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The role of combustion (and fuels) in a decarbonizing world

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Access to energy is essential for the modern world, yet at the same time, anthropogenic greenhouse gas emissions are caused by energy-related activities across all sectors due to the predominance of fossil fuels. Today, most of the primary energy is still being provided by fossil fuels, with combustion being a key technology. In order to combat climate change, energy has to be decoupled from greenhouse gas emissions, with electricity and electrification being important pathways towards a net-zero energy system. However, electricity also has drawbacks as an energy carrier, especially in the context of large-scale energy storage, but also for applications requiring high energy densities. This, in addition to providing dispatchable power generation capacities for grid balancing and covering longer periods of reduced renewable power generation, is expected to result in significant contributions of synthetic and biogenic fuels to the energy landscape. The main purpose of combustion-based technologies will change from providing most of the primary energy to the energy system to complementing variable renewable energies when and where needed. This change of purpose has consequences for the directions of combustion research and development: while traditional topics such as equipment efficiency and pollutant emissions such as NO_x will still be important, other topics such as more flexible and dynamic operation modes, hybrid applications and system integration will play a much bigger role in the future, along with the use of new fuels such as hydrogen or ammonia.

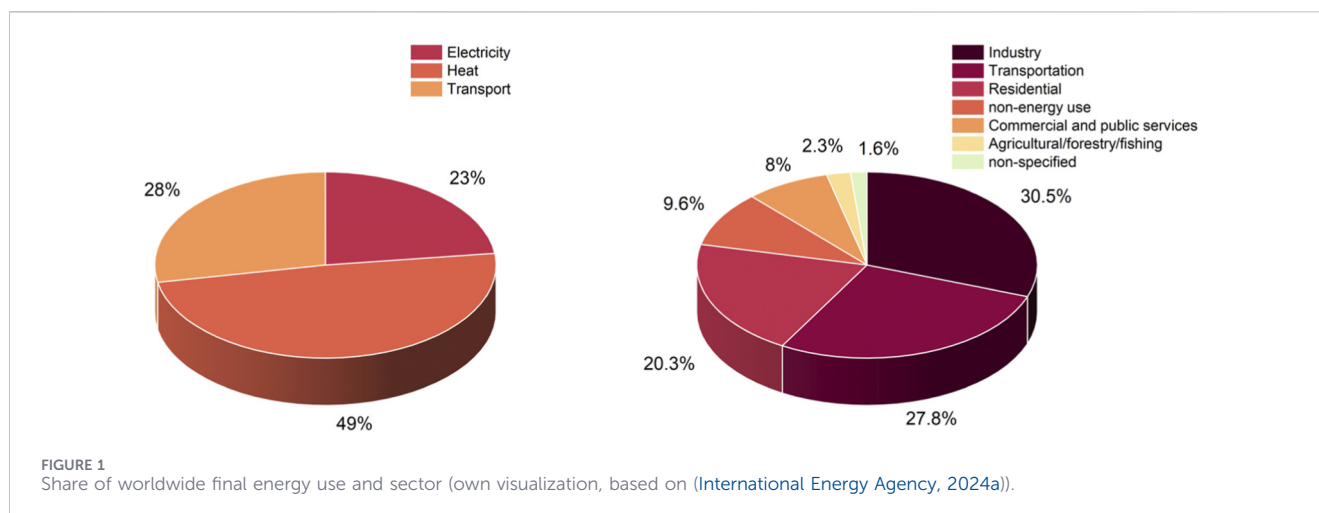
KEYWORDS

alternative fuels, combustion, decarbonization, electrification, energy, hydrogen

1 Introduction

The mastery of fire is generally considered to be one of the most fundamental achievements in early human civilizations, along with agriculture, pottery and writing. Today, combustion remains a key technology in the many fields of human activity which rely on energy, usually in combination with fossil fuels such as coal, oil or natural gas. Despite all advances in the deployment of renewable energies, almost 60% of the global electricity demand is still being covered by coal and gas-fired thermal power plants ([EMBER Energy, 2025](#)). However, often contrary to public perception, energy is more than just electricity which accounts for only slightly more than 20% of global final energy use ([International Energy Agency, 2024a](#); [Enerdata, 2025](#)).

In the transportation sector, mechanical energy is needed to move people and goods all over the world. Though electric vehicles are gaining importance in the light-duty sector and electric trains have been in operations in many parts of the world for decades, most vehicles today, ranging from cars to ships and aircraft, still use some kind of internal combustion engine. Similarly, stationary drive applications such as compressors or pumps are often powered by internal combustion engines.



Finally, about half of the world's energy demand is required as heat (International Energy Agency, 2024a). Heat is needed for a multitude of different purposes: to prepare food, make homes comfortable or to manufacture all kinds of materials and products. Many of these materials are, quite literally, the building blocks of modern society, for example, steel and non-ferrous metals, cement, glass, ceramics or the many products of the chemical industry. These materials are also very energy-intensive in their production, with the vast majority of industrial process heat still being provided by fossil fuels, natural gas in particular. About two-thirds of the global industrial energy demand is accounted for by process heating (BDEW, 2025; Fleiter et al., 2023; Hasanbeigi et al., 2021), making it the biggest energy consumer in this sector by a wide margin. Similarly, residential heating is still dominated by fuels in many parts of the world. Figure 1 (left-hand side) shows the shares of electricity, mechanical energy and heat in the global final energy demand (International Energy Agency, 2024a).

This review is based on the opening keynote given at the 2025 IFRF Conference on Sustainable and Safe Industrial Combustion in Sheffield (United Kingdom) (Leicher and Wieland, 2025). It aims to discuss the fundamental role that energy in general and combustion science and technology in particular have played in creating and maintaining modern society. It also acknowledges the problems that arise from the dependency on fossil fuels in terms of environmental and climate-related issues, given the inevitable production of greenhouse gases (primarily in the form of carbon dioxide (CO₂)) when burning fossil fuels.

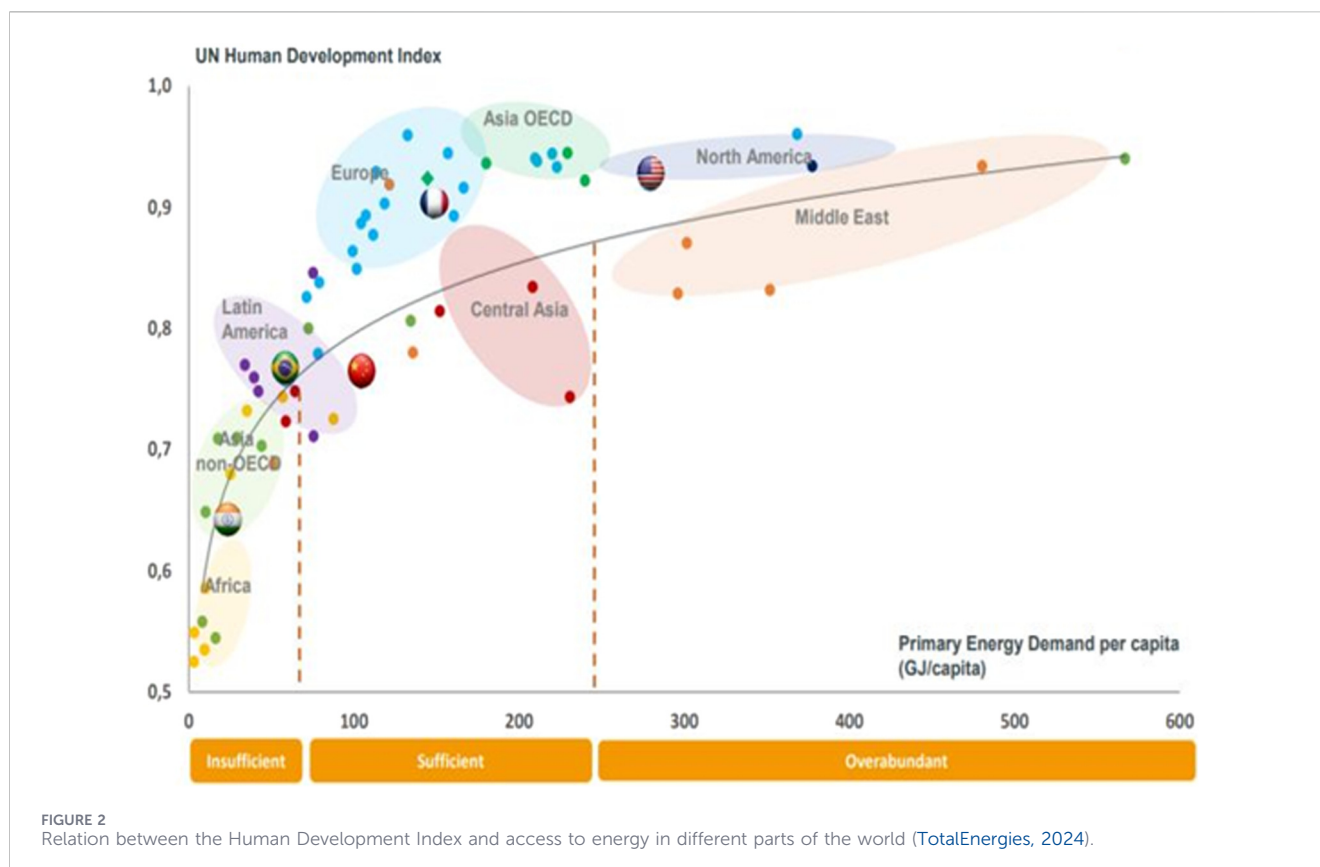
The future roles of fuels and combustion in general will then be explored, considering that electricity (from renewable or other carbon-free sources) and electrification of end-use applications are key components of decarbonization which are today expanding into applications that traditionally have been the domain of fuels, e.g., transportation or heating, but also energy storage. As IFRF's activities have always been centered on large-scale, stationary combustion applications such as thermal power plants and industrial furnaces and kilns, this article will concentrate on these types of equipment. However, similar discussions about the future of fuels and combustion engines are also going on in the transportation sector, especially in the context of hard-to-electrify

vehicle types such as aircraft or ocean-going vessels. Though the applications and their requirements are very different in these sectors, there are also some similarities which will briefly be addressed.

Electricity as an energy carrier has to deal with limitations of its own, which is why synthetic and biogenic fuels are expected to complement electricity-based applications and infrastructures when and where necessary or beneficial. The advantages and drawbacks of these fuels, mostly from the perspective of applications such as power plants and industrial process heating, will be discussed, with a focus on hydrogen and ammonia. Both ongoing and new challenges for combustion science and technology arise from these new fuels. Therefore, the article concludes with an overview of the state-of-the-art in applied combustion research for these new and different fuels as well as their full-scale implementation, and identifies topics where further research is needed.

2 The essential role of energy

Access to energy in its various forms is essential for human development and quality of life, as is underlined by Figure 2 (TotalEnergies, 2024). This diagram shows the Human Development Index (HDI) over the primary energy demand *per capita* in different parts of the world. The HDI is defined by the United Nations as a metric to quantify human quality of life with a single index, taking into account the economic situation in a country as well as societal aspects such as life expectancy or average education levels (UNDP, 2024). The closer the HDI is to unity, the better the local quality of life is deemed to be, at least in material terms. As the figure highlights, there is a very strong interdependence between HDI and primary energy demand. The fit is not linear however, instead distinct local differences can be observed. Quality of life is relatively similar in well-developed parts of the world such as the EU and North America, but the Americans expend more energy to achieve similar HDI levels. This saturation effect is likely due to several factors: energy in Europe has historically always been more expensive than in America, making energy efficiency a bigger priority for Europe. Also, many energy-intensive industries have shifted their operations from Europe to



other parts of the world in the last decades, primarily to East Asia, reducing European energy demand further. More striking, however, is the very strong relationship between access to energy and quality of life in regions where access to energy is generally insufficient, which can be seen on the left-hand side of the diagram. Energy scarcity generally hampers economic development, which often ties in with societal progress as well. On the other hand, even small improvements in energy accessibility lead to significant increases in local living standards. The diagram underscores how crucial reliable and affordable access to energy is for a country's prosperity.

2.1 Industrialization and global energy demand

Global energy demand has increased drastically with the onset of the Industrial Revolution, as highlighted by Figure 3. It is worth noting that for most of human history, mankind actually lived in decarbonized societies, with energy being supplied by traditional biomass for the most part, as well as some wind and hydro (Smil, 2018). However, with the Industrial Revolution came the need for more and more concentrated energy sources, starting with coal, then adding oil and natural gas, and later nuclear power and modern renewables such as wind turbines or photovoltaic panels to the energy portfolio. At the same time, new ways to harness energy were developed, beginning with the steam engine (which is often considered the starting point of the Industrial Age), and then later the internal combustion engine, widespread electrification, various heating technologies, and today information and communication technologies.

While these technological advances undoubtedly improved quality of life globally, they have also drastically increased global energy demand which so far, is still mostly being supplied by fossil fuels. Fossil fuels such as coal, oil or natural gas offer several crucial advantages: they are abundantly available, and can be efficiently and safely transported and stored. They have high energy densities and their combustion can also provide the high temperatures needed to produce essential and ubiquitous materials such as steel, non-ferrous metals, glass, cement ceramics or chemical products.

It is worth considering that, historically speaking, there has never actually been an energy transition in the sense that one energy carrier has been almost completely substituted by another on a global level across all applications. There have, however, been cases where one energy source has lost its role in certain applications. One example is town gas, a coal or sometimes naphtha-based synthesis gas. It was widely distributed and used in Europe and the United States as a fuel for cooking, heating and lighting, before it was substituted by natural gas and electricity in the latter half of the 20th century. However, even today there are regions in China where it is still in use (Gas Safety - Types of Domestic Fuel Gases and Their Properties, 2024; Kobayashi et al., 2025).

Despite all the changes in the global energy landscape, the amount of energy provided by traditional biomass is about the same as it was 200 years ago. According to the International Energy Agency, about 2 billion people worldwide do not have access to clean fuels or electricity to prepare their food and use traditional biomass such as wood or cow dung instead, with significant health hazards as a consequence. About 10% of the global population do not have access to electricity at all (International Energy Agency, 2025a).

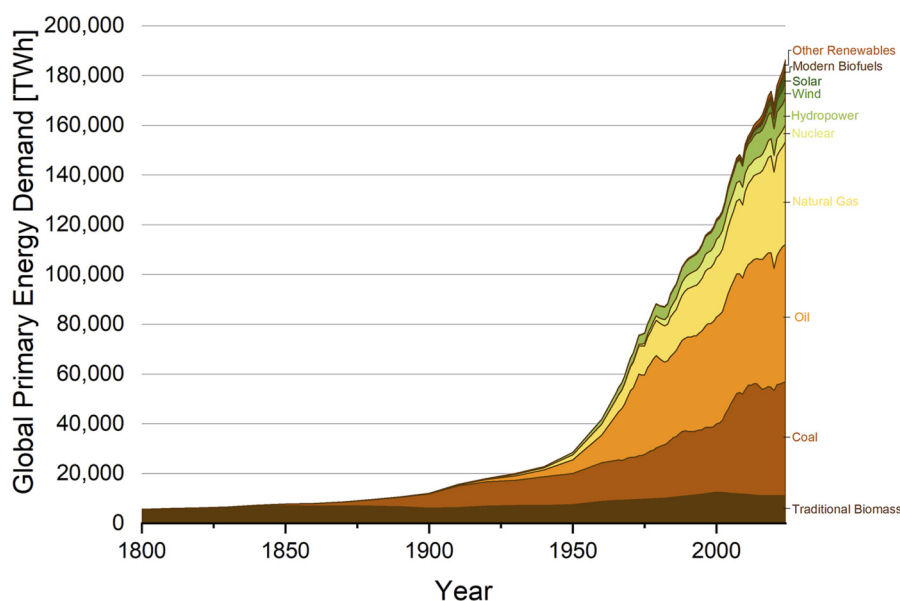


FIGURE 3
Historical evolution of primary energy demand (own visualization, based on data from (Energy Institute, 2025; Our World in Data, 2025; Smil, 2010)).

Similarly, global coal consumption, mostly used for power generation, has yet to show a significant decline (International Energy Agency, 2025b), while natural gas consumption has been steadily increasing over the last decades (Energy Institute, 2025). The massive deployment of renewable power generation capacities in recent years, in particular wind and solar, has not yet led to a reduction of fossil fuel utilization, as global energy demand is growing even stronger.

2.2 Greenhouse gas emissions and the need for decarbonization

The technological and societal progress that is a direct consequence of the Industrial Age has come at a price. The combustion of carbonaceous fuels such as coal, oil or natural gas inevitably produces carbon dioxide (CO₂) which has been identified as a greenhouse gas (GHG) that promotes global warming. Compared to pre-industrial levels, atmospheric CO₂ concentrations have more than doubled, and are today at about 425 ppm, emphasizing the scale of anthropogenic GHG emissions. Almost 75% of these anthropogenic greenhouse emissions are directly or indirectly (e.g., methane emissions from natural gas extraction, transmission and distribution) tied to energy use (Richie, 2020), with the second-biggest contributor being agriculture and forestry, another indispensable sector of human activity (cf. Figure 1, right-hand side). Consequently, global temperatures are rising, resulting in more frequent extreme weather events such as heat waves, droughts or flooding, often with severe consequences. Changing weather and climate patterns have an impact on agriculture, and have geopolitical implications as well, e.g., in terms of migration.

The obvious conclusion is that energy supply and utilization have to be decoupled from GHG emissions to limit the effects of climate change. There are additional aspects to consider, though, given the

paramount importance of secure and affordable access to energy for people and economies around the world. Global energy demand is expected to increase for several reasons: quality of life is increasing globally which generally entails a higher *per capita* energy demand, while the world population is increasing as well. Nations have to balance their commitments to mitigate climate change with the need for a secure energy supply at affordable prices for their citizens. At the same time, new technologies, in particular Artificial Intelligence (AI), are forecast to drastically increase demand for firm power supply (Global Gas Report, 2024; International Energy Agency, 2025c), putting further stress on existing power grids already coping with increasing shares of intermittent renewable power generation.

3 Decarbonization and electrification

Decarbonization, i.e., the transformation of today's fossil fuel-based global energy system towards an energy system primarily powered by renewable and sustainable energy sources on a global scale is an unprecedented endeavor in human history. Some authors (e.g., (Kullmann et al., 2023; Griffiths et al., 2025)) prefer the term “defossilization” in this context, as carbon will still be an essential component for many industrial processes and products, for example, in the chemical industry or in metallurgy. However, “decarbonization” seems to have become the more popular term in the public discussion and will be used in the remainder of this article which focuses on energy systems, not the use of fossil fuels as raw materials.

3.1 Electricity from renewable sources and electrification

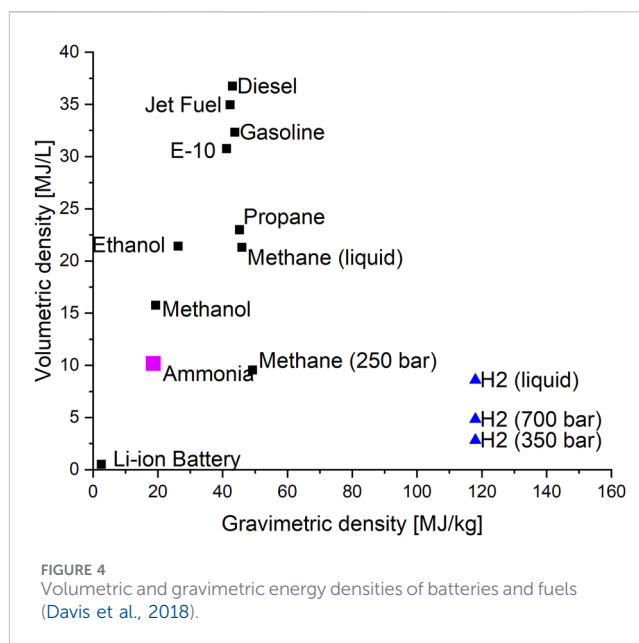
One of the essential tools to achieve the phase-out of fossil fuels is the electrification of many end-use applications, ranging from

individual mobility (e.g., battery-electric vehicles) and residential heating (e.g., heat pumps) to industrial manufacturing (e.g., electric process heating). Electricity is crucial for several reasons: it can be generated at scale from renewable sources such as wind, solar, hydro or geothermal sources, or alternatively by nuclear power, without producing GHG emissions. At the same time, electricity is a very versatile form of energy that can efficiently be transformed into either mechanical energy or heat when needed. In many end-use cases, electrification also entails substantial efficiency gains, as can be seen by comparing, for example, the efficiency of battery-electric vehicles to conventional vehicles with internal combustion engines in the transportation sector, or heat pumps (Rosenow et al., 2024) to gas-fired heating appliances in the context of low-temperature heat, e.g., for heating buildings. For other applications, e.g., high-temperature industrial process heating, efficiency gains by electrification may be less pronounced (Hasanbeigi et al., 2021; Friedmann et al., 2019).

In the context of decarbonization, the origin of electricity is essential: if the electricity is not generated by carbon-free or at least carbon-neutral means, much of the GHG emissions are just shifted from the end user to thermal power plants. In some cases, e.g., for high-temperature process heating, it can be shown that using a fossil fuel like natural gas in an industrial furnace can actually result in lower overall CO₂ emissions than a switch to an electric furnace supplied by an only partially decarbonized power grid (Leicher, 2024; Wüning, 2021), depending on the carbon intensity of the respective power grid. While the global carbon intensity of electricity has been decreasing, its evolution is dependent on the political momentum of the energy transition. For other applications, e.g., light-duty vehicles or residential heating by heat pumps on the other hand, this is less of an issue, as electrification will almost certainly lead to reduced overall emissions, as the efficiency gains are more substantial here (Rosenow et al., 2024; Naumann et al., 2022; Buber et al., 2022).

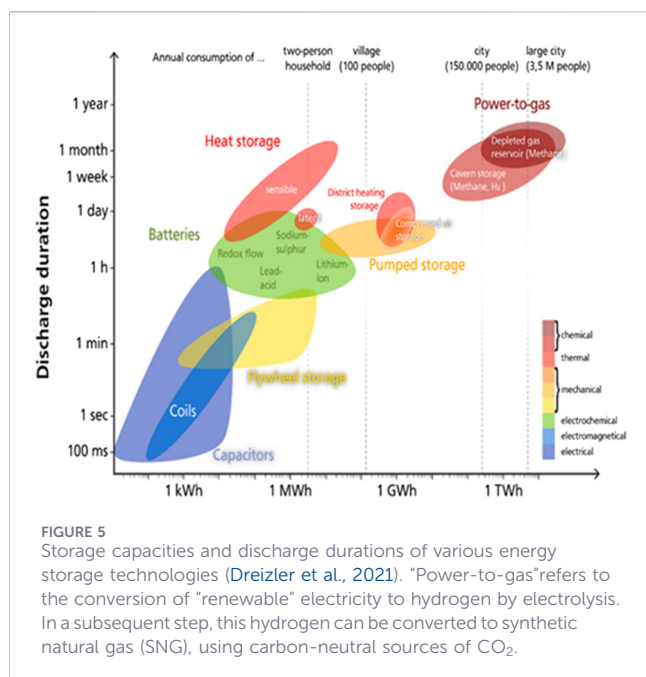
There are, however, more aspects to consider than just efficiency: many renewable energy sources, most notably wind and solar, are inherently intermittent which means they can only contribute to a firm and reliable power infrastructure in combination with suitably scaled energy storage facilities and/or flexible backup systems. This is particularly relevant for power grids as electricity supply and demand have to be continuously balanced. Other renewable options such as hydro or geothermal power are easier to integrate into power infrastructures since they can provide dispatchable power, but they are restricted by geographic and geologic suitability. Nuclear power, while being a mostly carbon-free power generation technology, faces challenges of its own: high investment costs, public acceptance, safety and security considerations as well as the question of long-term nuclear waste disposal.

Thus, the countries with the lowest CO₂ intensities in their power systems tend to rely on either hydro and geothermal (e.g., Norway) or nuclear power generation (France being the prime example), not wind or solar. Yet solar power is forecast to be the dominant source for electricity in the future (EMBER Energy, 2025; International Energy Agency, 2024b), and the integration of large shares of variable renewables into power infrastructures brings significant challenges, often leading to overall increasing system complexity and cost (International Energy Agency, 2024c).



Germany, currently the 3rd largest economy of the world by gross domestic product (GDP) and with a population of more than 80 million inhabitants, is a good example for the challenges that come with decarbonizing a modern industrialized economy. The nation has committed to become carbon-neutral by 2045 and has been investing significant funds into what is called the “Energiewende” (energy transition). In 2024, about 54% of the electricity produced in Germany came from renewable sources (mostly wind and solar, some hydro and biomass), compared to about 6.5% in 2000 (Stromerzeugung nach Energieträgern Strommix von 1990 bis, 2024). This translates however, to only about 20% of renewable energy in the final energy demand (Energieverbrauch in Deutschland im Jahre, 2024), as electricity accounted for about one-quarter of the final energy consumption. The carbon intensity of the German power mix was determined to be 386 g CO_{2eq}/kWh of electricity in 2023 (Energieverbrauch in Deutschland im Jahre, 2024), one of the highest values in the EU. It is insufficient to just consider electricity in the context of decarbonization, however. In fact, German industrial process heat demand alone was about on par with the entire German electricity generation from all sources in 2023 (BDEW, 2025).

One topic that has been gaining more traction in recent years is utility-scale energy storage, especially due to recent shifts in European energy supply and the growing contributions of inherently intermittent wind and solar power generation. This refers both to large-scale electricity storage, but also energy storage, e.g., in the form of natural gas. Germany today operates facilities to store about 260 TWh’s worth of natural gas, equal to almost one-third of the nation’s annual gas demand. These assets primarily serve to deal with seasonal demand shifts, as natural gas is for the most part used for residential heating and industrial manufacturing. Only about 13% of Germany’s gas demand is accounted for by power generation (Energieverbrauch in Deutschland im Jahre, 2024). In contrast, the available capacities of electric energy storage technologies are orders of magnitude smaller: in terms of pumped hydro, the current capacity is about



0.04 TWh with little potential for expansion (Schill and Kemfert, 2011). Total installed battery storage capacity is even lower with roughly 0.02 TWh in 2024 (Bundesverband Solarwirtschaft e.V., 2025), though installed battery capacities are growing rapidly. It is evident that providing security of electricity supply while relying heavily on intermittent energy sources is a challenge. Recently, Germany turned from a net electricity exporter to a net importer, although there are at the same time many instances when Germany exports surplus electricity to its European neighbors due to a lack of local storage capacity.

While the situation can be very different depending on local conditions, the example of Germany may serve as an indicator for the challenges involved in a full-scale energy transition towards renewable and sustainable energy sources for an industrialized nation.

3.2 The ongoing need for fuels

Electricity as an energy carrier offers many advantages, but also has certain drawbacks which may limit its suitability for some end-use applications as well as its functions in energy infrastructures. Batteries have much lower energy densities compared to fuels (cf. Figure 4), which affects the available range, endurance or payload capacity of vehicles like aircraft or ships, despite the higher efficiencies of the drive systems themselves. In the context of electricity infrastructures, utility-scale batteries can serve to provide electricity in the range of several hours which is sufficient for short-term generation shortages or peak-shaving, but they are unable to compensate for insufficient power generation over days or weeks (the so-called "Dunkelflaute"). This is highlighted by Figure 5, where various energy storage technologies are compared in terms of discharge durations and storage capacities. Only the so-called power-to-X technologies and pumped-storage solutions offer decarbonized long-term energy storage at utility scale. It has been the traditional role of fossil

fuels to provide long-term energy security, which is particularly relevant for energy-intensive industries. In Germany, for example, the natural gas grid transports about twice as much energy as the power grid (BDEW, 2025).

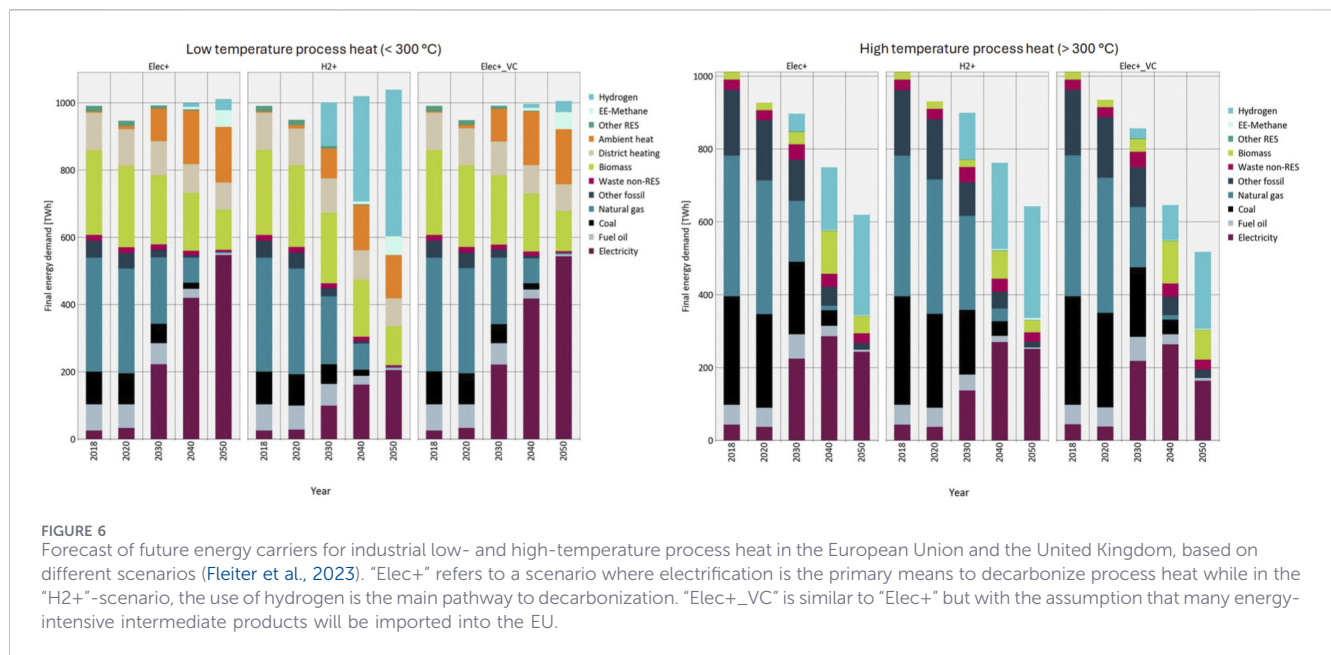
While the main role of fossil fuels today is to provide primary energy for the global energy system, coal, oil and natural gas serve other vital functions in terms of security of supply, grid balancing, energy storage and global distribution of energy. Fossil fuels are also an important feedstock for plastics, fertilizers and other chemicals, and serve as reducing agents in metallurgy. According to (Lieuwen et al., 2024), about 10% of the consumption of fossil fuels in the United States is accounted for by this non-energetic use, the share is likely similar in other parts of the world.

The functions fulfilled by fossil fuels in today's global energy system will still be required in a decarbonized future, and electricity alone seems incapable of fulfilling all these roles. Currently, both short and long-term deficits of renewable power generation are usually compensated by conventional thermal power plants, although in some countries, e.g., France, the output of nuclear power plants is modulated as well when required (Cany et al., 2018). At least for short-term grid load balancing, batteries are expected to play a much bigger role in the future. This trend can already be observed in the Californian power grid, though in 2024, the state still imported about 22% of its electricity demand from neighboring states (California Energy Commission, 2025). For longer periods of insufficient renewable power generation, dispatchable power generation capacities will still be required (International Energy Agency, 2024c).

Similarly, about 40% of global maritime shipping (UN Trade & Development Data Hub, 2025) serve to distribute energy around the world by transporting coal, oil and liquefied natural gas (LNG) today. Power grids, on the other hand, are typically used to distribute electricity over comparatively short distances over land. Given that the potentials for renewable energies, but also energy demands vary significantly around the world, the global distribution of decarbonized energy is a challenge that needs to be addressed. Global supply routes of hydrogen or hydrogen carriers from renewable sources are being discussed (Global Hydrogen Flows, 2022), as well hydrogen grids (Martin et al., 2024; Khayatzaheh et al., 2025; van Rossum et al., 2022) and HVDC power lines (HVDC: high voltage direct current) (H and umpert, 2012).

Synthetic fuels are one option to address these challenges: electricity from renewable sources is used to produce hydrogen (or hydrogen derivatives) and potentially synthetic hydrocarbons which then serve to store and transport energy at the scales required. Other options include bio-fuels (Ireson, 2022; Fiehl et al., 2017; Raina et al., 2024) or even metal fuels (de Goey, 2022; de Goey, 2025). All options have their specific advantages and drawbacks. Biomass potential, for example, is limited and there are ethical considerations as well, such as the "food-vs.-fuel" discussion (at least in case of 1st generation biomass). Biomass may be better utilized as a sustainable carbon source for the chemical industry instead of being used as fuel. The application of metal fuels on the other hand will likely be technologically restricted to certain use cases.

Especially when considering synthetic fuels such as hydrogen, ammonia or synthetic hydrocarbons, the benefits of using a fuel need to be weighed against the efficiency losses that inevitably come

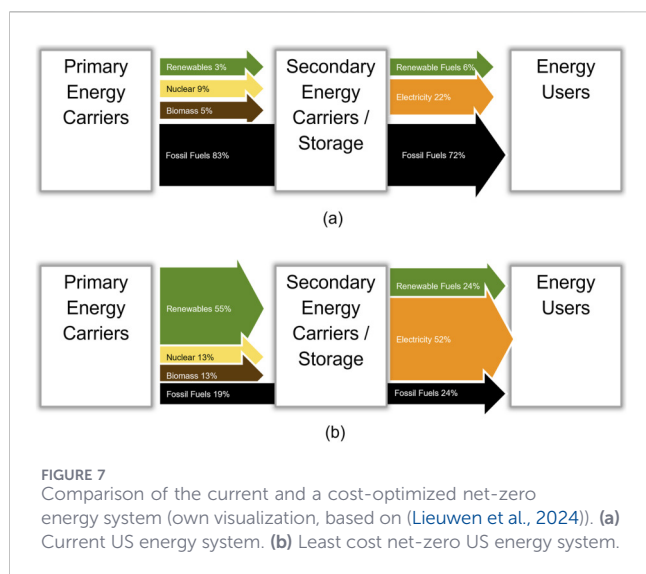


from fuel production and distribution, but also from combustion itself, as the direct use of electricity will almost certainly be more efficient. Similarly, the efficacy of synthetic fuels to reduce GHG emissions has to be considered over their entire life cycle and compared with alternative options, e.g., by conducting thorough life cycle assessments of direct electrification and the use of so-called "blue" and "green" hydrogen (i.e., hydrogen from steam reforming of natural gas with subsequent carbon capture and storage and hydrogen from electrolysis using renewable electricity) (Kaiser and Chowdhury, 2025; Uchida et al., 2025). In the case of synthetic hydrocarbon fuels, the origin of the required carbon has to be taken into account as well. There are applications, however, where the use of synthetically or biologically produced fuels seems inevitable, for instance in long-haul aviation and shipping (Lieuwen et al., 2024; Dreizler et al., 2021). Due to the low energy densities and high weight of even the most modern and advanced batteries, electric propulsion systems simply are not a technologically viable option here to achieve the necessary ranges, endurances and payload capacities. Instead, the respective industries are actively looking into synthetic aviation fuels (SAF) (Van Dyk and Saddler, 2021; Wang et al., 2024) or alternative fuels such as ammonia (Hansson et al., 2020) and methanol (From pilots to practice, 2025) in the context of maritime propulsion. Often, compatibility of new fuels with legacy equipment and infrastructure is a concern as well (Khayatzadeh et al., 2025; Uchida et al., 2025).

In other sectors, both increasing electrification and the use of alternative fuels are likely to play key roles in their decarbonization efforts, e.g., in high-temperature industrial process heating. It is generally expected that most of low-temperature process heating will be electrified, though biogenic fuels will also be used to some degree. The situation is, however, less clear-cut in high-temperature heating which is particularly relevant for many primary materials industries, e.g., metals, cement, glass or ceramics industries. The important role of synthetic fuels, and hydrogen in particular for high-temperature process heating, is highlighted in Figure 6, taken from (Fleiter et al., 2023), an extensive study where the shares of various energy sources

for process heating both for low and high temperature applications ($T > 300\text{ }^{\circ}\text{C}$) were estimated for different policy scenarios within the European Union and the United Kingdom. In total, three different scenarios were explored in this study: "Elec+" describes a policy scenario where the focus is on electrification as the primary pathway towards decarbonization. Correspondingly, "H2+" employs the use of hydrogen (from renewable sources) as the main tool. "Elec+_VC" finally is similar to "Elec+" but assumes that many energy-intensive intermediate products such as sponge iron or base chemicals will be imported into the EU27+United Kingdom by 2050. According to the study, the majority of low-temperature process heat will be provided by electricity, except for the "H2+" scenario where hydrogen plays the biggest role. More interesting, however, is the case of high-temperature process: across all considered scenarios, the shares of both electricity and hydrogen are roughly equal. This underlines that especially in high-temperature process heating, there will be many applications where synthetic fuels, despite their inherent challenges, will be the best option overall.

These findings highlight the complexity and diversity of high-temperature process heating. There are several reasons why hydrogen in particular is expected to play a significant role in energy-intensive industrial manufacturing processes: while electric heating tends to be more efficient, there can be technological limitations in terms of achievable heat flux densities, resulting either in reduced production rates or bigger furnaces (Fleiter et al., 2023; Leicher et al., 2024). Other considerations may concern product quality: many manufacturing processes involve more than just heat transfer. For some products and materials, the interaction between the material and the furnace atmosphere, e.g., in terms of O_2 concentrations in the flue gas, can be just as relevant to achieve the desired product qualities. In other cases, for example, aluminum recycling, electric furnaces cannot accept scrap which is strongly contaminated with organic residues from paints, lubricants or varnish, or, in the case of glass melting, large quantities of cullet, i.e., recycled glass. Also, dark glass colors are difficult to produce



electrically today (Meuleman, 2024). Many energy-intensive industries therefore pursue both increasing electrification and alternative fuels as decarbonization options, often depending on the specific product and process (Zier et al., 2021; Zier et al., 2023; Dell and a Rocca, 2025).

Finally, there is the question of balancing the power grid and ensuring security of electricity supply while integrating large shares of intermittent energy sources like wind and solar into power grids. Batteries and demand side management are valuable tools, but limited in scope to relatively short time spans and small capacities, compared to dispatchable fuel-based power generation options. Correspondingly, all major gas turbine manufacturers develop gas turbines which can be operated with hydrogen (in some cases also ammonia). Security of supply, grid balancing and cost optimization are prioritized by policymakers (Einigung zur Kraftwerksstrategie, 2024; Fuel Cell Works, 2025), despite the inherent loss of overall efficiency, compared to a fully electrified energy system. In fact, despite higher overall efficiencies and low power generation cost, an all-electric energy system is not likely to be more cost-effective than the existing fossil-fuel-based system, as the advantages of renewable electricity are counteracted by higher expenses for energy storage and transmission (Ueckerdt et al., 2013; Idel, 2022; Matsuo, 2022; Helm, 2025).

These considerations are reflected in forecasts about the share of electricity in final energy use. Lieuwen et al. (Lieuwen et al., 2024) for example, predict that in a net-zero cost-optimized U.S. energy system in 2050, about 52% of the final energy consumption will be accounted for by electricity, compared to 22% today, as is shown in Figure 7. The share of fossil fuels in primary energy is predicted to drop from 83% to 19%, while the share of “renewable fuels” in the end energy mix, in this context comprising both biogenic and synthetic fuels, is expected to increase by a factor of four. Evidently, the Americans also consider the continued use of some fossil fuels to be inevitable and plan to deploy carbon capture and storage technologies (CCS) or other carbon removal options to account for that. Wissmiller et al. (Nasta and Wissmiller, 2024) come to similar conclusions.

In a similar vein, a report of EURELECTRIC (the Federation of the European Electricity Industry (Final report, 2023)) expects a

share of electricity between 58 % and 71% in the end energy mix for the EU and United Kingdom by 2050, depending on various European policy frameworks (cf. Figure 8), the rest being synthetic and biogenic fuels of some kind.

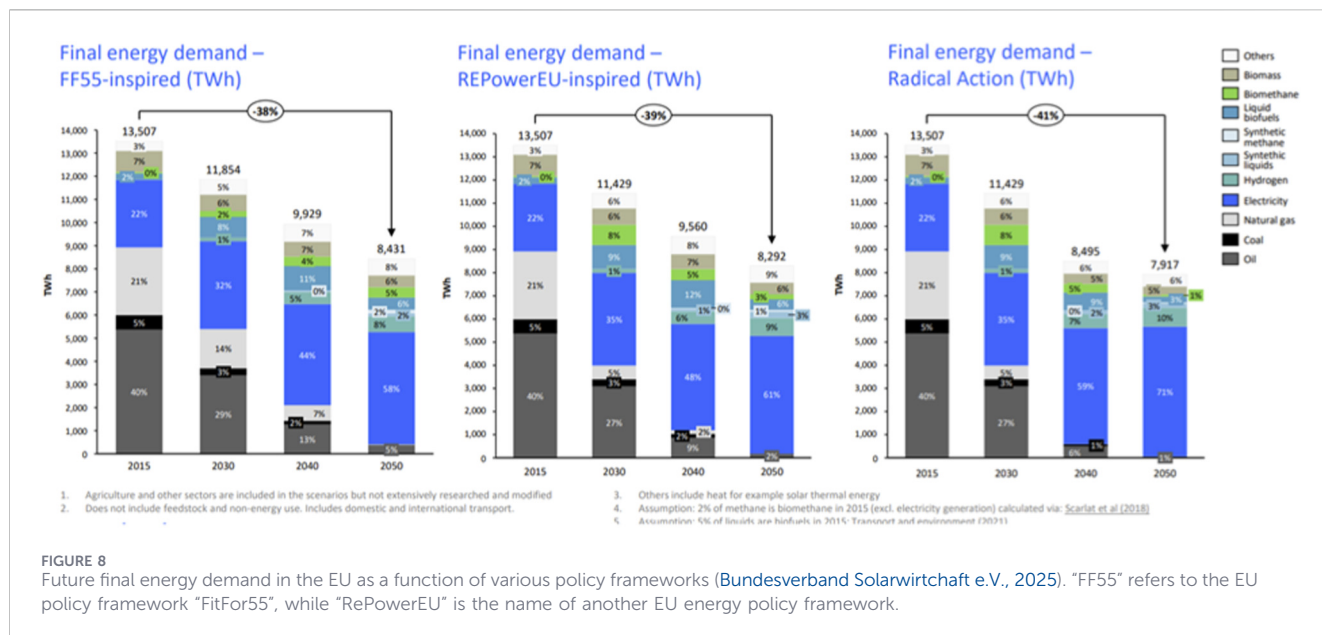
These studies underscore, however, that the role of fuels (and hence combustion) will change drastically in a decarbonized energy system of the future. Fossil fuels will no longer provide most of the primary energy needed, but instead, synthetic and biogenic fuels will serve to complement electricity from renewable and other sustainable sources to reliably provide energy when and where it is needed, and in whichever form it is required. This, of course, has consequences for the way combustion processes are designed and applied. Also, the advantages of using these fuels instead of direct electrification has to be weighed against the inherent inefficiencies which come with producing and using synthetic fuels.

4 Discussion: decarbonization strategies, alternative fuels and the need for research

The imperative to decarbonize energy provision, distribution and utilization while also ensuring security of supply and affordable cost in combination with a growing global energy demand is one of the major challenges of the 21st century. The predominance of renewable energy sources in a decarbonized energy system, in particular intermittent sources like wind and solar, will require a more complex system-level oriented and integrated approach, with sector coupling playing a much bigger role than today. Increased communication and interaction between various actors will be required, ranging from energy providers to operators of different infrastructure components (grids and energy storage at different levels and scales) all the way to various end-users, e.g., in the form of demand side management. But it will also create new research needs to optimize combustion processes and applications that are going to be an integral part of this new and evolving energy landscape.

4.1 Flexibility and hybrid systems

Flexibility is going to be a key feature for combustion applications in a decarbonized energy system, and it may come in many forms. Load flexibility is one aspect, both on the power generation side where both batteries and thermal power plants will be required to compensate for the volatility of wind and solar at different scales in terms of time and capacity, and to ensure security of supply. Power grids need to be balanced constantly in electricity demand and supply which means that for thermal power plants in particular, dynamic operation may well become even more relevant than efficiency. This trend can already be seen in the thermal power plant market in Europe: while historically, thermal power plants, especially those designed for baseload operation such as coal-fired plants, were designed for maximum efficiency in a relatively narrow operational window, the focus today is on units that can be ramped up and down quickly, as the grid requires. Gas turbine power plants in particular are considered well-suited for this task. But the need for greater flexibility is also found on the end-use side, for example, in the form of demand-side management, i.e., industrial production processes which can change their load profiles to help stabilize grid



infrastructures (Estelmann et al., 2018; Ausfelder et al., 2019; Fleischmann, 2018). Another option could be hybrid industrial furnaces and kilns that can switch between different energy carriers such as electricity and hydrogen, which could serve to help balance the power grids by providing ancillary and grid-services. In each of these applications, firing rates need to be modulated quickly, while at the same time complying with other requirements for equipment operation, e.g., maintaining combustion stability, pollutant emissions limits and, where applicable, product quality, is still needed. This, in combination with the need to use new, carbon-free or at least carbon-neutral fuels, provides new topics for applied combustion research. Hybrid furnaces and kilns are an interesting decarbonization option from another perspective as well. Hybrid heating itself is not new (Meuleman, 2024; Glass Online, 2021), but has so far usually been used to improve either the production process or for reasons of product quality, as operation with fossil fuels is often more economic today. For example, most modern gas-fired glass melting furnaces are equipped with booster electrodes (Zier et al., 2021) which serve both to provide additional energy input into the melt when needed to temporarily increase production, but also to control flow patterns in the molten glass to improve glass quality. In today's glass melting furnaces, around 10% of the overall energy input is provided by these electrodes (Overath, 2023). Future designs are planned to increase the electric energy input significantly as part of the industry's decarbonization efforts in their larger furnaces (e.g., for flat glass production), in addition to fully electric furnaces for smaller production rates (Meuleman, 2024; Zier et al., 2021). Current plans indicate that the oxy-fuel combustion of hydrogen will serve to fill the gap between the energy that can be electrically introduced into the furnace and the overall energy demand to achieve the desired production rates and qualities (Leisin and Radgen, 2022). Full electrification is often not an option, at least for larger glass melting furnaces, as the heat flux densities that can be achieved by electrodes are limited which severely limits production rates. There are also limitations in terms of some glass qualities and

the integration of large shares of recycled glass in fully electric melting processes (Meuleman, 2024). Modern electric arc furnaces, used for steel scrap recycling, are also usually equipped with supersonic gas-oxygen burners which serve multiple purposes: they provide additional energy input and can compensate for hot spots produced by the electrodes, reduce electrode degradation and improve overall efficiency, especially in the early phase of the production cycle when the scrap is still mostly solid in a packed bed and electric heating is therefore relatively inefficient. In the later stages of the cycle, once the metal is molten, the heat input is provided electrically while the burners serve as oxygen lances to inject oxygen into the melt. Equipment manufacturers are adapting these burners to operate with hydrogen or natural gas/hydrogen blends (Schüttensack et al., 2024; Krause et al., 2022).

4.2 Alternative fuels

Possibly the biggest challenge from a combustion point of view is the investigation of new fuels and their utilization in different kinds of equipment and applications. Some of the alternative fuels which are being discussed in the context of decarbonization have quite different combustion characteristics compared to conventional hydrocarbon fuels such as natural gas. Table 1 gives an overview of some essential fuel properties and combustion characteristics of methane (CH₄, representing here natural gas as a reference, but also biomethane and synthetic natural gas (SNG)), hydrogen (H₂), ammonia (NH₃), dimethyl ether (DME, CH₃OCH₃), a possible replacement fuel for liquefied petroleum gas (LPG), and methanol (CH₃OH). Both ammonia and methanol are discussed as fuels to decarbonize high-sea shipping (The Lloyd's Register Maritime Decarbonisation Hub, 2022). It is evident that the hydrocarbon fuels show quite similar properties and combustion characteristics when considering the gaseous phase of methanol (the condensation temperature of CH₃OH is 65 °C under standard conditions). This indicates that the changes necessary to adapt existing combustion applications to these "new" hydrocarbons

TABLE 1 Fuel properties and combustion characteristics of various fuels. All values given in the reference system (25 °C/0 °C, 1.01325 bar). Data from International Energy Agency (2025d), Leicher et al., (2022a).

Property	unit	Methane CH ₄	Hydrogen H ₂	Ammonia NH ₃	DME CH ₃ OCH ₃	Methanol CH ₃ OH
Net calorific value H _{i,v} (volume-based)	MJ/m ³	35.83	10.80	14.14	59.42	15,700 (l) 28.46 (g)
Net calorific value H _{i,m} (mass-based)	MJ/kg	50.03	120.0	18.60	28.89	19.9
Density ρ (0 °C)	kg/m ³	0.716	0.09	0.76	2.06	790 (l) 1.43 (g)
Superior Wobbe index W _s	MJ/m ³	53.28	48.24	22.0	51.66	-
Minimum air requirement Air _{min}	m ³ /m ³	9.524	2.381	3.571	14.29	7.143
Adiabatic combustion temperature T _{ad} (λ = 1 with air)	°C	1,951	2,106	1,798	2021	1,947
Laminar combustion velocity s _l (λ = 1, with air)	cm/s	38.57	209	6.8	40.0	40.9
Minimum ignition energy MIE	mJ	0.28	0.016	14	0.42	0.2
Methane number MN	-	100	0	-	-	-

should be relatively minor. The challenge in utilizing synthetic hydrocarbons lies not so much in the actual combustion, but in sourcing sufficient carbon from biogenic or other carbon-neutral sources, and in the overall efficiency of the production process, as each additional conversion process incurs additional efficiency losses. Hydrogen and ammonia, on the other hand, allow for a completely CO₂-free combustion, as long as these fuels are produced in a climate-neutral way, though it is worth pointing out that today, the vast majority of hydrogen is produced from hydrocarbons with significant GHG emissions at the site of its use (International Energy Agency, 2025d), primarily as a feedstock in the (petro-)chemical industry. Hydrogen has been a key component of decarbonization strategies for some time, especially for hard-to-electrify applications, while ammonia has so far mostly been considered as a hydrogen carrier medium, e.g., for the intercontinental transport of energy, as it is easier to store than compressed or liquid hydrogen. In recent years, however, there has also been a growing interest in the direct thermal use of ammonia (Kobayashi et al., 2019; Val et al., 2024; Valera-Medina, 2023), despite it being a toxic substance and a challenging fuel. In addition to its potential as a maritime fuel, ammonia could be interesting for stationary applications as well to supply fuel-based, decarbonized energy to remote locations that are not adequately connected to decarbonized energy infrastructures (Valera-Medina, 2024). Hydrogen and ammonia, are quite different fuels compared to hydrocarbons in terms of calorific properties like calorific values and the corresponding minimum oxygen and air requirements. These differences can be accounted for by changing the required volume flows of fuel and oxidizer in a technical combustion process. Even when considering caloric properties alone, some consideration is still required, however: for example, the Wobbe Index (cf. Table 1), often considered the most relevant interchangeability criterion for gaseous fuels (Slim et al., 2011;

Guidebook to Gas Interchangeability and Gas Quality, 2011), can only reasonably be applied to evaluate the interchangeability of chemically similar fuels (Leicher et al., 2022a). The comparison of methane and hydrogen is a good example here: though the Wobbe Indices only differ by -9.4%, combustion characteristics such as laminar combustion velocities or adiabatic combustion temperatures change drastically when switching from methane to hydrogen. CH₄/N₂ or CH₄/CO₂ blends with similar Wobbe Indices as pure hydrogen will, however, still behave more like pure methane than hydrogen in terms of combustion (Leicher, 2025). Arguably more important and technologically more challenging from the perspective of combustion, crucial characteristics such as adiabatic combustion temperatures, laminar combustion velocities and minimum ignition energy can be extremely different. In many ways, hydrogen and ammonia in particular are very different fuels, especially when compared to methane: the laminar combustion velocity of hydrogen is significantly higher than that of methane, while ammonia exhibits much lower laminar combustion velocities. The minimum ignition energy (MIE) of H₂ is much lower than that of typical hydrocarbons, whereas the MIE of NH₃ is orders of magnitude higher. This highlights the challenge to achieve a stable combustion process with pure ammonia (Biebl et al., 2025). There are safety aspects to consider as well: hydrogen is much easier to ignite than methane, while ammonia is toxic.

The differences in the laminar (and consequently, turbulent) combustion velocities in particular can pose significant challenges for the design of combustion equipment, especially for premixed burners which are today very common in modern gas turbines (Shivam et al., 2025; Gruber, 2025). For heavy-duty gas turbines in the power sector in particular, flame stabilization and safety-relevant issues such as flame flash back, flame lift-off and flame supervision

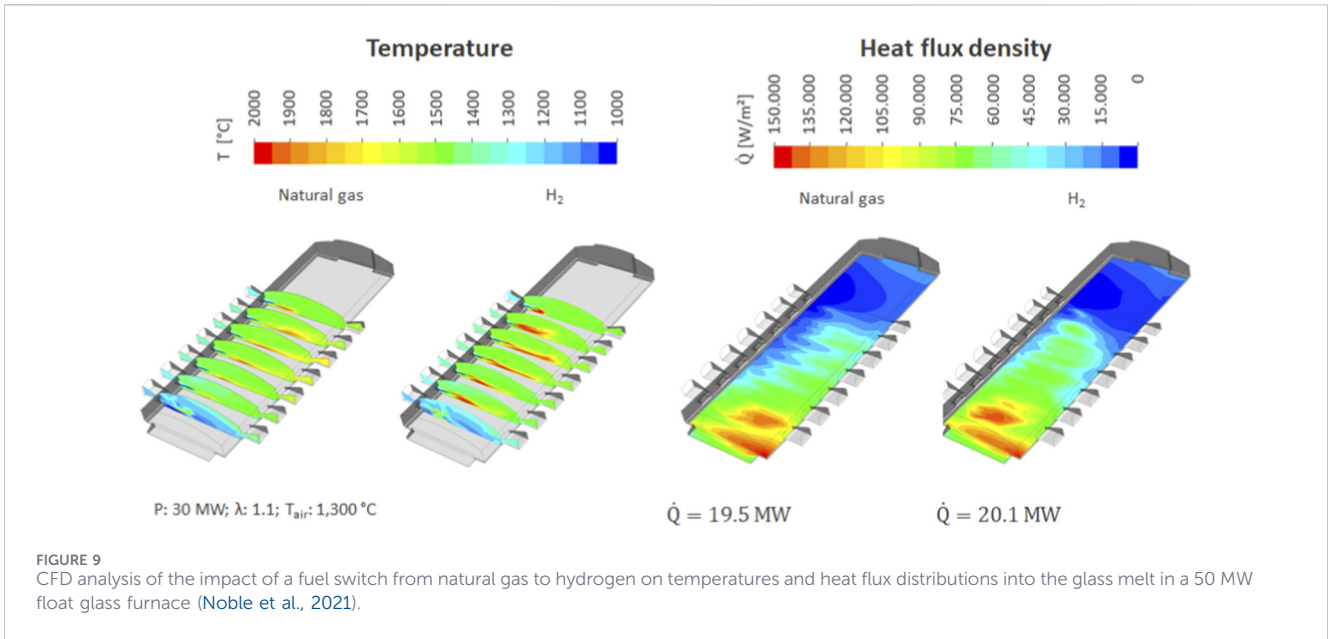


FIGURE 9 CFD analysis of the impact of a fuel switch from natural gas to hydrogen on temperatures and heat flux distributions into the glass melt in a 50 MW float glass furnace (Noble et al., 2021).

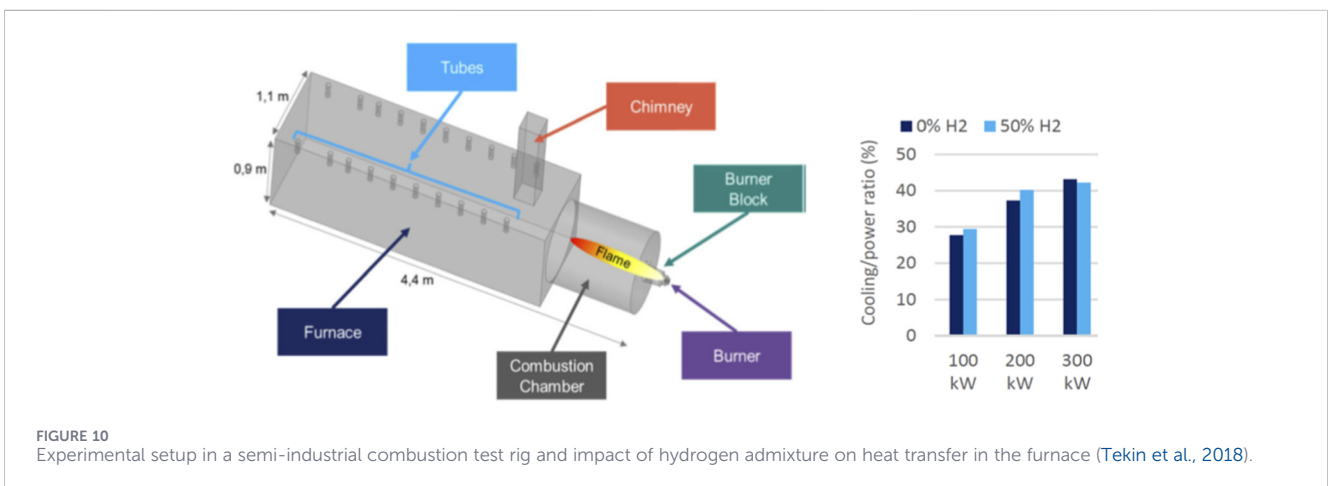
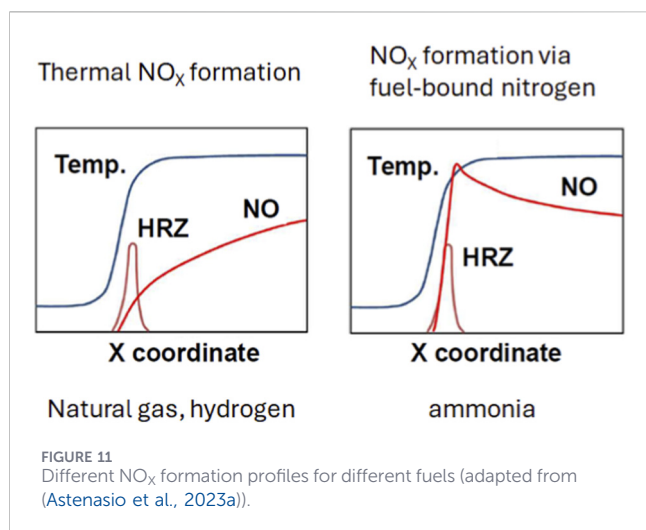


FIGURE 10 Experimental setup in a semi-industrial combustion test rig and impact of hydrogen admixture on heat transfer in the furnace (Tekin et al., 2018).

are of special concern. Given the large differences between these new fuels and common fuels such as natural gas, the potential to retrofit existing equipment is limited. New combustion technologies are required which take the peculiarities of hydrogen into account combustion (Lieuwen et al., 2024; Berger et al., 2022; Pitsch, 2022; Noble et al., 2021). Many gas turbine manufacturers favor either some kind of staged or sequential combustion process, or multiple smaller non-premixed hydrogen flames instead of one lean premixed flame, (Noble et al., 2021) (Tekin et al., 2018; Shivam et al., 2025; Bothien et al., 2019). Non-premixed burners, on the other hand, have already been shown to be more resilient, especially in the context of hydrogen as long as firing rate and air excess ratio are kept constant. This form of combustion can be predominantly found in thermal processing industries. Many non-premixed burners originally designed for natural gas have been proven to run safely with natural gas/hydrogen blends or even pure hydrogen, although other challenges, e.g., nitrogen oxides (NO_x) emissions, remain (Islami et al., 2024; Meynet et al., 2023; Gitzinger et al., 2022; Huber, 2021). Some investigations, based on both CFD simulations (CFD:

computational fluid dynamics) and experiments in semi-industrial test rigs highlight that the heat transfer performance is hardly affected by a fuel switch even to pure hydrogen in quantitative terms, though the radiation characteristics of hydrogen flames are very different from natural gas flames. This is highlighted, for example, by Figure 9, which showcases temperature and heat flux distributions from CFD simulations of a 30 MW float glass furnace operated with either natural gas as a reference case or hydrogen (Islami et al., 2024). As long as the fuel properties are adequately accounted for in the furnace control system and firing rate and air excess ratio are kept constant, the heat fluxes into the glass melt are almost identical. These findings are corroborated both by further CFD studies for oxy-fuel glass melting furnaces (Daurer et al., 2024), but also by measurements in a semi-industrial test rig (Meynet et al., 2023) for natural gas/hydrogen blends, as visualized in Figure 10. Similarly to the simulations, these experiments with firing rates between 100 and 300 kW and hydrogen admixture rates up to 50 vol.-% show that cooling requirements (which would correspond to the usable heat in the context of process heating), is hardly



affected by the change in fuel composition, as long as the main combustion-related parameters, i.e., firing rate and air excess ratio, are maintained constant. Consequently, retrofitting existing combustion equipment used for industrial process heating can be expected to be far easier, especially in the context of hydrogen, than a conversion to electric heating. These examples highlight that when discussing the use of alternative fuels for any given purpose, it is essential to consider both the fuel and the actual combustion technologies implemented. A heavy-duty gas turbine for power generation is, technologically speaking, very different from an industrial furnace in the metals, glass or ceramics industries.

Despite the need to decarbonize, operators of industrial equipment will still have to comply with increasingly stricter environmental regulations in terms of pollutant emissions. Nitrogen oxides (NO_x) often play a central role here and NO_x emissions reduction has been a long-standing focus of combustion research over the last decades. NO_x emission performance has to be considered when discussing alternative fuels such as hydrogen or ammonia. With most gaseous fuels, NO_x formation is primarily controlled by the thermal NO_x formation pathway: it is dependent on local temperatures and the simultaneous availability of oxygen in the process. Thus, hydrogen, given its much higher adiabatic combustion temperature when burned with air, has the potential to produce significantly higher emissions of NO_x than natural gas. However, most primary measures to inhibit NO_x formation, for example, flameless oxidation/MILD combustion (Cellek, 2020; Mayrhofer et al., 2021), fuel and/or air staging (Bothien et al., 2019), flue gas recirculation (Huber, 2021), or oxy-fuel combustion (Leicher and Giese, 2025) (von Schéele et al., 2022), work with hydrogen just as well as with conventional gaseous fuels as the NO_x formation mechanism remains the same. It has been shown that in many applications of non-premixed combustion, equal or even lower NO_x emissions can be achieved when burning hydrogen, compared to natural gas (Leicher and Giese, 2025; Astenasio et al., 2023a).

NO_x emissions from ammonia combustion, however, follow very different formation routes as they are dependent both on the thermal pathway, but also on the oxidation of fuel-bound nitrogen to nitrogen oxides (Kobayashi, 2025). NO_x emissions from ammonia combustion can potentially be extremely high

compared to the combustion of natural gas or hydrogen and require somewhat different mitigation approaches. In fact, in addition to actually achieving a stable ammonia combustion, reducing its NO_x emissions is one of the major technological challenges for the use of this carbon-free fuel (Kobayashi et al., 2019; Val et al., 2024). (Islami et al., 2024).

While thermal NO_x is, for the most part formed in the post-flame region and thus also increases with the residence times in the hot reaction and post-reaction zone, NO_x formation during the combustion of ammonia behaves fundamentally differently, as is visualized in Figure 11. NO_x peaks occur in the flame itself as part of the NH_3 oxidation process and then relax towards equilibrium values with increasing residence time. The availability of oxygen is one constraint for NO_x formation, which is why near-stoichiometric combustion can help reduce NO_x emissions. In addition to well-established pollutant species such as NO_x , other pollutants have to be considered as well, namely, nitrous oxides (N_2O) and NH_3 itself. Similarly to hydrogen combustion, the ways to achieve stable low- NO_x NH_3 combustion can differ greatly, depending on the actual application. Some gas turbine manufacturers are looking into staged combustion processes (often called RQL combustion in the context of gas turbines, Rich-Burn, Quick Quench, Lean-Burn (Kobayashi et al., 2019)) while in the context of non-premixed combustion, air staging (Biebl et al., 2025) or exhaust gas recirculation (Biebl, 2025) have been shown to help mitigate NO_x formation.

4.3 Industrial-scale implementation and its challenges

The need to decarbonize hard-to-electrify applications makes new fuels interesting options which previously would not have been considered worthwhile. At the same time, the wide variety and high degree of specialization found in large-scale stationary combustion processes mean that the task of successfully converting these processes and applications to new fuels such as hydrogen or ammonia are not restricted to combustion alone, but also to questions of product quality, effects on refractory materials and operational safety. There is also the issue of economic viability, in competition to direct electrification, but also in comparison to conventional and established fossil fuels, even when taking account aspects such as carbon taxes. Both in the case of electrification and the adoption of new fuels (particularly hydrogen, in this context), the impact on energy supply infrastructures needs to be considered as well. This is especially relevant for energy-intensive industries which usually require a continuous energy supply.

For hydrogen in particular, many of the combustion-related challenges have already been successfully addressed on the lab and semi-industrial scale, at least in the context of industrial process heating. Heat transfer performance and hence furnace efficiency have been shown to be quite similar to conventional natural gas combustion (Islami et al., 2024; Meynet et al., 2023). Many burner manufacturers have introduced hydrogen-ready products into the market or are actively investigating how their existing portfolio of products performs with both pure hydrogen and natural gas-hydrogen blends (Gitzinger et al., 2022; Huber, 2021; Astenasio et al., 2023b; Astenasio et al., 2023a; Mohanna et al., 2025).

Some often highly application-specific questions remain, e.g., the impact of hydrogen combustion on product or refractory quality (HyInHeat - D2, 2024). Investigations for the glass industry (Leicher et al., 2022b; Walter et al., 2024; Caudal and Riauté, 2025) show that while there can be changes in color and other glass quality criteria due to hydrogen combustion (compared to natural gas, the dominant fuel in the glass industry today), these changes often are not directly related to the hydrogen itself, but caused by the higher water vapor concentration in the furnace atmosphere when burning hydrogen. They can be compensated by modifications of the melting process parameters and ingredients in the raw materials. Investigations for the tiles and bricks industry come to similar conclusions (Poirier et al., 2025).

For the steel and aluminum industries, effects of hydrogen combustion on aluminum quality seem to be highly dependent on the actual product being investigated, with some more sensitive than others (Kosłowski et al., 2025; von Schéele and Zilka, 2020; Cirilli et al., 2025; Haapakangas et al., 2024; Airaksinen et al., 2023; Schwarz et al., 2025). Similarly, some commonly used refractory materials have been shown to be resistant to hydrogen or water-rich furnaces atmospheres, while others are more sensitive (Poirier et al., 2024a; Poirier et al., 2024b; Korschak et al., 2025). None of these issues seem to be insurmountable, and (von Schéele and Zilka, 2020) reports on a number of furnace installations in the steel and aluminum industries in Scandinavia already being routinely operated with hydrogen produced from hydropower.

The challenge of adopting hydrogen (and potentially ammonia) for decarbonizing industrial process heat and power generation is two-fold: there is a lack of experience with hydrogen combustion in full-scale processes which, given the size, cost and complexity of these pieces of equipment, is essential to generate trust in inherently risk-averse industries (Ancheyta, 2024), and there is the question of an adequate supply of fuel at economically viable prices.

While the first hydrogen-ready combustion equipment has become commercially available and some first “H₂-ready” furnaces and gas turbines have already been commissioned, the task of even temporarily exploring the use of hydrogen as a fuel in an industrial manufacturing environment involves not only scientific and engineering expertise, but is also a significant logistical effort, considering the quantities of hydrogen required, even with only a partial conversion of an existing plant. Keeley (Keeley, 2022) describes an industrial-scale investigation in a publicly funded research project in the United Kingdom where a 50 MW float glass furnace was to be operated with various hydrogen admixture rates (up to 20 vol.-%) into natural gas. Also, a single burner port was planned to be fired with 100% hydrogen. However, it was impossible to obtain neither the necessary quantities of hydrogen nor the trailers to transport the H₂ to the glass production site so that in the end, the admixture rate had to be limited to just 15 vol.-% for the full-furnace investigations. Single-port investigations were carried out with 100% H₂. Even so, trailers had to be switched about every 40 min to maintain a constant hydrogen supply to the furnace. Even just positioning multiple trailers on the premises while complying with safety regulations required extensive preparations. This example highlights the scope and complexities of full-scale industrial testing, which, however, is an essential step for the implementation of hydrogen (or other alternative fuels) both in the industrial manufacturing and power generation sectors. Publicly

funded research projects can help mitigate these risks to a degree, and in fact, several such projects are being carried out to address these challenges in different parts of the world (Valera-Medina, 2024; HyInHeat - D2, 2024; Leicher et al., 2020; H2AL, 2024; Caccamo, 2025).

4.4 Policy and regulatory issues

Though many technical questions are specific to a given purpose, some common considerations remain relevant for almost all applications. The biggest uncertainties for industrial-scale implementation of hydrogen (or other alternative fuels) today remain cost and logistics: the cost of hydrogen from carbon-free or neutral sources at scale is yet unknown (but expected to be highly dependent on local conditions (International Energy Agency, 2019)), and given the quantities required in energy-intensive industries or power generation, a hydrogen infrastructure will be required to ensure security of supply and cost-efficient transport at scale. The construction of such infrastructures is just getting started, e.g., the “Hydrogen Backbone” in north-western Europe (van Rossum et al., 2022). This creates a chicken-and-egg situation where industries are hesitant to commit due to lack of firm hydrogen supply while the extension of the growing hydrogen infrastructure is shaped by confirmed hydrogen demand from industry and the power sector. Some authors also question to what degree existing natural gas infrastructures can be repurposed for hydrogen (Martin et al., 2024), while the global gas industry seems confident that this is manageable (see, e.g., (Khayatzadeh et al., 2025)). The situation is similar for other alternative fuels where costs and availability are yet unclear.

Japanese companies have already demonstrated the technological viability of intercontinental shipping of liquefied hydrogen with a relatively small demonstration vessel and the corresponding loading and off-loading facilities in Australia and Japan respectively (Ohashi, 2022), but are currently holding off on producing bigger vessels. Similarly, the business case for a hydrogen-fired power plant which is to complement a power grid primarily supplied by intermittent wind and solar power generation is equally unclear as of yet, given that its annual runtime is expected to be low.

The lack of infrastructure is, however, a problem that is not restricted to hydrogen alone. In many countries, today's power grids were never designed to continuously provide large quantities of electricity (let alone low-carbon electricity) to industrial users. This has traditionally been the role of natural gas grids. This strain on existing power grids is further exacerbated by the forecasts for a growing demand for firm electricity supply for data centers and Artificial Intelligence, which is expected to increase rapidly in the coming years (International Energy Agency, 2025c). While some of these issues can be compensated to a degree by increased interconnectivity between national power grids (as is already the case in Europe, for example), this measure alone will not be sufficient, considering the drastically increasing electricity demand that comes with widespread electrification.

Many of the economic challenges described here are rather similar in the context of alternative fuels for transportation applications, namely, in long-haul aviation or maritime shipping. Growth rates for synthetic climate-friendly fuels such as SAF or

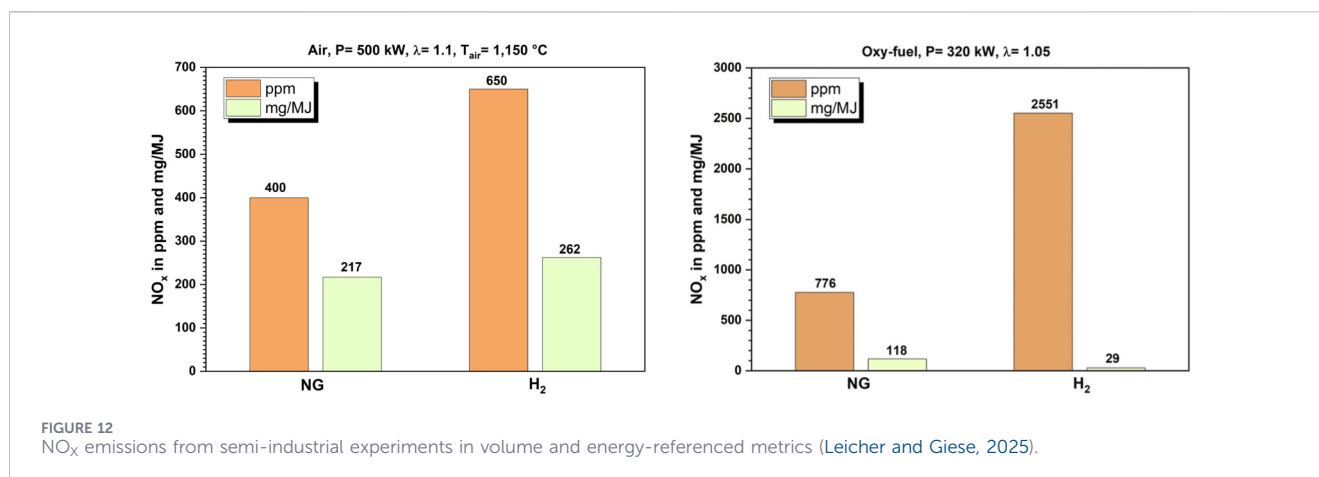


FIGURE 12
NO_x emissions from semi-industrial experiments in volume and energy-referenced metrics (Leicher and Giese, 2025).

methanol (for shipping) are lower than expected (Disappointingly Slow Growth, 2024; S & P Global, 2024) and the new fuels are not yet economically competitive with conventional fuels.

Again, cost and supply are the main challenges, not technology itself.

The large-scale deployment of wind and solar power generation or electric vehicles was supported by a variety of policies ranging such as fixed feed-in tariffs, tax reductions or public subsidies. Similarly, the growth of alternative fuels for stationary, but also mobile applications, will depend on initial support from policymakers, especially when competing with fossil fuels (Brand et al., 2025). Such measures may range from tax breaks (and/or carbon taxes), emissions trading systems (ETS), contracts for difference (Cfd), mandated quotas for renewable fuels or even outright state planning, such as the 15th Five-Year Plan in the People's Republic of China (2026–2030) (Jargad, 2025; Xin, 2025) which, for example, specifically emphasizes the role of hydrogen as a secondary energy source for transportation, industry and power generation. The actual support mechanisms vary significantly, depending on national policies and circumstances.

When considering the economic viability of alternative fuels, be it for stationary or for mobility applications, it is generally insufficient to just consider the Levelized Cost of Energy (LCOE): due to the high degree of volatility of wind and solar power, additional measures such as batteries or expanded grid infrastructure are required to ensure security of supply. However, these aspects are not taken into account by the traditional definition of the LCOE which looks at power generation alone. Therefore, other metrics, e.g., full-system LCOE have to be used to assess the overall economic performance of alternative fuels (Ueckerdt et al., 2013; Idel, 2022; Matsuo, 2022; Moraski et al., 2025). Additional factors have to be taken into account as well, e.g., the potential repurposing of existing infrastructures (e.g., natural gas pipelines (Khayatzaadeh et al., 2025) or refueling stations) for use with synthetic fuels, reducing investment costs.

Finally, there are also regulatory issues to consider, e.g., concerning hydrogen qualities in future hydrogen grids. In the EU, there is a consensus developing that there should be two groups of hydrogen quality, one mostly intended for thermal use (a minimum H₂ concentration of 98 vol.-% is proposed here) and one group of higher purity for more sensitive end-use applications

such as fuel cells or processes in the chemical industry (Technische Regel - Arbeitsblatt DVGW G260 A and Gasbeschaffenheit, 2021; Hydrogen Quality Specification, 2022). In some cases, e.g., hydrogen-powered vehicles and their refueling stations, international standards are already in place (e.g., ISO 19880). In some instances, e.g., with SAF, these fuels can often be specifically designed to comply with existing fuel standards, allowing for the continued use of equipment and infrastructure.

Another question is how to quantify and compare the emissions of air-quality relevant pollutants like NO_x fairly and consistently between different fuels and even electricity. The current industrial practice in the EU and elsewhere is to prescribe NO_x emission limits as concentrations in the dry flue gas that equipment operators have to comply with. However, if fuels change significantly, e.g., when switching from natural gas to hydrogen, this is no longer a valid approach as the flue gas composition, particularly the water vapor content, change drastically. NO_x concentrations in the flue gas of a natural gas combustion thus cannot easily be compared with emissions from a hydrogen combustion process, so either conversion factors or alternative metrics to quantify pollutant emissions are needed (Leicher and Giese, 2025; Leicher and Giese, 2024; Schmitz et al., 2023; Douglas et al., 2022), e.g., in the form of [mg_{NO_x}/t_{product}] or [mg_{NO_x}/MJ], i.e., referenced to a product quantity or the energy input into the process. These new metrics would even allow a meaningful comparison of emissions from fuel-based heating with emissions from electric heating equipment in a consistent manner. For example, the German emissions regulations (Umweltmessung, 2021) already prescribe NO_x emission limits for fully electric glass melting furnaces, using the unit [mg/t_{glass}]. Figure 12 shows a comparison of NO_x emissions in different metrics, based on experiments on a semi-industrial scale (Leicher and Giese, 2025).

5 Conclusion and outlook

Key take-aways

- Combustion is still the key cross-sectional technology in all energy-related activities, but also responsible for the majority of anthropogenic greenhouse gas emissions.

- The role of combustion and fuels will have to change in a decarbonizing world.
- Energy (in all its forms) needs to be decoupled from GHG emissions, though security of supply is paramount.
- Electricity (from renewable and other low-carbon sources) is essential to achieve climate goals ... but electricity brings challenges of its own.
- Alternative fuels can serve to complement electricity, both on a system-level, but also for hard-to-electrify end-use applications.
- Flexibility of all actors in the energy systems and in all forms will become more important than ever before.
- New fuels bring new R&D challenges, and revive some old ones.

Ever since the beginning of the Industrial Age, human society has been powered by fossil fuels that have been providing most of the energy needed across all sectors of human activity. Easy and affordable access to energy has permitted unprecedented progress in quality of life for increasing parts of the global population. Combustion was and still remains a key technology in all sectors related to the use of energy, but the use of fossil fuels is also responsible for the vast majority of anthropogenic GHG emissions. At the same time, global energy demand is expected to continue to grow.

In order to limit climate change, energy and GHG emissions need to be decoupled, and electrification, powered by electricity from carbon-free sources, is a crucial component in the transformation of global energy systems. Electricity can be generated at scale without GHG emissions and can efficiently be converted into other forms of energy like heat or mechanical energy when and where needed. However, electricity-based energy storage and transport options are limited in scale which makes them unsuited for some purposes. These are essential functions for a global energy system, which are today still being provided en passant by fossil fuels. Intermittent renewable power generation options like wind and solar also create challenges for power grids, where demand and supply have to be continuously balanced. While this intermittency is today compensated largely by the flexible operation of thermal power plants, increasing shares of variable power generation will create challenges in this regard, especially when dispatchable generation from fossil fuel-fired power plants is being phased out at the same time. Finally, there are limitations to electrification in some end-use sectors such as aviation, long-distance shipping or some industrial high-temperature process heating applications.

These fundamental changes in the energy landscape define new roles for fuels and combustion. They will no longer serve as the most important means to convert primary energy into useful energy (be it heat, mechanical energy or electricity), but instead they will be used as a necessary complement to intermittent renewable energy sources, ensuring that sufficient energy is available when and where needed. This means that flexible and dynamic operation, especially in the context of thermal power plants, but also with industrial demand-side management and hybrid industrial equipment, will become even more important than they are today. These more flexible modes of operation will require more integration between power generation assets, infrastructure operators and end-users than today. Finally, they will also cover

certain end-use applications where electrification options are technologically or even physically limited.

The fuels will change as well: with fossil fuels being phased out, new synthetic or biogenic fuels will serve as large-scale energy storage options in conjunction with batteries, as energy vectors (for example, in the intercontinental energy trade) or to provide energy to end-use applications ill-suited for direct electrification. While some of these fuels, e.g., biomethane, biomass or synthetic natural gas (SNG) are chemically very similar to conventional fuels, others such as hydrogen and ammonia show very different combustion characteristics which bring new tasks for combustion science and engineering. Existing technologies have to be adapted and optimized to the new fuels or completely new systems have to be developed to use these fuels in a safe, efficient and environmentally friendly way.

Especially in the energy-intensive thermal processing industries, a lot of progress has already been made adapting existing equipment and complex manufacturing processes to new fuels, hydrogen in particular. However, industrial-scale implementation is still lagging behind, as it involves significant risks and the cost and availability of low-carbon hydrogen are as of yet unclear. Nevertheless, experience with full-scale systems is essential, and many publicly funded research projects, e.g., in the EU or Japan, try to address these challenges.

With all the efforts in decarbonizing the global energy systems, the role and relevance of energy, in whichever form, has not fundamentally changed. Security of supply, affordable accessibility and environmental impact are still of paramount importance, and a net-zero energy system that does not satisfy these criteria as well is not fit-for-purpose. This challenge, along with a globally growing energy demand, driven by globally rising standards of living and by new technologies such as Artificial Intelligence, will define combustion research, but also energy-related technologies more broadly, in decades to come.

Author contributions

JL: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing. AG: Conceptualization, Formal Analysis, Methodology, Resources, Supervision, Validation, Visualization, Writing – review and editing. CW: Conceptualization, Data curation, Methodology, Resources, Supervision, Validation, Visualization, Writing – review and editing.

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Conflict of interest

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References

- Airaksinen, S., Haapakangas, J., Laukka, A., Heikkinen, E.-P., and Fabritius, T. (2023). Oxide scale formation of stainless steels with different heating methods - effects of hydrogen as fuel. *Steel-Research International*. 95, 2300334. doi:10.1002/srin.202300334
- Ancheyta, J. (2024). The handicap of new technologies: nobody wants to be the first for commercial application. *Processes* 12 (3), 467. doi:10.3390/pr12030467
- Astenasio, D., Bissoli, M., Della Rocca, A., Malfa, E., and Wuppermann, C. (2023a). Flexible hydrogen heating technologies, with low environmental impact. *Matériaux and Tech*. 111. doi:10.1051/mattech/2023018
- Astenasio, D., Della Rocca, A., and Leoncini, C. (2023b). "Tenova ultra low NOx regenerative burners working with hydrogen and oxygen enrichment," in *Joint meeting of the Belgian and Italian* (Florence, Italy: Sections of the Combustion Institute). Available online at: <https://www.combustion-institute.it/proceedings/XXXXV-ASICI/papers/45proci2023.IX6.pdf> (Accessed September 1, 2025).
- Ausfelder, F., von Roon, S., and Seitz, A. (2019). "Herausgeber. Flexibilitätsoptionen in der Grundstoffindustrie II: analysen | Technologien | Beispiele. Frankfurt am Main, Germany," in *DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e.V.*
- BDEW (2025). "Energieflussbild der Bundesrepublik Deutschland 2023 in TWh," Berlin, Germany: BDEW Bundesverband der Energie- und Wasserwirtschaft e. Available online at: https://www.bdew.de/media/documents/1_Energieflussbild_Deutschland_2023_TWh_detailliert.svg (Accessed August 1, 2025).
- Berger, L., Attili, A., and Pitsch, H. (2022). Intrinsic instabilities in premixed hydrogen flames: parametric variation of pressure, equivalence ratio, and temperature. Part 1 - dispersion relations in the linear regime. *Combust. Flame* 240, 121935. doi:10.1016/j.combustflame.2021.111935
- Biebl, M. (2025). Entwicklung und experimentelle Untersuchung eines schadstoffarmen Brennersystems zur Dekarbonisierung von industrieller Prozesswärme durch flexible Nutzbarkeit von erneuerbar erzeugten Brenngasen und Prozessgasen [PhD Thesis]. Universität Duisburg-Essen: Essen, Germany. Available online at: <https://d-nb.info/1367460735/34>.
- Biebl, M., Leicher, J., Giese, A., and Wieland, C. (2025). A comprehensive study of non-premixed combustion of ammonia and its blends: flame stability and emission reduction. *Fuel* 386 (134501), 134501. doi:10.1016/j.fuel.2025.134501
- Bothien, M. R., Ciani, A., Wood, J. P., and Fruechtel, G. (2019). Towards decarbonized power generation with gas turbines by using sequential combustion for burning hydrogen. *J. Eng. Gas Turbines Power*. doi:10.1115/1.4045256
- Brand, U., Hausknost, D., Brad, A., Eyslein, G., Krams, M., Maneka, D., et al. (2025). Structural limitations of the decarbonization state. *Nature Climate Change* 15, 927–934. doi:10.1038/s41558-025-02394-y
- Buberger, J., Kersten, A., Kuder, M., Eckerle, R., Weyh, T., and Thiringer, T. (2022). Total CO₂-equivalent life-cycle emissions from commercially available passenger cars. *Renew. Sustain. Energy Rev.* 159, 112158. doi:10.1016/j.rser.2022.112158
- Bundesverband Solarwirtschaft e.V. (2025). *Speicherkapazitäten 2024 um 50 Prozent gewachsen*. Berlin, Germany: Bundesverband Solarwirtschaft e.V. Available online at: https://www.solarwirtschaft.de/datawall/uploads/2025/01/250131_Speicherbilanz2024.pdf (Accessed March 1, 2025).
- Caccamo, C. (2025). *H2Glass - decarbonising our future* in IFRF Conference on Sustainable and Safe Industrial Combustion (Sheffield, UK).
- California Energy Commission (2025). 2024 total system electric generation. Available online at: <https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2024-total-system-electric-generation> (Accessed March 1, 2025).
- Cany, C., Mansilla, C., Mathonnière, G., and Da Costa, P. (2018). Nuclear power supply: going against misconceptions. Evidence of nuclear flexibility from the French experience. *Energy* 151, 289–296. doi:10.1016/j.energy.2018.03.064
- Caudal, J., and Riauté, N. (2025). "H₂ combustion, from R and D developments to industrial demonstration," in IFRF Conference on Sustainable and Safe Industrial Combustion (Sheffield, UK).
- Cellek, M. S. (2020). Flameless combustion investigation of CH₄/H₂ in the laboratory-scaled furnace. *Int. J. Hydrogen Energy* 45 (60), 35208–35222. doi:10.1016/j.ijhydene.2020.05.233
- Cirilli, F., Di Cataldo, M., Jochler, G., Luzzo, I., Sergi, C., Zacchetti, N., et al. (2025). "Hybrid TeChnologies for sustainable steel reheating - HyTecHeat," *IFRF Conf. Safe Sustain. Industrial Combust.*
- Daurer, G., Schwarz, S., Demuth, M., Gaber, C., and Hochenauer, C. (2024). Evaluation of numerical modeling and combustion characteristics of hydrogen oxy-fuel combustion in a semi-industrial furnace. *Fuel* 369 (131690), 131690. doi:10.1016/j.fuel.2024.131690
- Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., et al. (2018). Net-zero emissions energy systems. *Science* 360 (eaas9793). doi:10.1126/science.aas9793
- Della Rocca, A. (2025). A perspective on the decarbonization in the metals industry. *Appl. Energy Combust. Sci.* 21. doi:10.1016/j.jaecs.2024.100312
- de Goey, P. (2022). "Metal powder as circular energy carriers," in *Keynote lecture: 13Th European conference on industrial furnaces and boilers (INFUB13)*. Algarve, Portugal.
- de Goey, P. (2025). "The iron power cycle," in *Keynote: IFRF Conference for Sustainable and Safe Industrial Combustion 2025* (Sheffield, UK).
- Disappointingly Slow Growth (2024). "SAF production," IATA: International Air Transport Association: Montreal, Canada. Available online at: <https://www.iata.org/en/pressroom/2024-releases/2024-12-10-03/>.
- Douglas, C., Emerson, B., Lieuwen, T., Martz, T., Steele, R., and Noble, B. (2022). NOx emissions from hydrogen-methane fuel blends. *Ga. Tech. - Strateg. Energy Inst.* Available online at: https://research.gatech.edu/sites/default/files/inline-files/gt_epri_nox_emission_h2_short_paper.pdf (Accessed June 1, 2025).
- Dreizler, A., Pitsch, H., Scherer, V., Schulz, C., and Janicka, J. (2021). The role of combustion science and technology in low and zero impact energy transformation processes. *Appl. Energy Combust. Sci.* 7, 100040. doi:10.1016/j.jaecs.2021.100040
- Einigung zur Kraftwerksstrategie (2024). "Bundesministerium für Wirtschaft und Klimaschutz," Berlin, Germany. Available online at: <https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2024/02/20240205-einigung-zur-kraftwerksstrategie.html> (Accessed September 5, 2025).
- EMBER Energy (2025). *Global electricity review*. London, UK: EMBER Energy. Available online at: <https://ember-energy.org/app/uploads/2025/04/Report-Global-Electricity-Review-2025.pdf> (Accessed September 5, 2025).
- Enerdata (2025). World energy and climate statistics - Yearbook. *Enerdata*. Available online at: <https://yearbook.enerdata.net/electricity/share-electricity-final-consumption.html>.
- Energieverbrauch in Deutschland im Jahre (2024). *AGEB AG energiebilanzen e.V.; 2025*. Berlin, Germany. Available online at: https://ag-energiebilanzen.de/wp-content/uploads/AGEB_Jahresbericht2024_20250616_dt.pdf (Accessed September 5, 2025).
- Energy Institute (2025). Statistical review of world energy. *Energy Inst.* Available online at: <https://www.energyinst.org/statistical-review/resources-and-data-downloads>.

- Estelmann, S., Dietrich, R.-U., and Seitz, A. (2018). "Herausgeber. Flexibilitätsoptionen in der Grundstoffindustrie I: methodik | Potenziale | Hemmnisse," in *Frankfurt am Main, Germany: DECHEMA, Gesellschaft für Chemische Technik und Biotechnologie e.V.*
- Fiehl, M., Leicher, J., Giese, A., Görner, K., Fleischmann, B., and Spielmann, S. (2017). Biogas as a co-firing fuel in thermal processing industries: implementation in a glass melting furnace. *Energy Procedia* 120, 302–308. doi:10.1016/j.egypro.2017.07.221
- Final report (2023). *Decarbonisation speedways*, 114. Brussels, Belgium: Eurelectric. Available online at: https://www.eurelectric.org/wp-content/uploads/2024/06/extended-full-report_decarbonisation-speedways.pdf (Accessed September 5, 2025).
- Fleischmann, B. (2018). "Flexible use of (renewable/regenerative) electric power when melting container glass," in *GlassTrend-Seminar "how to face the technological challenges of the paris climate agreement?"* (Marktheidenfeld/Würzburg, Germany).
- Fleiter, T., al-Dabbas, K., Clement, A., and Rehfeldt, M. (2023). *Metis 3 - study S5: the impact of industry transition on a CO2-neutral European energy system*. Karlsruhe, Germany: Fraunhofer ISI. Available online at: <https://op.europa.eu/en/publication-detail/-/publication/72954c87-327a-11ee-83b8-01aa75ed71a1> (Accessed March, 20, 2025).
- Friedmann, S. J., Fan, Z., and Tang, K. (2019). *Low-carbon heat solutions for heavy industry: sources, options, and costs today*. New York, USA: Columbia University - Center on Global Energy Policy. Available online at: https://www.eesi.org/files/LOW-CARBON_HEAT_SOLUTIONS.pdf (Accessed February 20, 2024).
- From pilots to practice (2025). Methanol and ammonia as shipping fuels. *Cph. Den. Get. Zero Coalition - Glob. Marit. Forum*. Available online at: https://downloads.ctfassets.net/gk3lrimph5v/4ZTPDYMWxR9HxeYAJW4omJ/26a4ca208a5d8bb7da385b3f607bcf5/Getting_to_Zero_Coalition-From_pilots_to_practice__Methanol_and_ammonia_as_shipping_fuels.pdf (Accessed September 5, 2025).
- Fuel Cell Works (2025). China commissions world's largest 100% hydrogen gas turbine at 30 MW. *Fuel Cell Works*. Available online at: <https://fuelcellworks.com/2025/12/29/clean-energy/china-commissions-world-s-largest-100-percent-hydrogen-gas-turbine-at-30mw> (Accessed December 29, 2025).
- Gas Safety - Types of Domestic Fuel Gases and Their Properties (2024). EMSD - Electrical and mechanical services department - the government of the Hong Kong special administrative region. Available online at: https://www.emsd.gov.hk/en/gas_safety/gas_safety_tips_to_users/types_of_domestic_fuel_gases_and_their_properties/index.html#:~:text=Its%20major%20components%20are%20hydrogen,of%20town%20gas%20is%2024 (Accessed September 21, 2025).
- Gitzinger, H.-P., Schröder, L., and Rieken, M. (2022). Veränderungen durch Wasserstoff beim Betrieb von Rekuperator-, Impuls- und Flachflammenbrennern. *Prozesswärme* (1), 40–45.
- Glass Online (2021). 50 years of electric melting with SORG and Heinz-GLAS. *Glass Online*. Available online at: <https://www.glassonline.com/50-years-of-electric-melting-with-sorg-and-heinz-glas/> (Accessed September, 2024).
- Global Gas Report (2024). *Int. Gas. Union*. Available online at: <https://www.igu.org/resources/global-gas-report-2024-edition/>.
- Global Hydrogen Flows (2022). *Hydrogen trade as a key enabler for efficient decarbonization*. Hydrogen Council/McKinsey and Company: Brussels, Belgium. Available online at: <https://hydrogencouncil.com/wp-content/uploads/2022/10/Global-Hydrogen-Flows.pdf>.
- Griffiths, S., Sovacool, B., Iskandarova, M., and Walnum, H. J. (2025). Bridging the gap between defossilization and decarbonization to achieve net-zero industry. *Environ. Res. Lett.* 20 (2), 024063. doi:10.1088/1748-9326/adaed6
- Gruber, A. (2025). "Recent advances and remaining challenges for clean and efficient carbon-free combustion in heat and power applications," in *Keynote lecture: workshop between clean hydrogen partnership and NEDO on hydrogen/ammonia combustion technologies* (Japan: Kobe).
- Guidebook to Gas Interchangeability and Gas Quality (2011). BP/IGU. Available online at: <http://www.igu.org/gas-knowhow/publications/igu-publications/Gas%20Interchangeability%202011%20v6%20HighRes.pdf>.
- Humpert, C. (2012). Long distance transmission systems for the future electricity supply - analysis of possibilities and restrictions. *Energy* 48 (1), 278–283. doi:10.1016/j.energy.2012.06.018
- H2AL (2024). Decarbonising aluminium recycling with hydrogen. Available online at: <https://h2al.ulb.be/>
- Haapakangas, J., Riikonen, S., Airaksinen, S., Heikkinen, E.-P., and Fabritius, T. (2024). Oxide scale formation on low-carbon steels in future reheating conditions. *Metals* 14 (189), 189. doi:10.3390/met14020189
- Hansson, J., Fridell, E., and Brynolf, S. (2020). On the potential of ammonia as a fuel for shipping. *Lighthouse - Swed. Marit. Competence Cent.* Available online at: https://fudinfo.trafikverket.se/fudinfoexternwebb/Publikationer/Publikationer_004101_004200/Publikation_004185/FS2_2019_The%20potential%20of%20ammonia%20as%20fuel%20for%20shipping.pdf.
- Hasanbeigi, A., Kirshbaum, L. A., Collison, B., and Gardiner, D. (2021). *Electrifying U.S. industry: a technology and process-based approach to decarbonization*. Global Efficiency Intelligence: Tampa Bay, USA.
- Helm, D. (2025). The price of energy and the system costs of renewables. Available online at: <https://dieterhelm.co.uk/energy-climate/the-price-of-energy-and-the-system-costs-of-renewables/>.
- Huber, A. (2021). Impact of hydrogen and mixtures of hydrogen and natural gas on forced draught gas burners. *Heat Processing* (1), 27–32.
- Hydrogen Quality Specification (2022). *EASEE-gas Eur. Assoc. Streamlining Energy Exch. - Gas*. Available online at: https://easee-gas.eu/download_file/DownloadFile/36/cbp-2022-001-01-hydrogen-quality-specification.
- HyInHeat - D2 (2024). 1 - impact of H2 heating on product quality, yield and refractory. *Oulu, Finml.* Available online at: https://hyinheat.eu/results/impact-of-h2-heating-on-product-quality-yield-refractory/?utm_source=linkedin&utm_medium=social&utm_campaign=week30.
- Idel, R. (2022). Levelized full system costs of electricity. *Energy* 259, 124905. doi:10.1016/j.energy.2022.124905
- International Energy Agency (2019). *The future of Hydrogen - Seizing today's opportunities*. Paris, France: International Energy Agency. Available online at: https://webstore.iea.org/download/direct/2803?fileName=The_Future_of_Hydrogen.pdf.
- International Energy Agency (2024a). *World Energy outlook 2023*. Paris, France: International Energy Agency.
- International Energy Agency (2024b). *Renewables 2024 - analysis and forecast to 2030*. Paris, France. Available online at: <https://iea.blob.core.windows.net/assets/17033b62-70a5-4144-8dd0-651c8b6ca24/Renewables2024.pdf>.
- International Energy Agency (2024c). *Integrating solar and wind - global experience and emerging challenges*. Paris, France: International Energy Agency. Available online at: <https://www.iea.org/reports/integrating-solar-and-wind>.
- International Energy Agency (2025a). *SDG7: data and projections*. Paris, France: International Energy Agency. Available online at: <https://www.iea.org/reports/sdg7-data-and-projections>.
- International Energy Agency (2025b). *Coal 2024 - analysis and forecast to 2027*. Paris, France: International Energy Agency. Available online at: <https://iea.blob.core.windows.net/assets/a1ee7b75-d555-49b6-b580-17d64ccc8365/Coal2024.pdf>.
- International Energy Agency (2025c). *Energy and AI*. Paris, France: International Energy Agency. Available online at: <https://iea.blob.core.windows.net/assets/601eac9-ba91-4623-819b-4ded331ec9e8/EnergyandAI.pdf>.
- International Energy Agency (2025d). *Global Hydrogen Review 2025*. Paris, France: International Energy Agency. Available online at: <https://iea.blob.core.windows.net/assets/12d92ecc-e960-40f3-af5-b2de690ab6b/GlobalHydrogenReview2025.pdf>.
- Ireson, R. (2022). *The potential to decarbonise the glass industry using hydrogen and biofuel technologies*. Berlin, Germany: 26th International Congress on Glass.
- Islami, B., Giese, A., Biebl, M., and Nowakowski, T. (2024). "Impact of natural gas-hydrogen blends and pure hydrogen on combustion in glass melting furnaces, as well as spatially-resolved green hydrogen production potential in the German state of North Rhine-Westphalia (NRW)," in *97th DGG glass-technology conference*. Germany: Aachen.
- Jargad, S. (2025). China's five-year plan confronts economic reform amid geopolitical competition. *The Strategist*. Available online at: <https://www.aspistrategist.org.au/chinas-five-year-plan-confronts-economic-reform-amid-geopolitical-competition/>
- Kaiser, R., and Chowdhury, A. M. (2025). Hydrogen-Powered marine vessels: a rewarding yet challenging route to decarbonization. *Clean Technologies* 7 (3), 68. doi:10.3390/cleantechnol7030068
- Keeley, A. (2022). "Hydrogen combustion on a float glass furnace," in 26th International Congress on Glass (Berlin, Germany).
- Khayatzadeh, A., Köppel, W., Gehrmann, S., Schwigon, A., Pattina, T., Schrader, A., et al. (2025). An overview of the decarbonisation of the natural gas system with hydrogen. *Dtsch. Ver. Gas- Wasserfaches e.V. (DVGW)*. Available online at: https://www.dvgw.de/medien/dvgw/en/publications/decarbonisation_eng_dvgw-2025.pdf.
- Kobayashi, H. (2025). "Overview of hydrogen/ammonia combustion technologies in Japan - from an academic perspective," in *Keynote lecture workshop between clean Hydrogen partnership and NEDO on Hydrogen/Ammonia combustion technologies* (Japan: Kobe).
- Kobayashi, H., Hayakawa, A., Kunkuma, K. D., Somarathne, A., and Okafor, E. C. (2019). Science and technology of ammonia combustion. *Proc. Combust. Inst.* 37, 109–133. doi:10.1016/j.proci.2018.09.029
- Kobayashi, H., Wu, K. T., and Bell, R. L. (2025). *Thermochemical regenerator: a high efficiency heat recovery System for Oxy-Fired glass furnaces*. Aachen, Germany: 1st Joint Meeting DGG-ACerS GOMD.
- Konschak, A., Maier, J., Friedrich, H., Cölle, D., and Bonzeck, T. (2025). *Effects of H2 combustion atmosphere on commercial refractory materials*. Germany: International Colloquium on Refractories Aachen.
- Koslowski, E., Giese, A., Michelis, C., and Hackert-Oschätzchen, M. (2025). *Gemeinsamer Abschlussbericht zum Forschungsvorhaben Werkstoffliche Grundlagenuntersuchungen für den Einsatz von regenerativem Wasserstoff bei der Herstellung von Sekundäraluminium (Akronym: H2-Alu)*. Essen: Gas- und Wärme-Institut Essen e.V./HMT Höfer Metall Technik GmbH and Co KG/Otto-von-Guericke

- Universität; 2025 S. 68. Available online at: https://www.gwi-essen.de/medien/publikationen/abschlussberichte/2024/h2_alu.pdf.
- Krause, F., Kemminger, A., Odenthal, H.-J., Wilkomm, J., Schleifenbaum, J. H., Goßrau, C., et al. (2022). "Design, simulation and testing of additive manufactured hydrogen burners used in the EAF," in 9th European Oxygen Steelmaking Conference, 6th European Conference on Clean Technologies (Aachen, Germany).
- Kullmann, F., Linßen, J., and Stolten, D. (2023). The role of hydrogen for the defossilization of the German chemical industry. *Int. J. Hydrogen Energy* 48, 38936–38951. doi:10.1016/j.ijhydene.2023.04.191
- Leicher, J. (2024). "Going all-electric? Alternative fuels for decarbonized (high-temperature) process heat," in Keynote Lecture, 14th European Conference on Industrial Furnaces and Boilers (INFUB14) (Algarve, Portugal).
- Leicher, J. (2025). "The role of LNG quality when designing industrial gas appliances," in MARCOGAZ TechForum on LNG quality (MARCOGAZ: Brussels, Belgium). Available online at: <https://www.youtube.com/watch?v=ZLX0GbF4pM0>.
- Leicher, J., and Giese, A. (2024). "High-temperature hydrogen combustion and NOx emissions: physical and regulatory aspects," in 97th DGG Glass Technology Conference (Aachen, Germany).
- Leicher, J., and Giese, A. (2025). Impact of hydrogen combustion on NOx emissions - physical and regulatory considerations. *IFRF Conf. Sustain. Safe Industrial Combust.* Sheffield, UK.
- Leicher, J., and Wieland, C. (2025). "The role of combustion (and fuels) in a decarbonizing world," in *Opening keynote, IFRF conference; 2025 on sustainable and safe industrial combustion.* Sheffield, UK.
- Leicher, J., Giese, A., and Overath, J. (2020). *The HyGlass Project: decarbonising the glass industry with hydrogen.* Glass International.
- Leicher, J., Schaffert, J., Cigarida, H., Tali, E., Burmeister, F., Giese, A., et al. (2022a). The impact of hydrogen admixture into natural gas on residential and commercial gas appliances. *Energies* 15, 777. doi:10.3390/en15030777
- Leicher, J., Islami, B., Giese, A., Görner, K., and Overath, J. (2022b). "Investigations into the use of natural gas/hydrogen blends and hydrogen for decarbonization in the glass industry," in 13th International Conference on Industrial Furnaces and Boilers (INFUB13) Albufeira (Portugal).
- Leicher, J., Giese, A., and Wieland, C. (2024). Electrification or hydrogen? The challenge of decarbonizing (High-Temperature) process heat. *J - Multidiscip. Sci. J* 7 (4), 439–456. doi:10.3390/j7040026
- Leisin, M., and Radgen, P. (2022). *Glas 2045 - dekarbonisierung der Glasindustrie.* Düsseldorf, Germany: Bundesverband Glasindustrie e.V./IER Universität Stuttgart. Available online at: <https://www.bvglas.de/dekarbonisierung/bv-glas-roadmap-zur-dekarbonisierung-der-glasindustrie/>.
- Lieuwen, T., Emerson, B., Acharya, V., and Gupta, I. (2024). Roles for combustion in a net-zero CO2 Society. *Proc. Combust. Inst.* 40 (1-4), 105753. doi:10.1016/j.proci.2024.105753
- Martin, P., Oeko, I. B., Esquivel-Elizondo, S., Kupers, R., Cebon, D., Baxter, T., et al. (2024). A review of challenges with using the natural gas system for hydrogen. *Energy Sci. and Eng.*, 1–18. doi:10.1002/ese3.1861
- Matsuo, Y. (2022). Re-Defining System LCOE: costs and values of power sources. *Energies* (15). doi:10.3390/en15186845
- Mayrhofer, M., Koller, M., Seemann, P., Bordbar, H., Prieler, R., and Hochenauer, C. (2021). MILD combustion of hydrogen and air - an efficient modelling approach in CFD validated by experimental data. *Int. J. Hydrogen Energy* 47 (9), 6349–6364. doi:10.1016/j.ijhydene.2021.11.236
- Meuleman, R. (2024). "The Electrification of the glass industry: past, present and future," in 97th DGG Glass-Technology Conference (Aachen, Germany).
- Meynet, N., Grandin, G.-A., Gobin, C., Lefebvre, F., and Honoré, D. (2023). "Experimental characterization of hydrogen impact on the flame structure and NOx emissions inside a semi-industrial furnace," in *Rouen, Frankreich.*
- Mohanna, H., Lumbreras, J., Losacker, J., Caillat, S., Mira, D., and Schmitz, N. (2025). "New lateral burner for 0 to 100 % hydrogen flexibility in steel reheating," in IFRF Conference on Sustainable and Safe Industrial Combustion (Sheffield, UK).
- Moraski, J., Ovist, M., and Spokas, K. (2025). *Beyond LCOE: a systems-oriented perspective for evaluating electricity decarbonization pathways.* Clean Air Task Force: Rotterdam, The Netherlands. Available online at: <https://cdn.catf.us/wp-content/uploads/2025/06/12134742/beyond-lcoe.pdf>.
- Nasta, A., and Wissmiller, D. (2024). *Designs for net-zero energy systems: Meta-analysis of U.S. Economy-Wide decarbonization studies.* Des Plaines, USA: GTI Energy/Low-Carbon Resources Initiative. Available online at: https://www.gti.energy/wp-content/uploads/2024/02/Meta-Analysis-of-U.S.-Economy-Wide-Decarbonization-Studies_Feb2024.pdf.
- Naumann, G., Schropp, E., and Gaderer, M. (2022). Life cycle assessment of an air-source heat pump and a condensing gas boiler using an attributional and a consequential approach. *Procedia CIRP* S, 351–356. doi:10.1016/j.procir.2022.02.058
- Noble, D., Wu, D., Emerson, B., Sheppard, S., Lieuwen, T., and Angello, L. (2021). Assessment of Current capabilities and near-term availability of hydrogen-fired gas turbines considering a low-carbon future. *J. Eng. Gas Turbines Power* 143 (4), 041002. doi:10.1115/1.4049346
- Ohashi, T. (2022). *World's first liquefied hydrogen carrier.* Mailand, Italien. Available online at: <https://www.gastechevent.com/media/y25pz22e/world-s-first-liquefied-hydrogen-carrier-tetsuya-ohashi-kawaskai.pdf>.
- Our World in Data (2025). Global primary energy consumption by source. Available online at: <https://ourworldindata.org/grapher/global-energy-substitution>.
- Overath, J. (2023). *Zukunft Gas. Webinar "Bei Wasserstoff voll aufdrehen in der Industrie.* Die Gas- und Wasserstoffwirtschaft: Berlin, Germany. Available online at: <https://nl.gas.info/H2%20aufdrehen/2023-02-09/Bundesverband%20Glasindustrie%2C%20Johann%20Overath.pdf>.
- Pitsch, H. (2022). Subtleties and complexities of hydrogen combustion - why does hydrogen burn so fast? *IFRF TOTeM48 Hydrogen Decarbonization*
- Poirier, T., Hody, S., and Taddeo, L. (2024a). "Estimation de l'impact de H2 comme combustible sur les réfractaires: Focus sur l'attaque par la vapeur d'eau," in *Journées du Groupe Français de la Céramique et de la Société Française de Métallurgie et de Matériaux* (Limoges, France).
- Poirier, T., Taddeo, L., and Hody, S. (2024b). "Estimation of the impact of 10-100 % H2 admixtures in natural gas fuel on the lifetime of industrial kilns," in International Gas Union Research Conference (IGRC) (Canada: Banff).
- Poirier, C., Honoré, D., Lacour, C., Torres, O., Houidi, S., Blanchard, L., et al. (2025). "An integrated approach of the potential of hydrogen combustion for the decarbonization of tiles and bricks industry," in IFRF Conference on Sustainable and Safe Industrial Combustion (Sheffield, UK).
- Raina, N., Chuetor, S., Charoenkool, P., Jiradechakorn, T., Sereenonchai, C., Phojaroen, J., et al. (2024). "2 - opportunities and challenges in the production of biofuels from waste biomass," in *Biofuels, biogas and value-added products* (S: Woodhead Publishing Ltd), 23–43. Available online at: <https://www.sciencedirect.com/science/article/edited-volume/abs/pii/B9780443191718000067>.
- Richie, H. (2020). Our World in Data. Sector by sector: where do global greenhouse gas emissions come from? Available online at: <https://ourworldindata.org/ghg-emissions-by-sector>.
- Rosenow, J., Gibb, D., Nowak, T., and Lowes, R. (2024). Heating up the global heat pump market. *Nature Energy* 7 (October), 901–904. doi:10.1038/s41560-022-01104-8
- S and P Global (2024). Orsted scraps Swedish FlagshipONE emethanol project under development. *S and P Glob.* Available online at: <https://www.spglobal.com/commodity-insights/en/news-research/latest-news/energy-transition/081524-orsted-scrap-s-swedish-flagshipone-e-methanol-project-under-development>.
- Schill, W.-P., and Kemfert, C. (2011). Modeling strategic electricity storage: the case of pumped hydro storage in Germany. *Energy J.* 32 (3). doi:10.5547/issn0195-6574-ej-vol32-no3-3
- Schmitz, N., Sankowski, L., Busson, E., Echterhof, T., and Pfeifer, H. (2023). NOx emission limits in a fuel-flexible and defossilized industry - quo vadis? *Energies* 16 (15), 5663. doi:10.3390/en16155663
- Schüttensack, L., Reinicke, A., and Echterhof, T. (2024). Application of hydrogen operated burners in the electric arc furnace. Available online at: <https://iopscience.iop.org/article/10.1088/1757-899X/1309/1/012011>.
- Schwarz, S., Daurer, G., Plank, B., Krull, H.-G., Sztitnick, A., Lakhdari, M. A., et al. (2025). A comparative experimental analysis of the scale formation of various steel grades during reheating under hydrogen and natural gas air-fuel and oxy-fuel combustion conditions. *Int. J. Hydrogen Energy* 101, 1105–1115. doi:10.1016/j.ijhydene.2024.12.279
- Shivam, P. J., Noble, D. R., Emerson, B., and Lieuwen, T. (2025). Back to the future: revisiting nonpremixed designs for fuel flexible (H2/NH3/CH4), low NOx combustion. *J. Eng. Gas Turbines Power.* doi:10.1115/1.4068587
- Slim, B. K., Darmeveil, H. D., Gersen, S., and Levinsky, H. B. (2011). The combustion behaviour of forced-draught industrial burners when fired within the EASEE-gas range of Wobbe Index. *J. Nat. Gas Sci. Eng.* 3 (5), 642–645. doi:10.1016/j.jngse.2011.07.004
- Smil, V. (2010). *Energy transitions: history, requirements, prospects.* Santa Barbara, USA: Praeger.
- Smil, V. (2018). *Energy and civilization: a history.* Cambridge, USA: MIT Press.
- Stromerzeugung nach Energieträgern (Strommix) von 1990 bis (2024). "(in TWh) in Deutschland insgesamt," Berlin, Germany: AGEBA AG Energiebilanzen e.V. Available online at: <https://ag-energiebilanzen.de/wp-content/uploads/2025/02/STRERZ-Abgabe-2025-06.pdf>.
- Technische Regel - Arbeitsblatt DVGW G260 (A), Gasbeschaffenheit (2021). Bonn, Germany: deutscher Verein des Gas-und Wasserfaches e.V. (DVGW).
- Tekin, N., Ashikaga, M., Horikawa, A., and Funke, H. (2018). Enhancement of fuel flexibility of industrial gas turbines by development of innovative hydrogen combustion systems. *Gas Energy.* (2).
- The Lloyd's Register Maritime Decarbonisation Hub (2022). *Zero carbon fuel monitor July 2022 update.* London, UK: The Lloyd's Register Maritime Decarbonisation Hub. Available online at: https://maritime.lr.org/1/941163/2022-08-01/4k2yc/941163/1659347389AEGVRgZM/mo_22_08_lr_zero_carbon_fuel_monitor.pdf.

- TotalEnergies (2024). *TotalEnergies Energy Outlook 2024*. Paris, France: TotalEnergies S.A. Available online at: https://totalenergies.com/sites/g/files/nytnzq121/files/documents/totalenergies_TotalEnergies_presentation_Energy_Outlook_2024_EN.pdf.
- Uchida, N., Onorati, A., Novella, R., Agarwal, A. K., Abdul-Manan, A. F., Casal Kulzer, A., et al. (2025). E-fuels in IC engines: a key solution for a future decarbonized transport. *Int. J. Engine Res.* 26 (11), 1675–1702. doi:10.1177/14680874251325296
- Ueckerdt, F., Hirth, L., Luderer, G., and Edenhofer, O. (2013). *System LCOE: what are the costs of variable renewables*. Potsdam: Potsdam Institute for Climate Impact Research. Available online at: https://www.pik-potsdam.de/members/edenh/publications-1/SystemLCOE.pdf/@download/file/Ueckerdt%20et%20al_System_LCOE%20-%20what%20are%20the%20costs%20of%20variable%20renewables_2013.pdf.
- Umweltmessung (2021). Neufassung der Ersten Allgemeinen Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz (Technische Anleitung zur Reinhaltung der Luft - TA Luft). Available online at: <https://umweltmessung.com/wp-content/uploads/TA-Luft-2021-1.pdf>.
- UN Trade and Development Data Hub (2025). World seaborne trade by type of cargo, annual (analytical). Available online at: <https://unctadstat.unctad.org/datacentre/dataviewer/US.SeaborneTrade>.
- UNDP (2024). *Human Development Report 2023/2024 technical notes*. United Nations Development Programme: New York, USA. Available online at: https://hdr.undp.org/sites/default/files/2023-24_HDR/hdr2023-24_technical_notes.pdf.
- Valera-Medina, A., Viguera-Zumiga, M. O., Shi, H., Mashruk, S., Alnajideen, M., Alnasif, A., et al. (2024). Ammonia combustion in furnaces: a review. *Int. J. Hydrogen Energy* 49, 1597–1618. doi:10.1016/j.ijhydene.2023.10.241
- Valera-Medina, A. (2023). "Insights into a future running on Ammonia Combustion," in *Keynote lecture: 11th European combustion meeting* (Rouen, France).
- Valera-Medina, A. (2024). "AMBURN - Ammonia for boilers in rural locations," in Ammonia Energy Association Annual Conference (New Orleans, USA). Available online at: <https://ammoniaenergy.org/wp-content/uploads/2024/11/A-Valera-Medina-2024.pdf>.
- Van Dyk, S., and Saddler, J. (2021). Progress in commercialization of biojet/Sustainable aviation fuels (SAF): technologies, potential and challenges. 95.
- van Rossum, R., La Guardia, G., Wang, A., Kühnen, L., and Overgaag, M. (2022). *European hydrogen backbone - a European hydrogen infrastructure vision covering 28 countries*. Utrecht, Netherlands: European Hydrogen Backbone. Available online at: <https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf>.
- von Schéele, J., and Zilka, V. (2020). Successful use of flameless oxyfuel in steel reheating. *Metal*. doi:10.37904/metal.2020.3460
- von Schéele, J., Carlsson, A., Jonsson, M., Frank, E., and Adendorff, M. (2022). "New oxyfuel technology for energy-efficient and ultra-low NOx annealing of steel," in *Albufeira* (Portugal).
- Walter, D., Boehm, P., Drünert, F., Fleischmann, B., and Löber, N.-H. (2024). "The influence of hydrogen (co-)firing on the physical and chemical properties of different glasses - results originating from the projects HyGlass and H2-Glas (IGF 21745 N)," in 97th Glass-Technology Conference (Germany: Aachen).
- Wang, B., Ting, Z. J., and Zhao, M. (2024). Sustainable aviation fuels: key opportunities and challenges in lowering carbon emissions for aviation industry. *Carbon Capture Sci. and Technol.* 13, 100263. doi:10.1016/j.ccst.2024.100263
- Wünning, J. G. (2021). Future heating of industrial furnaces. *Heat Processing* 1, 23–26.
- Xin, Z. (2025). Hydrogen upping ante in green energy portfolio. *China Dly*. Available online at: <https://www.chinadaily.com.cn/a/202511/04/WS69095ac8a310f215074b8d00.html>.
- Zier, M., Stenzel, P., Kotzur, L., and Stolten, D. (2021). A review of decarbonization options for the glass industry. *Energy Convers. Manag.* X 10, 100083. doi:10.1016/j.ecmx.2021.100083
- Zier, M., Pflugradt, N., Stenzel, P., Kotzur, L., and Stolten, D. (2023). Industrial decarbonization pathways: the example of the German glass industry. *Energy Convers. Manag.* X (17), 100336. doi:10.1016/j.ecmx.2022.100336