Hydrogen engine combustion

Background: With abundant land and renewable energy resources, some countries are advantageously poised to produce green hydrogen at low cost and to implement a hydrogen economy for domestic use or export to their neighboring countries with high energy demands. This is because, unlike electricity, hydrogen can be stored and transported over long distances at lower cost. In particular for countries such as Australia and Chile, their geographic locations and well-established reputation as reliable conventional energy exporters could make them major hydrogen suppliers targeting their neighbors with net demands, such as China, Japan and Korea [1]. In fact, such collaboration is already underway with a joint project between Australia and Kawasaki Heavy Industries (Japan) to build a hydrogen supply chain between the two countries, wherein Japan is forecasted to import 900,000 tons of hydrogen by 2030 [2]. This strategic hydrogen export opportunity is estimated to add as much as AUD10 billion to Australia's economy by 2040 in a high hydrogen demand scenario [2]. These figures have significant growth potential, considering that industrial applications, for instance oil refining (33%), ammonia production (27%), methanol production (11%) and steel production (3%) currently dominates the use of hydrogen and drives more than 50% of the demand; while the use of hydrogen for power generation and propulsion only accounts for 1–2% of the total consumption [2, 3]. For the power generation sector, the low utilization could be attributed to the lack of hydrogen distribution infrastructure and the slow development of hydrogen powertrain that can efficiently and cost-effectively convert hydrogen into power. Therefore, there is significant room for growth for increased hydrogen usage in the power generation sector, as technologies surrounding hydrogen distribution, usage and storage continue to improve and mature.

Technological challenges: Traditionally, hydrogen-fuelled internal combustion engines (ICEs) use a port-fuel-injection (PFI) approach—with hydrogen mixed into the intake air in the intake manifold or port. While implementing PFI benefits from a straightforward conversion of existing engines, the approach is susceptible to undesired combustion phenomena, such as pre-ignition, knocking, flame backfiring and volumetric efficiency loss. An alternative fuelling approach is to inject hydrogen directly into the engine cylinder during the compression stroke. Depending on the injection pressure and injection timing, the alternative hydrogen direct-injection (DI) approach can to some extent alleviate the pre-ignition issue of the hydrogen-PFI by reducing the duration of interaction of the fuel-air mixture with the hot spots within the engine combustion chamber. As the fuel injection can occur after the inlet valves are closed, the DI approach also avoids the back-fire problem, which arises from the presence of flammable mixture in the intake, as well the volumetric efficiency loss problem, which is due to hydrogen gas displacing air in the intake. The improved efficiency, power density, and safety benefits that hydrogen-DI can offer over hydrogen-PFI fuel motivate the recent interest in hydrogen-DI technology.

Aim: This project aims to demonstrate the value and performance of highly efficient heavy-duty, compression-ignition (CI) engines operating on renewable hydrogen in power generation applications. We focus on advancing technology relating to hydrogen diesel dual-fuel operation—hydrogen is directly injected into the cylinder, with ignition achieved by a separate diesel injection for operating a hydrogen engine.

This project, which was first performed in partnership with the University of Melbourne, and industrial partners, including MAN-ES and Caterpillar via ARENA, and now with Rio Tinto via Trailblazer Universities, seeks to address the knowledge gap through a combination of experimental, simulation and techno-economical studies.

Achievements: Our group has produced one of the most comprehensive experimental datasets on hydrogen auto-igniting jets under compression-ignition engine conditions, as well as one of the most detailed hydrogen-diesel dual-fuel direct-injection studies conducted under realistic engine-relevant pressures and temperatures. These datasets provide critical insights for model development, validation, and future engine-system design. They have also been modelled and analysed by leading international research groups, including Lund University, Shanghai Jiao Tong University, the Technical University of Denmark, POLIMI, and others, demonstrating the global impact and relevance of our work.

In parallel, our group has achieved significant progress with a UNSW-patented high-pressure (up to 350 bar) hydrogen direct injection technology. Recent engine performance tests demonstrated a hydrogen substitution of up to 90% of the energy input in a retrofitted compression-ignition engine, resulting in a 10% efficiency increase and a 70% reduction in CO_2 emissions compared to a diesel-only baseline.

Beyond research-focused studies, we have also conducted detailed techno-economic analyses assessing the potential integration of this technology into Australian solar farms to support baseload renewable power generation. In parallel, we performed a comprehensive upstream-to-downstream assessment of how the technology could be deployed to decarbonise mining operations, evaluating system-level feasibility and operational impacts. This work has been carried out in close collaboration with industry partners, ensuring that our research remains aligned with real-world operational needs and pathways to commercial adoption.

The project is still ongoing and has resulted in two PhD theses and multiple published journal articles from our group.

PhD theses:

1. Rorimpandey P., "Hydrogen-diesel dual-fuel combustion in compression-ignition engine conditions", PhD thesis, 2024.
2. Yip H.L., "Hydrogen jet combustion in engine-relevant conditions", PhD thesis, 2022.

Journal publications:

Technoeconomical analysis

1. Li J., Shankar M., Zhai G., Wang C., Yeoh G.H., Kook S. and Chan Q.N., "Techno-economic analysis of hydrogen-diesel dual-fuel engines as a transitional decarbonisation strategy for mining haul trucks", Energy & Fuels, Accepted 8th November 2025. DOI: 10.1021/acs.energyfuels.5c04119.
2. Li J., Wang C., Zhai G., Li Q., Lim S.H., Abdoli S., Kook S., Yeoh G.H. and Chan Q.N., "Evaluating the techno-economic feasibility of hydrogen-fuelled reciprocating engines for renewable base-load power generation", Energy Conversion and Management 311: 118515, 2024. DOI: 10.1016/j.enconman.2024.

Review papers:

1. Rorimpandey P., Aryal K., Zhai G., Xu S., Pang K.M., Yeoh G.H., Yeoh G.H., Kook S. and Chan Q.N., "A review of the fundamental understanding of hydrogen-diesel direct injection combustion: Recent advances and future outlook", Energy & Fuels 39: 16538-26560. DOI: 10.1021/acs.energyfuels.5c02216.
2. Yip H.L., Srna A., Yuen A.C.Y., Kook S., Taylor R.A., Yeoh G.H., Medwell P.R. and Chan Q.N., " A review of hydrogen direct injection for internal combustion engines: Towards carbon-free combustion", Applied Sciences: Progress in Combustion Diagnostics, Science and Technology, 9: 4842, 2019. DOI: 10.3390/app9224842.

Fundamental experimental studies:

1. Yip H.L., Zhai G., Rorimpandey P., Kook S., Hawkes E.R. and Chan Q.N., "Experimental study of laser-ignited hydrogen jet flame evolution under simulated direct-injection diesel engine conditions", International Journal of Hydrogen Energy 93: 1060-1070, 2024. DOI: 10.1016/j.ijhydene.2024.10.217.

2. Rorimpandey P., Zhai G., Kook S., Hawkes E.R. and Chan Q.N., "Effects of jet interaction angle on the ignition and combustion characteristics of hydrogen-diesel dual-fuel direct injection", International Journal of Hydrogen Energy 67: 172-191, 2024. DOI: 10.1016/j.ijhydene.2024.04.166.
3. Rorimpandey P., Zhai G., Kook S., Hawkes E.R. and Chan Q.N., "Effects of energy-share and ambient oxygen concentration on hydrogen-diesel dual-fuel direct-injection (H2DDI) combustion in compression-ignition conditions", International Journal of Hydrogen Energy 49: 1346-1361, 2024. DOI: 10.1016/j.ijhydene.2023.11.106
4. Yip H.L., Srna A., Zhai G., Wehrfritz A., Kook S., Hawkes E.R. and Chan Q.N., "Laser-induced plasma-ignited hydrogen jet combustion in engine-relevant conditions", International Journal of Hydrogen Energy 48: 1568-1581, 2023. DOI: 10.1016/j.ijhydene.2022.09.296
5. Rorimpandey P., Yip H.L., Srna A., Zhai G., Wehrfritz A., Kook S., Hawkes E.R. and Chan Q.N., "Hydrogen-diesel dual-fuel direct-injection (H2DDI) combustion under compression-ignition engine conditions", International Journal of Hydrogen Energy 48: 766-783, 2023. DOI: 10.1016/j.ijhydene.2022.09.241
6. Yip H.L., Srna A., Wehrfritz A., Kook S., Hawkes E.R. and Chan Q.N., "A parametric study of autoigniting hydrogen jets under compression-ignition engine conditions", International Journal of Hydrogen Energy, 2022. DOI: 10.1016/j.ijhydene.2022.04.253
7. Yip H.L., Srna A., Liu X., Kook S., Hawkes E.R. and Chan Q.N., "Visualization of hydrogen jet evolution and combustion under simulated direct-injection compression-ignition engine conditions", International Journal of Hydrogen Energy, 45: 32562-32578, 2020. DOI: 10.1016/j.ijhydene.2020.08.220

Engine studies:

1. Zhao Y., Chan Q.N. and Kook S., "Application of hydrogen single and split injection strategies in a direct-injection pilot-diesel ignition engine", Applied Thermal Engineering, accepted 25th November 2025.
2. Heaton A.G., Chan Q.N. and Kook S., "The influence of hydrogen injection timing and energy proportion on flame developments in a dual direct injection optical diesel engine", Applications in Energy and Combustion Science 24: 100382, 2025. DOI: 10.1016/j.jaecs.2025.100382.
3. Liu X., Yang L., Chan Q.N. and Kook S., "Split injection strategies for a high-pressure hydrogen direct injection in a small-bore dual-fuel diesel engine", International Journal of Hydrogen Energy 57: 904-917, 2024. DOI: 10.1016/j.ijhydene.2024.01.065
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Numerical studies:

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2. Evans A., Wang Y., Srna A., Wehrfritz A., Hawkes E.R., Liu X., Kook S., Chan Q.N., "Mechanisms of NOx production and heat loss in a dual-fuel hydrogen compression ignition engine," SAE Technical Paper 2021-01-0527, SAE WCX Digital Summit, April 2021, DOI: 10.4271/2021-01-0527.

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Funding:
- 2023-2026: Retrofitting technology for mining engines: Shaun Chan, Shawn Kook - Department of Education Trailblazer Universities for Recycling and Clean Energy (ATRaCE).

- 2018-2022: Enabling efficient, affordable and robust use of renewable hydrogen in transport and power generation: Michael Brear, Yi Yang, Robert Gordon, Mohsen Talei, Evatt Hawkes, Shawn Kook, Shaun Chan - ARENA project 2018/RND011.

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