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DEVELOPMENT OF HIGH PERFORMANCE (LOW NO_X) DOMESTIC HYDROGEN BOILERS

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FROM AMBITION TO REALITY

One of the major challenges for the current energy transition is a drastic reduction in carbon intensity to meet the targets set by climate agreements. Decarbonizing energy-related end-user processes is an important step in achieving these targets. A sustainable route to reduce the carbon intensity is to replace natural gas by green hydrogen. Nationally and internationally, there is a lot of attention on hydrogen, as evidenced by the many strategies, visions, reports and investments of governments and globally operating companies. The challenge now is not in the ambition, but in changing the timeline: from hydrogen on the horizon to hydrogen in our homes, businesses and transport systems. To reach the level where societies and industry can reap the benefits of hydrogen on a large scale, all stakeholders will need to pay attention to demonstrating safety, enabling infrastructure, scaling up technology and stimulating the development of value chains through policy.

In this paper hydrogen for heating technology in houses is becoming reality. Local authorities, gas and power network operators, housing corporations and equipment manufacturers are currently investigating how homes can be heated safely and efficiently with clean hydrogen. Recently Bekaert and DNV GL both successfully developed a residential hydrogen boiler showing excellent combustion performance. The paper demonstrates how hydrogen boilers can become a safe, carbon-free and cost-effective heating technology for the future.

HYDROGEN FOR BUILT ENVIRONMENT

Natural gas will become the world's largest low-carbon energy source in the mid-2020s [1], accounting for nearly 30% of the global energy supply in 2050. The success of a hydrogen energy economy is closely aligned with the future of natural gas, renewable energy, and carbon capture and storage (CCS) technology [2]. While hydrogen gas produced from renewable energy (green hydrogen) is the industry's ultimate destination, analysis shows that the sector can only realistically scale up to large volumes and infrastructure with carbon-free hydrogen produced from fossil fuels combined with CCS technology (blue hydrogen).

Hydrogen is an energy carrier that can be broadly applied in industry, in mobility, in the energy sector and in the built environment. The majority of today's natural gas consuming sectors, (i.e. industry, transport, power generation and heating) use combustion as a primary process. In a combustion process, chemical energy is transformed into heat. Combustion processes mostly occur at relatively high temperatures. These high temperatures enable combustion processes to be very useful in a large number of applications. A challenge for the combustion of natural gas is the substantially high emission of CO_2.

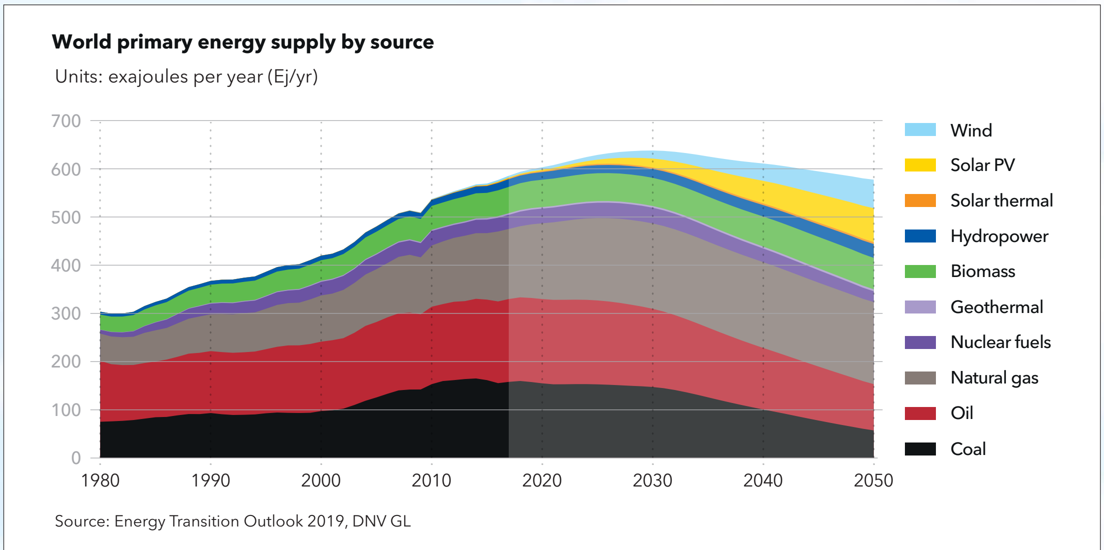

Figure 1: Natural gas will become the world's largest low-carbon energy source in the mid-2020s accounting for nearly 30% of the global energy supply in 2050

WHY BURN HYDROGEN?

Drastic reduction of CO_2 emissions has become a paramount, global target since the start of this century. Since the combustion of hydrogen does not produce CO_2, the replacement of natural gas by green hydrogen offers a sustainable route to reduce the carbon intensity for heating processes. Another major advantage to the use of hydrogen for heating processes is that, in principle, existing gas equipment can be retrofitted, resulting in a short time-to-market with only limited investment costs.

The design challenge for hydrogen combustion is that the combustion properties of hydrogen substantially differ from those of natural gas [e.g. 3, 4]. For example, hydrogen has a much higher burning velocity and flame temperature in comparison to natural gas. As a result, without changing the design of equipment, replacement of natural gas by hydrogen results in, for example, burner overheating, possibly flame flash-back and increased NO_x formation. However, these differences in combustion properties also offer opportunities to improve the performance of gas equipment.

NOx LEVELS ARE MUCH HIGHER FOR HYDROGEN?

Over recent decades, increasingly stringent regulations for NO_x emissions have been a driving force behind the development of new, sophisticated combustion technologies. When designing dedicated equipment for hydrogen combustion, we use established knowledge regarding NO_x formation to develop effective NO_x control strategies.

The main mechanisms of NO_x formation in gas-fired boilers is thermal NO formation. In the thermal NO mechanism, nitrogen and oxygen react to form NO_x molecules. To break the nitrogen bonds, high temperatures are needed, which makes this NO_x formation strongly temperature dependent as illustrated in figure 3. Given that the temperature of a hydrogen flame is much higher than a natural gas flame (up to about 200°C higher), the NO_x formation increases when switching to hydrogen combustion [5]. Research work on industrial burners [4, 5], gas turbines [6, 8] and car and truck engines [9], show increased NO_x emissions when hydrogen was used as fuel.

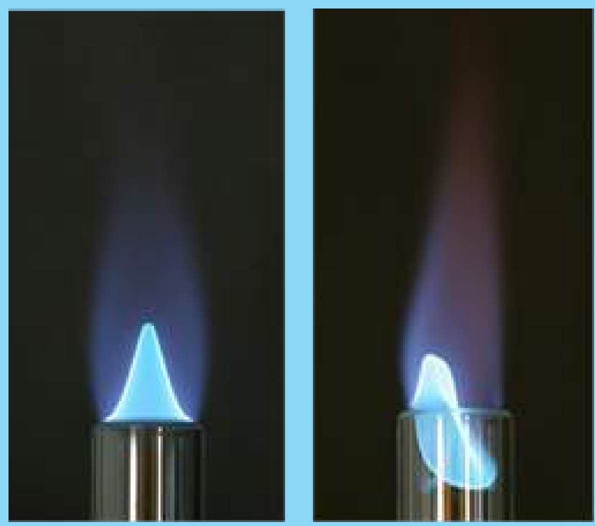

Figure 2: Flame flashback (left) in burner caused by adding hydrogen to natural gas

As a result, designers of combustion equipment [5, 6, 10] focus on lowering the flame temperature to reduce NO_x formation. The flame temperature of a hydrogen flame can be reduced by, for example, increasing the excess of combustion air, applying burner stabilisation or using flue gas recirculation. The high burning velocity of hydrogen allows us to substantially increase the excess of combustion air and/or apply flue gas recirculation without running into flame stability issues. Another strategy is to lower the residence time by, for example, increasing the velocity of the hydrogen/air mixture or by enhancing the mixing of the reactants and simultaneously reducing the residence time of these reactants in the hot spots of the flame.

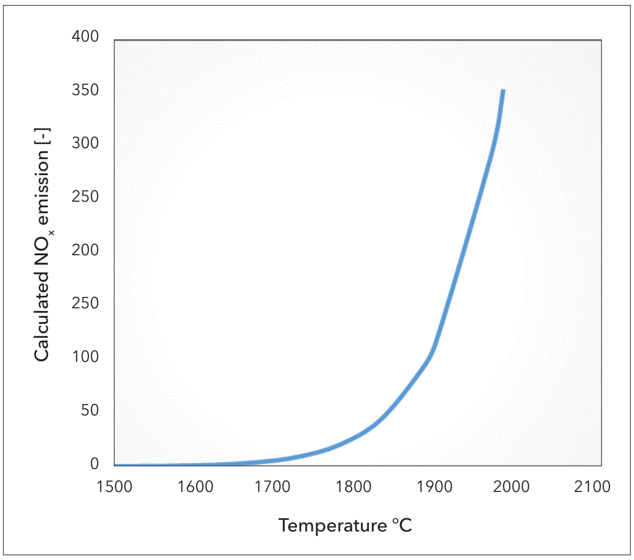

Figure 3: Calculated thermal NO formation as function temperature

RECENT RESIDENTIAL HYDROGEN BOILER DEVELOPMENTS

Decarbonization of the built environment is a big challenge, especially for existing residences with poor to average cost-effective insulation possibilities.
In Rozenburg [7] and in Hoogeveen, houses are (going to be) heated with hydrogen. In the project 'Waterstofwijk Hoogeveen', 22 parties have been collaborating since 2018 to create a blueprint for residential areas in The Netherlands, in which a complete 100% green hydrogen system is designed, and in which hydrogen-fired boilers are chosen as the dominant heating technology.

Recently, Bekaert and DNV GL/GasTerra independently developed a hydrogen boiler by adapting an existing domestic boiler. Despite differences in burner design, both hydrogen boilers show excellent combustion performance, having similar efficiency as natural gas boilers. The NO_x mitigating strategies demonstrated here make use of shortening the residence time or flue-gas recirculation, or a combination. As can be seen in figure 4, measurements on NO_x-emissions in both devices show values that are substantially lower than values generally measured in comparable boilers running on natural gas.

Business studies indicate that implementation of retrofit hydrogen appliances result in much higher NO_x levels [11,12]. Such studies are based on a one-to-one replacement of natural gas by hydrogen. In contrast, the developments shown here demonstrate that the NO_x emissions of hydrogen combustion can actually be much lower compared to natural gas.

NO_x mitigating strategies discussed here are successfully used in larger input systems, like commercial and industrial boilers [5]. This is an important point to be made, as outdated information suggesting higher NO_x-emissions with hydrogen as a replacement fuel seems to be resonated by politicians and policy makers.

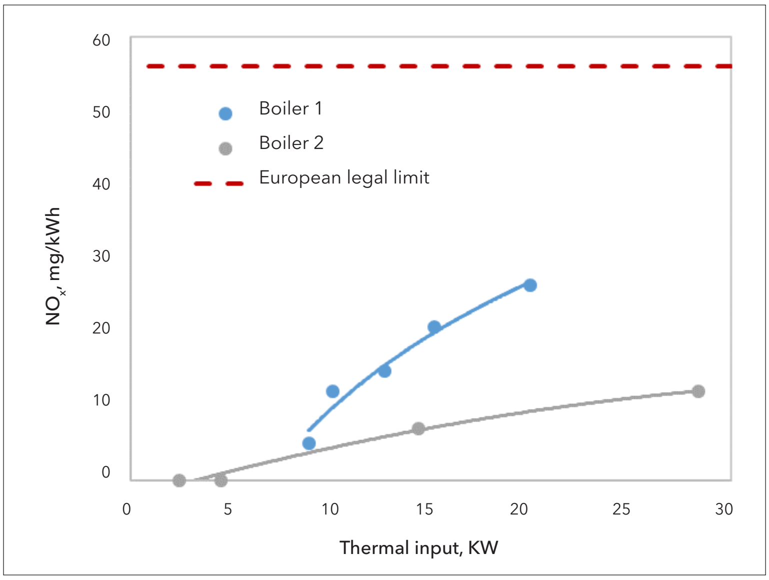

Figure 4 - Left: DNV GL/Gasterra (boiler 1) and Bekaert (boiler 2) condensing boilers in Rozenburg demonstration
Right: No_x emission measured in hydrogen boiler 1 & 2 at different thermal loads

CONCLUSION

A successful adaptation solution to convert existing natural gas boilers to hydrogen is developed which facilitates the introduction of (green) hydrogen in the built environment, enabling substantial CO_2 emission reduction. In this white paper we demonstrate a safe and a reliable performance of residential hydrogen boilers. Additionally, we show that NO_x mitigating strategies result in NO_x levels that are much lower than the legal European limits. These mitigating strategies can also be applied to commercial and industrial heating systems.

This makes hydrogen boilers an important safe, carbon-free, low NO_x, cost effective and direct-replacement heating technology for the built environment.

ACKNOWLEDGEMENTS

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