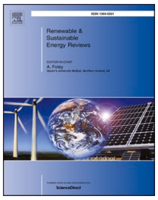
Renewable and Sustainable Energy Reviews 235 (2026) 116975

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Hydrogen-argon power cycle for next-generation zero-emission energy transition

Qiang Cheng [a,*], Joakim Kapp [a], Viljam Grahn [b], Zeeshan Ahmad [b], Jari Hyvönen [b], Ville Vuorinen [a], Armin Wehrfritz [c], Ossi Kaario [a]

[a] Department of Mechanical Engineering, School of Engineering, Aalto University, 00076, Aalto, Finland
[b] Wärtsilä Finland Oy, Vaasa, FI-65101, Finland
[c] Department of Mechanical and Materials Engineering, University of Turku, Turun Yliopisto, FI-20014, Finland

ARTICLE INFO

Keywords:
Hydrogen-argon power cycle
Zero-emission combustion
Nitrogen-free combustion
Hydrogen engines
Thermal efficiency

ABSTRACT

Hydrogen is widely regarded as a cornerstone energy carrier for achieving net-zero emissions; however, its combustion in conventional air-based engines inevitably leads to nitrogen oxide formation due to high-temperature reactions between oxygen and nitrogen. The hydrogen-argon power cycle (H_2-APC) replaces nitrogen with argon as the working fluid to fundamentally decouple combustion from both carbon and nitrogen chemistry. This carbon- and nitrogen-free combustion concept enables intrinsically zero emission, while simultaneously enhancing thermal efficiency owing to argon's high specific heat ratio and inert thermophysical properties. This review provides a comprehensive and critical assessment of the current state of H_2-APC research, including thermodynamic cycle analysis, combustion kinetics, mixing dynamics, flame stabilization, and abnormal combustion phenomena. Both numerical modelling and experimental demonstrations are systematically reviewed. The analysis highlights key advantages of H_2-APC operation, including elevated efficiency limits, extended ultra-lean combustion regimes, and suppressed pollutant formation. At the same time, the review identifies major technical and system-level challenges, notably improved abnormal combustion, argon supply and recycling, cost and infrastructure constraints. To address the challenges, mitigation strategies such as water injection, pre-chamber and advanced ignition concepts, and closed-loop argon recycling architectures are critically discussed. Finally, the review outlines future research priorities, including high-fidelity optical diagnostics, validated kinetic and turbulence-chemistry interaction models, and integrated techno-economic and life-cycle assessments. Overall, the H_2-APC represents a transformative pathway for sustainable power generation and propulsion, positioning zero-emission internal combustion engines as a viable complement to renewable and electrified energy systems.

1. Introduction

As the global focus on reducing emissions and achieving sustainability intensifies, internal combustion engines (ICE) faces increasing growing environmental constraints. Carbon dioxide (CO_2) is a major greenhouse gas (GHG), which is known to cause a temperature increase and subsequently climate change. Aside from CO_2 emissions, one of the most significant challenges in conventional combustion systems is the formation of nitrogen oxides (NO_x), which occur when nitrogen (N_2), e.g. from air, reacts with oxygen (O_2) during high-temperature combustion. This review explores an innovative approach that eliminates carbon and N_2 from the combustion process, resulting in zero CO_2 and NO_x emissions.

H_2 has been extensively studied as a carbon-free fuel, offering an attractive solution for future power and propulsion systems, which produces only water vapor during combustion. However, H_2 combustion in conventional air-breathing engines still generates NO_x due to high-temperature N_2-O_2 oxidization [1]. As H_2 began to emerge as a leading candidate for clean energy in the early 21st century, researchers started introducing H_2 as a fuel into power and propulsion system, and further replacing air with Ar-O_2 to achieve net-zero emission goal [2]. The combination of H_2 and Ar in combustion systems represented a breakthrough because Ar, can remove N_2 entirely, creating an N_2-free combustion cycle. Meanwhile, the higher specific heat ratio of Ar (γ_{Ar} =

---

* Corresponding author.
E-mail address: qiang.cheng@aalto.fi (Q. Cheng).

https://doi.org/10.1016/j.rser.2026.116975
Received 27 October 2025; Received in revised form 24 March 2026; Accepted 1 April 2026

1.67) also boosts thermal efficiency, making the system more energy efficient. The H_2-APC is a relatively recent innovation in the realm of thermodynamic cycles aimed at increasing efficiency and reducing emissions in ICE [3]. While the concept of using inert gases like Ar in power generation systems is novel, it draws upon the principles of thermodynamic cycles that have evolved over more than a century of engineering developments.

The history of the H_2-APC begins with the development of basic thermodynamic cycles, such as the Otto and Diesel cycles [4]. These conventional thermodynamic cycles form the foundation of ICE design. In both, O_2 serves as the oxidizer for the fuel, while N_2 functions as the primary working gas in the cylinder, transferring heat and enabling pressure work during expansion. Although N_2 is largely inert under standard conditions, it becomes chemically active at high combustion temperatures, leading to the NO_x formation. This inherent behaviour of N_2 not only limits combustion efficiency but also contributes to pollutant emissions. To improve engine efficiency and reduce harmful emissions like NO_x, researchers began exploring alternative working fluids. In the latter half of the 20th century, researchers began exploring the use of inert gases such as helium (He) and Ar in closed power cycles due to their unique properties [5], [6]. The application of Ar, specifically, in ICE started gaining attention in the late 20th and early 21st centuries due to its high specific heat ratio ($\gamma_{Ar} = 1.67$), compared to N_2 ($\gamma_{N_2} = 1.4$), leading to higher thermal efficiency and inert nature, which prevents the formation of NO_x during combustion, making it an ideal candidate for environmentally friendly combustion processes [7].

In the 2010s, researchers began developing simulation models and experimental setups to explore the potential of H_2-APC for use in ICE. The goal was to create a system that not only maximizes efficiency but also meets zero-emission standards by eliminating both CO_2 and NO_x emissions. By the 2020s, the H_2-APC had evolved into a promising solution for next-generation stationary power systems. Preliminary studies have focused on developing 1D and 3D computational models using tools like GT-Power [7] and computational fluid dynamics (CFD) simulations [8] to optimize H_2-O_2-Ar combustion cycles. These models allow researchers to simulate the thermodynamic properties of the cycle, optimize the application of Ar, and study the impacts of varying compression ratios, fuel mixtures, and equivalence ratios. For instance, Wang et al. [9] highlighted the potential of H_2-APC engines to achieve thermal efficiencies up to 70%, using the variable specific heat ratio with Otto/Miller cycle. Ding et al. [10] combined 1D and 3D simulations, focused on improving thermal efficiency in H_2-APC. This study highlighted the enhancement of direct H_2 injection into the engine performance of Ar cycle, by improving the indicated mean effective pressure (IMEP) and reducing combustion instability. A 57% of IMEP was achieved in optimized conditions. Ramogonino et al. [11] presented a hybrid 1D-3D simulation methodology for optimizing hydrogen-fueled spark ignition (SI) engines using Ar. The hybrid approach allowed for reliable predictions of combustion efficiency and heat release, demonstrating the practicality of this zero-emission technology for industrial-scale applications. Sierra Aznar et al. [12] explored closed-loop Ar cycles with both 1D and 3D modelling to simulate the performance of methane-based APC with CO_2 capture. The results showed that APC could achieve high thermal efficiencies while capturing nearly 100% of CO_2 produced during combustion. Dong et al. [6] focused on the use of Ar split cycles to recover exhaust energy and enhance thermal efficiency. The 1D simulations demonstrated up to 75% exhaust energy recovery compared to traditional engines. Millo et al. [13] developed a methodology combining 0D, 1D, and 3D models to optimize argon power cycle engines for both performance and emissions. The hybrid approach allowed for efficient parameter sweeps in 1D before refining combustion details in 3D simulations.

Several experimental studies have also been conducted to demonstrate the concept from the practical scenario. Mansor and Shioji [14] fundamentally investigated the feasibility of Ar-circulated H_2 engines in a constant-volume combustion chamber (CVCC). The ignition delay time (IDT), flame characteristics and heat release rate under various conditions were compared under Ar-O_2 and N_2-O_2 atmosphere. Hodgson et al. [15] presented a comprehensive thermodynamic model for closed-loop H_2-Ar Brayton cycles and explores several modifications to enhance efficiency and power output. While the H_2-He cycle offers higher efficiency primarily due to its superior thermophysical properties. The H_2-Ar cycle strikes a balance between cost and performance, offering a promising pathway for zero-emission power generation using renewable H_2 and O_2. Prashanth et al. [16] explored stratified combustion techniques to improve thermal efficiency in H_2-Ar engines. The experimental results indicated that stratification allowed for better control over combustion dynamics.

Even though the H_2-APC has emerged as an advanced modification of existing thermodynamic cycles, aimed specifically at achieving zero emissions by leveraging the clean combustion of H_2 and the inert properties of Ar, its long-term efficiency and system integration require further investigation. The cycle offers significant improvements in thermal efficiency, combustion stability, and emission reduction, making it an attractive solution for decarbonizing transportation and stationary power systems [17]. However, some significant challenges obstacle its widespread application, such as, the high cost of H_2, Ar and O_2 [18], abnormal combustion caused instability (e.g., pre-ignition and knocking) [19,20], and complex engine modification for Ar recycling [20]. Meanwhile, managing fuel delivery, O_2 supply, exhaust recirculation, and ensuring proper mixing of gases are all challenges that must be addressed in both engine design and control systems.

In this review, we provide a comprehensive overview of the current state of research on H_2-APC power cycles, emphasizing their role in enabling zero-emission combustion and their potential to transform future power and propulsion technologies. The review further aims to:

(i) synthesize existing knowledge on the thermodynamic advantages of the H_2-Ar cycle.
(ii) examine the fundamental combustion characteristics of H_2-O_2-Ar mixtures.
(iii) assess advanced engine technologies and control strategies developed for H_2-Ar systems.

In addition, the paper highlights key benefits such as zero CO_2 and NO_x emissions, high thermal efficiency, and improved combustion stability, while critically analysing the challenges related to argon cost, abnormal hydrogen combustion phenomena, and engine design modifications. Beyond summarizing experimental and numerical studies, the review seeks to integrate findings across disciplines, identify consistent trends and knowledge gaps, and propose targeted research priorities. These include the development of accurate kinetic models, high-fidelity diagnostics of H_2-Ar-O_2 combustion, scalable argon recycling methods, and techno-economic evaluations. By articulating these objectives, the review not only consolidates the current understanding of H_2-APC but also provides practical guidance and recommendations for advancing this emerging zero-emission technology toward large-scale implementation.

2. The future of the ICE

2.1. *The key application fields of ICE*

Despite electrification of the transport sector advancing rapidly, certain key applications of ICE remain challenging to replace due to specific operational demands, energy density requirements, and infrastructure limitations [4]. These applications rely on the unique capabilities of ICE, especially for high energy needs, extended range, and challenging environments. The key application fields include stationary power generation systems (e.g., mission-critical and backup, continuous power and peak shaving), heavy-duty long-haul transportation, marine and shipping industries, commercial and cargo aircraft, agricultural and construction equipment, military vehicles and equipment, all of which require high energy density and high reliability, which current battery technologies cannot provide. Fig. 1 summarizes the expected availability and feasibility of technologies for future power and propulsion systems. It indicates that the ICE will continue to be irreplaceable in applications that demand high energy density, extended range, robustness in extreme environments, and lack of charging infrastructure. Transitioning these sectors to lower-emission ICE technologies, such as those fueled by H_2, biofuels, ammonia, or synthetic fuels, can help bridge the gap to a more sustainable future while maintaining operational capabilities.

2.2. *Scenarios of market demand for ICEs and alternative technologies*

Fig. 2 shows the ICE market transformation scenarios normalized on base demand in 2019 [21]. The demand for ICE and alternative powertrains in the coming decades will depend on economic, regulatory, and environmental factors. The market scenarios for emissions taxation, renewable fuel adoption, and green infrastructure development will also significantly affect the ICE market transformation. Scenario 1 assumes low CO_2 taxation (<\$40/ton) and minimal regulatory change. Fossil fuels remain dominant, with limited availability of green H_2 and e-fuels. By 2050, ICE fueled by fossil and sustainable sources hold 33% of the market, while hybrids and electric vehicles expand to 37% and 18%, respectively. This slow transition reflects a modest shift towards emission reduction. Scenario 2 features a higher CO_2 tax (~\$100/ton) and incentives for green H_2 adoption, replacing 5% of natural gas by 2025. By 2050, hybrids capture 47% of the market, electric solutions 35%, and ICE, mainly using sustainable fuels, hold 18%. This scenario illustrates a more aggressive transition driven by policy support and hydrogen infrastructure expansion. Scenario 3 envisions stringent regulations with CO_2 taxation above \$100/ton, aiming to drastically reduce emissions. By 2050, the market is dominated by electric (44%) and fuel cell vehicles (45%), with traditional ICE reduced to just 11%. This scenario assumes rapid e-fuel and H_2 adoption, along with infrastructure growth, as ICE are phased out or retrofitted for niche uses.

Despite the growth of alternative technologies, the ICE market is projected to see steady demand in the near term. According to the market size forecast, ICE sales will grow from \$246.8 billion in 2023 to \$396.9 billion by 2032, as shown in Fig. 3(a), driven by demand in emerging markets, technological improvements in fuel efficiency, and existing fossil fuel infrastructure. Ultimately, while the market shifts toward lower-emission technologies, ICE will retain a notable presence due to their adaptability, cost-effectiveness, and the gradual pace of infrastructure development for substitutes. Fig. (b) illustrates the market share by region for 2022. It is highlighted that ICE is essential globally, with significant market shares in both developed and developing regions.

3. Impacts of the H_2-APC ICE on the global environment and economy

Considering the disadvantages of conventional fossil fuel ICEs, the H_2-APC can be a key player in the H_2 economy as countries and industries strive to meet net-zero emission goals by 2050. In this section, the impacts of H_2-APC ICE on the global environment and economy will be comprehensively discussed.

3.1. *Impact of the H_2-APC on the environment*

CO_2 emissions are the primary driver of global temperature rise. Fig. 4(a) illustrates CO_2 emissions from energy and industrial production across different fuel types, along with the global average temperature relative to the 1961-1990 baseline [23]. Since then, average temperatures have increased by more than 0.8 °C, corresponding to about 1.2 °C above pre-industrial levels. Fig. 4(b) illustrates NO_x emissions, which is a major byproduct of fossil fuel combustion that significantly contributes to air pollution and poses a threat to human health. The rapid increase in NO_x emissions since the Industrial Revolution aligns with the large-scale adoption of fossil fuels. NO_x emissions peaked around the year 2000, reflecting the widespread industrial and transportation activities. Although stricter environmental regulations have led to a slight decline in emissions since then, the levels remain considerably high.

Fig. 5 compares the life-cycle carbon intensity of major electricity generation technologies, expressed as specific CO_2 emissions (kg CO_2) [24]. Fossil-based pathways exhibit orders-of-magnitude higher emissions, with coal (~970 kg CO_2) and natural gas (~439 kg CO_2) dominated by direct carbon oxidation during combustion. In contrast, low-carbon technologies, including nuclear, wind, hydropower, and solar exhibit substantially lower life-cycle emissions (<120 kg CO_2), where the remaining carbon footprint arises primarily from upstream activities such as material extraction, component manufacturing, construction, and end-of-life processing, rather than from operational energy conversion. This comparison highlights the fundamental necessity of renewable and carbon-free energy systems for deep decarbonization: eliminating carbon at the point of energy conversion is far more effective than incremental efficiency improvements within carbon-based pathways. Even with advanced efficiency and emission control technologies, conventional combustion systems remain intrinsically constrained by

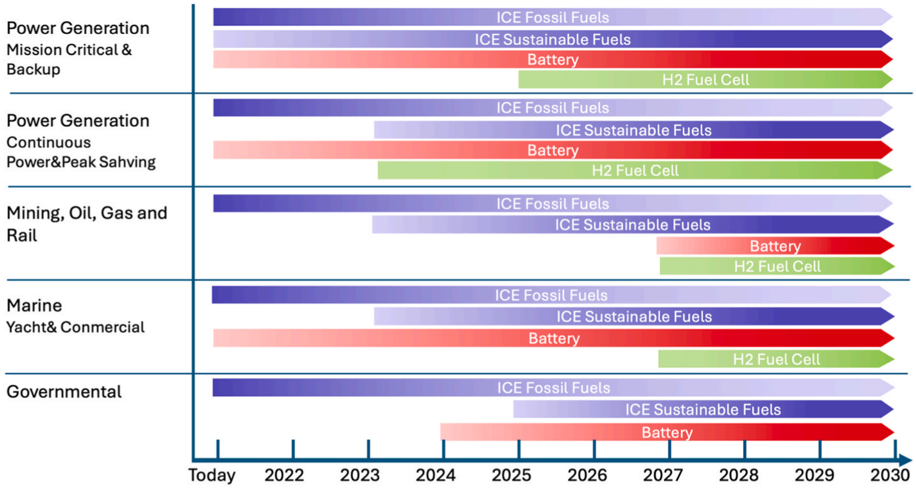


Fig. 1. Expected availability and feasibility of technologies for power propulsion systems [21].

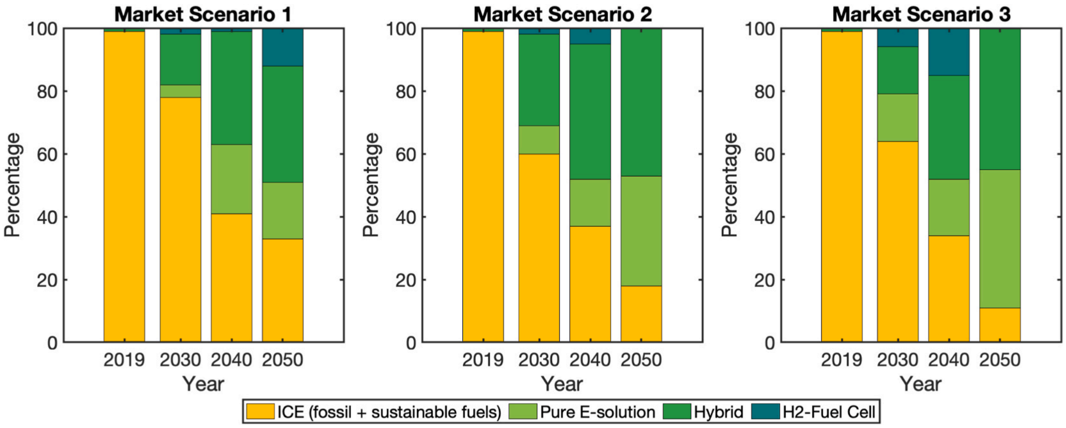


Fig. 2. Market transformation scenarios normalized to 2019 baseline demand [21].

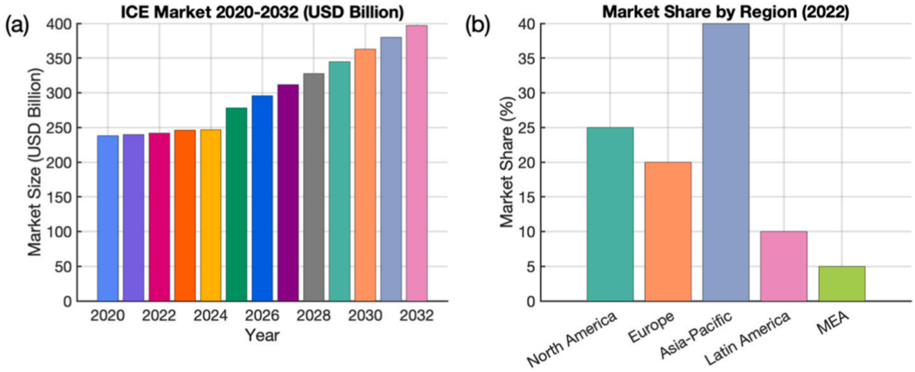


Fig. 3. (a) Global ICE market size 2020-2030, (b) market share by region 2022 [22].

fuel-bound carbon, which sets a lower bound on achievable life-cycle emissions. This observation directly motivates the H_2-APC as a pathway to decouple high-temperature combustion from carbon chemistry, enabling combustion-based power generation with life-cycle emissions approaching those of established low-carbon and renewable technologies.

Other emissions, resulting from natural gas and ammonia combustion systems, can also significantly contribute to GHG emissions and air pollution. Examples include methane slip (CH_4-slip), a potent GHG with a global warming potential of 28-30 times greater than that of CO_2, and nitrous oxide (N_2O), which is not only a strong GHG but also contributes to ozone layer depletion. Fig. 6 illustrates the emission profiles and environmental impacts associated with these gases under varying combustion conditions. Their mitigation requires advanced combustion strategies, emission control technologies, and the integration of cleaner energy systems to minimize their release and environmental footprint effectively.

Considering net-zero emission of the H_2-APC systems, which present a promising pathway for sustainable energy transformation, offering substantial environmental advantages. This advanced cycle facilitates zero-emission power generation by eliminating CO_2 and NO_x emissions with significantly enhanced energy efficiency (resulting from the increase in thermal efficiency of H_2-APC engines). However, the widespread implementation of the H_2-APC faces several challenges, including the development of robust H_2 production and Ar recycling infrastructures, as well as the scaling of supporting technologies. Despite these obstacles, advancing research, innovation, and policy frameworks will be pivotal in overcoming these barriers and harnessing the full environmental benefits of this technology.

3.2. *Impact of the H_2-APC on the economy*

The global energy infrastructure has undergone significant transformation since the industrial revolution. Fig. 7 provides an overview of primary energy consumption from fossil fuels (Fig. 7(a)), highlighting the contributions of coal (Fig. 7(b)), oil (Fig. 7(c)), and natural gas (Fig. 7(d)) for each country. These maps emphasize that fossil fuels remain the dominant source of energy despite the growth of renewables, particularly in countries with large populations. Despite advancements in renewable energy, fossil fuels remain a critical component of energy systems worldwide. To achieve a sustainable energy future, it is imperative to accelerate the transition toward renewable, low-carbon energy sources, substantially reducing the reliance on fossil fuels in the coming decades.

Renewable H_2 represents a transformative solution for decarbonizing high-emission sectors, such as heavy industry, electricity generation, steel production, mining, marine and long-haul transportation. Its versatility as an energy carrier enables storage, transportation, and on-demand conversion into electricity; however, these processes remain associated with significant technical and infrastructure challenges, particularly related to storage density, distribution, and cost, which must be addressed for large-scale deployment in future energy systems. With more than 70 countries implementing national H_2 strategies, and resulting in demand for low-emissions H_2 grew 10% in 2023, underscoring its pivotal role in transitioning to a cleaner, more sustainable energy landscape [25]. Fig. 8(a) illustrates the geographic distribution of clean H_2 projects and associated investments, reflecting the momentum toward integrating H_2 into global energy systems. Fig. 8(b) shows the regional investments required to develop announced renewable H_2 projects by 2030, amounting to $680 billion globally. Europe leads significantly in investment needs, followed by Latin America,

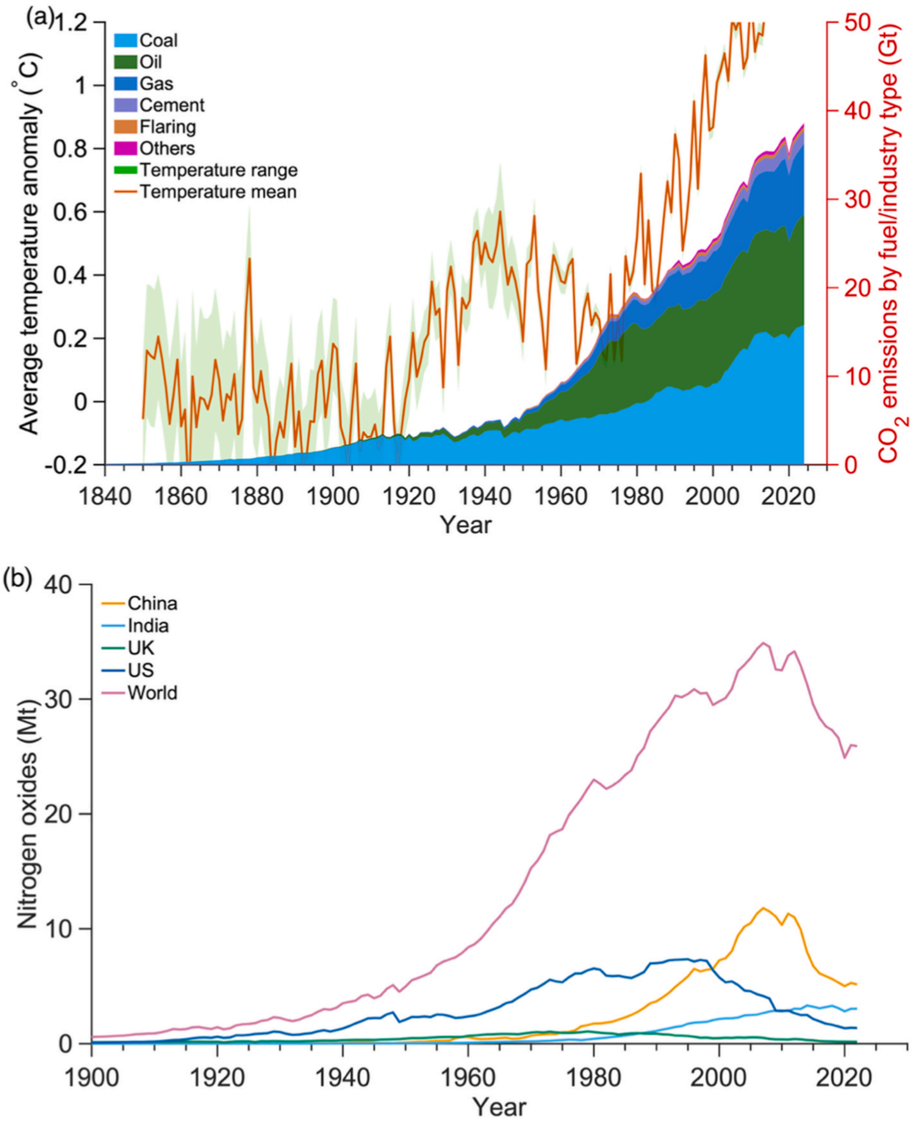


Fig. 4. The main emissions from the conventional fossil fuel combustion, (a) relation between CO_2 emissions and global warming, (b) NO_x emissions by region [23].

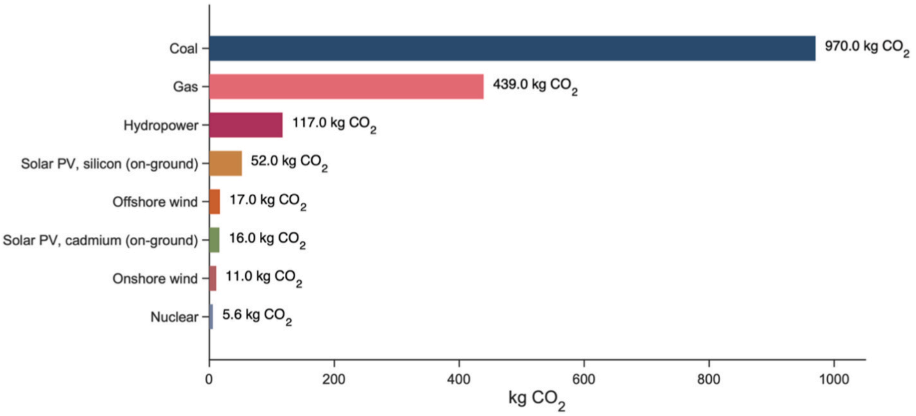


Fig. 5. Life-cycle carbon intensity of electricity generation technologies [24].

North America, and Oceania. This reflects accelerating global momentum in advancing renewable H_2 infrastructure, emphasizing the critical role of the H_2 economy in the energy transition. It also highlights the pressing need to address regional disparities in investment to achieve decarbonization targets and support the global shift toward sustainable and low-carbon energy systems [26].

In this context, the H_2-APC concept aligns with the global energy transition by utilizing renewable H_2 as a zero-carbon energy carrier

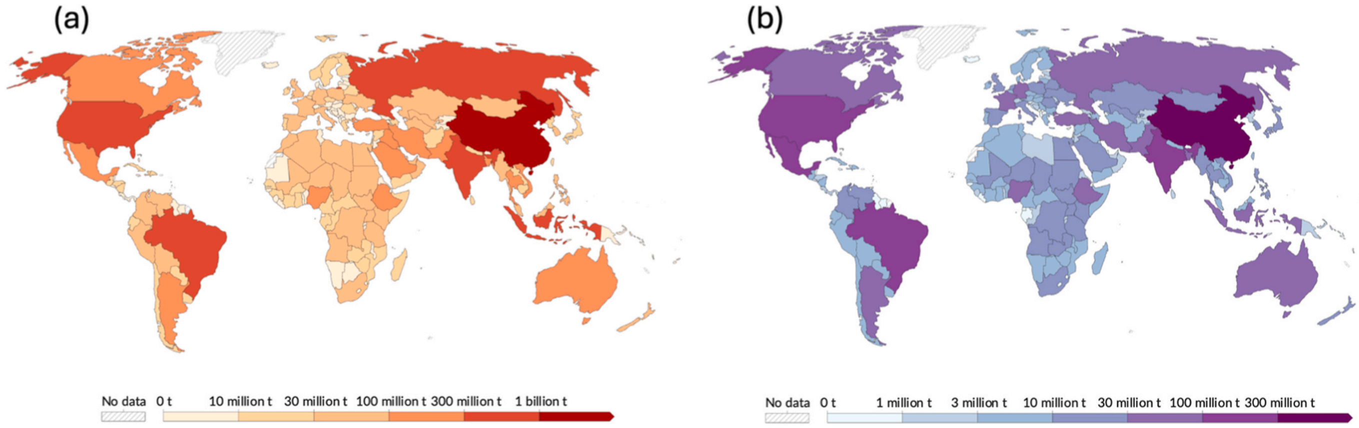


Fig. 6. Other emissions contributing to global warming, (a) CH_4-slip, (b) N_2O [24].

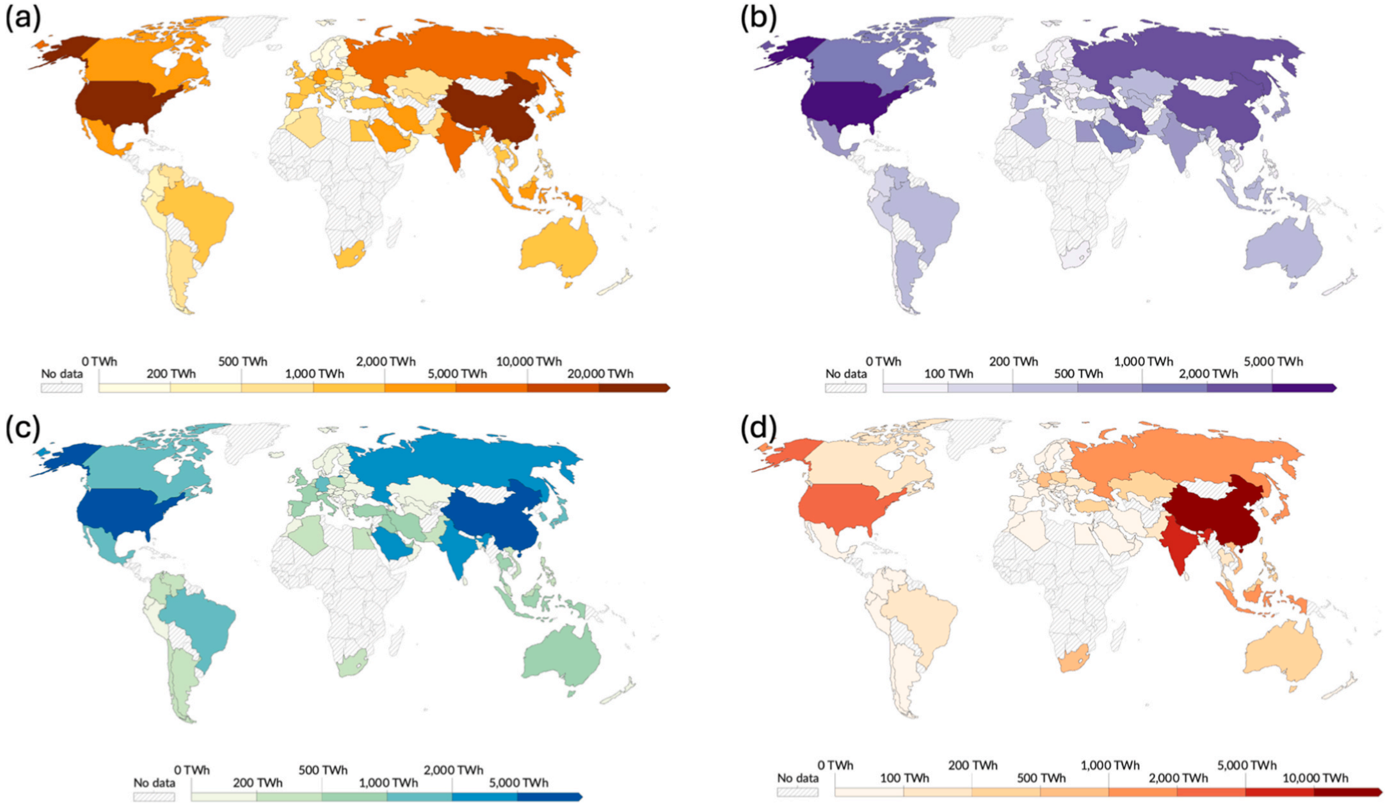


Fig. 7. The amount of primary energy is consumed in each country, (a) fossil fuels, (b) coal, (c) oil, and (d) gas [23].

within a high-efficiency power generation framework, while explicitly acknowledging the well-known challenges associated with H_2 storage, transportation, and infrastructure deployment. Beyond its thermodynamic novelty, the H_2-APC engine can contribute to improving the economic feasibility of H_2 adoption by reducing H_2 demand per unit of useful energy output, rather than by simplifying H_2 logistics. Owing to the substantially higher thermal efficiency achievable with H_2-APC engines compared with conventional air-breathing engines, less H_2 is required to deliver the same power output. This efficiency gain can partially offset the high costs associated with H_2 production, storage, and distribution during early deployment phases, without implying that these challenges are eliminated. Moreover, the H_2-APC architecture offers flexibility during the transition toward a H_2-based energy system. The same closed-cycle, high-efficiency engine platform can, in principle, operate with alternative fuels such as e-fuels or other low-carbon fuels, enabling near-term reductions in emissions and fuel consumption while H_2 infrastructure continues to mature. In this role, the H_2-APC should be viewed not as a solution to H_2 storage and transport challenges, but as a demand-reducing and efficiency-enhancing bridge technology that can ease the economic and logistical burden of the transition.

3.3. *H_2-APC for an integrated energy transition*

To contribute to the energy transition, the H_2-APC can be designed to drive an integrated energy transition by utilizing H_2 as a key enabler, particularly for sectors that cannot easily decarbonize with green electricity alone. Fig. 9 demonstrates the integration of green H_2 produced through PtG (Power-to-Gas) technology powered by renewable sources (e.g., wind and solar) into the H_2-APC, which creates a zero-emission cycle. H_2 serves as a renewable energy carrier, while Ar recycling

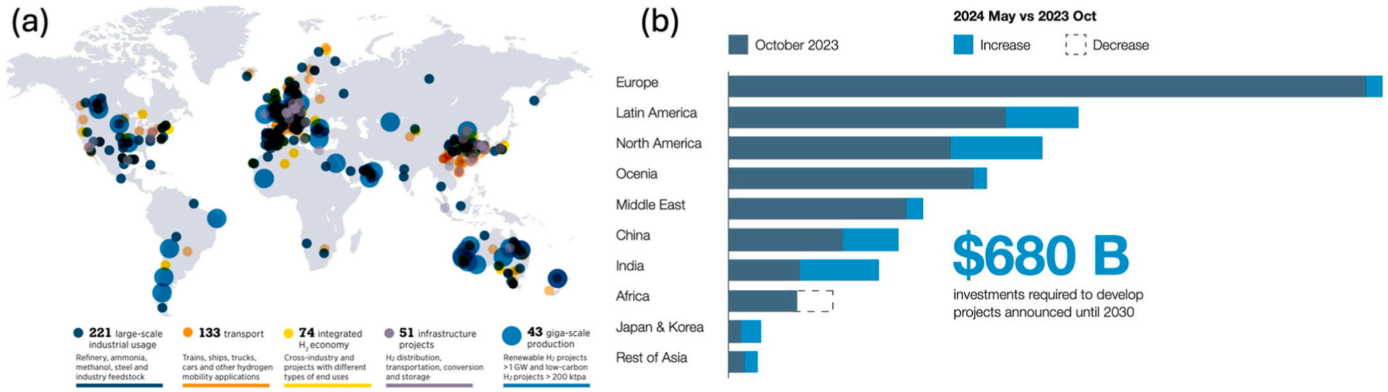


Fig. 8. Global energy transition to the H_2 economy (a) clean H_2 projects and investment around the world, (b) investments required to develop projects announced through 2030 [25].

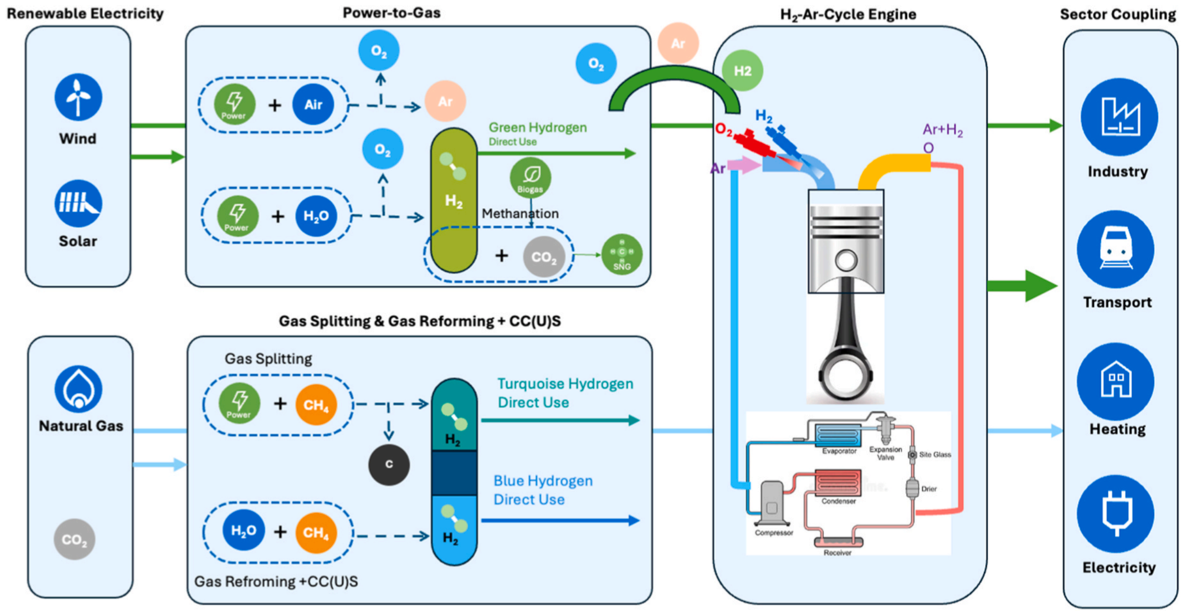


Fig. 9. H_2-APC for an integrated energy transition.

within the cycle enhances the overall sustainability and reduces dependency on continuous Ar supply. This process enables large quantities of renewable energy to be stored in the form of green H_2, addressing one of the core challenges of the energy transition: energy storage. Moreover, the H_2-APC can be adapted across sectors such as industrial processes, heating, and electricity generation. H_2 produced through renewable PtG systems can be applied in H_2-APC, supporting its operation as a clean, high-efficiency power source. Additionally, blending H_2 into existing natural gas grids provides an infrastructure-ready pathway for H_2-APC deployment, making it feasible to expand into multiple sectors.

3.4. Comparison with other H_2-based power systems

In addition to H_2-APC, several alternative H_2-based technologies have been extensively studied in the literature, most notably H_2 fuel cells (H_2-FC) [28] and H_2-fueled gas turbines (H_2-GT) [29]. Each of these options offers distinct advantages and faces different limitations depending on application scale, operating conditions, and system integration requirements [29]. H_2-FC, such as proton-exchange membrane (PEM) and solid oxide fuel cells (SOFC), are characterized by high electrical efficiency and inherently low pollutant emissions due to electrochemical energy conversion. However, H_2-FC face challenges related to high capital cost, material durability, sensitivity to fuel impurities, and limited tolerance to rapid load transients, especially in large-scale or heavy-duty applications. H_2-GT, by contrast, are well suited for large-scale power generation and grid balancing, offering high power density and operational flexibility. Their performance, however, is constrained by high flame temperatures, NO_x mitigation requirements when air is used as the oxidizer, and efficiency penalties at part load. The H_2-APC represents a distinct thermodynamic pathway that differs fundamentally from both electrochemical and Brayton-cycle-based systems. A qualitative comparison between H_2-APC systems and other H_2-based power generation technologies is summarized in Table 1.

4. Theoretical background and principles of H_2-APC

In this section, H_2-APC, an innovative energy system, is introduced as a novel approach that replaces N_2 with Ar as the working fluid in ICE, paired with H_2 as a zero-carbon fuel. The critical role of N_2 in NO_x emissions is analysed, highlighting how eliminating N_2 effectively mitigates these harmful pollutants. Additionally, the unique physical properties of Ar, such as its high γ_{Ar} and low thermal conductivity, are discussed in detail, emphasizing their contributions to improved thermal

Table 1
H_2-based power generation technologies.

Technology	Conversion principle	Typical efficiency, %	Emissions	Advantages	Limitations
H_2-APC ICE	Internal combustion with Ar-diluted H_2-O_2 working fluid	50-65% (engine-level, projected) 70-85% (ideal/theoretical cycle)	CO_2-free; nitrogen-based NO_x intrinsically suppressed	High efficiency potential; high power density; engine-based flexibility; compatibility with existing ICE infrastructure	Argon recycling required; oxygen supply needed; combustion stability and system integration challenges
H_2-FC (PEM/SOFC)	Electrochemical conversion	45-65% (system-level)	Near-zero local emissions	High efficiency at low-medium power; quiet operation; no combustion instability	High capital cost; durability and materials constraints; limited transient capability; impurity sensitivity
H_2-GT	Brayton cycle with H_2 combustion	35-45% (simple cycle) 50-60% (combined cycle)	CO_2-free; NO_x mitigation required with air	High power output; mature turbomachinery; grid-scale applicability	NO_x control complexity; high flame temperature; part-load efficiency penalties
H_2-Air ICE	Internal combustion with air	38-45% (current state-of-the-art) 45-50% (advanced concepts)	CO_2-free; NO_x formation likely	Mature technology; low cost; fast transients	NO_x emissions; lower efficiency ceiling; knock limitations

efficiency of H_2-APC engines.

4.1. N_2 in combustion and NO_x formation

In conventional ICE, atmospheric air, composed of roughly 78% N_2, 21% O_2 and ~1% Ar, is adopted for combustion. Combustion in air-breathing engines inevitably leads to NO_x formation through one or more well-established mechanisms, depending on operating conditions and fuel composition. For instance, the thermal-NO (extended Zeldovich) mechanism, prompt and intermediate nitrogen pathways, notably the NNH and N_2O routes, play an important role in NO_x formation during H_2 combustion under certain conditions [30]. The NNH pathway becomes relevant in high-temperature H_2 flames, particularly in fuel-rich or locally stoichiometric regions, where reactions involving NNH intermediates (e.g., $N_2+H\rightarrow NNH$, followed by $NNH + O\rightarrow NO + NH$) provide an additional route for rapid NO formation [31]. This mechanism has been shown to contribute non-negligibly to total NO_x emissions in H_2-air combustion, especially under conditions of high flame temperature and strong radical concentrations. Additionally, the N_2O pathway is primarily active at lower to intermediate temperatures and under lean or highly diluted conditions, where N_2O can form through reactions involving N_2, O, and HO_2 radicals, followed by N_2O decomposition to NO [32]. Although generally less dominant than the thermal-NO route at very high temperatures, the N_2O mechanism can contribute appreciably to NO_x formation in H_2 flames operating at moderate temperatures or during transient combustion phases. Fig. 10 depicts the major reaction steps involved in NO_x conversion, along with the optimized molecule geometries of N_2, NO, N_2O, and NO_2 obtained using density functional theory (B3LYP/6-311 + g(d, p)) [33]. Regarding the reaction mechanism of NO_x formation, Maroa et al. [34] explored the primary mechanisms of NO_x formation in combustion, such as the Zeldovich (thermal NO_x), Fenimore (prompt NO_x), and fuel-bound NO_x routes. It provides a comprehensive analysis of the chemical kinetics involved in NO_x formation and reduction strategies. Alagumalai et al. [1] investigated the influence of combustion temperature on NO_x emissions in gasoline and diesel engines, analysing how the flame temperature affects the thermal NO_x formation. England et al. [35] have comprehensively reviewed the NO_x formation during combustion of various fossil fuels, and discussed emerging control technologies like staged combustion and flue gas recirculation. Li et al. [36] revealed the micro-chemical mechanisms of NO_x conversion and obtained accurate kinetic data by employing advanced quantum chemistry methods to systematically explore the pathways of NO_x formation and reduction, thereby determining new rate coefficients.

These studies provide a detailed understanding of NO_x formation and reduction under conventional ICE conditions, revealing the intrinsic link between N chemistry, combustion temperature, and operating parameters. However, in the context of H_2-APC, the relevance of the NNH and N_2O pathways is fundamentally altered. When N_2 is removed from the working fluid and replaced by Ar, these nitrogen-based NO_x formation routes are effectively eliminated, leaving thermal-NO formation suppressed by the absence of N_2. Consequently, H_2-O_2-Ar combustion offers

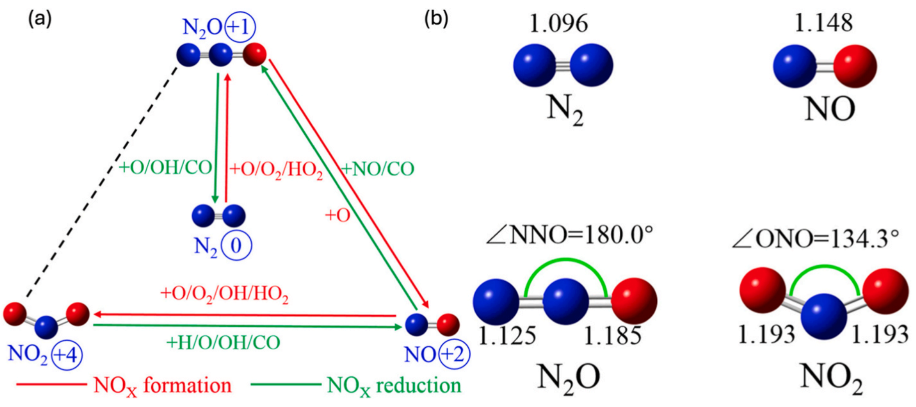


Fig. 10. (a) Key reaction pathways in NO_x conversion and (b) geometries (in Å and deg) of N_2, NO, N_2O, and NO_2 optimized via the density functional theory (B3LYP/6-311 + g(d,p)) [27].

an inherent advantage in achieving ultra-low or near-zero NO_x emissions, provided that nitrogen ingress from air leakage or residual gases is minimized [27]. This distinction highlights the importance of considering all major NO_x formation pathways when comparing air-based H_2 combustion with Ar-diluted or N-free power cycles.

4.2. Physical properties of Ar

Ar is a noble gas that constitutes about 1% of the earth atmosphere, which is more abundant than the other inert gases, e.g., helium (He), neon (Ne), krypton (Kr), xenon (Xe), radon (Rn), and oganesson (Og). Table 2 summarizes the physical properties of the Ar compared to the H_2, He, N_2, CO_2 and O_2. Owing to relatively high atomic weight (39.948) and density (1.669 kg m^{-3} at 15 °C and 1 bar), Ar is denser than air (relative density = 1.38), in contrast to light gases such as H_2 and He. Unlike N_2 and O_2, which are chemically active under high-temperature combustion conditions, Ar is chemically inert and does not participate in oxidation or reduction reactions. Its boiling point (−185.9 °C) is comparable to that of N_2 and O_2, facilitating separation from air using mature cryogenic technologies. These properties make Ar particularly attractive as a working fluid for advanced combustion cycles, as it enables high-temperature operation without contributing to NO_x formation or carbon-based emissions, while remaining more readily available and economically viable than other noble gases.

Fig. 11 depicts the function of thermal conductivity and temperature of the Ar, N_2, He and H_2-75% Air. As a monatomic gas, Ar has a lower molar heat capacity than N_2, which leads to higher adiabatic flame temperatures for H_2-O_2-Ar mixtures at comparable dilution levels. This elevated flame temperature enhances reaction rates and increases the energy available for conversion to useful work, contributing to the high theoretical efficiencies associated with H_2-APC operation. Moreover, H_2-O_2-Ar mixtures typically exhibit equal or higher laminar flame speeds than H_2-air mixtures, consistent with the increased flame temperature. At the same time, strong Ar dilution reduces reactant concentrations and alters transport properties, which can moderate flame propagation when dilution becomes sufficiently high or under elevated pressure. This behaviour can be advantageous for combustion stability in high-pressure environments by limiting pressure-rise rates and suppressing knock-like phenomena. In addition, the lower thermal conductivity of Ar (~0.016 W/m·K) than N_2 (~0.026 W/m·K) [38] reduces heat transfer from the flame to surrounding surfaces, thereby decreasing flame quenching and wall heat losses with stratification mixing strategies. The combined effects of higher flame temperature and reduced heat loss enable higher effective heat-release utilization, which is particularly beneficial for high-efficiency power cycles where maximizing the fraction of fuel energy converted to work is critical.

4.3. Life-cycle CO_2 emissions across hydrogen production pathways

Fig. 12 shows the average lifecycle carbon intensities of typical H_2 production methods based on Carbon Solutions analysts through the use of peer-reviewed published literature and tools such as GREET Lifecycle Model from Argonne National Laboratory [40–42]. Both autothermal reforming (ATR) [43] and steam methane reforming (SMR) [44] are compatible with carbon capture technologies, enabling substantial CO_2 reductions when the captured carbon is permanently stored. In comparison, electrolysis-based H_2, when powered predominantly by zero-carbon electricity from renewable or nuclear sources, offers the greatest greenhouse gas reductions among the pathways, with CO_2 emissions as low as 8.8 g/MJ. However, the feasibility of H_2 as a widespread fuel is challenged by infrastructure needs and production costs.

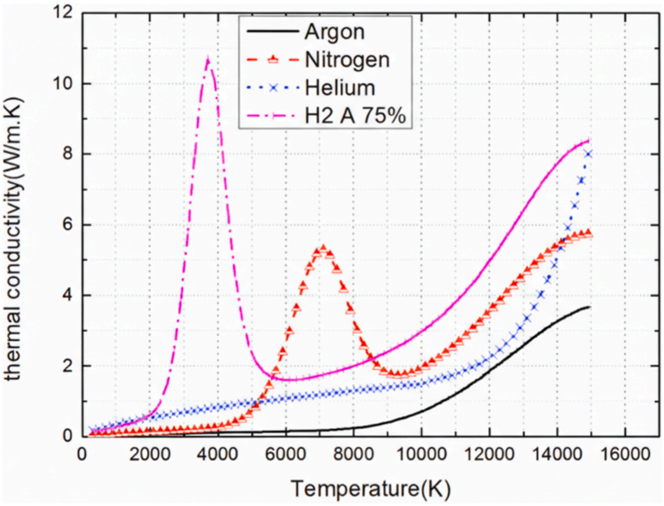


Fig. 11. Thermal conductivity of Ar, N_2, He and H_2-75% Air [39].

4.4. Theoretical thermodynamics benefits of H_2-APC

Although any monoatomic gas could theoretically serve as an ideal working fluid, Ar is chosen for the H_2-APC due to its relative abundance, affordability, and ability to create effective gas-tight seals [46]. Compared to air-breathing engines, Ar-based systems show remarkable improvements in thermal efficiency. Fig. 12 Illustrate theoretical thermal efficiency of ideal Otto cycles operating with Ar-O_2 and N_2-O_2 mixtures (Diesel cycle has a similar trend with Otto cycle but slightly lower theoretical thermal efficiency). The calculation based on the Eqs. (1) and (2) maps a function of compression ratio (CR) and O_2 molar fraction for (a) Ar-O_2 and (b) N_2-O_2 mixtures with thermal efficiency [47], as shown in Fig. 13. The exceptionally high theoretical thermal efficiencies for H_2-APC, exceeding 70% and reaching up to approximately 85% under idealized conditions, originate primarily from fundamental thermodynamic properties of the working fluid rather than from hydrogen chemistry alone. The dominant factor is the significantly higher specific heat ratio of monatomic Ar ($\gamma \approx 1.67$) compared to diatomic N_2 in air ($\gamma \approx 1.40$). In ideal Otto- and Diesel-type cycles, thermal efficiency increases monotonically with γ for a given CR, such that replacing N_2 with Ar intrinsically raises the upper efficiency limit. The reported efficiencies are obtained under idealized assumptions, including high compression ratios (typically CR ≈ 5-25), controlled O_2 molar fractions (approximately 10-30%) with the balance being inert

Table 2
Basic chemical and physical properties of H_2, Ar, He, N_2, CO_2 and O_2 [37].

Type of gas	Content in the air (vol%)	Boiling point at 1.013 bar (°C)	Atomic weight and mean molecular weight reps	Density at 15 °C, 1 bar (kg/m^3)	Relative density regarding the air (=1) at 15 °C, 1 bar	Chemical activity
Ar	0.934	−185.9	39.948	1.669	1.38	Inert
H_2	0.5×10^{-6a}	−252.9	2.016	0.085	0.06	Reducing
He	5.2×10^{-6a}	−268.9	4.002	0.167	0.14	Inert
N_2	78.084	−195.8	28.013	1.170	0.91	Reactive
CO_2	0.033^a	-78.5^b	44.011	1.849	1.44	Oxidizing
O_2	20.946	−183.0	31.998	1.337	1.04	Oxidizing

Note: a) It is not obtained from the atmosphere. b) Sublimation temperature.

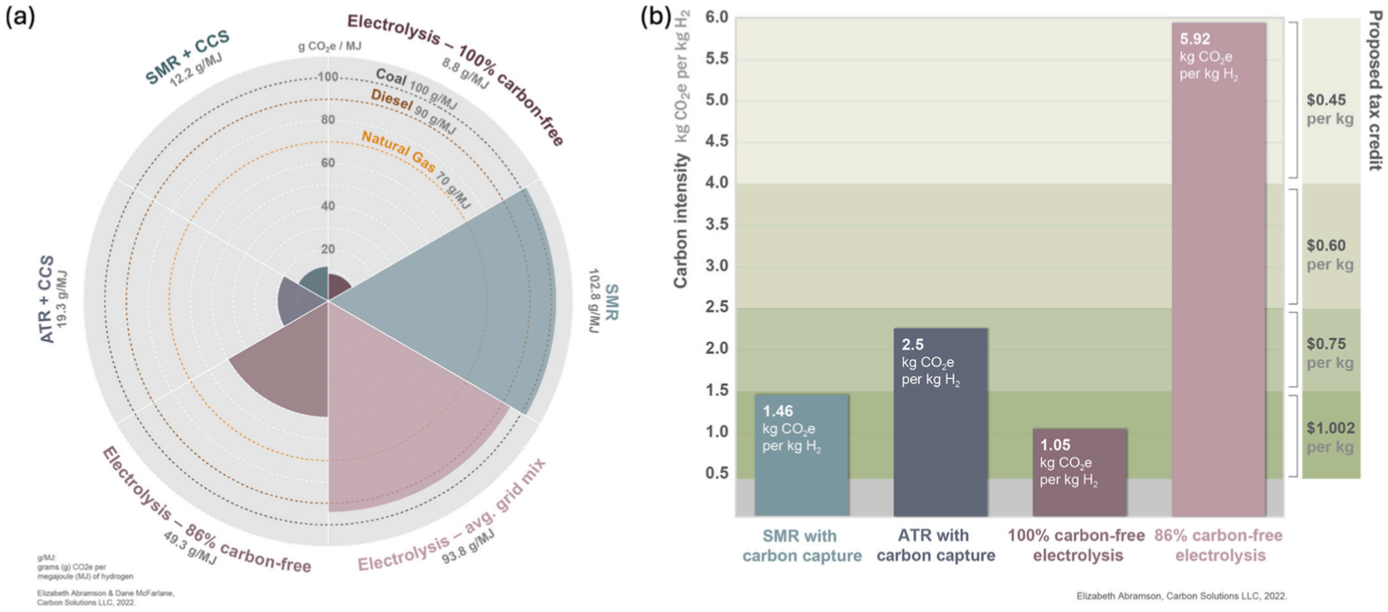


Fig. 12. (a) Average lifecycle carbon intensities of typical H_2 production methods, (b) Proposed tax credit values for typical ranges of H_2 lifecycle intensity [45].

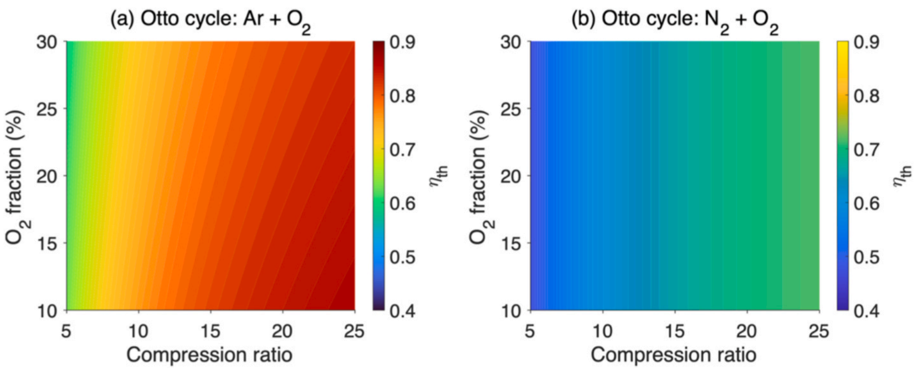


Fig. 13. Thermal efficiency of an Otto cycle for different working fluids, (a) Ar + O_2, (b) N_2+O_2.

diluent, complete combustion, ideal-gas behaviours, and the neglect of heat transfer, friction, and pumping losses. These values therefore represent thermodynamic upper bounds intended to benchmark the maximum potential of H_2-APC rather than directly achievable brake efficiencies in practical systems.

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}} \tag{1}$$

where r is the compression ratio and k is the specific heat ratio $c_p/\ c_v$

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right] \tag{2}$$

where r_c is the cutoff ratio, which corresponds the ratio of the cylinder volumes after and before the combustion process

5. Fundamentals of H_2-APC

The H_2-APC offers several advantages over traditional air-breathing combustion cycles, particularly in terms of efficiency, emissions reduction, and combustion stability. In this section, the comprehensive review for the fundamental studies on the H_2-APC will be discussed.

5.1. H_2-jet development in the Ar atmosphere

Prior to the combustion, the H_2 injection or the H_2-Ar-O_2 mixing strategies are crucial for the high-efficient and stable combustion. Previous studies on the conventional air breathing H_2 engine indicated that premixed H_2 potentially causes a high tendency of abnormal combustion, such as pre-ignition, knocking, backfire, etc [48]. Therefore, H_2 direct injection (H_2-DI) could offer an optimal solution for the H_2-APC [49]. Fig. 14(a) demonstrates the H_2-DI in Ar environment with high-speed schlieren. Mansor et al. [50] and Peters et al. [51] experimentally investigated the H_2-jet developments for different conditions of injection pressure, ambient pressure and nozzle diameter in Ar and N_2 atmospheres in a constant-volume vessel. The results indicated that the development of the H_2-jet in Ar is slower at the same ambient pressure than that in N_2 due to the higher density of Ar. As shown in Fig. 14(b), Diepstraten et al. [52] assessed the adequacy of the widely used software package CONVERGE employing RANS combined with a detailed chemistry combustion model by comparing simulation results of a turbulent, igniting planar H_2 jet with a direct numerical simulation. The results show that mass and momentum transport is predicted satisfactorily. Significant differences in temperature and species mass-fraction profiles between N_2 and Ar diluted cases arise because H_2 combustion operates predominantly in a high Damköhler number regime, where chemical time scales are much shorter than turbulent mixing time scales

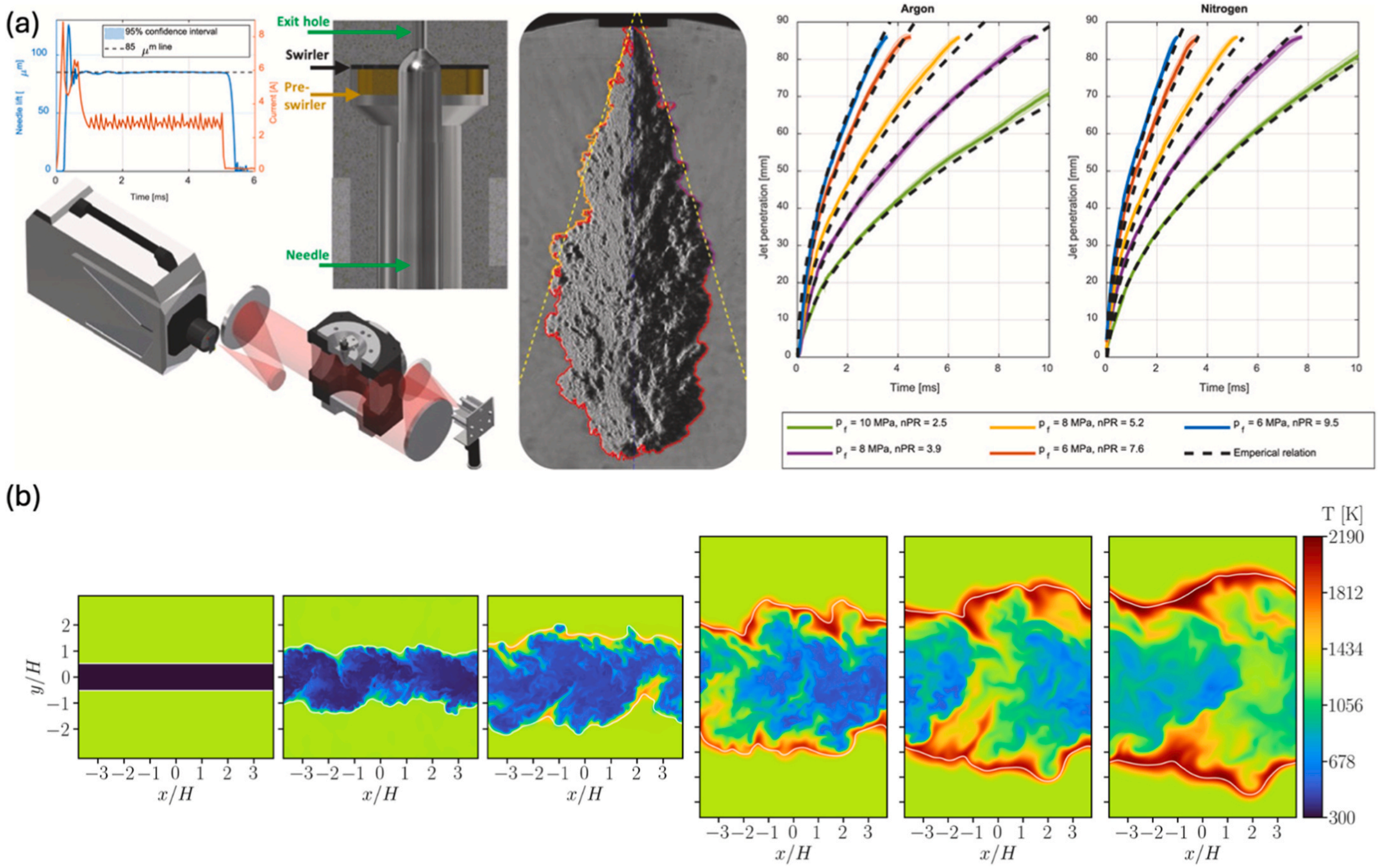


Fig. 14. Experimental and numerical studies on the H_2 jet in Ar atmosphere. (1) non-reactive H_2 jet with schlieren [50], (b) evolution of diffusion H_2 flame temperature with DNS simulation [52].

[53]. Under these conditions, reactions proceed rapidly once mixing occurs, and flame structure is governed primarily by intrinsic chemical kinetics and the thermophysical properties of the working fluid. For Ar diluted H_2-O_2 mixtures, the combination of fast H_2 oxidation kinetics and higher flame temperatures further increases the Damköhler number, reducing the sensitivity of local reaction rates to turbulence intensity. Consequently, temperature and major species profiles tend to exhibit laminar or quasi-laminar characteristics even in turbulent flows, with turbulence mainly affecting large-scale transport and flame wrinkling rather than local chemistry. The observed profile differences therefore reflect the dominance of fast kinetics and thermophysical effects, rather than a true absence of turbulence-chemistry interaction, particularly under engine-relevant high-pressure conditions.

5.2. H_2-Ar-O_2 combustion mechanisms

The H_2-Ar-O_2 combustion mechanism has been widely studied due to its application in achieving efficient and cleaner combustion systems. The following review provides a comprehensive exploration of advancements in the H_2-Ar-O_2 combustion mechanism and their implications for ignition, flame propagation, combustion stabilization, and pollutant formation.

The ignition delay time (IDT) of H_2 under Ar-diluted H_2-O_2 conditions is governed by the interplay between fast high-temperature chain-branching chemistry and pressure-dependent low-temperature radical pathways, with Ar influencing both thermodynamic and kinetic aspects of ignition [54]. Owing to its low molar heat capacity, Ar dilution leads to higher compressed-gas and post-compression temperatures compared to N_2-diluted mixtures at identical dilution ratios, which generally shortens IDT along engine-relevant compression trajectories. From a kinetic perspective, H_2 ignition is controlled by the competition between chain-branching reactions (e.g., $H + O_2 \rightarrow O + OH$) and chain-propagation/termination pathways involving HO_2 and H_2O_2, which importance increases with pressure. Under Ar-rich conditions, uncertainties in third-body efficiencies and pressure fall-off behaviour for reactions such as $H + O_2(+M) \rightleftharpoons HO_2(+M)$ and $H_2O_2(+M) \rightleftharpoons 2OH$ become particularly relevant, as Ar differs significantly from N_2 and H_2O in its collisional energy transfer characteristics [55]. As a result, Ar dilution accelerates ignition through thermal effects, predictive modelling of IDT remains sensitive to the treatment of pressure-dependent HO_2/H_2O_2 chemistry and bath-gas-specific third-body parameters, especially at the high pressures and temperatures characteristic of H_2-APC engines.

The combustion behaviour of H_2-based mixtures under Ar dilution is governed by complex kinetic interactions that are highly sensitive to pressure, equivalence ratio, and bath-gas composition. Burke et al. [56] focus on uncertainties in reaction rate parameters and kinetic model assumptions, identifying the significant influence of HO_2 formation and consumption under high-pressure, low-temperature conditions. They highlight the need for nonlinear bath-gas mixture rules to improve flame speed predictions. Gong et al. [57] emphasized the interplay between chain-branching and termination reactions in laminar flame velocity, with equivalence ratio impacting flame structure and reaction zones. Duynslaegher et al. [58] investigate NH_3-H_2-Ar flames, revealing that equivalence ratio strongly affects NO formation, while Levin and Zhuravskaya [59] explore Ar and ozone additions in H_2-air detonations to stabilize detonation waves and lower product temperatures. Yan et al. [60] differentiate fuel-borne N_2 pollutants from thermal NO_x, proposing reduction strategies tailored for clean engines. Pang et al. [61] refined reaction rates for key Ar-diluted reactions, offering better alignment with observed ignition delays.

Even though the above studies have explored the fundamental reaction mechanisms of H_2-Ar-O_2 combustion, accurate kinetic modelling of this system under engine-relevant conditions remains an open challenge, primarily due to uncertainties in pressure-dependent H_2 oxidation pathways and the scarcity of high-fidelity validation data at elevated pressures and temperatures. Additional uncertainties arise in chain-termination and branching balance at elevated pressures, as well as in transport properties and preferential-diffusion effects that strongly influence H_2 flame structure. While advanced numerical simulations, including DNS and CFD with detailed chemistry [62,63], have provided valuable insight into flame dynamics, ignition, and abnormal combustion tendencies in H_2-based systems, their validation has largely relied on fundamental configurations such as laminar flames, shock tubes, rapid compression machines, and constant-volume vessels, typically at pressures and turbulence levels lower than those encountered in operating H_2-APC engines. Direct validation against engine-relevant optical data covering high pressure, high dilution, strong turbulence-chemistry interaction, and transient compression-expansion trajectories remains limited. Consequently, further coordinated experimental campaigns combining high-fidelity optical diagnostics with engine-like conditions are required to robustly constrain kinetic models and to bridge the gap between fundamental simulations and practical H_2-APC operation.

5.3. H_2-Ar-O_2 combustion characteristics

The H_2-Ar-O_2 combustion characteristics have been fundamentally studied to reveal several insights into H_2-Ar-O_2 combustion characteristics, influencing thermal efficiency, flame speed, and emissions. Fig. 15 (a) presents the simulated and experimental laminar flame speeds for premixed H_2 flames under various diluents at ambient pressure and temperature. As shown, argon dilution leads to higher laminar burning velocities than N_2 or CO_2 at equivalent dilution fractions. This enhancement is primarily driven by thermodynamic effects: because argon has a lower molar heat capacity, a larger fraction of the released chemical energy contributes to increasing the flame temperature, resulting in a higher adiabatic flame temperature (T_{ad}). The elevated T_{ad} accelerates elementary reaction rates through their exponential temperature dependence, thereby increasing the laminar flame speed. However, the net effect on the laminar burning velocity (S_L) is not determined by flame temperature alone. It also depends on the degree of dilution and transport properties of the mixture, including thermal diffusivity and species diffusion, which can counteract the thermal acceleration at high dilution levels. Consequently, while Ar dilution generally enhances S_L at moderate dilution ratios, the balance between thermal and transport effects ultimately governs the observed flame speed trends. Other studies emphasized that replacing N_2 with Ar as a working fluid extends flammability limits, increases thermal efficiency due to its high specific heat ratio, and effectively eliminates NO_x emissions [64]. Wei et al. [65] investigated the impact of inert gas dilution on combustion in a confined space, showing that Ar, while less effective than CO_2, slows flame propagation and reduces pressure oscillations compared to N_2. Quan Reyes et al. [66] delved into the H_2-Ar-Cycle, emphasizing its ability to substantially enhance efficiency and eliminate emissions when used in H_2-O_2 systems. Their simulations revealed the critical role of preferential diffusion and turbulence on ignition dynamics and flame kernel development. Fig. 15(b) illustrates the IDT and subsequent flame development for H_2 jets in Ar-O_2 and air atmospheres [57]. In Ar-rich dilution, the IDT trends are governed by a complex interplay between thermodynamic and kinetic factors. Thermodynamically, the high specific heat ratio of argon ($\gamma = 1.67$) leads to a more rapid temperature rise during compression, which generally tends to shorten the IDT relative to N_2-diluted systems under similar engine trajectories. Kinetically, third-body effects at high pressure must be considered, as Ar acts as a weaker third body for certain termination reactions compared to N_2 or CO_2.

Moreover, exergy-based analyses could provide a powerful framework for quantifying the fundamental thermodynamic losses in H_2 flames and for assessing different diluents modify entropy generation and combustion efficiency. Fig. 16 illustrates the exergy losses in H_2 flames diluted with Ar, N_2, and CO_2, as investigated by Zhang et al. [67]. Their analysis decomposed the total exergy destruction into contributions from heat conduction, mass diffusion, chemical reactions, and incomplete combustion. The results showed that Ar dilution reduces exergy losses associated with conduction, diffusion, and chemical reactions, primarily because Ar's inert nature and low thermal diffusivity lead to lower entropy generation during combustion. However, the reduced heat capacity of Ar also lowers the flame temperature gradient and reaction rate, which can slightly increase incomplete combustion losses if the mixture is not properly optimized. These findings are particularly relevant for the H_2-APC), where Ar acts as the primary working fluid rather than just a diluent. Similarly, Durocher et al. [68] investigated H_2-air flames with varying Ar dilution ratios, emphasizing the need for improved kinetic models to better predict reaction rates and radical behaviour under Ar-rich, low-NO_x conditions. Together, these studies provide valuable insights for designing and optimizing H_2-Ar combustion systems, ensuring that efficiency gains from Ar dilution are not offset by incomplete reaction losses or kinetic limitations.

The above studies explicits that H_2-fueled engines operating under Ar-diluted combustion conditions exhibit combustion characteristics

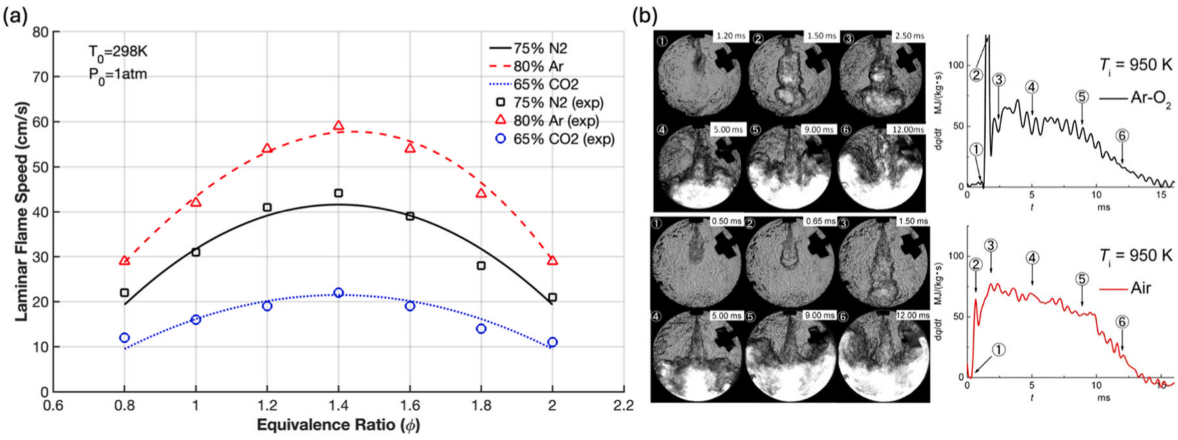


Fig. 15. Comparison of the flame characteristics of H_2 combustion under Ar-O_2 and air atmospheres, (a) simulated and experimental laminar flame speeds of premixed H2 flames with N_2, Ar and CO_2 as diluents. (P0 = 1 atm, T0 = 298 K). (b) Flame development and combustion process under Ar-O_2 and air atmospheres ($r_{O_2} = 21\%$, $p_i = 4$ MPa, $p_j = 8$ MPa, $d_N = 0.8$ mm, and $T_i = 950$ K).

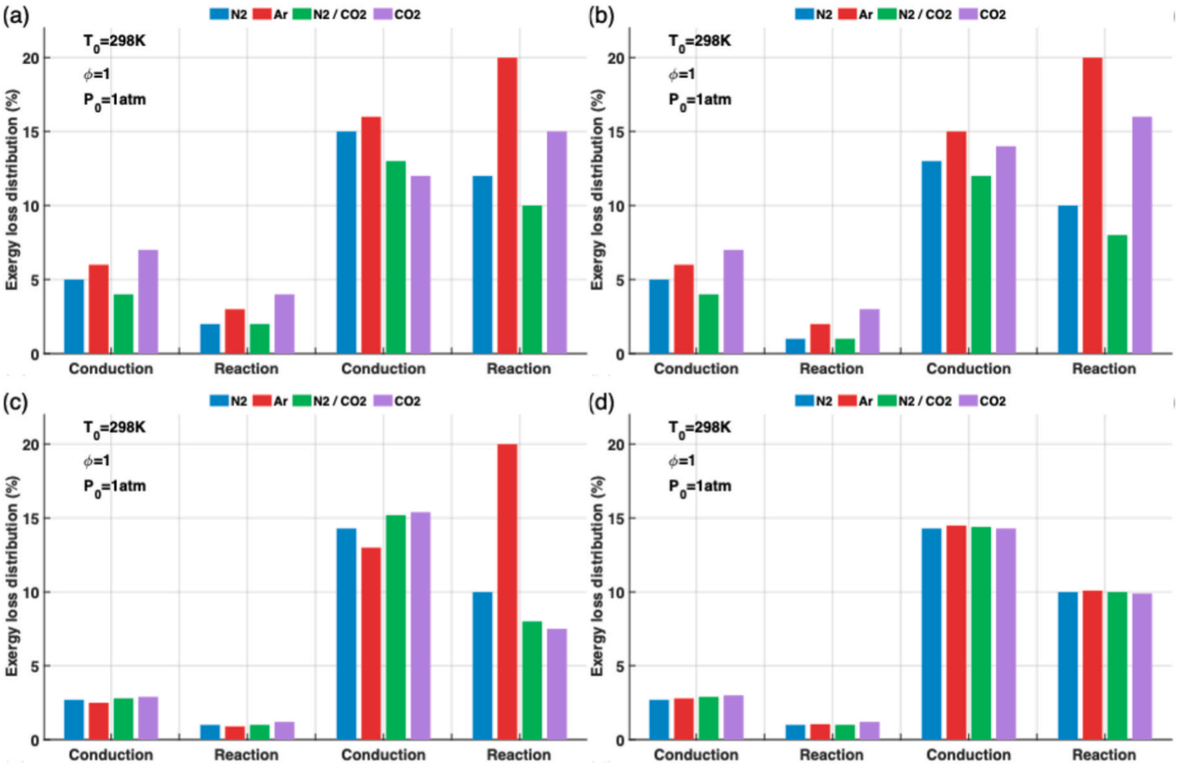


Fig. 16. Premixed H_2 flames with N_2, Ar, N_2/CO_2 and CO_2 as diluents. ($P_0 = 1$ atm, $T_0 = 298$ K, $\varphi = 1.0$). (a) Exergy loss from each source, (b) Chemical effects of N_2, Ar, N_2/CO_2 and CO_2 on exergy losses distribution, (c) Thermal effects of N_2, Ar, N_2/CO_2 and CO_2 on exergy losses distribution, (d) Exergy loss from each source in the premixed H_2 flames under the transport effects of N_2, Ar, N_2/CO_2 and CO_2 [67].

that differ fundamentally from those of conventional N_2- or CO_2-diluted systems. These differences arise from the combined effects of thermodynamic properties, which alongside transport properties and intrinsically fast chemical kinetics of H_2. As a result, abnormal combustion phenomena, such as pre-ignition and knock, constitute a key challenge for H_2-APC engines, particularly at high CR. Table 3 summarizes the qualitative comparison of combustion characteristics and abnormal-combustion propensity for H_2-O_2 mixtures diluted with Ar, N_2, and CO_2. It is concluded that H_2-O_2-Ar mixtures offer a higher theoretical efficiency potential, reaching optimal indicated thermal efficiencies as high as 70%, but operate within a narrower combustion-stability window than N_2- or CO_2-diluted systems. This trade-off necessitates advanced combustion control strategies to exploit the thermodynamic advantages of Ar while mitigating the risks of abnormal combustion.

Table 3
Qualitative comparison of combustion characteristics and abnormal-combustion propensity for H_2-O_2 mixtures diluted with Ar, N_2, and CO_2.

Diluent	Flame temperature & flame speed	Ignition delay (engine trajectory)	Knock/pre-ignition propensity	Dominant exergy-loss tendency
Ar	Highest flame temperature; fastest flame development	Shorter effective IDT due to higher compressed-gas temperature	**High** if phasing is not controlled	Lower exhaust exergy in ideal cycles; risk of increased irreversibility during abnormal combustion
N_2	Intermediate flame temperature and flame speed	Intermediate IDT	Moderate; broader stability margin than Ar	Balanced exergy partitioning; NO_x formation constraint
CO_2	Lowest flame temperature; strongest flame-speed suppression	Longest IDT; strong autoignition suppression	Low	Higher dilution penalties; increased exhaust/combustion irreversibility for given work output

5.4. Flame stability and combustion emission control

The use of Ar in combustion processes plays a crucial role in enhancing flame stability and enabling more controlled combustion. This section explores advancements in the use of Ar-diluted H_2 combustion systems, highlighting the potential to enhance efficiency and control flexibility.

Levin et al. [59,69] investigated the addition of Ar and ozone to H_2-air mixtures, demonstrating that this approach effectively reduces wave velocity and detonation product temperatures without increasing detonation cell size, thus stabilizing detonation waves under channel disturbances. Mansor et al. [70] studied heat loss mechanisms in Ar-compressed systems, finding that higher ambient pressures increase heat flux, particularly near combustion chamber walls. These insights provide valuable data for mitigating energy losses in Ar-circulated H_2 engines. Radulescu et al. [71] highlighted the stabilizing role of Ar in detonation dynamics by examining its influence on reaction-zone structure and pressure-wave behaviour, showing that Ar dilution reduces temperature sensitivity and enhances detonation stability. Although the investigated system involved acetylene-oxygen mixtures, the observed effects such as changes in detonation cell size, stability limits, and pressure-wave dynamics were governed primarily by the thermodynamic and gas-dynamic properties of Ar, including its low heat capacity and influence on sound speed, rather than by fuel-specific chemical pathways. These same physical mechanisms apply to H_2-O_2 systems, where Ar dilution similarly modifies energy release rates, wave propagation characteristics, and thermodynamic stiffness. Jin et al. [72]

expanded on these findings by demonstrating that high Ar dilution ratios extend flammability limits and reduce flame-initiation periods, making ultra-lean combustion feasible for spark-ignition engines.

Regarding the combustion emission control, Rangrazi et al. [73] compared N_2 and Ar dilution effects on NO_x emissions, revealing that Ar is more effective at reducing NO_x, while N_2 dilution promotes more complete combustion. Tao et al. [74] further quantified NO_x suppression, showing that Ar dilution reduces flame length and offers specific benefits for NO_x emissions and thermoacoustic instability control.

In conclusion, the unique thermal properties and dilution effects of Ar offers transformative benefits for H_2 combustion, paving the way for efficient, stable, and low-emission power systems across various applications. Replacing N_2 with Ar completely eliminates NO_x emissions, one of the primary pollutants from ICE. This breakthrough allows for cleaner combustion without the complex aftertreatment systems like selective catalytic reduction (SCR). The potential environmental benefits include improved air quality and reduced health risks from N_2-based pollutants.

6. Availability of H_2-APC engines studies

This section provides a comprehensive review of concrete studies on H_2-APC engine, including both numerical and experimental investigations, along with an analysis of the challenges identified in previous studies.

6.1. Numerical studies

Numerical simulations have been pivotal in advancing the understanding and optimization of the H_2-APC for high-efficiency and zero-emission ICE. Jin et al. [75] explored anti-knocking strategies for the H_2-APC, demonstrating that increased Ar dilution (up to 95%) significantly extends IDTs and enhances thermal efficiency. By employing ultra-lean combustion and water injection, knocking was mitigated while maintaining efficiency levels as high as 70%. Pang et al. [61] further confirmed the effectiveness of in-cylinder water injection for knock suppression, optimizing injection timing and mass to achieve a balance between knock control and power performance. Xie et al. [76] investigated the flammability limits and ignition behaviour of H_2 in Ar-O_2 atmospheres. CR greater than 12.5 enabled autoignition, with optimal performance achieved at specific Ar dilution ratios and O_2 levels. The study highlighted the role of advanced ignition timing and excess oxygen in achieving high thermal efficiencies of up to 55%. Ding et al. [77] and Hafiz et al. [78,79] examined the impact of H_2-DI and CR on combustion dynamics with CFD simulation. The results indicated that H_2-DI strategy is possible to postpone heat release (CA50), suppress knocking, and improve efficiency by creating stratified mixtures. Increasing CR enhanced in-cylinder pressure, but necessitated strategies to manage heat release rates effectively. Studies by Quan Reyes et al. [66] and Zhou et al. [80] emphasized the importance of numerical models, such as Reynolds-averaged Navier-Stokes (RANS), for predicting turbulent combustion and emissions. These models demonstrated the ability of Ar to increase thermal efficiency and reduce emissions, with H_2-APC engine showing potential for gross indicated efficiencies exceeding 50%. Numerical studies have been essential for advancing H_2-APC research by revealing the mechanisms governing knock suppression, ignition control, flame dynamics, and efficiency enhancement under Ar-diluted conditions. These numerical investigations will bridge theoretical efficiency limits with practical engine design strategies, providing critical guidance for the development of stable, zero-emission H_2-APC engines. However, a unified framework that couples validated chemical kinetics, turbulence-chemistry interaction, and system-level optimization under engine-relevant conditions remains lacking, limiting predictive design of high-efficiency H_2-APC engines.

6.2. Experimental studies

Experimental investigations have highlighted several key aspects of its operation, challenges, and potential improvements. Cui et al. [81] demonstrated that H_2 exhibits a pronounced knock tendency, requiring advanced anti-knock strategies such as ultra-lean combustion, water injection, or fuel replacement. The results showed that water injection at optimal timings during the exhaust stroke reduced knock intensity, allowing higher compression ratios and maintaining thermal efficiency near 53.5%. Wang et al. [82] observed efficiency improvements of up to 53.1%, attributed to higher thermal conversion efficiency and faster combustion. The effects of H_2-DI injection were found to extend the operational boundary and improve combustion control. Experimental studies reveal that Ar dilution significantly affects ignition behaviour. High Ar concentrations increase IDTs and flame-initiation periods, as demonstrated by Jin et al. [83–85]. These effects can be mitigated by optimizing injection timing and excess O_2 ratios, enabling stable operation even under ultra-lean conditions. More recently, Wang et al. [86] demonstrated both theoretically and experimentally for a H_2-APC engine, which achieved a net indicated thermal efficiency (nITE) exceeding 70%, significantly surpassing conventional H_2-air engines. By combining high Ar dilution ($\chi_{Ar} \approx 85\%$), ultra-lean combustion, high intake pressure, H_2-DI injection, and port water injection for knock suppression, the authors achieved a peak nITE of 70.2%. Water injection has been proven effective in suppressing knock [87]. While H_2-APC engines can achieve zero CO_2 and NO_x emissions, methane-fueled APC concepts require integrated carbon-capture systems to approach net-zero operation. Sierra Aznar et al. [12,87] demonstrated the potential of integrating carbon capture with APC technology for zero-emission operation. The previous experimental studies have established the feasibility of ultra-high-efficiency, zero-emission H_2-APC operation, nevertheless, identifying critical pathways for further advancement, highlighting the need for fundamental investigations of H_2 jet dynamics, ignition and flame development under Ar-diluted conditions, together with system-level optimization of injection strategies, ignition concepts, and combustion modes to fully exploit the potential of H_2-APC engines.

6.3. Challenges of H_2-APC engine

The main challenge of the H_2-APC engines is from the abnormal combustion of H_2, which has been well explored in the conventional H_2 engines [88]. Fig. 17 illustrates pre-ignition characterized by spontaneous combustion and pronounced pressure oscillations in an optical engine. Pre-ignition happens before the spark ignition even at $\lambda = 4$, which induces strong pressure oscillations due to the spontaneous combustion or knocking [88]. This observation is consistent with previous studies investigating knock phenomena in H_2-O_2-Ar mixtures and comparing their behavior with conventional air-gasoline mixtures in variable compression ratio engines [89]. The results indicate that Ar dilution significantly alters the stability, amplitude, and frequency of knock-induced pressure oscillations, thereby improving combustion controllability at elevated pressures. To explore effective approaches for mitigating abnormal combustion and to evaluate the potential for achieving stable H_2 combustion with significant thermal-efficiency improvement under an Ar-O_2 atmosphere, the feasibility of a high-efficiency, zero-emission, Ar-circulated H_2 engine for automotive applications has been investigated [90,91]. The results indicate that H_2 led to more pronounced knocking compared to CH_4, preventing stable operation at excess O_2 ratios <2.1 and compression ratio 9.6.

Recent H_2-APC studies conducted in an optical engine at Aalto University reveal a distinct pre-ignition behaviour that differs fundamentally from conventional H_2-air combustion [92]. The H_2-APC exhibits a distinct pre-ignition behavior that differs fundamentally from conventional hydrogen-air combustion. As shown in Fig. 18, the upper image sequence for H_2-APC at $\lambda = 4$ exhibits spatially extended

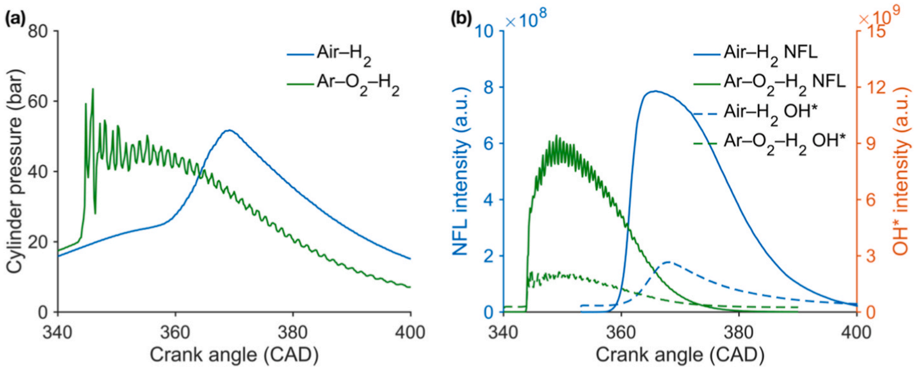


Fig. 17. Comparison of the cylinder pressure and integrated natural flame luminosity of premixed combustion of H_2-APC at ultra-lean conditions (λ = 4) and conventional H2-air combustion at lean condition (λ = 1.4).

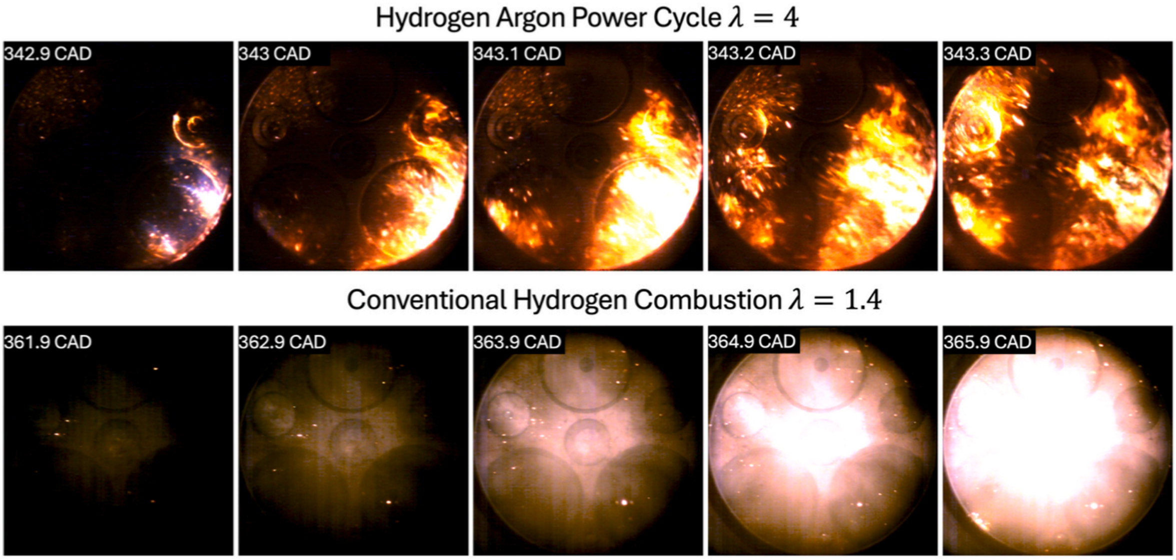


Fig. 18. Comparison of the natural flame luminosity of premixed combustion of H_2-APC at ultra-lean conditions (upper row: $\lambda = 4$) and conventional H_2-air combustion at lean condition (lower row: $\lambda = 1.4$).

luminous structures at 342.9-343.1 CAD (the start of the spark is at 350 CAD), indicating the onset of early chemical activity prior to spark ignition. This pre-ignition behaviour is promoted by the thermophysical properties of Ar dilution. The high specific heat ratio and low molar heat capacity of Ar lead to elevated auto-ignition temperatures during compression, while its low thermal conductivity reduces heat losses to the chamber walls [92]. As a result, localized regions, particularly near hot surfaces or residual gas pockets reach auto-ignition-relevant temperatures earlier in the cycle, even under ultra-lean conditions. In contrast, the lower sequence corresponding to conventional H_2-air combustion (λ = 1.4) shows normal combustion with regular flame propagation.

6.4. *Engine design modifications*

Implementing the H_2-APC requires substantial modifications to traditional engine designs, including adjustments to fuel injection systems, compression ratios, ignition timing, and additional subsystems like water injection for performance optimization and knock prevention. Beyond these modifications, developing compatible components for large-scale deployment, such as Ar recycling systems, remains a significant technical challenge.

For fuel injection systems, Ding et al. [10,77] and Sierra Aznar et al. [87] comprehensively compared port and direct H_2 injection strategies. Their results demonstrated that optimizing the timing of direct H_2 injection and incorporating ultra-lean combustion achieved a maximum gross indicated thermal efficiency of 53.72%. Split H_2 direct injection, which involves fine-tuning the first and second injection timings and ratios, significantly suppressed knock and further enhanced thermal efficiency compared to single H_2 injection strategies. Complementarily, Kim et al. [93] highlighted the potential of pre-chamber (PC) combustion, which accelerates combustion rates by creating multiple turbulent hot jets, promoting uniform and timely combustion in the main chamber while reducing knock tendencies. Deng et al. [49] also provided critical insights into optimizing H_2 injection strategies under Ar-diluted conditions.

Water injection has emerged as a promising approach for knock suppression. Jin et al. [84,85] demonstrated that water injection effectively controls knock in H_2-APC engines with minimal impact on efficiency. Tang et al. [7] showed that port water injection reduces knock intensity and optimizes combustion; however, excessive water injection negatively affects combustion and leads to thermal efficiency losses. Wang et al. [90] numerically investigated high-temperature direct water injection (DWI) in H_2-Ar-O_2 premixed combustion relevant to H_2-APC, focusing on spray evaporation, atomization, and flame-spray interaction under post-combustion conditions. These results highlight the critical role of water injection strategy and spray morphology in achieving effective knock suppression without compromising flame propagation and efficiency in H_2-APC engines. Additionally, water produced during combustion can be reused for injection, requiring only a small storage buffer.

Wang et al. [17] proposed a next-generation Ar/Miller power cycle engine design achieving an indicated thermal efficiency of 58.6% through a compression ratio of 11, an expansion-compression ratio of 1.5, and an Ar dilution ratio of 91%. Operating such an engine with an Ar-O_2 mixture in a spark-assisted compression ignition mode improves efficiency by up to 50% compared to air-based spark-ignited cycles while nearly eliminating NO_x emissions. These advancements collectively prove the potential and technical feasibility of the H_2-APC engine.

6.5. Summary of combustion control strategies for H_2-APC engines

Table 4 identifies combustion-control strategies for high-compression-ratio H_2-APC engines form an integrated framework for suppressing abnormal combustion while preserving the thermodynamic advantages of Ar dilution. Direct thermal management approaches, most notably water or steam injection [7,61,86], mitigate pre-ignition and knock by increasing the effective heat capacity of the charge and reducing end-gas temperatures during the critical late-compression period. Complementary mixture-formation and ignition strategies, including stratified H_2 direct injection and pre-chamber ignition [49,62,77,79] enable stable and repeatable combustion under ultra-lean global conditions by decoupling flame initiation from bulk mixture reactivity. In particular, pre-chamber ignition systems generate high-energy turbulent jet flames rich in active radicals [93,94], which promote rapid and spatially distributed ignition in highly diluted mixtures. This mechanism is especially advantageous for H_2-APC operation, where elevated specific heat ratios and high dilution levels can otherwise hinder reliable ignition and increase cycle-to-cycle variability.

Table 4

Summary of combustion control strategies for H_2-APC engines.

Strategy	Mechanism	Key Implementation & Best Practice	Availability & H_2-APC Fit
Water Injection	Increases effective heat capacity (C_p); reduces end-gas temperature to suppress autoignition and knock.	Late compression or near-TDC injection. Target hot-spots (valves, crevices) rather than uniform port addition.	Since steam is an exhaust byproduct, H_2O management is natively compatible with the closed-loop APC concept.
Stratified Charge	Maintains a lean, low-reactivity end-gas while providing a locally ignitable mixture near the spark.	Late-cycle direct injection (DI) with multiple pulses; wall-avoiding targeting to prevent oil-induced pre-ignition.	Standard in modern high-performance H_2 engines; essential for managing Ar-cycle reactivity.
Pre-chamber Ignition	Provides high-energy jets to enable stable ignition of ultra-lean global mixtures.	Use of active or passive pre-chambers to achieve fast, controllable burn rates at high dilution.	Specifically fits H_2-APC by supporting high γ operation without sacrificing stability at $\lambda > 2$.
Effective CR Management (Miller Cycle)	Lowers effective compression temperature via early/late valve closing while keeping high expansion ratios.	Variable Valve Timing (VVT) and boosting systems to decouple compression from expansion.	A key "efficiency-without-knock" pathway already common in high-CR engine concepts.
Thermal & Hardware Controls	Eliminates physical triggers for pre-ignition (hot spots, deposits, oil droplets).	Intake temperature control, specialized coatings, and optimized crevice/material designs.	Fundamental hardware adjustments independent of the specific working fluid.
Closed-loop Control Systems	Provides real-time feedback and adjustment of ignition, DI timing, and dilution levels.	Fast-response knock sensing and ECU-integrated phasing control.	Crucial for H_2-APC due to its narrow stability margin; leverages existing sensor technologies.

In addition to combustion phasing control, thermal and hardware-oriented strategies play a critical role in suppressing abnormal combustion triggers [50,91]. Surface-induced pre-ignition, often initiated by hot spots, deposits, or lubricating oil droplets, becomes increasingly significant in hydrogen engines operating at high temperature and pressure. Mitigation approaches include advanced thermal management of intake air and engine components, application of low-reactivity coatings, and optimized combustion chamber and crevice design to minimize local temperature gradients and prevent unintended ignition sites. These hardware-level interventions are particularly important in H_2-APC systems, where high reactivity and rapid heat release amplify sensitivity to localized thermal inhomogeneities.At the system level, effective compression-ratio control through Miller-type valve strategies [6,17,80,94] together with fast closed-loop regulation of ignition timing [20,48] fueling, and dilution, is essential for operating within the narrow stability margin imposed by the high specific heat ratio of argon-rich working fluids. Collectively, these measures address the fundamental thermal, kinetic, and phasing challenges of H_2-APC, thereby enabling practical zero-emission power cycles that approach ultra-high theoretical efficiencies while maintaining knock-free operation.

7. Future directions

7.1. Ar recycling and cost reduction

A closed-loop Ar cycle is central to both the sustainability and economic viability of H_2-APC systems; however, its practical implementation poses several non-trivial engineering challenges. The primary technical hurdles in designing an effective Ar recycling system arise from the complex composition of the engine exhaust, which consists predominantly of water vapor from H_2 combustion, residual unburned gases, and trace contaminants originating from lubricant oil decomposition, including hydrocarbons and particulates. Efficient Ar recovery therefore requires not only high separation selectivity but also robust tolerance to moisture and contaminants, as well as minimal parasitic energy consumption [48].

From a system-design perspective, the first critical step in Ar recycling is water management. Given the high water content of H_2 combustion exhaust, condensation-based separation is an essential pre-treatment stage to remove water vapor and reduce downstream separation load. Following dehydration, further purification is required to eliminate trace hydrocarbons, CO_2, and particulate matter associated with lubricated engine operation, all of which can degrade separation performance and long-term system reliability.

Among the available gas separation technologies, membrane separation, pressure swing adsorption (PSA), and cryogenic distillation have emerged as the most relevant options, each with distinct advantages and limitations. Polymeric membrane separation is particularly attractive due to its modularity, relatively low capital cost, and compatibility with continuous engine operation. Chourou et al. [46] developed a one-dimensional model for hollow-fiber membrane gas separation and demonstrated that membrane-based systems can be cost-effectively integrated with large internal combustion engines, especially in applications coupled to intermittent renewable energy sources. While membranes generally exhibit moderate selectivity for noble gases and may require multi-stage configurations, their low energy penalty and scalability make them promising candidates for Ar recycling in H_2-APC engines. Pressure swing adsorption (PSA) represents another viable approach for Ar recovery, exploiting differences in adsorption affinity under cyclic pressure variations [95]. PSA systems can achieve relatively high Ar purity and are commercially mature; however, their performance is sensitive to moisture and trace contaminants, necessitating effective upstream gas conditioning. In addition, the cyclic compression and regeneration steps introduce non-negligible energy penalties, which must be carefully balanced against the overall cycle efficiency gains. Membrane separation technology [96] offers a modular and energy-efficient alternative for argon recovery, particularly suited to decentralized or engine-integrated applications, although its separation purity is typically lower than that of cryogenic distillation [97] and depends strongly on membrane selectivity and operating conditions. From an environmental perspective, reliance on cryogenic separation can offset some of the greenhouse gas benefits of zero-carbon combustion if the required energy is supplied from fossil-based sources. Consequently, cryogenic methods are more suitable for centralized Ar production rather than on-board or near-engine recycling.

Overall, the feasibility of a closed-loop Ar cycle depends on the development of integrated separation architectures that combine water condensation, contaminant removal, and Ar recovery with minimal energy and material penalties. As illustrated in Fig. 19, closed-loop recycling concepts, particularly those based on membrane or hybrid membrane-PSA systems offer a promising pathway to reduce Ar consumption, lower operating costs, and minimize environmental impact. Advancing such technologies is therefore a critical enabler for translating the high theoretical efficiency of H_2-APC engines into practical, large-scale zero-emission power systems.

From an economic perspective, the viability of H_2-APC systems with closed-loop Ar recycling is governed by the balance between capital expenditure (CAPEX) [98] associated with Ar separation and recycling infrastructure and operational expenditure (OPEX) [99] linked to energy consumption for separation, compression, and auxiliary systems. At small scales, CAPEX dominates due to the cost of separation units, compressors, and heat exchangers; however, at larger deployment scales, these fixed costs can be amortized over higher energy throughput, significantly reducing the effective Ar cost per unit of electricity produced. In long-duration operation, OPEX becomes increasingly important and is primarily driven by the energy penalty of Ar purification and oxygen production [100]. Integration with low-cost renewable electricity can therefore substantially lower lifecycle costs, particularly in smart-grid and combined heat and power (CHP) applications. Continued advances in membrane- and PSA-based separation technologies are expected to reduce both CAPEX (through modularization and compact design) and OPEX (through improved selectivity and lower pressure requirements), while unresolved challenges related to high-purity argon recovery from moisture- and contaminant-rich exhaust streams remain a key research need [101]. Table 4 summarizes the dominant cost drivers and performance trade-offs of candidate argon recovery technologies for engine-integrated H_2-APC systems. Table 5 summarizes the principal Ar recovery and purification technologies applicable to closed-loop H_2-APC systems, highlighting their separation performance, energy penalty, and suitability for engine-integrated implementation.

7.2. Advanced combustion control

Beyond isolated thermodynamic or combustion effects, the performance of H_2-APC systems is governed by a balance between efficiency enhancement, combustion stability, and system complexity. The competing effects indicate that optimal H_2-APC operation is inherently application-dependent, requiring integrated optimization across combustion processes, thermodynamic cycle design, and balance-of-plant considerations. From a system perspective, the value of the H_2-APC concept lies not in maximizing a single metric, such as peak temperature or theoretical efficiency but in enabling controllable, high-efficiency operation within practical engine and infrastructure constraints.

At the combustion-system level, advanced control strategies play a central role in reconciling high efficiency with stable operation. Ar dilution contributes to knock mitigation by moderating reaction rates and reducing peak combustion temperatures, thereby enabling the use of higher compression ratios and supporting improved thermal efficiency [86]. Injection strategy plays a crucial role among all the combustion control strategies. Fig. 20 schematically summarizes four representative injection configurations, illustrating how injection timing and spatial separation of reactants can be tailored to address the competing requirements of efficiency, knock resistance, and combustion stability in H_2-APC engines. In Fig. 20(a), simultaneous PFI of H_2 and O_2

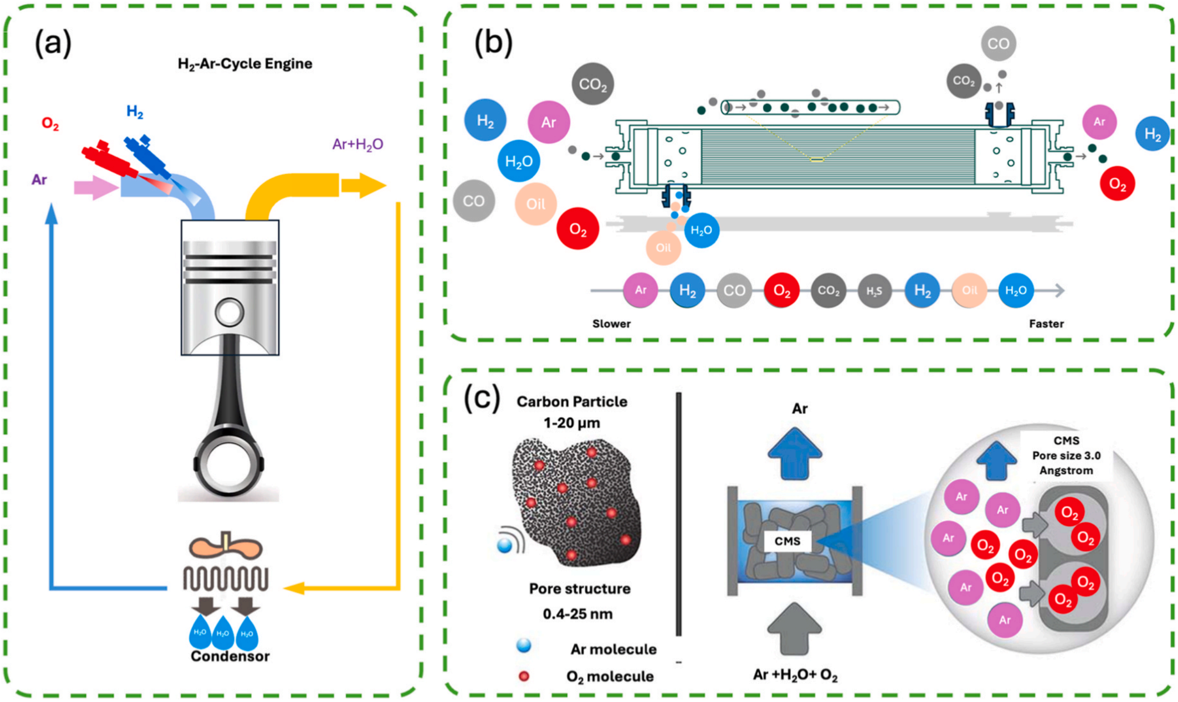


Fig. 19. Ar recycling strategies. (a) closed-loop systems, (b) membrane separation technology, (c) PSA.

Table 5
Ar recovery and purification options for closed-loop H_2-APC systems.

Technology	Principle	Typical Ar purity	Energy penalty	Key advantages	Key limitations	Suitability
Condensation	Water vapor is condensed from exhaust	Low-moderate (pre-treatment step)	Very low	Essential first step for H_2 exhaust; simple and robust; removes dominant H_2O fraction	Does not separate Ar from other dry gases; requires downstream separation	**Mandatory pre-treatment**
Membrane separation (polymeric/hollow fiber)	Selective permeation based on gas diffusivity and solubility	Moderate (single stage); high (multi-stage)	Low	Modular, compact, continuous operation; low CAPEX; scalable; compatible with ICE integration	Limited single-stage selectivity for noble gases; sensitive to contaminants; may require multi-stage design	**Highly promising**
Pressure Swing Adsorption (PSA)	Cyclic adsorption/desorption under varying pressure	Moderate-high	Moderate	Commercially mature; capable of relatively high purity	Sensitive to moisture and oil vapors; cyclic compression increases parasitic losses	**Viable**, but requires careful exhaust conditioning
Hybrid membrane-PSA systems	Membrane pre-concentration followed by PSA polishing	High	Moderate	Combines low-energy pre-separation with high final purity; flexible design	Increased system complexity; higher CAPEX	**Very promising** for high-purity, closed-loop APC systems
Cryogenic distillation	Phase separation via compression and refrigeration	Very high (>99.9%)	High	Highest purity; industrially proven at large scale	High energy demand; large footprint; unsuitable for decentralized/on-board use	**Poor** for engine-level recycling; suitable for centralized Ar production

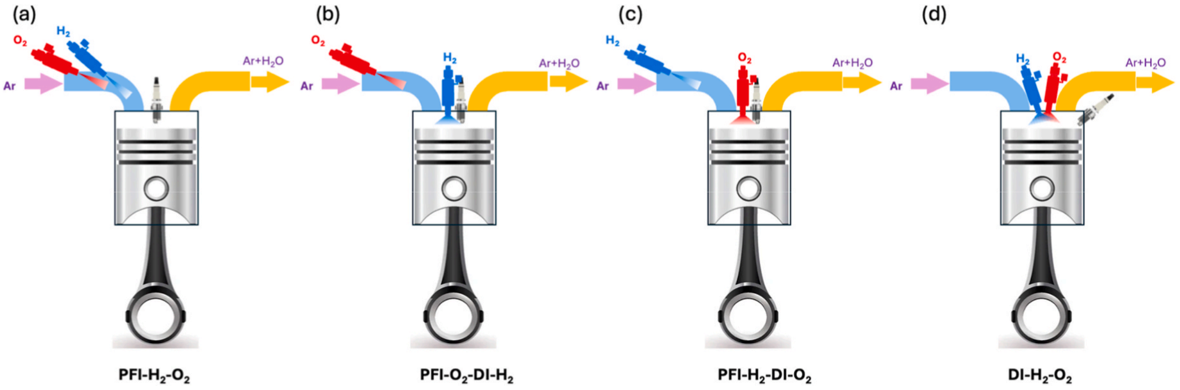


Fig. 20. Gas mixing strategies of H_2-APC(a) PFI-H_2-O_2, (b) PFI- O_2-DI- H_2, (c) PFI-H_2-DI-O_2, (d) DI-H_2-O_2.

promotes a largely premixed charge, which offers easy control and low-cost system but remains susceptible to abnormal combustion at high compression ratios. Fig. 20(b) introduces direct injection of H_2 (DI- H_2) combined with port-injected O_2 (PFI-O_2), enabling stratification mixtures. This configuration improves knock resistance by limiting end-gas reactivity and allows flexible control of ignition timing. Conversely, Fig. 20(c) employs direct injection of O_2 (DI-O_2) with port-injected H_2 (PFI-H_2), offering additional leverage over local equivalence ratio and O_2 availability, which can be advantageous for stabilizing ignition under ultra-lean or highly diluted conditions. Fig. 20(d) illustrates full DI of both H_2 and O_2, providing the highest degree of spatial and temporal control over mixture stratification. This approach enables targeted mixing near the ignition source, reduced wall heat losses, and minimized pre-ignition risk, albeit at the cost of increased injector and control complexity.

The above injection strategies can be further enhanced by advanced ignition concepts, such as pre-chamber ignition [93,94] or low-temperature plasma ignition [102], which introduce highly reactive radicals or jet flames to reliably initiate combustion in dilute, high-pressure environments. When combined with Ar dilution, such integrated injection-ignition strategies extend stable operating limits, mitigate knocking tendencies, and allow operation at higher CR.

Furthermore, as illustrated in Fig. 21, the complexity and flexibility introduced by advanced injection and ignition strategies (Fig. 20) naturally motivate the adoption of advanced combustion control frameworks, particularly those based on machine learning (ML) [103]. The multiple degrees of freedom enabled by combined PFI/DI of H_2 and O_2, variable Ar dilution levels, and novel ignition concepts create a high-dimensional control space that is difficult to optimize using conventional rule-based or map-based control approaches. ML algorithms provide a powerful means to exploit this flexibility by learning nonlinear relationships between operating conditions, control inputs, and combustion outcomes.

By integrating ML-based controllers into the H_2-APC system, real-time optimization of key combustion parameters, such as ignition timing, pressure-rise rate, local equivalence ratio, injection timing and sequencing, and dilution level can be achieved across a wide range of loads and transient conditions. This data-driven approach enables adaptive control of mixture stratification and combustion phasing, allowing the engine to operate close to optimal efficiency limits while actively suppressing abnormal combustion phenomena such as knock or pre-ignition. In Ar-diluted H_2 combustion, where small deviations in temperature or reactivity can rapidly shift the stability margin, ML-based control is particularly valuable for maintaining robust operation. Moreover, coupling ML algorithms with high-fidelity sensing (e.g., in-cylinder pressure, optical diagnostics, fast exhaust measurements) enables continuous self-optimization of the combustion process in response to fuel variability, ambient conditions, and system aging.

7.3. Scale-up and commercialization

The scale-up and commercialization of the H_2-APC concept require an integrated development pathway that couples advances in engine technology with fuel supply infrastructure and system-level

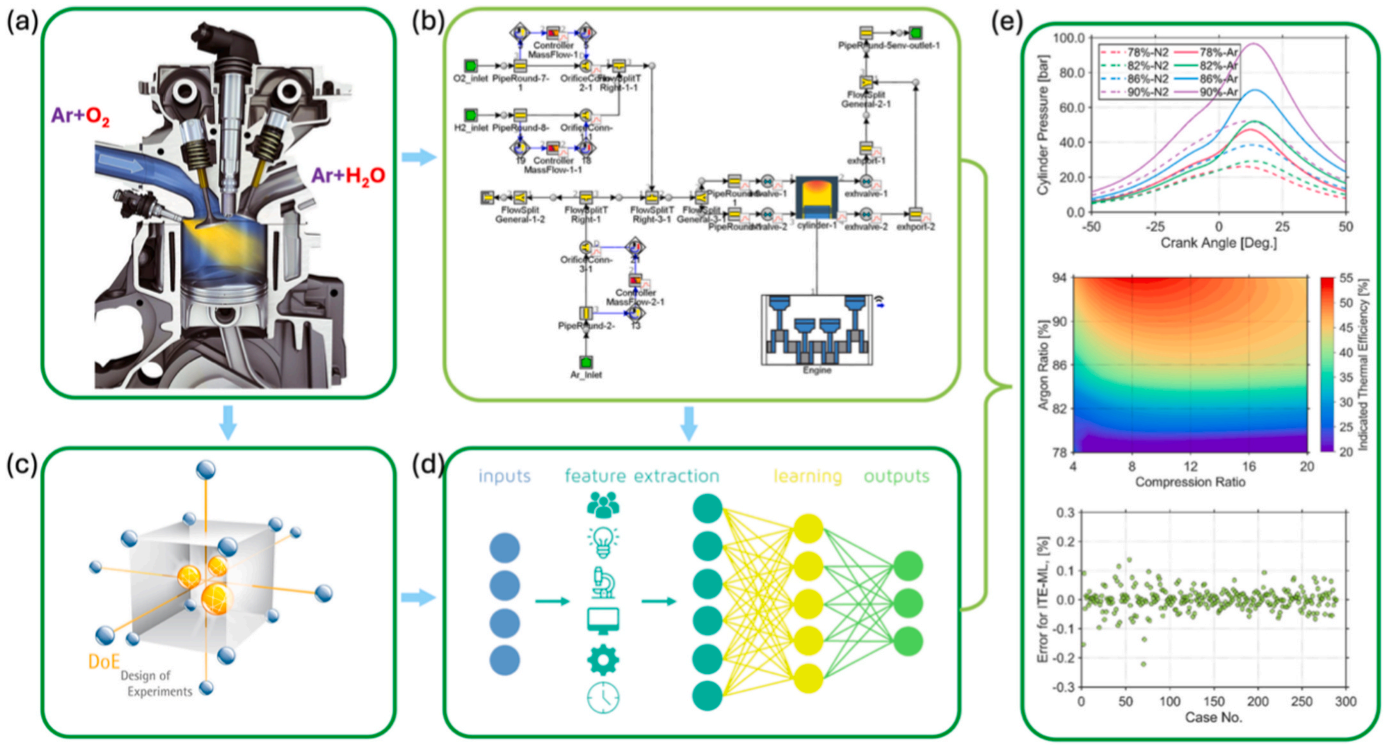


Fig. 21. Methodology for the APC engine simulation and optimization. (a) Concept of the APC engine, (b) 1D APC engine modelling, (c) design of the experiment (DoE), (d) data-driven machine learning for optimization, (e) simulation results analysis [103].

optimization. As illustrated in Fig. 20, this pathway is anchored in renewable energy sources, where electricity from wind or solar is used for green H_2 and O_2 production via electrolysis, together with cost-effective Ar separation from air [104]. Laboratory-scale experiments and high-fidelity simulations have established the fundamental efficiency and zero-emission potential of the H_2-APC; however, pilot-scale demonstrations are essential to bridge the gap toward real-world deployment. Such pilots must validate durability, efficiency, combustion stability, and Ar-loop operability under realistic thermal loads, transient operation, and long-duration cycling. In parallel, robust supply chains for H_2, O_2, and Ar, including safe storage, transport, and on-site handling must be developed to support scalable deployment.

Building on the system architecture depicted in Fig. 22, the techno-economic performance of prospective pilot and commercial H_2-APC power plants is governed by a small set of tightly coupled parameters whose influence varies by application. At the power plant level, CAPEX is dominated by the Ar recycling loop, including separation units, compression, heat exchangers, and gas conditioning, particularly for small and decentralized installations. Order-of-magnitude assessments suggest that a ±10% variation in Ar loop efficiency or parasitic energy

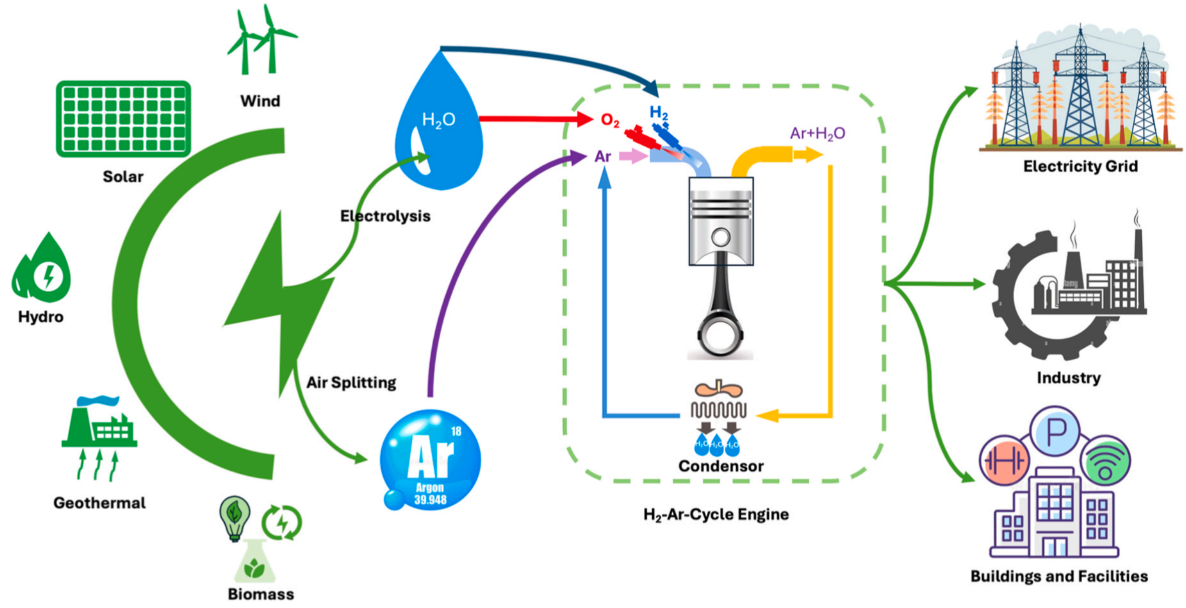


Fig. 22. Scale-up N_2-free and H_2-APC for high-efficient and ultra-lower emissions.

demand can induce a ~2-5% change in net electrical efficiency and a comparable ~3-6% change in levelized cost of electricity (LCOE), with the highest sensitivity occurring at pilot scale. The scale and source of H_2 and O_2 production, as indicated in Fig. 22, exert an even stronger leverage for stationary plants supplied by large-scale green H_2, O_2, and Ar and separation-related OPEX can dominate total LCOE, whereas integration with low-cost renewable electricity can reduce LCOE by up to ~10% relative to small-scale or fossil-derived supply chains.

Application-specific effects further shape system economics. In combined heat and power (CHP) configurations, effective utilization of waste heat, as shown in Fig. 22. This significantly relaxes sensitivity to Ar-loop losses and renewable energy cost, making long engine lifetime and extended maintenance intervals particularly valuable. Consequently, the economic viability of H_2-APC systems depends on application-specific optimization strategies, such as high-throughput stationary plants benefit primarily from scale and efficient Ar recycling, CHP systems from thermal integration and durability, and grid-balancing units from robust combustion control and long component life under cyclic operation. These considerations underscore the need for integrated techno-economic analyses, explicitly linking the system architecture in Fig. 22 with Ar-loop performance, renewable fuel pathways, and engine lifetime.

8. Conclusion

Despite challenges related to cost and system integration, ongoing research into combustion dynamics, advanced diagnostics, and engine optimization will pave the way for the widespread adoption of this technology. This review paper highlights the key benefits and challenges of H_2-APCcombustion and outlines the research directions necessary to achieve large-scale deployment. As the world moves toward a H_2 economy, N_2-free combustion technologies will play a crucial role in enabling cleaner, more efficient power systems. The key conclusions from this review paper are summarized as follows:

1) This review work introduces a C- and N-free combustion concept for H_2-APC engines, which offer a pathway toward intrinsically CO_2-free operation and the elimination of NO_x formation. By decoupling emissions control from aftertreatment requirements and instead addressing it at the combustion-system level, the H_2-APC concept provides a technically robust route toward near-zero-emission internal combustion engines. This approach is particularly relevant for energy-intensive and regulated sectors, where stringent emission limits must be met without compromising efficiency, durability, or operational flexibility.
2) The theoretical thermodynamic basis of H_2-APC engines is examined to clarify the fundamental mechanisms underlying their efficiency potential. The review highlights the role of thermophysical properties of Ar, particularly its high effective specific heat ratio, in enhancing ideal cycle efficiency when N_2 is replaced at comparable dilution levels. At the same time, the discussion explicitly recognizes that the efficiency gains depend on dilution regime, compression ratio, and system integration, rather than on the chemical inertness of the working fluid alone.
3) H_2-Ar-O_2 combustion is characterized by fast chain-branching kinetics coupled with altered thermophysical properties that enable high efficiency but narrow the stable operating window. Ar dilution affects flame behaviour through heat capacity and transport effects rather than chemical inertness, influencing flame temperature, pressure-rise rates, and thermo-diffusive stability under high-pressure conditions. While these features support rapid energy release, they also increase susceptibility to abnormal combustion such as knock and pressure oscillations at high compression ratios. Stable operation therefore relies on integrated mixture stratification, advanced ignition strategies, and adaptive control to balance efficiency gains with robust combustion stability.
4) To enable feasible and large-scale deployment of H_2-APC engines, future research should prioritize the development of energy-efficient Ar recovery and recycling systems, together with scalable, low-carbon H_2 and O_2 production pathways. The main focus should be placed on minimizing the parasitic energy penalty and capital cost associated with the Ar loop, as well as on integrating renewable electricity into fuel and working-fluid supply chains. Addressing these system-level challenges alongside combustion stability and durability considerations will be essential for translating the high theoretical efficiency of H_2-APC concepts into practical, economically viable power-generation technologies.
5) Effective combustion control in H_2-APC engines is essential to manage the high reactivity of H_2 and the distinct thermophysical properties introduced by Ar dilution. Optimized H_2 and O_2 injection strategies, combined with water injection, can stabilize flame dynamics and suppress knocking by moderating local reactivity and peak temperature, enabling more controllable combustion under high-efficiency operating conditions. In this context, machine-learning-based control frameworks offer a powerful tool to coordinate these multiple control levers in real time, adapting injection timing, dilution level, and ignition phasing in response to changing load and boundary conditions.
6) The future research should prioritize optimizing Ar production and recycling, developing advanced combustion models, and exploring real-world applications in sectors such as transportation, power generation, CHP, etc. Long-term adoption of the H_2-APCcould contribute significantly to reducing emissions across multiple industries, supporting global efforts to combat climate change and achieve sustainable energy goals. The review concludes by recommending integrated strategies to address remaining challenges, including advances in engine design and development of supportive infrastructure, to fully realize the potential of H_2-APC engines in a zero-emission environment.

CRediT authorship contribution statement

Qiang Cheng: conceptualization, investigation, methodology, data curation, formal analysis, writing – original draft, writing – review & editing. Joakim Kapp: writing – review & editing. Viljam Grahn: writing – review & editing. Zeeshan Ahmad: investigation, validation. Jari Hyvönen: supervision, writing – review & editing. Armin Wehrfritz: writing – review & editing. Ville Vuorinen: resources, writing – review & editing, validation. Ossi Kaario: resources, supervision, writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Qiang Cheng and Ville Vuorinen report financial support was provided by Research Council of Finland. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The present study has been financially supported by the Research Council of Finland (Grant nos. 363639 and 371894) and the authors acknowledge Wärtsilä Co. for funding and academic contribution.

Data availability

Data will be made available on request.

References

[1] Alagumalai A, Jodat A, Mahian O, Ashok B. Chapter 2 - NOx formation chemical kinetics in IC engines. In: Ashok B, editor. NOx Emission Control Technologies in Stationary and Automotive Internal Combustion Engines. Elsevier; 2022. p. 39–68. https://doi.org/10.1016/B978-0-12-823955-1.00002-4.

[2] de Boer PCT, Hulet J-F. Performance of a hydrogen-oxygen-noble gas engine. Int J Hydrogen Energy 1980;5:439–52. https://doi.org/10.1016/0360-3199(80)90024-5.

[3] Homan HS, Reynolds RK, De Boer PCT, McLean WJ. Hydrogen-fueled diesel engine without timed ignition. Int J Hydrogen Energy 1979;4:315–25. https://doi.org/10.1016/0360-3199(79)90006-5.

[4] Reitz RD, Ogawa H, Payri R, Fansler T, Kokjohn S, Moriyoshi Y, Agarwal A, Arcoumanis D, Assanis D, Bae C, Boulouchos K, Canakci M, Curran S, Denbratt I, Gavaises M, Guenthner M, Hasse C, Huang Z, Ishiyama T, Johansson B, Johnson T, Kalghatgi G, Koike M, Kong S, Leipertz A, Miles P, Novella R, Onorati A, Richter M, Shuai S, Siebers D, Su W, Trujillo M, Uchida N, Vaglieco BM, Wagner R, Zhao H. IJER editorial: the future of the internal combustion engine. Int J Engine Res 2020;21:3–10. https://doi.org/10.1177/1468087419877990.

[5] Ikegami M, Miwa K, Shioji M. A study of hydrogen fuelled compression ignition engines. Int J Hydrogen Energy 1982;7:341–53. https://doi.org/10.1016/0360-3199(82)90127-6.

[6] Dong G, Du Q, Li L, Atkins A, Morgan R. A high efficiency zero-emission argon split cycle engine. Int J Engine Res 2022;23:865–75. https://doi.org/10.1177/14680874221076098.

[7] Tang Y, Deng J, Xie K, Jin S, Li L. Effect of port water injection on the knock and combustion characteristics for an argon power cycle hydrogen engine. In: SAE International; 2024. https://doi.org/10.4271/2024-01-2612.

[8] Babayev R, Andersson A, Dalmau AS, Im HG, Johansson B. Computational characterization of hydrogen direct injection and nonpremixed combustion in a compression-ignition engine. Int J Hydrogen Energy 2021;46:18678–96.

[9] Wang C, Jin S, Deng J, Ding W, Tang Y, Li L. Future high-efficiency and zero-emission argon power cycle engines: a review. Inte J Automot Manuf Mater 2023:2. 2.

[10] Ding W, Deng J, Wang C, Deng R, Yang H, Tang Y, Ma Z, Li L. Operating and thermal efficiency boundary expansion of argon power cycle hydrogen engine. Processes 2023;11:1850.

[11] Ramognino F, Sforza L, Cerri T, Lucchini T, Onorati A, Novella R. A fast and reliable CFD approach to design hydrogen SI engines for industrial applications. In: SAE Technical Paper; 2023.

[12] Sierra Aznar M, Chorou F, Chen J-Y, Dreizler A, Dibble RW. Experimental and Numerical Investigation of the Argon Power Cycle. American Society of Mechanical Engineers; 2018. V001T01A006.

[13] Millo F, Piano A, Rolando L, Accurso F, Gullino F, Roggio S, Bianco A, Pesce F, Vassallo A, Rossi R. Synergetic application of zero-, one-, and three-dimensional computational fluid dynamics approaches for hydrogen-fuelled spark ignition engine simulation. SAE Int J Engines 2021;15:561–80.

[14] Mansor MRA, Shioji M. Investigation of the combustion process of hydrogen jets under argon-circulated hydrogen-engine conditions. Combust Flame 2016;173:245–57.

[15] Hodgson M, Roy S, Roskilly AP, Smallbone A. The performance and efficiency of novel oxy-hydrogen-argon gas power cycles for zero emission power generation. Energy Convers Manag 2021;244:114510.

[16] Prashanth K, Shaik A. Experimental investigation of argon gas induction on diesel engine performance and emission characteristics: a comprehensive study on de-NOx techniques. Process Saf Environ Prot 2021;152:471–81.

[17] Wang C, Jin S, Deng J, Li L. An innovative argon/miller power cycle for internal combustion engine: thermodynamic analysis of its efficiency and power density. Automot Innovat 2023;6:76–88.

[18] Saedi M, Mehrpooya M, Delpisheh M, Zaitsev A. Proposal and energy/exergy analysis of a novel cryogenic air separation configuration for the production of neon and argon. Chem Pap 2022;76:7075–93.

[19] Jin S, Deng J, Xie K, Liang X, Wang C, Ding W, Li L. Knock control in hydrogen-fueled argon power cycle engine with higher compression ratio by water port injection. Appl Energy 2023;349:121664.

[20] Ngwaka U, Wu D, Happian-Smith J, Jia B, Smallbone A, Diyoke C, Roskilly AP. Parametric analysis of a semi-closed-loop linear joule engine generator using argon and oxy-hydrogen combustion. Energy 2021;217:119357.

[21] Preiss O. The future of internal combustion engines as seen by rolls-royce power systems. https://www.mtu-solutions.com/na/en/technical-articles/2021/the-future-of-internal-combustion-engines-as-seen-by-rolls-royce-power-systems.html; 2021.

[22] Paste S. Internal Combustion Engine Market Size, Share, Growth, Report 2025 to 2034. 2025.

[23] Institute E. Statistical Review of World Energy (2024). 2024. https://ourworldindata.org/.

[24] Hoesly ea. Community Emissions Data System (CEDS) – with Major Processing by Our World in Data. 2024.

[25] IEA. Global Hydrogen Review 2024. 2024. Paris.

[26] IEA, Global Hydrogen Review 2022, n.d.

[27] Bhaskaran A, Sharma D, Roy S, Singh SA. Technological solutions for NOx, SOx, and VOC abatement: recent breakthroughs and future directions. Environ Sci Pollut Control Ser 2023;30:91501–33.

[28] Das V, Padmanaban S, Venkitusamy K, Selvamuthukumaran R, Blaabjerg F, Siano P. Recent advances and challenges of fuel cell based power system architectures and control–A review. Renew Sustain Energy Rev 2017;73:10–8.

[29] Venizelou V, Poullikkas A. The effect of carbon price towards green hydrogen power generation. Renew Sustain Energy Rev 2025;211:115254.

[30] Correa SM. A review of NOx formation under gas-turbine combustion conditions. Combust Sci Technol 1993;87:329–62.

[31] Miller JA, Bowman CT. Mechanism and modeling of nitrogen chemistry in combustion. Prog Energy Combust Sci 1989;15:287–338.

[32] Glarborg P, Miller JA, Ruscic B, Klippenstein SJ. Modeling nitrogen chemistry in combustion. Prog Energy Combust Sci 2018;67:31–68.

[33] Abkari A, Chaabane I, Guidara K. DFT (B3LYP/LanL2DZ and B3LYP/6311G+ (d, p)) comparative vibrational spectroscopic analysis of organic–inorganic compound bis (4-acetylanilinium) tetrachlorocuprate (II). Phys E Low-dimens Syst Nanostruct 2016;81:136–44.

[34] Maroa S, Inambao F. Biodiesel, Combustion, Performance and Emissions Characteristics. Springer Nature; 2020.

[35] England G, Heap M, Pershing D, Nihart R, Martin G. Mechanisms of NOx Formation and Control: Alternative and Petroleum-Derived Liquid Fuels. Elsevier; 1981. p. 163–74.

[36] Li Z, Zhang W, Chen Z, Ren Z, Ning S, Li M. A kinetics mechanism of NOX formation and reduction based on density functional theory. Sci Total Environ 2023;867:161519.

[37] Tusek J, Suban M. Experimental research of the effect of hydrogen in argon as a shielding gas in arc welding of high-alloy stainless steel. Int J Hydrogen Energy 2000;25:369–76.

[38] Murphy A. Demixing in free-burning arcs. Phys Rev 1997;55:7473.

[39] Aissa A, Abdelouahab M, Noureddine A, Elganaoui M, Pateyron B. Ranz and marshall correlations limits on heat flow between a sphere and its surrounding gas at high temperature. Therm Sci 2015;19:1521–8.

[40] Dincer I, Acar C. Smart energy solutions with hydrogen options. Int J Hydrogen Energy 2018;43:8579–99.

[41] Wei J, Ge Q, Yao R, Wen Z, Fang C, Guo L, Xu H, Sun J. Directly converting CO2 into a gasoline fuel. Nat Commun 2017;8:15174.

[42] Dranseike D, Cui Y, Ling AS, Donat F, Bernhard S, Bernero M, Areeckal A, Lazic M, Qin X-H, Oakey JS. Dual carbon sequestration with photosynthetic living materials. Nat Commun 2025;16:3832.

[43] Li Q, García-Muelas R, López N. Microkinetics of alcohol reforming for H2 production from a FAIR density functional theory database. Nat Commun 2018;9:526.

[44] Yuan Y, Zhou J, Bayles A, Robatjazi H, Nordlander P, Halas NJ. Steam methane reforming using a regenerable antenna–reactor plasmonic photocatalyst. Nat Catal 2024;7:1339–49.

[45] Abramson Elizabeth, Emma Thomley, Dane McFarlane. An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization, (Great Plains Institute, February 2022). https://scripts.betterenergy.org/CarbonCaptureReady/GPI_Carbon_and_Hydrogen_Hubs_Atlas.pdf.

[46] Chourou F, Aznar MS, Chen J-Y, Dreizler A. A New Efficient Model for Multicomponent Membrane Separation and Application to the Argon Power Cycle. 2017.

[47] Pulkrabek WW. Engineering Fundamentals of the Internal Combustion Engine. 2004.

[48] Chen Z, Tomita Y. Effect of working gas composition on combustion and knocking in argon closed-cycle hydrogen engine. In: SAE technical paper; 2023.

[49] Deng J, Zhong H, Gong Y, Gong X, Li L. Studies on injection and mixing characteristics of high pressure hydrogen and oxygen jet in argon atmosphere. Fuel 2018;226:454–61.

[50] Mansor MRA, Nakao S, Nakagami K, Shioji M. Study on Hydrogen-Jet Development in the Argon Atmosphere. Springer; 2012. p. 177–84.

[51] Peters M, Maes N, Dam N, van Oijen J. Characterizing and visualizing the direct injection of hydrogen into high-pressure argon and nitrogen environments. Int J Hydrogen Energy 2024;66:304–15.

[52] N. Diepstraten, D.Q. Reyes, J. van Oijen, Modeling of Non-Premixed Hydrogen Jet Combustion in an Argon/Oxygen Environment Via Direct and Reynold's Averaged Numerical Simulations, (n.d.).

[53] Sun H, Yang S, Jomaas G, Law CK. High-pressure laminar flame speeds and kinetic modeling of carbon monoxide/hydrogen combustion. Proc Combust Inst 2007;31:439–46.

[54] Tang C, Man X, Wei L, Pan L, Huang Z. Further study on the ignition delay times of propane–hydrogen–oxygen–argon mixtures: effect of equivalence ratio. Combust Flame 2013;160:2283–90.

[55] Carleton KL, Kessler WJ, Marinelli WJ. Hydrogen atom+ oxygen+ M (= N2, H2O, Ar) three-body rate coefficients at 298-750 K. J Phys Chem 1993;97:6412–7.

[56] Burke MP, Chaos M, Ju Y, Dryer FL, Klippenstein SJ. Comprehensive H2/O2 kinetic model for high-pressure combustion. Int J Chem Kinet 2012;44:444–74.

[57] Gong Y, Huang X, Deng J, Li L. Experimental and numerical study on combustion characteristics of super lean H2–O2 premixed laminar flame in argon atmosphere. Int J Hydrogen Energy 2020;45:21956–68.

[58] Duynslaegher C, Jeanmart H, Vandooren J. Flame structure studies of premixed ammonia/hydrogen/oxygen/argon flames: experimental and numerical investigation. Proc Combust Inst 2009;32:1277–84.

[59] Levin V, Zhuravskaya T. Detonation combustion of a hydrogen–air mixture with additives of argon and ozone. J Eng Phys Thermophys 2023;96:1759–68.

[60] Yan Y, Yin Z, Yang R, Ou J, Xie T, Liu Z, Liu J. Characteristics of fuel-borne nitrogen pollutants in hydrogen–ammonia mixtures using argon–oxygen

atmosphere under engine conditions. J Energy Resour Technol, Part A: Sustainable and Renewable Energy 2025;1:022305.

[61] Pang K, Zhang X, Huo C, Xu Y, Zu B. Numerical simulation of the effect of In-Cylinder water spraying on the knock and combustion characteristics of a hydrogen-argon oxygen engine. In: SAE technical paper; 2023.

[62] Ballatore A, Somers L, van Oijen J. A parametric study of high-pressure direct injections of hydrogen in an argon–oxygen environment by using large-eddy simulation and tabulated chemistry. Fuel 2025;397:135440.

[63] Quan Reyes DA, Diepstraten N, Ballatore A, Roekaerts D, van Oijen J. Direct, large eddy, and Reynolds-averaged navier-stokes simulations of hydrogen periodic planar jets in argon. Flow Turbul Combust 2026;116:15.

[64] Morovatiyan M, Shahsavan M, Aguilar J, Baghirzade M, Mack JH. An assessment of hydrogen addition to methane combustion with argon as a working fluid in a constant volume combustion chamber. Combust Sci Technol 2022;194:2395–413. https://doi.org/10.1080/00102202.2020.1870454.

[65] Wei H, Xu Z, Zhou L, Zhao J, Yu J. Effect of hydrogen-air mixture diluted with argon/nitrogen/carbon dioxide on combustion processes in confined space. Int J Hydrogen Energy 2018;43:14798–805.

[66] Reyes DQ, Roekaerts D, van Oijen J. Direct numerical simulation of igniting non-premixed hydrogen combustion for the argon power cycle. Proc Combust Inst 2024;40:105553.

[67] Zhang J, Han D, Huang Z. Second-law thermodynamic analysis for premixed hydrogen flames with diluents of argon/nitrogen/carbon dioxide. Int J Hydrogen Energy 2019;44:5020–9.

[68] Durocher A, Meulemans M, Versailles P, Bourque G, Bergthorson JM. Back to basics–NO concentration measurements in atmospheric lean-to-rich, low-temperature, premixed hydrogen–air flames diluted with argon. Proc Combust Inst 2021;38:2093–100.

[69] Levin V, Zhuravskaya T. Control of Detonation Combustion of a Hydrogen–Air Mixture by Argon and Ozone Addition. Springer; 2021. p. 320–4.

[70] Mansor MRA, Nakagami K, Kondo Y, Shioji M. Study of heat loss mechanism in argon-circulated hydrogen engine combustion chamber wall surface conditions. Energy Rep 2022;8:815–26.

[71] Radulescu MI, Ng HD, Lee JH, Varatharajan B. The effect of argon dilution on the stability of acetylene/oxygen detonations. Proc Combust Inst 2002;29:2825–31.

[72] Jin S, Huang X, Deng J, Gong Y, Zhong H, Li L. Initiation characteristics of spark-ignited premixed hydrogen-oxygen flames with diluents of argon/nitrogen/carbon dioxide. Int J Hydrogen Energy 2021;46:21212–21.

[73] Rangrazi A, Niazmand H, Heravi HM. Experimental study of argon dilution effects on NO x emission in a non-premixed flame in comparison with nitrogen. Kor J Chem Eng 2013;30:1588–93.

[74] Tao C, Zhou H, Hu L. Effect of carbon dioxide, argon, and helium jets on the synchronous control of combustion instability and NOx emission. Asia Pac J Chem Eng 2021;16:e2597.

[75] Jin, S., Deng, J., Li, L., Thermodynamic and chemical analysis of the effect of working substances on the argon power cycle, SAE Technical Paper 2021-01-0447, 2021, https://doi.org/10.4271/2021-01-0447.

[76] Xie, K., Deng, J., Jin, S., Li, L., Numerical study on flammability limit and performance of compression-ignition argon power cycle engine with fuel of hydrogen, SAE Technical Paper 2021-01-0391, 2021, https://doi.org/10.4271/2021-01-0391.

[77] Ding W, Deng R, Deng J, Wang C, Li L. Combustion characteristics optimization and thermal efficiency enhancement by stratified charge of hydrogen direct injection for argon power cycle hydrogen engine. Int J Engine Res 2024;25:1461–75.

[78] Hafiz NM, Mansor MRA, Mahmood WMFW. Simulation of the combustion process for a CI hydrogen engine in an argon-oxygen atmosphere. Int J Hydrogen Energy 2018;43:11286–97.

[79] Hafiz, N., Mansor, M., Wan Mahmood, W., Shioji, M., Simulation of the effect of initial temperature and fuel injection pressure on hydrogen combustion characteristics in argon-oxygen compression ignition engine, SAE Technical Paper 2016-01-2227, 2016, https://doi.org/10.4271/2016-01-2227.

[80] Zhou W, Wang H, Gao J, Zhou S. Effects of using argon, hydrogen and syngas on performance and emissions of a heavy-duty natural gas/diesel RCCI engine at low load. Int J Hydrogen Energy 2024;77:958–74.

[81] Cui W, Wang C, Deng J, Su X, Wu Z, Li L. Effects of hydrogen and methane anti-knocking characteristics on the efficiency and power output in argon power cycle engines. Int J Hydrogen Energy 2024;83:70–8.

[82] Wang C. Efficiency enhancement and lean combustion performance improvement by argon power cycle in a methane direct injection engine. SAE Int J Adv Current Pract Mobil 2023;6:2518–27. 339925.

[83] Jin S, Agarwal S, Zhu D, Fernandes R, Li L, Shu B. Experimental and modeling study on the autoignition behavior of H2-O2 mixtures under atmospheric pressure for argon power cycle engines. Proc Combust Inst 2024;40:105710.

[84] Jin S, Deng J, Xie K, Liang X, Wang C, Ding W, Li L. Knock control in hydrogen-fueled argon power cycle engine with higher compression ratio by water port injection. Appl Energy 2023;349:121664. https://doi.org/10.1016/j.apenergy.2023.121664.

[85] Jin S, Shu B, He X, Fernandes R, Li L. A study on autoignition characteristics of H2-O2 mixtures with diluents of Ar/N2 in rapid compression machine for argon power cycle engines. Fuel 2021;303:121291. https://doi.org/10.1016/j.fuel.2021.121291.

[86] Wang C, Deng J, Cui W, Su X, Li L. Theoretical and experimental researches on the pathway to achieve a net indicated thermal efficiency of 70 % by an argon power cycle hydrogen-fueled engine. Int J Hydrogen Energy 2026;198:152765. https://doi.org/10.1016/j.ijhydene.2025.152765.

[87] Sierra Aznar M, Chorou F, Chen J-Y, Dreizler A, Dibble RW. Experimental and numerical investigation of the argon power cycle. In: ICEF2018, Volume 1: Large Bore Engines; Fuels; Advanced Combustion; 2018. https://doi.org/10.1115/ICEF2018-9670.

[88] White CM, Steeper RR, Lutz AE. The hydrogen-fueled internal combustion engine: a technical review. Int J Hydrogen Energy 2006;31:1292–305. https://doi.org/10.1016/j.ijhydene.2005.12.001.

[89] N. Killingsworth, V. Rapp, D. Flowers, S. Aceves, J. Chen, R. Dibble, Characteristics of knock in hydrogen-oxygen-argon SI engine, in: Report Number: LLNL-CONF-424554, Research Org.: Lawrence Livermore National Laboratory (LLNL), Livermore, CA, 23 AD. [https://www.osti.gov/biblio/975231].

[90] Wang H, Bai Y, Kang Z, Li Y. Numerical investigation on high temperature direct water injection characteristics within hydrogen/oxygen/argon premixed combustion process. Fuel Process Technol 2025;272:108219.

[91] Kuroki, R., Kato, A., Kamiyama, E., Sawada, D., Study of high efficiency zero-emission argon circulated hydrogen engine, SAE Technical Paper 2010-01-0581, 2010, https://doi.org/10.4271/2010-01-0581.

[92] Kapp J, Cheng Q, Vuorinen V, Kaario O. Optical Investigation of Argon Power Cycle (APC), SAE Technical Paper. 2026. p. 1–328.

[93] Kim J, Scarcelli R, Beardsell G, Strickland T, Nilsen C, Aznar MS. Modeling pre-chamber assisted efficient combustion in an argon power cycle engine. In: SAE Technical Paper; 2024.

[94] Sharma E, Kim J, Strickland T, Scarcelli R, et al. Effect of geometrical manipulation of the pre-chamber design parameters on the combustion performance of an argon power cycle engine. SAE Int. J. Adv. Curr. Prac. Mobil. 2025;7(5):2473–85. https://doi.org/10.4271/2025-01-8405.

[95] Si H, Hong Q, Chen X, Jiang L. Pressure swing adsorption for oxygen production: adsorbents, reactors, processes and perspective. Chem Eng J 2025;509:161273.

[96] Harlacher T, Melin T, Wessling M. Techno-economic analysis of membrane-based argon recovery in a silicon carbide process. Ind Eng Chem Res 2013;52:10460–6.

[97] Wilcox J. Cryogenic distillation and air separation. In: Carbon Capture. Springer; 2012. p. 219–29.

[98] Cai R, Krzystowczyk E, Braunberger B, Li F, Neal L. Techno-economic analysis of chemical looping air separation using a perovskite oxide sorbent. Int J Greenh Gas Control 2024;132:104070.

[99] Susarla N, Haghpanah R, Karimi I, Farooq S, Rajendran A, Tan LSC, Lim JST. Energy and cost estimates for capturing CO2 from a dry flue gas using pressure/vacuum swing adsorption. Chem Eng Res Des 2015;102:354–67.

[100] Maroukis G, Georgiadis MC. Modeling, simulation, and techno-economic optimization of argon separation processes. Chem Eng Res Des 2022;184:165–79.

[101] Luberti M, Ahn H. Design of an industrial multi-bed (V) PSA unit for argon concentration. Separ Purif Technol 2021;261:118254.

[102] Starikovskaia S. Plasma-assisted ignition and combustion: nanosecond discharges and development of kinetic mechanisms. J Phys Appl Phys 2014;47:353001.

[103] Zhang C, Chen G, Yu C, Qiao Y, Dong Q, Cheng Q, Kaario O. Machine learning-assisted optimization of thermodynamics and combustion in hydrogen argon power cycle engines. Int J Hydrogen Energy 2026;222:154167.

[104] Bagarello S, Campagna D, Benedetti I. A survey on hydrogen tanks for sustainable aviation. Green Energy Intell Transp 2025;4:100224.