H2CHP

Hydrogen-fuelled linear generator for combined heat and power.

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Contents

1. Executive Summary

This report presents the outcomes of H2CHP's Hydrogen Innovation Initiative demonstration of a modular hydrogen-to-electricity linear generator for behind-the-meter power applications on the CEME campus in Rainham, East London. The project was undertaken by H2CHP with CEME as host site and Durham Energy Institute providing advisory support on microgrids, documentation review and dissemination. The project sought to demonstrate how hydrogen can be converted into flexible electrical power on a live site using an innovative free-piston linear generator architecture integrated with local hydrogen infrastructure and a microgrid context.

The project addressed not only generator development and commissioning, but also the practical requirements for safe hydrogen integration on site. This included external hydrogen supply arrangement, interface panel design, pressure control and relief, venting strategy, gas detection, hazardous area assessment, and DSEAR compliance work undertaken with Rhizome Energy. In parallel, H2CHP worked with Clean Air Power to identify suitable hydrogen injectors and the associated fittings required for integration with the test platform.

By February 2026, major progress had been made in encapsulation of the linear generator stator slices for hydrogen operation, cold commissioning of the linear electrical machines, delivery and installation activities, hydrogen supply and safety design, and injector integration work. In addition to the technical programme, the generator was displayed publicly at the CEME Hydrogen Summit, helping to support dissemination and stakeholder engagement around the project.

The principal value of the project is that it demonstrates a credible route by which a novel hydrogen-fuelled linear generator can be prepared for deployment in an operational environment, while generating practical lessons on site readiness, hydrogen safety, electrical integration, commissioning strategy, component selection and public demonstration. The project therefore contributes to the wider hydrogen industry by addressing a practical route from prototype development towards operational demonstration in a real-world setting.

To address the broader analytical and validation outputs originally proposed for the project, this report is supported by three substantive appendices covering the rapid EV charging use case, hydrogen combustion simulation, and the initial hydrogen test results obtained at CEME, together providing a clearer view of the generator's technical and commercial trajectory.

2. Introduction

The purpose of this report is to document the H2CHP Hydrogen Innovation Initiative demonstration, summarise the activities undertaken, present the principal findings, and share lessons that may be relevant to future hydrogen demonstration projects. The report has been prepared to provide a clear public account of the project and its relevance to the wider hydrogen sector.

H2CHP is developing a free-piston linear generator designed to convert hydrogen into electrical power for distributed and behind-the-meter applications. The technology is intended to offer a modular alternative for sites requiring flexible low-carbon power, with potential relevance to campuses, industrial facilities, transport-related infrastructure and other locations where resilient local generation is valuable. The system uses a linear architecture rather than a conventional crankshaft-based engine arrangement, with the aim of enabling efficient, responsive and fuel-flexible operation.

Prior to this demonstration project, the generator had been developed and operated in a non-hydrogen test configuration. The demonstration therefore required a transition to a hydrogen-ready system suitable for safe site deployment. A key part of this transition was the completion of targeted engineering modifications to support hydrogen compatibility, durability and safe operation under live test conditions.

The objective of the demonstration was to advance the practical deployment of this technology in a real site environment at CEME in Rainham, East London. This included preparing the generator for hydrogen operation, undertaking the supporting safety and supply-system design, progressing commissioning activities, and demonstrating the technology in a setting that would also support wider dissemination and stakeholder engagement. The project was intended not only to test the generator itself, but also to show how a novel hydrogen power technology can be integrated safely and credibly within an operational environment.

3. Project Description

Unlike a conventional reciprocating engine-generator set, the H2CHP system replaces the cranktrain with a piston-mounted linear translator operating within a linear generator. This architecture was presented as enabling cycle-by-cycle control of compression and phasing, with the potential to support very lean hydrogen combustion, rapid load response, and high part-load efficiency. The demonstrator was described as a 120 kW package, with a pathway to scaling to higher outputs through modular configuration.

As the demonstration host, CEME offered a relevant operational setting as the site already has hydrogen production and refuelling infrastructure and a campus innovation environment suited to public demonstration. The project consortium also included Durham Energy Institute as advisory partner on microgrids and dissemination.

The Hydrogen Innovation Initiative project did not begin from a blank sheet. Prior to the hydrogen demonstration phase, H2CHP had already developed and tested the generator on other fuels. Building on that existing test platform, the project focused on the additional engineering required to convert it into a hydrogen-ready demonstrator. This included hydrogen-specific modifications to the linear electrical machines and mover assembly, together with hydrogen supply-system design, safety-case development, injector selection, and site integration work.

Alongside the core generator work, the project required the design and procurement of a hydrogen supply system to support safe testing and demonstration. Rhizome Energy was engaged to design the hydrogen supply arrangement and undertake the associated safety studies. This included the hydrogen supply P&ID, site layout, hazardous area layout, safety study and DSEAR assessment for the hydrogen feed from the external manifolded cylinder pack, through the pressure control and relief interface panel, and onwards to the test rig.

The project timeline ran broadly from late 2025 to March 2026. The work programme covered design freeze, safety and risk reviews, procurement, site enabling works, delivery and placement, hook-up, cold commissioning, staged hydrogen introduction, site acceptance testing, test campaign, reporting and dissemination.

4. Demonstration Activity

The demonstration activity centred on preparing and integrating the H2CHP generator for hydrogen-fuelled operation in a microgrid context. Planned activity included installation of the generator package at CEME, hydrogen supply integration, connection to the campus electrical system, commissioning, staged introduction of hydrogen, and performance testing under representative operating conditions. The project also included the intention to document the connection method, operating rules and safety case for future replication.

The equipment base for the demonstration included the free-piston linear generator, linear electrical machines, converter and controls, hydrogen injectors and associated hardware, gas detection and purge systems, acoustic enclosure elements, and measurement equipment for commissioning and test verification.

A substantial element of the activity concerned hydrogen safety and supply-system design. In collaboration with Rhizome Energy, H2CHP developed a hydrogen supply arrangement consisting of an external cylinder pack, an interface panel with pressure regulation and pressure relief, vent routing to a dedicated stack, and a controlled feed to the test rig. The arrangement was designed so that high-pressure hydrogen storage and the primary pressure reduction equipment remained outside the building, as well as allowing a path for exhaust gases to leave the test rig safely, bypassing potential hazards in CEME's existing exhaust ventilation system. The internal test area was supported by active ventilation, gas detection and automatic isolation. Two gas detectors were specified above the test rig and linked to the control system to trigger shut-off in the event of elevated hydrogen concentration.

The project also included hazardous area assessment and DSEAR compliance work. This identified the key release scenarios associated with the hydrogen supply system, the corresponding ignition risks, the control measures required, and the resulting zone classifications around the external supply and venting equipment. The work established a structured safety basis for operation, including leak testing, use of hydrogen-rated hoses and fittings, directed venting away from personnel, pressure reduction prior to entry to the workshop, gas detection alarms, emergency procedures, and visual identification of hazardous areas.

Methodologically, the project followed a staged commissioning approach. This included off-site preparation, factory acceptance testing of converter and interlocks, delivery and placement, mechanical and electrical hook-up, cold commissioning and gas-free checks, followed by staged hydrogen introduction and then a wider test campaign. This approach reduced technical and safety risk by resolving equipment and integration issues before live hydrogen operation.

The project also included an outward-facing dissemination element. The generator was displayed at the CEME Hydrogen Summit, providing an opportunity to present the technology to industry stakeholders, demonstrate physical progress, and generate public engagement through event visibility and LinkedIn communications.

5. Results and Analysis

At the time of reporting, the results presented are initial technical, integration and commissioning results rather than final performance characterisation. The project completed encapsulation of the stator slices for hydrogen operation, representing an enabling modification required for safe hydrogen use. Cold commissioning of the linear electrical machines was also completed, with no mechanical interference found between mover and stator. In parallel, hydrogen injectors were sourced through work with Clean Air Power, with modification required to the injector sleeve and associated interface arrangements.

A second major area of result was the completion of a structured hydrogen safety design package. Through work with Rhizome Energy, the project developed the hydrogen supply design, site layout, hazardous area layout, safety study and DSEAR assessment needed to support safe on-site operation. This was important because it translated the hydrogen demonstration from a general concept into a defined engineered arrangement with explicit control measures and operational boundaries.

The safety work confirmed that the hydrogen supply system could be considered compliant for the intended demonstration use, subject to the specified control measures and operational discipline. It also identified important vulnerabilities and practical engineering considerations, including the importance of correct installation quality, inspection of fittings and hoses, control of venting, avoidance of ignition sources, and long-term seal-material selection where repeated or sustained hydrogen service is expected.

A third result area was dissemination and stakeholder visibility. Displaying the generator at the CEME Hydrogen Summit gave the project a public demonstration dimension beyond the test programme itself. This helped show physical progress, supported engagement with industry and ecosystem stakeholders, and strengthened the project's dissemination outcomes.

The project had identified intended performance outputs including efficiency, start and stop behaviour, ramp rate, turndown, hydrogen consumption, emissions, and microgrid behaviour. Those remain the correct categories for the work programme.

The original proposal identified a broader set of intended outputs, including electrical performance mapping, hydrogen utilisation, NOx mapping under lean combustion, power-quality observations, an economic assessment of campus microgrid integration and rapid EV charging use cases, and a replicable integration blueprint. Some of these outputs were not completed experimentally within the initial reporting period, but the project has since advanced the supporting analytical and testing work required to address them. This report is therefore supported by three substantive appendices addressing the principal analytical and validation outputs originally proposed. Appendix A presents the rapid EV charging techno-economic study for grid-constrained deployment of the generator. Appendix B presents the hydrogen HCCI simulation study and its implications for expected performance and emissions behaviour. Appendix C records the initial hydrogen test results obtained at CEME and explains their significance for the subsequent development programme.

6. Challenges and Solutions

Several project challenges emerged during delivery. One recurring issue was the availability and integration of a suitably sized hydrogen injector. This was progressed through work with Clean Air Power, including identification of suitable injectors and the associated fittings, together with modification of the injector sleeve and interface arrangements. This provides a useful example of how a demonstration can surface real component-selection and integration issues that are not always obvious at the concept stage.

Another significant challenge was the conversion of the machine from a petrol-capable test configuration to a hydrogen-ready system. This required targeted engineering modifications to support hydrogen compatibility and long-term durability, together with substantial rework and careful reassembly. Those changes were necessary to establish confidence in the suitability of the machine for hydrogen exposure, but they also added time, effort and technical risk to the programme.

Commissioning risk associated with the linear electrical machines remained an important issue following these hydrogen-readiness modifications. Cold commissioning was a key milestone and confirmed that the feared mechanical interference between mover and stator did not occur. This underlined both the importance of the earlier modification work and the value of staged commissioning before hydrogen operation.

Safe hydrogen integration within a working site environment presented a further challenge. This required more than simply supplying hydrogen to the rig. It required a full engineered solution covering pressure reduction, relief, vent routing, gas detection, hazardous area definition, operating procedures and emergency controls. Working with Rhizome Energy, the project addressed this challenge through their formal safety study, DSEAR assessment, hazardous area layout and hydrogen supply design.

The interface between external high-pressure hydrogen storage and the indoor test environment also required careful resolution. The adopted solution was to keep the cylinder pack and interface panel outside, reduce pressure before entry to the building, vent to a dedicated elevated stack, and use gas detection and automatic isolation at the rig. This reduced the consequences of indoor release and provided a clearer safety case for operation.

The project also had to communicate progress in a way that reflected the realities of hydrogen demonstration work. In practice, substantial value is created through enabling engineering work, safety case development, component identification, commissioning and stakeholder engagement, even before full live demonstration is achieved. Displaying the generator at the CEME Hydrogen Summit helped communicate that wider progress while the technical programme continued.

Figure 1 Display at the CEME Hydrogen Summit

7. Key Learnings

The first key learning was that hydrogen demonstration projects of this type depend heavily on careful interface engineering. Success depends not only on the generator itself, but also on injector selection, fittings, supply architecture, venting, control logic, gas detection and site layout.

The second key learning was that safety engineering must be treated as a core project workstream rather than a later compliance exercise. The work undertaken with Rhizome Energy shows the importance of formal hydrogen supply design, hazardous area assessment, DSEAR review and explicit operational controls when moving from laboratory development towards site demonstration.

The project also demonstrated that staged commissioning was essential. The project's sequence from equipment preparation to cold commissioning, gas-free checks, safety integration and only then staged hydrogen introduction is a robust model for first-of-a-kind hydrogen power demonstrations.

The project also showed that host-site context mattered strategically. CEME was valuable not merely as a venue but as an enabling environment with hydrogen infrastructure, dissemination opportunities and an audience for innovation. The public display of the generator at the CEME Hydrogen Summit shows how a demonstration site can support both technical progress and ecosystem engagement.

The final key learning was that meaningful value in hydrogen demonstration projects is often created before full performance maturity is reached, through design maturation, safety-case development, commissioning progress, supplier integration and visible evidence of delivery.

Figure 2. Installation at CEME

8. Implications for the Hydrogen Industry

This project is relevant to a wider industry trend towards decentralised low-carbon power, flexible microgrids and site-level hydrogen use cases. The demonstration was designed to link hydrogen supply and end use within a local system, using CEME's hydrogen capability and a behind-the-meter application model. This makes the project particularly relevant to campuses, business parks and industrial sites seeking alternatives to conventional standby or peaking plant.

The inherently modular architecture of the linear generator is also a key driver for commercial scalability. By allowing units to be deployed in parallel configurations, the system can scale from a single 120 kW module to multi-megawatt arrays, enabling a 'pay-as-you-grow' approach to site decarbonisation that minimises initial capital risk for early adopters.

The project also has implications for how hydrogen demonstration projects are delivered. It shows that successful deployment depends on parallel progress across several domains: core power-conversion technology, fuel-system engineering, injector and component supply chain, hazardous area assessment, operational procedures, and public stakeholder engagement.

More specifically, the work with Rhizome Energy illustrates the degree of engineered detail required to support safe hydrogen operation, while the work with Clean Air Power illustrates the importance of specialist supply-chain partners in resolving injector and fitting requirements. These are useful lessons for other developers pursuing hydrogen-fuelled engines or related distributed power systems.

The project also demonstrates the importance of visibility and ecosystem engagement. Public display of the generator at the CEME Hydrogen Summit helped translate the project from an internal engineering exercise into a sector-facing demonstration of progress. For the wider hydrogen industry, that matters because confidence in deployment pathways is built not only through data, but also through visible, credible evidence of engineering delivery.

9. Conclusion

The H2CHP Hydrogen Innovation Initiative demonstration has shown the practical steps required to prepare and integrate a novel hydrogen-fuelled linear generator for deployment in a live site context. Working with CEME and Durham Energy Institute, and supported by safety engineering from Rhizome Energy and injector integration work with Clean Air Power, the project established a credible operational setting, progressed hydrogen-specific hardware adaptation, completed cold commissioning milestones, developed a defined hydrogen supply and safety architecture, and supported public dissemination through the CEME Hydrogen Summit.

The strongest evidenced outcomes from the current material are therefore readiness, integration, safety and dissemination outcomes rather than final power-performance outcomes. That remains significant, because it demonstrates that the H2CHP linear generator has progressed through the critical early steps required to move from concept into credible real-world deployment.

The report is now supplemented by analytical and test appendices that address the broader outputs originally proposed for the project, including the rapid EV charging use case, hydrogen combustion simulation, and the initial hydrogen test results obtained at CEME.

The demonstrator had previously been configured for petrol operation rather than hydrogen. Achieving hydrogen readiness therefore required targeted engineering modifications to support compatibility, durability and safe operation under live hydrogen test conditions.

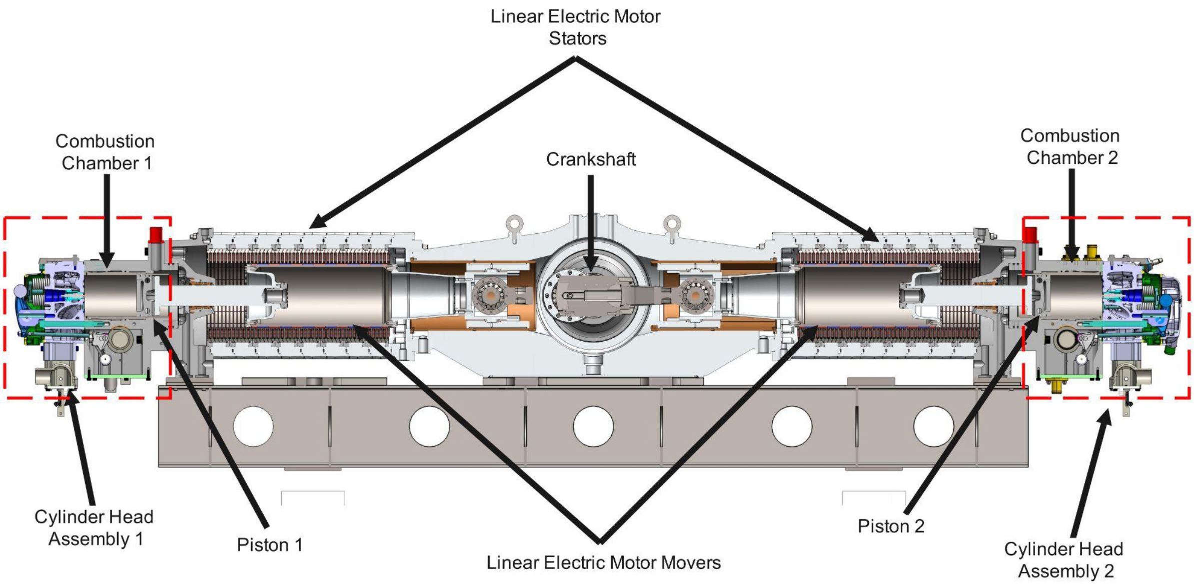

Figure 3 Sectional View with labels of the current test rig configuration. The red boxes indicate the location of the Ricardo-supplied research-grade engine blocks.

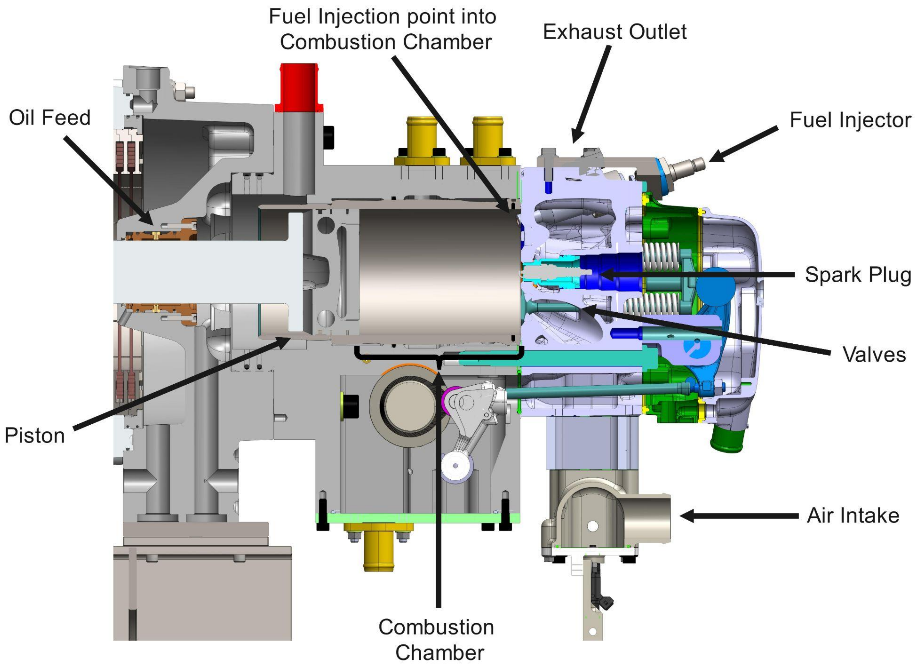

Figure 4: Sectional View of Cylinder Head and Combustion Chamber (located at each end of the test rig) with labels of each component.

Appendix A. Rapid EV Charging at Grid-Constrained Sites: Techno-Economic Assessment of H2CHP Generator Integration

A1. Purpose

This appendix sets out the commercial case for the H2CHP generator in one of the most important emerging applications for distributed low-carbon power: rapid EV charging at grid-constrained sites. The central problem in this market is not whether rapid charging technology exists, but whether sufficient power can be accessed, when and where it is needed, on commercially useful timescales. This appendix shows how the H2CHP architecture can address that constraint directly, creating a practical route to earlier deployment, stronger asset utilisation, and reduced dependence on slow and costly network reinforcement.

For this assessment, a representative case of six 150 kW rapid chargers is considered, giving a total peak charger demand of 900 kW. This is a demanding but realistic use case for campuses, business parks, transport hubs and other constrained sites seeking to expand charging capacity. The analysis shows that the H2CHP system provides a compelling route to enabling that capacity by introducing new on-site dispatchable power rather than relying on reinforcement or very large battery storage.

A2. Strategic Relevance

At many rapid charging sites, the commercial opportunity already exists, but the required grid capacity does not. A six-charger site rated at 150 kW per charger requires 900 kW of peak power, which is already well beyond the level of supply readily available at many innovation campuses, business parks and transport locations. In practice, securing that level of connection can require several years and substantial reinforcement cost, making deployment commercially unattractive within the timeframe that developers and site operators actually need.

That is exactly where the H2CHP proposition is strongest. The system is not intended to displace a strong and readily available grid connection where one already exists. Its value lies in making constrained sites viable by supplying new on-site dispatchable power behind the meter. This changes the structure of the problem. Instead of treating rapid charging as something that must wait for network reinforcement, it enables charging capacity to be created locally and used when it is most valuable.

This is a highly relevant use case for the H2CHP architecture because it combines three features that favour the technology:

- high-value electricity demand;
- large and variable peak loads;
- a strong commercial penalty associated with waiting for reinforcement.

A3. Representative Charging Case

The representative case assessed in this appendix is:

- six rapid chargers;
- 150 kW per charger;
- 900 kW peak charger demand;
- grid import capacity limited to 200 kW;
- H2CHP generator providing on-site dispatchable power;
- only a very small battery or flywheel assumed for nuisance transients and switching events, rather than for bulk energy storage.

This creates a stretching but commercially relevant scenario. A 200 kW grid connection can support only a small fraction of the 900 kW peak charging requirement. In a conventional constrained-grid architecture, the shortfall would be addressed by adding substantial battery storage, which quickly becomes expensive because the battery must cover not only peak power but also sustained energy throughput as utilisation rises.

The H2CHP approach addresses the problem differently. Rather than stretching a limited grid connection through large-scale battery storage, it introduces new on-site power capacity directly. The key commercial question is therefore not whether a constrained grid connection can be made to work in principle, but which architecture provides the most practical and economically credible route to meaningful charging throughput.

A4. Competing Architectures

The central comparison in this appendix is between two plausible ways of solving the same constrained-site problem.

Architecture 1: 200 kW grid connection plus large battery
This architecture uses the grid as the continuous source of energy and relies on a large battery to bridge the gap between the 200 kW grid connection and the 900 kW charging peak.

Architecture 2: H2CHP generator with only a very small transient buffer
This architecture uses the H2CHP generator to provide the charging power directly. A very small battery or flywheel is included only to absorb nuisance transients, switching disturbances and other short-duration edge effects. It is not required to act as a large energy-bearing asset.

This distinction is important. A constrained-grid-plus-battery system is fundamentally a way of stretching a limited grid connection in time. The H2CHP system is fundamentally a way of creating new on-site power capacity.

A5. System Design Logic

Rapid EV charging has a dual character. Peak demand is set by coincidence of charging sessions and can rise sharply within seconds. Total energy throughput, by contrast, accumulates over hours. These are different technical problems.

In the representative case considered here, six 150 kW chargers create a total peak demand of 900 kW, while the constrained grid connection provides only 200 kW. The resulting shortfall is 700 kW.

A grid-plus-battery architecture can bridge that shortfall, but only by storing energy in advance and then replenishing it through the same constrained connection. As utilisation rises, the battery must be sized not only for power but also for substantial energy throughput, which rapidly increases cost and makes the system commercially heavy.

The H2CHP solution addresses the problem differently. Rather than relying on a large battery to make up the difference, it introduces new on-site dispatchable power. Because the H2CHP generator architecture is intended to support rapid load following, only a very small battery or flywheel is required to smooth nuisance transients. The architecture therefore avoids the need for a large energy buffer and is structurally better suited to sustained high-throughput charging.

A6. Core Assumptions

Table A1. Assumptions used in the indicative assessment

Parameter	Assumption
Number of chargers	6
Charger rating	150 kW
Peak charger demand	900 kW
Available grid import	200 kW
Grid electricity price	20 p/kWh
Hydrogen price	£4/kg
Generator net electrical efficiency	60%

FPEG CapEx	£550/kW
FPEG O&M	1.2 p/kWh
Asset life	10 years
WACC	10%
Operating hours	7,000 h/year
Charger utilisation	70%
Daily charging window	8 hours

The hydrogen price assumption of £4/kg is used as a realistic project working value for this assessment. In this context, the use case is stationary power generation, not a greenfield transport refuelling business.

A7. H2CHP Indicative Delivered Electricity Cost

The indicative delivered electricity cost from the H2CHP generator is built up from three components:

- fuel cost;
- operating and maintenance cost;
- annualised capital charge.

At £4/kg hydrogen and 60% net electrical efficiency, the hydrogen fuel cost equates to 20.0 p/kWh of electricity produced. O&M is assumed at 1.2 p/kWh. Using a 10-year asset life and 10% WACC, the annualised capital charge contributes 1.28 p/kWh at 7,000 operating hours per year. The resulting indicative delivered electricity cost is 22.48 p/kWh.

Table A2. Indicative delivered electricity cost build-up for the H2CHP generator

Cost element	Value
Fuel cost	20.00 p/kWh
O&M	1.20 p/kWh

Annualised capital charge	1.28 p/kWh
Total indicative delivered electricity cost	22.48 p/kWh

This is a strong result. Under the stated assumptions, the generator delivers electricity at a cost only modestly above the assumed constrained-grid import price of 20 p/kWh, while solving a problem that the constrained grid alone cannot solve: lack of deployable site power.

A8. Grid Constraint and Residual Power Requirement

Table A3. Peak power balance at the representative charging hub

Metric	Value
Peak charger demand	900 kW
Available grid import	200 kW
Residual requirement beyond grid import	700 kW
Grid share of peak demand	22.2%
Non-grid share of peak demand	77.8%

A 200 kW grid connection can support only 22.2% of the 900 kW peak demand. The remaining 700 kW must be met by some alternative architecture. That is the central commercial case for H2CHP in this application.

A9. Battery-Only Workaround: First-Cut Sizing

To test the competing constrained-grid-plus-battery architecture, a simple first-cut estimate can be made using the following utilisation assumptions:

- 70% average charger utilisation;
- 8-hour daily operating window;
- 20-minute average charging session.

Under those assumptions, the six 150 kW chargers have an average charging load of 630 kW and deliver approximately 5.04 MWh per day. A 200 kW grid connection can supply only 1.60 MWh over the same 8-hour period. The remaining daily energy shortfall is therefore approximately 3.44 MWh.

That means a battery-only workaround is not a modest buffer. It is a multi-megawatt-hour energy asset.

Table A4. Daily energy balance under the battery-only workaround

Metric	Value
Average charging load at 70% utilisation	630 kW
Daily charging energy over 8 hours	5.04 MWh/day
Daily grid energy over 8 hours	1.60 MWh/day
Daily energy shortfall to be supplied by battery	3.44 MWh/day

Allowing for round-trip losses, depth-of-discharge limits, degradation margin and reserve, a sensible first-pass installed battery size is therefore around **4 MWh**.

A10. Indicative Battery Cost and Delivered Electricity Cost

Representative utility-scale storage benchmarks imply that a 4 MWh battery is likely to require capital expenditure on the order of £0.6m to £1.2m, depending on exact system specification and cost basis. A representative utility-scale battery round-trip efficiency of around 85% is also a reasonable assumption for first-pass comparison.

Using the same 10-year life and 10% WACC as the H2CHP case, the annualised capital charge for a 4 MWh battery in this cost range is approximately £98k to £202k per year. Spread across the 1,256 MWh/year delivered by the battery, this implies a capital contribution of roughly 7.8 p/kWh to 16.1 p/kWh.

If the battery is charged using 20 p/kWh grid electricity and 85% round-trip efficiency is assumed, the effective energy cost of delivered battery electricity is approximately 23.5 p/kWh.

This gives an indicative delivered electricity cost for the battery workaround of approximately:

- 31.3 p/kWh at the low battery CapEx case;
- 39.6 p/kWh at the high battery CapEx case.

Table A5. Indicative delivered electricity cost for the 200 kW grid + 4 MWh battery workaround

Cost element	Low case	High case
Grid energy adjusted for battery losses	23.5 p/kWh	23.5 p/kWh
Annualised battery capital charge	7.8 p/kWh	16.1 p/kWh
Total indicative delivered electricity cost	31.3 p/kWh	39.6 p/kWh

This is the decisive comparison. Once the battery is sized to do the actual job required, the constrained-grid-plus-battery workaround is materially more expensive than the H2CHP solution under the stated assumptions.

A11. Comparison of Architectures

Table A6. Comparison of constrained-site charging architectures

Feature	200 kW grid + large battery	H2CHP generator + very small battery or flywheel
Source of sustained site energy	Grid, time-shifted through battery	On-site dispatchable generation
Response to short peaks	Strong	Strong
Ability to support sustained high utilisation	Limited by battery energy and recharge time	Strong
Dependence on constrained grid connection	High	Low

Battery requirement	Large, energy-bearing asset	Small, transient-only buffer
Indicative delivered electricity cost	31–40 p/kWh	22.48 p/kWh

The contrast is clear. The battery-based option can manage short peaks, but becomes structurally weak at sustained high utilisation because it must repeatedly cover a large power deficit and then recharge through a connection that remains limited to 200 kW. The H2CHP architecture solves this by shifting the sustained energy burden away from the battery and onto dispatchable generation.

A12. Rapid Charging Revenue Context

Indicative UK rapid charging prices provide useful context for the value of enabled charging capacity. Public rapid and ultra-rapid charging prices in the UK have recently been observed at weighted average levels around **71–76 p/kWh**, with major-network rapid prices ranging from around **55 p/kWh to 89 p/kWh**.

Table A7. Illustrative rapid charging retail price context

Retail charging benchmark	Value
Conservative benchmark	55 p/kWh
Mid benchmark	71 p/kWh
Upper benchmark	76 p/kWh

These figures matter because they show the economic value of enabling charging throughput at constrained sites. The strategic question is not whether H2CHP electricity is cheaper than unconstrained grid power in abstraction. It is whether H2CHP enables commercially meaningful charging throughput where the alternative is a physically constrained site, delayed deployment, or a very large battery workaround.

A13. Role of the Very Small Buffer

In the H2CHP architecture considered here, the battery or flywheel is not intended to serve as the primary energy source for the site. Its role is much narrower and more precise.

It is included only to absorb:

- nuisance transients;
- switching disturbances;
- very short-duration edge effects;
- other high-frequency events that are undesirable to pass directly through the power system.

This is a key point of differentiation. In the battery workaround, the battery is central and must carry both power and energy deficits. In the H2CHP architecture, the generator supplies the charging power directly and follows demand dynamically. The buffer is therefore small by design and serves only as a power-conditioning element.

A14. Figures

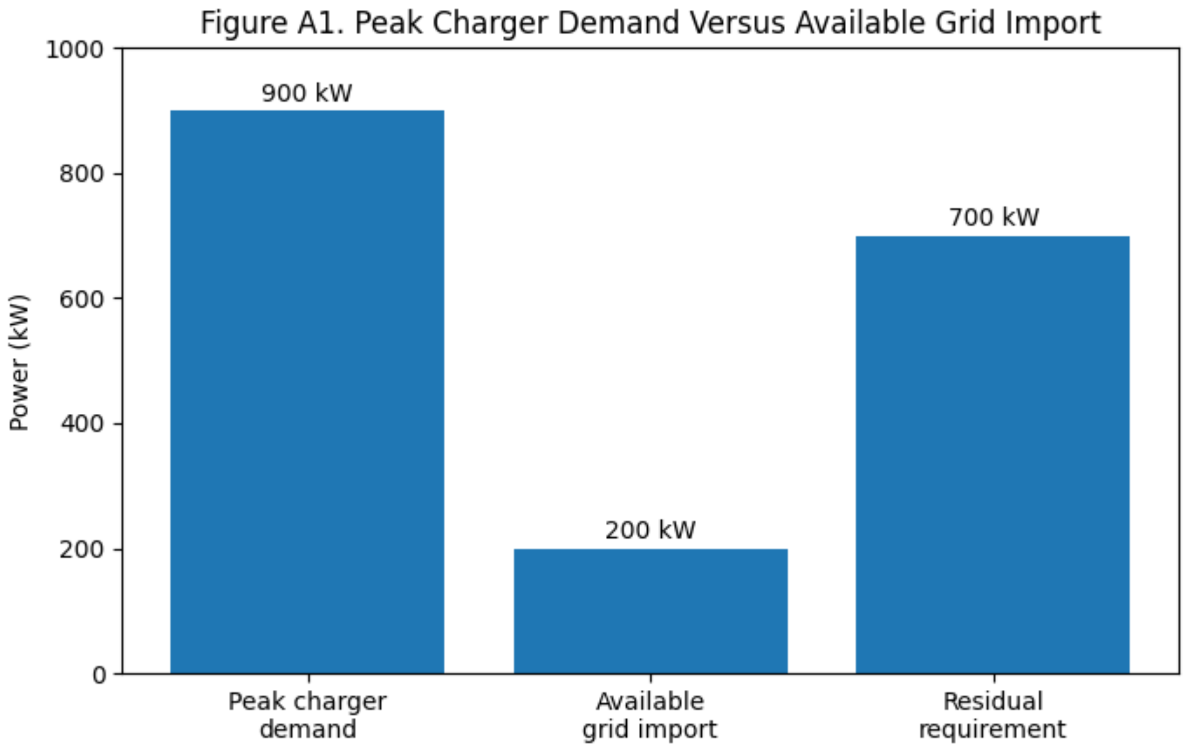

Figure A1. Peak Charger Demand Versus Available Grid Import Comparison of the 900 kW peak demand from six 150 kW rapid chargers with the available 200 kW grid import. The figure shows the scale of the residual power requirement that must be supplied by the on-site architecture.

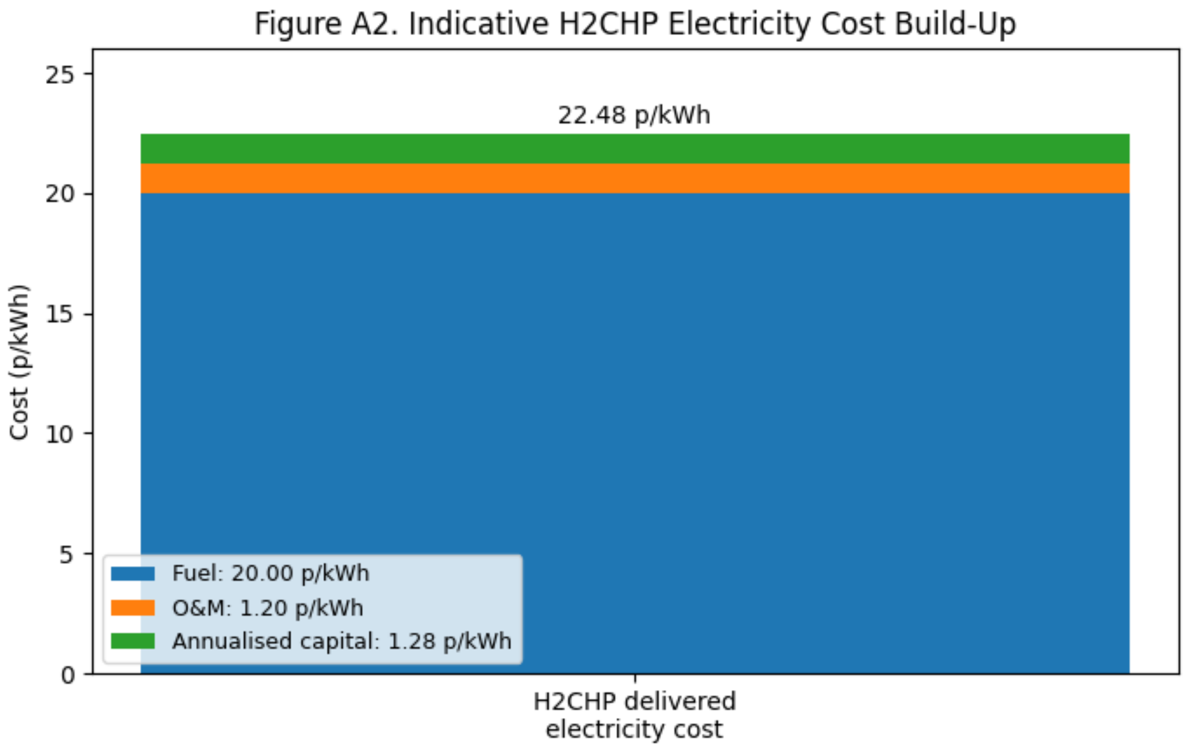

Figure A2. Indicative H2CHP Electricity Cost Build-Up Breakdown of the indicative delivered electricity cost from the H2CHP generator under the stated assumptions. Fuel is the dominant cost component (12p/kWh@60%, 20p/kWh) , with smaller contributions from O&M and annualised capital charge.

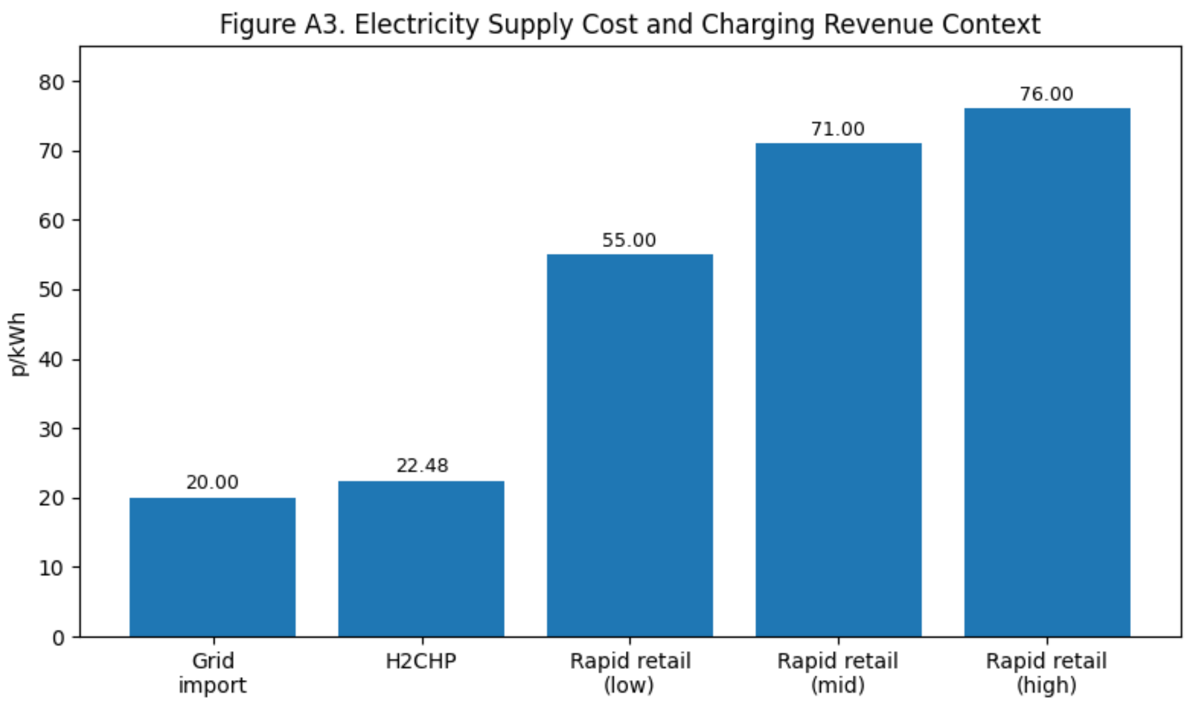

Figure A3. Electricity Supply Cost and Charging Revenue Context Comparison of constrained-grid electricity cost, indicative H2CHP delivered electricity cost, and representative UK rapid charging retail prices. The figure illustrates the commercial value of enabling charging throughput at constrained sites.

A15. Conclusion

This analysis shows that the H2CHP generator offers a compelling solution for rapid EV charging at grid-constrained sites.

In the representative case assessed here, six 150 kW chargers create a peak demand of 900 kW, while the available grid connection provides only 200 kW. A constrained-grid-plus-battery workaround can bridge that gap only by relying on a large energy-bearing battery of around 4 MWh, which must repeatedly cover the site’s energy deficit and then recharge through the same constrained connection.

The H2CHP architecture offers a fundamentally stronger solution. Rather than stretching limited grid capacity through a large battery, it introduces new on-site dispatchable power. Because the free-piston generator is designed to follow rapid changes in demand effectively, only a very small battery or flywheel is required for nuisance transients and switching events.

Under the assumptions used here, the H2CHP generator delivers electricity at an indicative cost of **22.48 p/kWh**, compared with an estimated **31–40 p/kWh** for the 200 kW grid plus 4 MWh battery workaround. On that basis, H2CHP is not simply a technically feasible option. It is a commercially stronger architecture for constrained sites whose objective is sustained high-power charging rather than occasional peak support.

That is the strategic significance of the H2CHP proposition: it converts a weak and constrained electrical connection into a platform capable of supporting meaningful rapid charging throughput, with lower dependence on reinforcement and without the burden of a very large battery-only workaround.

Appendix B. Hydrogen HCCI Simulation Study: Efficiency Potential and Emissions Control

B1. Purpose

This appendix summarises the hydrogen HCCI simulation work undertaken on the current crank-constrained Ricardo research engine in support of the H2CHP hydrogen development programme. The study examines hydrogen-only operation in order to assess the relationship between operating condition, indicated efficiency and NOx behaviour, and to identify the combustion regime most relevant to further development.

B2. Position of the Study

The results presented in this appendix relate to a Ricardo research engine used for hydrogen combustion development and should be interpreted on that basis. They do not represent the final H2CHP commercial linear generator design. Their purpose is to inform combustion understanding, operating-window selection and subsequent development priorities.

B3. Scope of the HCCI Study

The hydrogen HCCI study considers hydrogen-only operation across a range of equivalence ratios on the present crank-constrained Ricardo research engine. The case considered here corresponds to a compression ratio of 29:1, with intake conditions fixed and equivalence ratio used as the principal variable.

The study is useful because it defines the central trade-off in the hydrogen development programme. As fuelling is increased, output rises, but emissions increase sharply and efficiency falls. Conversely, lean hydrogen operation offers the most favourable combination of indicated efficiency and low NOx. The significance of the study therefore lies in identifying the operating regime most relevant to subsequent development.

B4. Key Results

Table B1. Summary of hydrogen HCCI simulation results

Equivalence ratio (φ)	Peak gas pressure	Indicated power	Indicated specific fuel consumption	Indicated thermal efficiency	NOx
0.2	46.86 bar	14.51 kW	55.07 g/kWh	54.5%	26.45 ppmvd
0.3	63.46 bar	20.08 kW	57.44 g/kWh	52.2%	1,849 ppmvd
0.4	75.83 bar	24.37 kW	60.85 g/kWh	49.3%	14,510 ppmvd
0.5	86.14 bar	28.66 kW	62.43 g/kWh	48.1%	17,389 ppmvd

The simulation results show a consistent pattern. As equivalence ratio increases, peak gas pressure and indicated power both rise. At the same time, indicated specific fuel consumption worsens, indicated thermal efficiency falls, and NOx increases sharply.

The leanest case, at φ = 0.2, produced the highest indicated thermal efficiency together with the lowest predicted NOx in the simulated set. This result indicates that the Ricardo research engine is capable of combining strong indicated efficiency with comparatively low predicted NOx under appropriately lean operating conditions.

B5. Interpretation

The study shows that hydrogen performance is highly sensitive to operating point, with marked differences in efficiency and emissions behaviour across the simulated range.

The leanest case is the most attractive because it combines the highest indicated thermal efficiency, the lowest specific fuel consumption, and the lowest predicted NOx. As the mixture becomes richer, output increases, but efficiency falls, fuel consumption rises, and NOx reaches levels that would be difficult to accommodate in a practical low-emission power product.

This is an important result, because it provides a clear basis for selecting the operating regime most relevant to subsequent development. The modelling indicates that the preferred direction for the hydrogen programme is lean operation under disciplined combustion control.

B6. Conclusions from the Study

Three conclusions may be drawn from the study.

1. Hydrogen HCCI is technically credible on the Ricardo research engine
The present crank-constrained Ricardo research engine exhibits analytically credible hydrogen HCCI behaviour and provides a sound basis for further combustion development.

2. High efficiency potential is visible under lean operation
The simulated results indicate that hydrogen operation can achieve strong indicated efficiency under appropriately lean conditions. This does not represent final system efficiency, but it is sufficient to demonstrate that the underlying combustion direction is technically promising.

3. Emissions control is highly dependent on operating regime
The NOx response is strongly sensitive to equivalence ratio. The study therefore indicates that the route to a commercially viable hydrogen product depends not simply on hydrogen operation itself, but on selecting and controlling the appropriate operating regime.

B7. Strategic Implications for H2CHP

The simulation work materially strengthens the technical case for the H2CHP hydrogen programme.

First, it supports the decision to focus on hydrogen-only operation. The modelling shows that hydrogen is a technically viable fuel for the present development engine and is capable of delivering strong indicated efficiency under lean conditions.

Second, it indicates that the principal challenge is one of optimisation rather than basic feasibility. The engine can produce attractive results under the right conditions; the task is therefore to develop the machine and control system so that operation can be maintained consistently in that region.

Third, it identifies an important route to differentiation. A hydrogen linear generator that combines strong efficiency with acceptable NOx through disciplined operating-window control would represent a technically and commercially differentiated product.

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B8. Figures

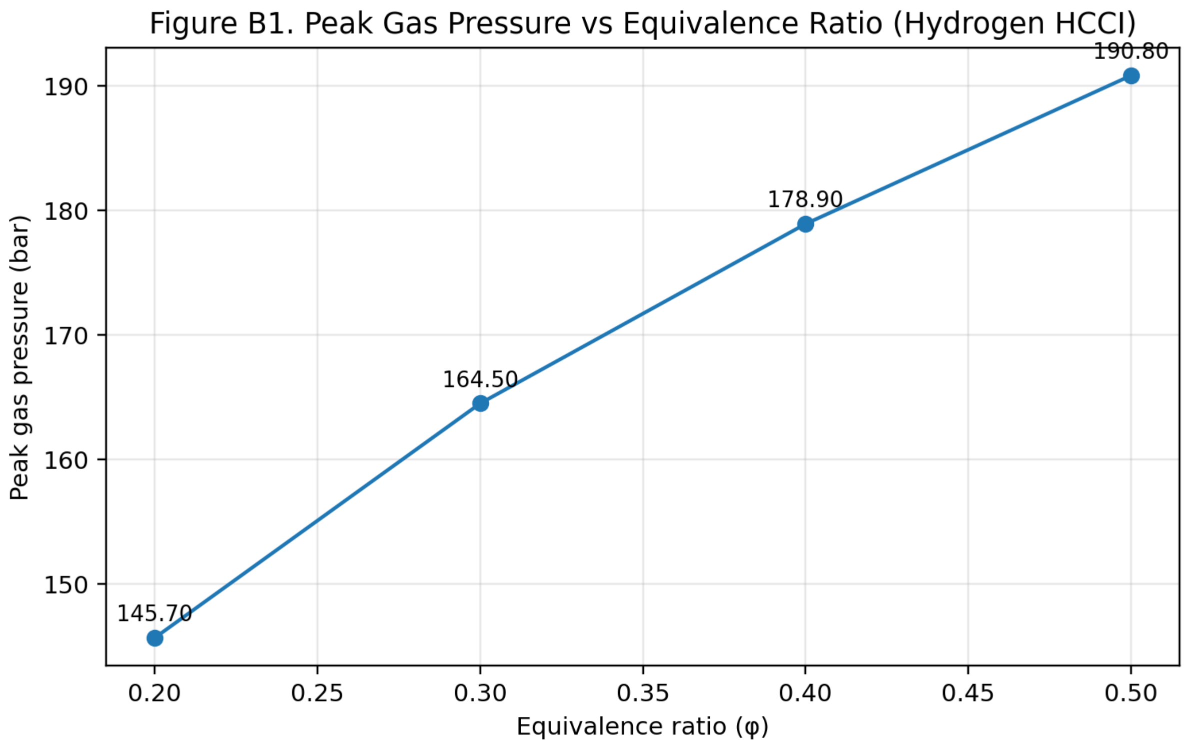

Figure B1. Predicted peak gas pressure for hydrogen HCCI operation at different equivalence ratios. Peak pressure rises as fuelling increases.

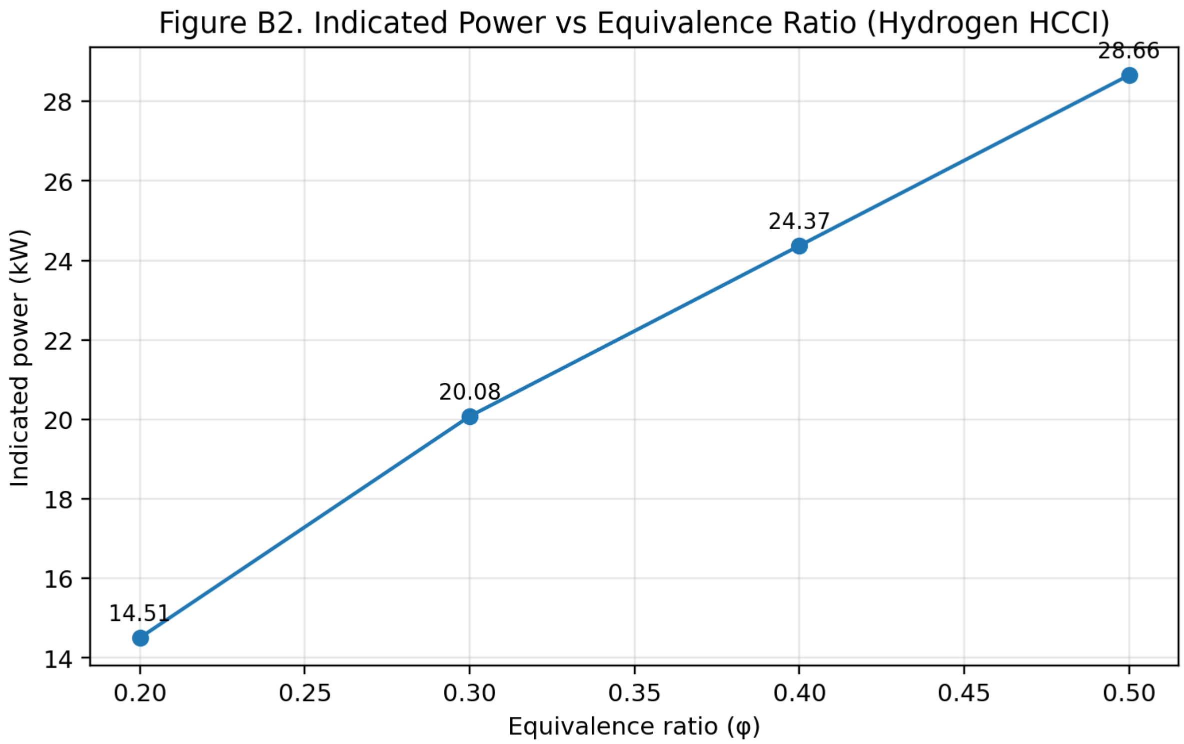

Figure B2. Predicted indicated power for hydrogen HCCI operation at different equivalence ratios. The model shows increasing output as the mixture becomes richer.

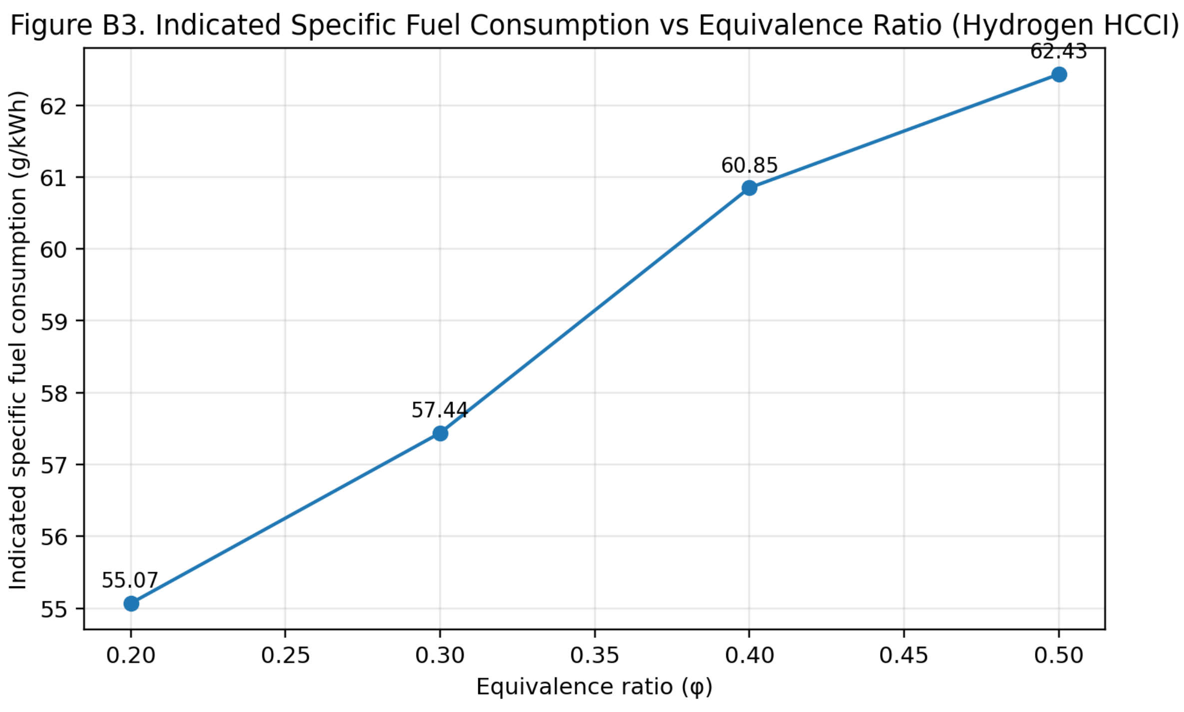

Figure B3. Predicted indicated specific fuel consumption for hydrogen HCCI operation at different equivalence ratios. Fuel consumption per unit of output increases as the mixture becomes richer.

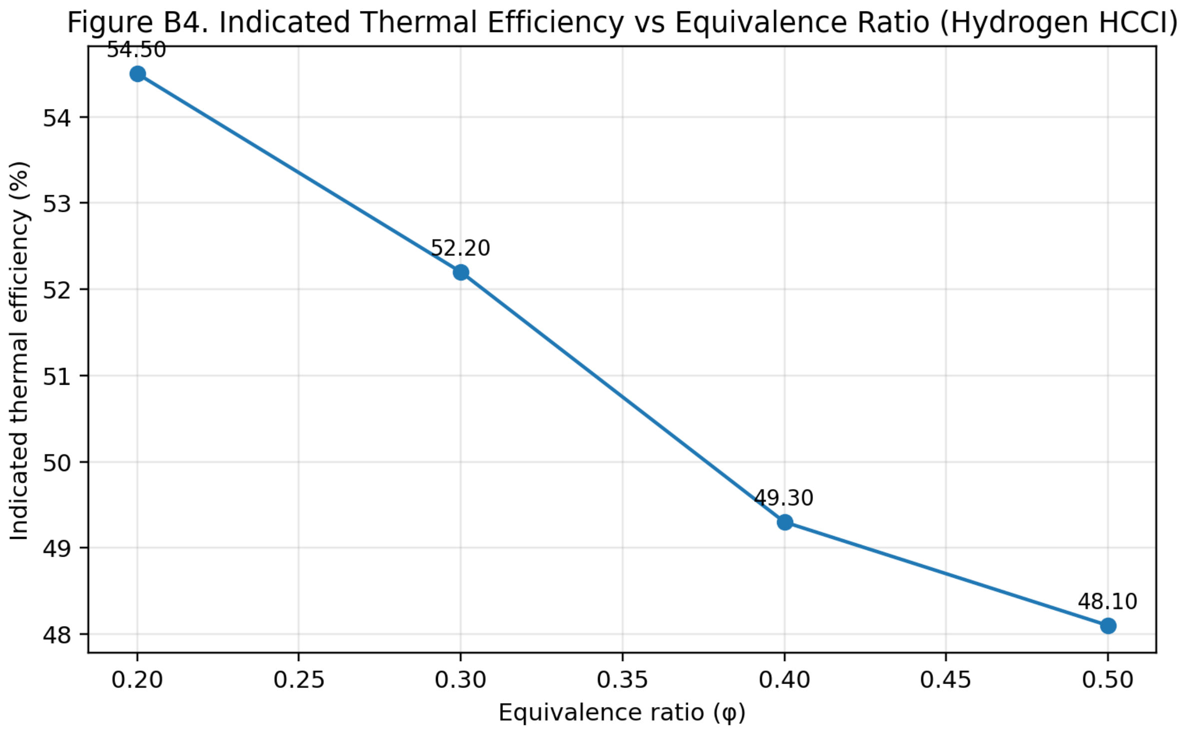

Figure B4. Predicted indicated thermal efficiency for hydrogen HCCI operation at different equivalence ratios. The highest efficiency occurs in the very lean case.

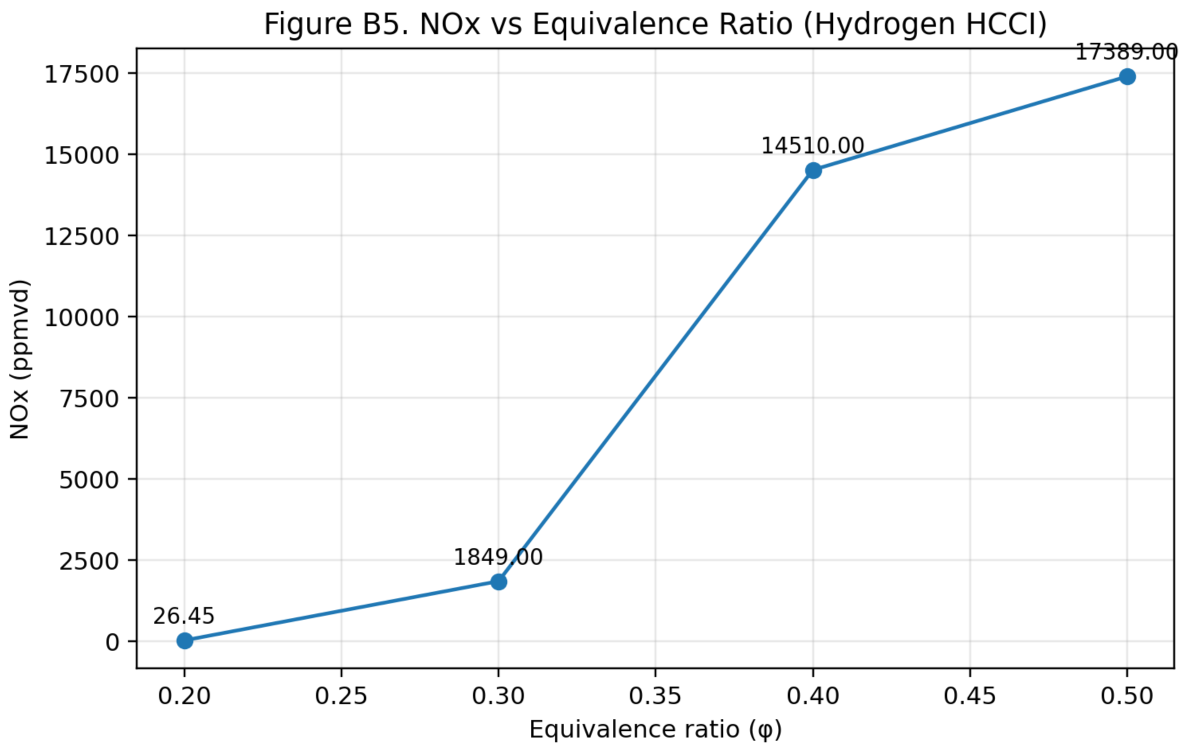

Figure B5. Predicted NOx for hydrogen HCCI operation at different equivalence ratios. The figure shows the sharp increase in NOx as the mixture becomes richer.

B9. Limitations

The simulation work should be interpreted with the following points in mind. It relates to a crank-constrained Ricardo research engine rather than the final H2CHP commercial design. It provides combustion-level and indicated-performance outputs rather than a validated net electrical efficiency for the complete generator package. It should therefore be understood as analytical support for the hydrogen programme rather than as experimental validation. Its value lies in informing combustion understanding and identifying the operating regime most relevant to subsequent development.

B10. Conclusion

The hydrogen combustion simulation work provides a strong analytical basis for the H2CHP hydrogen programme. It shows that hydrogen-only operation on the Ricardo research engine is technically credible and capable of meaningful indicated efficiency. It also shows that the emissions case depends strongly on operating regime and that maintaining reasonable NOx is inseparable from combustion control and operating-window selection.

The most important conclusion is that lean hydrogen operation offers the most favourable combination of indicated efficiency and predicted NOx within the simulated range. Taken together, the results support the technical promise of the H2CHP approach and identify a clear direction for the next phase of development.

Appendix C. Hydrogen Test, Initial Data Collection and Validation at CEME

C1. Purpose

This appendix records the first successful hydrogen-running campaign completed at CEME and sets out its technical significance for the H2CHP linear generator programme. The purpose of this phase was to demonstrate controlled hydrogen operation on the current development rig, confirm that the hydrogen fuel system and safety architecture functioned correctly under live conditions, and collect the first instrumented dataset linking hydrogen combustion events to generated electrical output.

This phase was not intended to represent the final performance of the H2CHP linear generator. It was designed as a controlled first hydrogen-running campaign that moves the programme from hydrogen readiness into live operation and establishes a credible basis for the next stage of development

C2. Test Configuration

The hydrogen tests were conducted on the current development rig in a deliberately conservative first-fire configuration. The objective of this phase was to establish safe, controlled and repeatable hydrogen operation before extending the operating window or increasing load.

The test conditions were therefore selected to prioritise ignition control, operating stability and safe progression rather than power maximisation. The resulting dataset should be interpreted in that context.

C3. Test Outcome

Hydrogen ignition was achieved successfully and the linear generator was run repeatedly on hydrogen under controlled conditions. The campaign established:

- successful hydrogen ignition;
- repeatability of ignition and short-duration hydrogen running;
- stable operating speed during the test window;
- useful electrical power generation from the linear electrical machines;
- satisfactory live behaviour of the hydrogen supply and shutdown architecture.

This is a meaningful development milestone. It demonstrates that the H2CHP linear generator has moved beyond hydrogen-readiness work and cold commissioning into genuine live hydrogen operation with instrumented data capture.

C4. Data Collected

The principal data collected during the test campaign included:

- cylinder pressure trace;
- spark current trace;
- injector control signal;
- spark trigger signal;
- electrical power output from the LEMs;
- operating speed and run duration;
- associated operating observations.

The recorded traces show a coherent sequence of injector actuation, spark event and pressure response. The pressure rise following the ignition event is clearly distinguishable from the background compression behaviour, confirming genuine hydrogen-fired combustion rather than simple motoring.

C5. Measured Electrical Output

The initial hydrogen campaign produced measurable electrical output under live hydrogen firing.

This result should be interpreted as an early proof-of-operation milestone rather than as a statement of final architecture performance. The campaign was conducted under deliberately conservative first-fire conditions selected to establish safe and repeatable hydrogen operation on the current development rig.

C6. Interpretation of the Measured Power

The measured electrical output obtained in this campaign was produced under deliberately conservative first-fire conditions and is therefore not representative of the intended H2CHP linear generator architecture. The significance of the result lies in the fact that live hydrogen firing, repeatable operation and useful electrical generation were all demonstrated on the rig.

This is important because it confirms the core direction of travel of the programme. The immediate objective of the campaign was not to maximise output, but to establish controlled hydrogen operation and generate the first live dataset from which broader optimisation can proceed. In that sense, the result is best understood as a de-risking milestone: it demonstrates that the linear generator can be ignited and operated on hydrogen in a controlled and repeatable manner, and that the next phase can focus on extending the operating window and increasing output under more representative conditions.

C7. Technical Significance

The significance of the campaign lies not in the absolute power number alone, but in what it demonstrates technically and strategically.

The campaign shows that:

- the hydrogen supply and safety architecture functioned correctly under live conditions;
- the linear generator can be started and operated on hydrogen;
- hydrogen operation can be repeated in a controlled way;
- useful electrical output can be generated under live hydrogen firing;
- the programme has now advanced into measured hydrogen operation.

That is a substantial milestone. It provides a credible technical foundation for the next stage of development, including broader operating-window exploration, improved control integration, higher fuelling levels and more representative running conditions.

C8. Limitations of the Immediate Campaign

This first hydrogen-running phase was intentionally narrow in scope. It did not attempt to deliver:

- full performance mapping;
- full efficiency mapping across the operating envelope;
- emissions characterisation;
- durability assessment;
- application-level operating profiles.

Those outputs remain part of the broader development pathway, but they were appropriately outside the scope of this first live hydrogen campaign.

C9. Conclusion

The initial hydrogen test campaign at CEME successfully demonstrated controlled live hydrogen operation on the H2CHP development rig and produced the first measured dataset linking hydrogen combustion events to generated electrical output.

The electrical output obtained in this first-fire campaign should not be interpreted as representative of the intended H2CHP linear generator architecture. The campaign was conducted under deliberately conservative conditions chosen to establish safe and repeatable operation. In that context, the result is technically significant and commercially encouraging. It shows that the H2CHP linear generator has moved beyond preparation and cold commissioning into genuine live hydrogen operation, and it establishes a credible basis for the next phase of development and performance growth.

C10. Figures

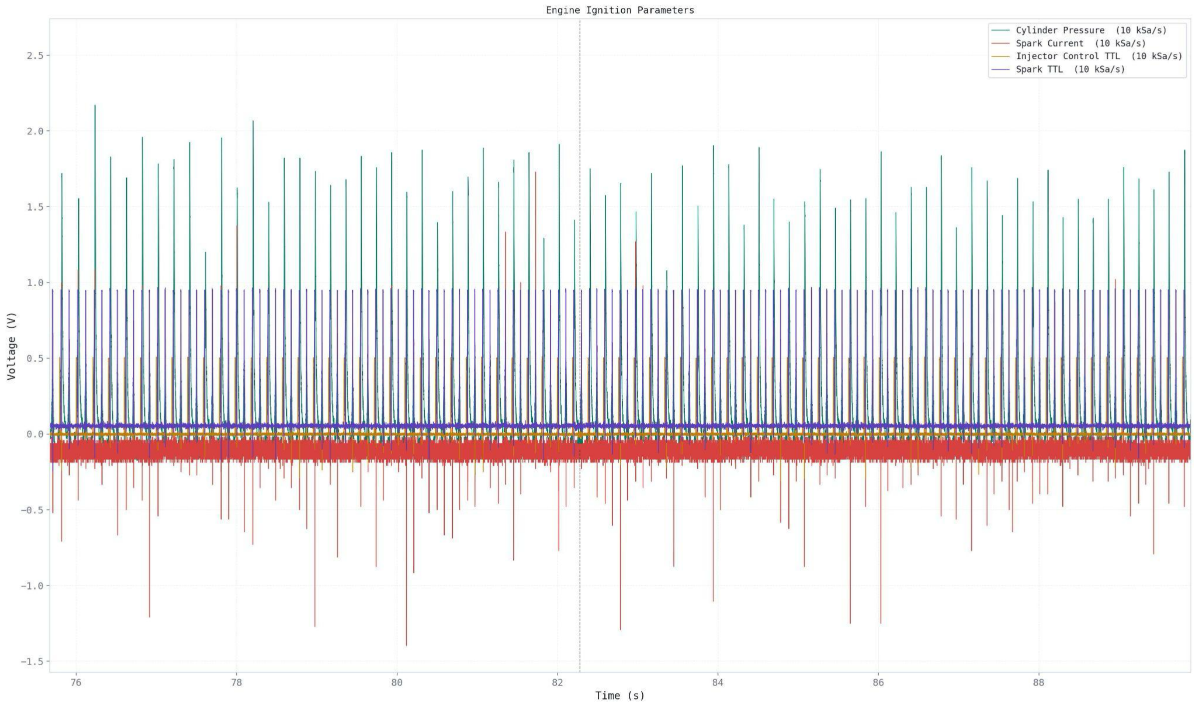

Figure C1. Plot of engine ignition parameters during run showing stable operation

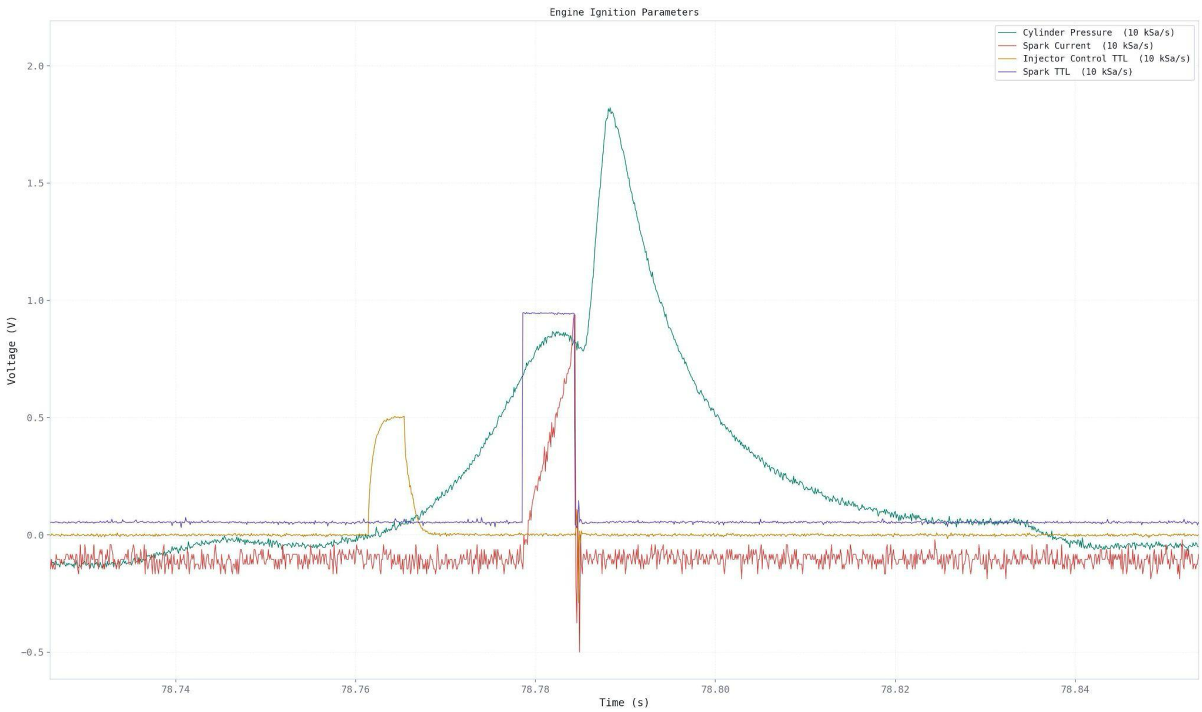

Figure C2. Plot of engine ignition parameters for single combustion event

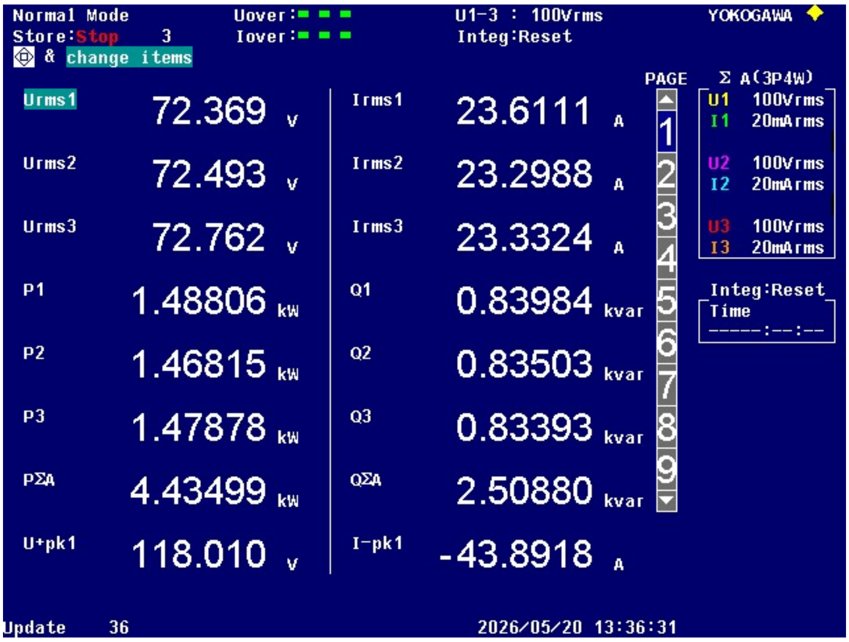

Figure C3. Data capture for single cycle showing LEM power generation

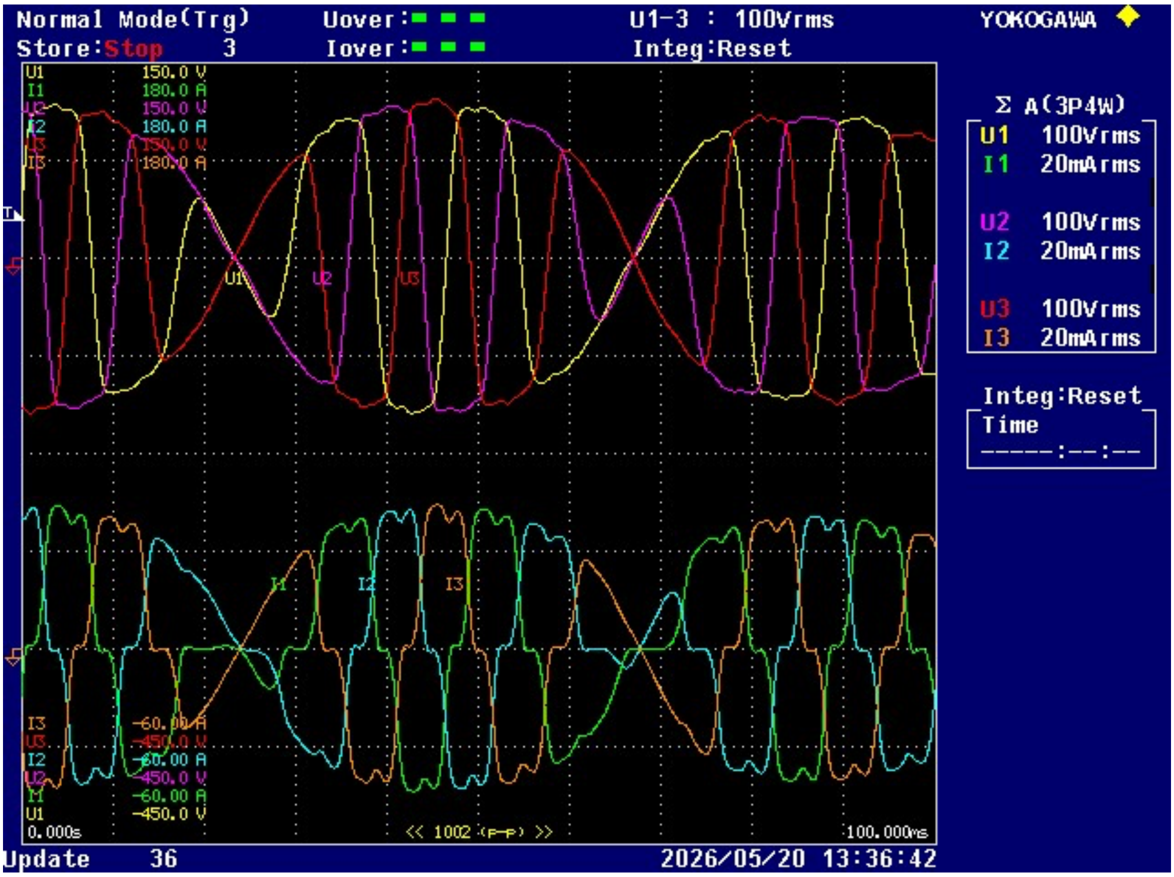

Figure C4. Plot showing continuous LEM power generation