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Advancing Green Hydrogen Integration: Experimental Analysis of a Commercial Boiler

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Abstract

In the context of the energy transition towards a sustainable model, green hydrogen [1] has emerged as a pivotal element in the development of clean technologies. The production process of this energy vector involves electrolysis, which is driven by renewable energies such as wind and solar power. The present project entails the design, assembly and commissioning of a test bench, the purpose of which is to evaluate a commercial boiler that operates exclusively on green hydrogen.

The installation incorporates high-precision measurement and control systems, enabling the monitoring of critical parameters such as temperature, pressure and flow rate during combustion tests.Additionally, it encompasses the development of a programmable logic controller (PLC)-based automated system capable of real-time data recording.

The preliminary findings underscore the viability of green hydrogen as a clean and sustainable fuel, demonstrating its capacity to eliminate direct CO_2 emissions while exhibiting notable efficiency in domestic hot water (DHW) applications.

However, challenges associated with hydrogen supply and combustion control were also identified, creating opportunities for future optimisation.

This research not only validates the technical feasibility of employing green hydrogen in combustion systems, which are responsible for the majority of CO_2 emissions, but also contributes to advancing the global energy transition.

Key words: Green hydrogen, boiler, combustion, energy transition, energy efficiency.

1. Introduction

The energy transition towards a sustainable model is reshaping how energy is produced and consumed. In this context, green hydrogen, obtained through electrolysis using renewable energy, stands out as a clean and promising solution capable of eliminating CO_2 emissions in key sectors [2]. However, its implementation presents significant technical challenges.

The high reactivity and flame speed of hydrogen demand optimised combustion systems to ensure safety and operational efficiency. Additionally, its low energy density complicates storage and transportation, while its potential to produce nitrogen oxides (NO_x) under certain conditions requires rigorous combustion control. These challenges, combined with the need to adapt existing infrastructures, highlight the importance of detailed experimental studies.

This work focuses on the design, assembly, and commissioning of an experimental facility to evaluate a commercial boiler operating exclusively with green hydrogen. Alongside assessing its performance and efficiency, the project examines the long-term effects of hydrogen use on critical components, such as the burner.

The facility integrates advanced measurement and control systems to provide insights into operational parameters. The results will inform the optimisation of combustion systems, fostering the safe integration of green hydrogen in heating applications and advancing efforts toward global energy sustainability.

2. Materials and methods

A significant accomplishment of this project is the design and implementation of the test bench, which was developed to analyse the behaviour of a commercial boiler. This facility has been constructed and modified to operate exclusively with green hydrogen.

Test bench design

The test bench, shown in Fig. 1, was designed to integrate all the elements necessary to assess both the thermal efficiency of the boiler and the long-term impact of hydrogen on key components such as the burner. The installation includes the following components:

- Commercial boiler: the Ferroli HYDROHELIX 28C, adapted to operate with pure hydrogen, designed to maximise efficiency through latent heat recovery.

- Hydrogen supply system: consisting of bottles of green hydrogen produced by electrolysis, a pressure reducer and a high-precision mass flow controller to ensure a stable supply, plus an additional regulator just before the boiler inlet to ensure the correct pressure.
- Advanced instrumentation:
  - Pressure and temperature sensors conveniently distributed in the heating, DHW and hydrogen circuits.
  - Ultrasonic flowmeters to monitor water flows in real time.
- Control and data acquisition system: implemented by means of a Siemens S7-1200 PLC, which allows the supervision and recording of all critical variables. This system automates data collection, facilitating data analysis and minimising human error.

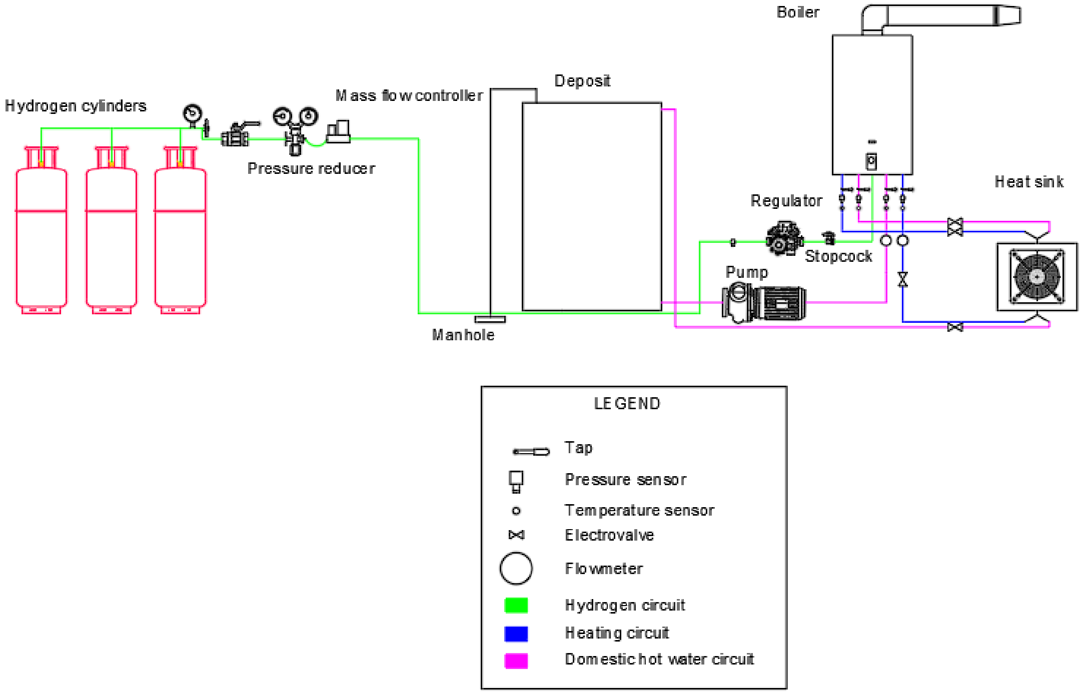

Fig. 1. Test bench scheme

Implementation of the test bench

The implementation of the bench required:

- Integration of components: all elements were assembled ensuring compatibility between sensors, boiler and control systems.
- Automation and programming: A program was developed in TIA Portal V18 for the PLC, which included:
  - Configuration of analogue inputs and outputs for sensors and actuators.
  - Creation of data blocks to record variables such as temperature, pressure and flow rate.
  - Configuración para registrar automáticamente los datos en archivos digitales en formato CSV para su posterior análisis.

Electrical panel design

An electrical panel was designed to centralise and protect the connection of all devices in the system. This panel includes:

- A main switch to disconnect the entire installation in case of maintenance or emergency.
- Individual circuit breakers to protect each component against overloads or short circuits.
- Power supply that converts the mains voltage (230 V AC) to 24 V DC to power the PLC and sensors.
- Modular organisation for easy access and future expansion.

Validation tests

Prior to the initiation of the trials, meticulous calibration and validation tests were conducted on all sensors and control systems to ensure reliable operation.

3. Preliminary results and discussions

The first bench tests provided initial data on the behaviour of the system, allowing an analysis of the most relevant aspects. The results are presented below.

Inlet and oulet temperatures

Fig. 2 shows the evolution of the temperatures in the DHW and heating circuits. In DHW mode, the outlet temperature (orange) is significantly higher than the inlet temperature (green), with a stable behaviour indicating efficient heat transfer.

In heating mode, the flow (yellow) and return (pink) temperatures show marked oscillations, especially at the beginning of the cycles. The smaller differential between the two reflects less efficient heat transfer in this mode, suggesting areas for improvement in flow control and regulation.

Fig. 2. Temperature evolution

Domestic hot water and heating flow rates

As demonstrated in Fig. 3, the flow rates in domestic hot water (DHW) and heating modes have been observed to evolve over time. The DHW flow rate (green line) has remained relatively stable, maintaining an average of 13-14 L/min. In contrast, the heating mode (orange line) has exhibited a more substantial increase, reaching an average of 18 L/min. It is important to note that the drops to zero in both graphs correspond to programmed stops between test cycles, a necessary process for transitions and verifications. The operational stability is noteworthy, however, the discrepancy between the two flow rates could be optimised to enhance efficiency.

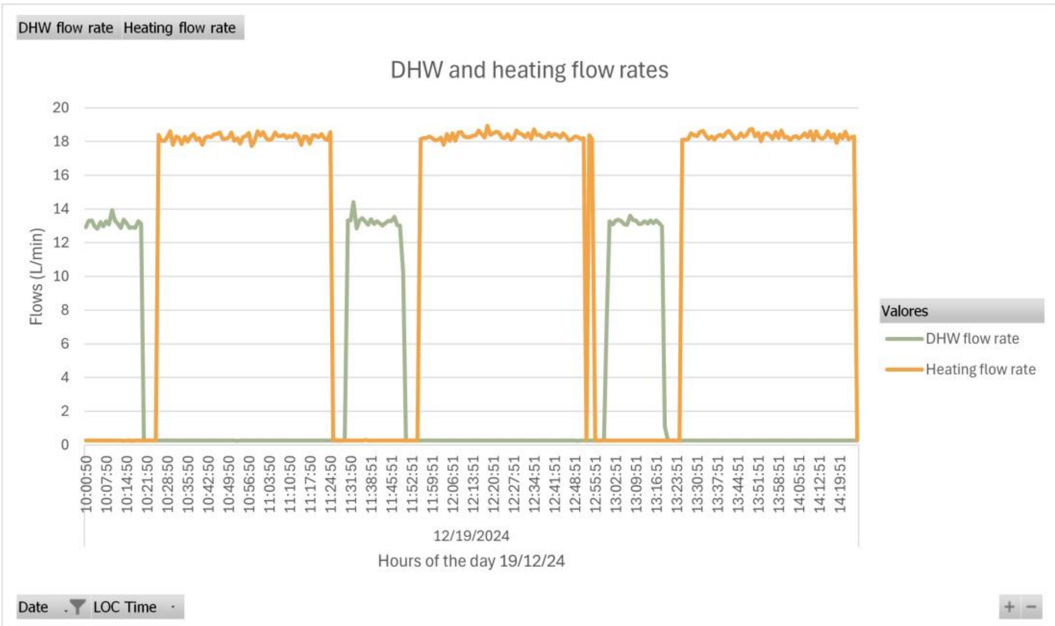

Fig. 3. DHW and heating flow rates on 19/12/24

Domestic hot water and heating thermal capacities

Fig. 4 shows the evolution of the thermal power in DHW (green line) and heating (orange line) modes. In DHW mode, the power reached values close to 25 kW, showing a stable and adequate performance for the high thermal demand. On the other hand, in heating mode, the power was considerably lower, fluctuating between 4 and 8 kW due to the lower demand in this mode. The observed interruptions correspond to the programmed stops between cycles. As mentioned above, these results show the good performance in DHW and the need to optimise the heating mode to improve the overall efficiency.

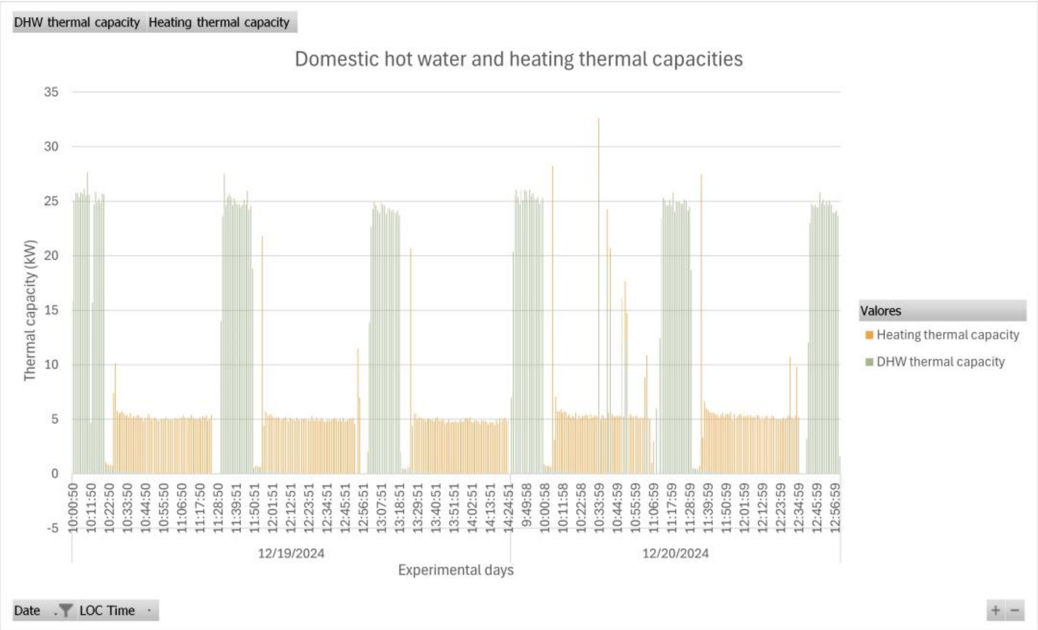

Fig. 4. Domestic hot water and heating thermal capacities

DHW and heating efficiencies

Fig. 5 shows the evolution of the efficiencies in DHW (green line) and heating (orange line) modes during the 19/12/24 tests. In DHW mode, the efficiencies reached values close to 90% during the operating periods, reflecting a consistent thermal performance. In contrast, in heating mode, efficiencies rarely exceeded 20%, with occasional peaks that were not sustained, due to the low thermal demand and the characteristics of the system in this mode.

The efficiency drops in both modes are due to the transitions and programmed stops between cycles, clearly visible in the graph. This behaviour highlights the good performance of the system in DHW and the need for adjustments to optimise the heating mode and reduce energy losses.

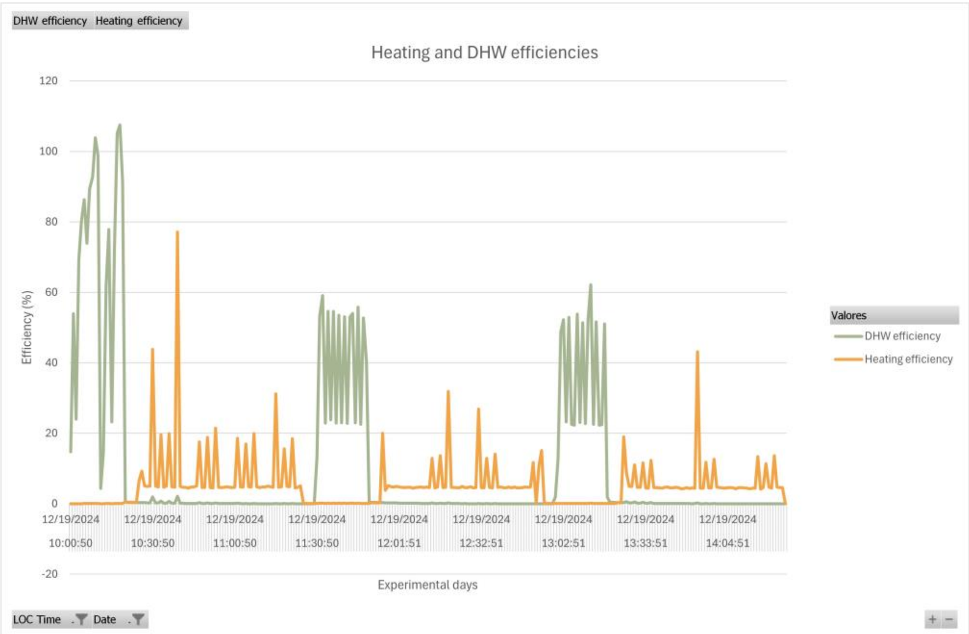

Fig. 5. Heating and DHW efficiencies on 19/12/24

The experimental tests conducted on the test bench have enabled the assessment of the performance of the boiler when operated with green hydrogen in domestic hot water (DHW) and heating modes. In the DHW mode, the system demonstrated optimal functionality, attaining efficiencies of up to 90% and outputs approaching 25 kW. However, the transitions between cycles occasionally resulted in minor fluctuations.
Conversely, in the heating mode, the efficiency was found to be considerably lower, with mean values falling below 20%. Additionally, issues were identified with the PID mass flow controller, leading to fluctuations in hydrogen supply and affecting combustion stability.Limitations were also detected in the heat sink, which resulted in the supply and return temperatures reaching equilibrium rapidly in the heating mode, thereby reducing the system's capacity to maintain efficient heat transfer.
These findings underscore the necessity for refinement in the regulation of hydrogen flow and the design of critical components to enhance the efficacy of heating mode operation.

4. Conclusion

The production of green hydrogen from renewable sources is of increasing importance in the pursuit of decarbonisation and sustainability objectives in various sectors, including air conditioning. This work has demonstrated the feasibility of developing an experimental facility to evaluate a commercial boiler that operates exclusively on hydrogen. This represents a significant step towards the integration of this fuel in real applications.
The design and commissioning of the test bench combined advanced materials and equipment, such as a mass flow controller, high-precision sensors and an automated data acquisition system, enabling detailed monitoring of key parameters and providing a rigorous approach to experimental analysis.
The results obtained demonstrate the test bed's outstanding performance in domestic hot water (DHW) mode, with efficiencies close to 90% and stable thermal operation. However, in heating mode, areas for improvement were identified, such as fluctuations in hydrogen supply and heat sink limitations, which affected thermal efficiency and operational stability.These findings emphasise the importance of optimising hydrogen flow control and redesigning key components to maximise performance.
This project is demonstrative of the technical feasibility of using green hydrogen in commercial systems and highlights its potential to drive future research and development, reinforcing its role as a key player in the energy transition [3] to a more sustainable model.

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