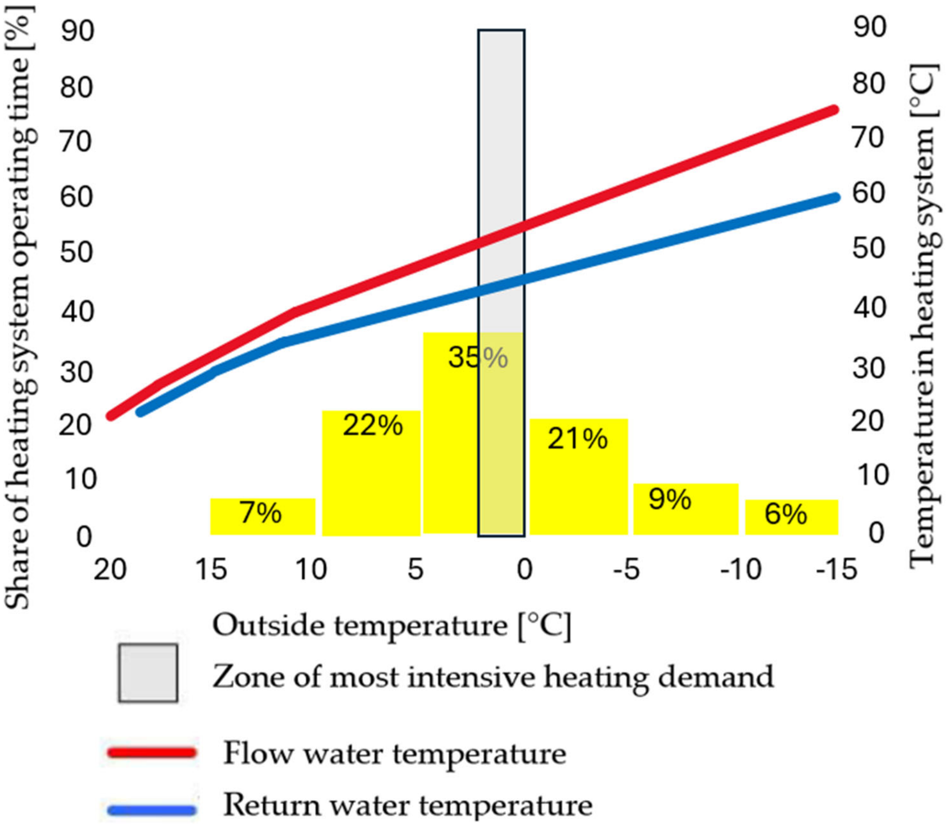

**Figure A3.** Diagram of boiler operation depending on external temperature (for heating system 75/60 °C).

From these facts follows another advantage of condensing boilers: their ability to achieve high efficiency precisely at lower boiler loads, which is the case for most of the heating season. In other words, unlike standard and low-temperature boilers, condensing boilers are most efficient during the most frequent operation in the heating season, i.e., at lower loads.

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