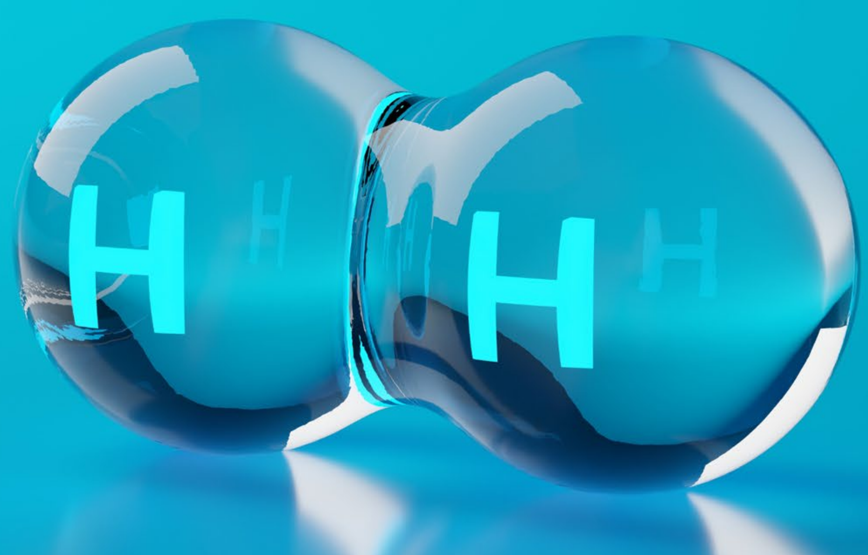
BEIS Low Carbon H_2 Supply 2 Competition - HS2135

Microwave Energy System for Distributed Hydrogen Production from Natural Gas with Very Low CO_2 Emissions

Feasibility Study Report

October 2022



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1. Executive Summary

Hydrogen is the most abundant element in the universe and is poised to play a key role in the coming low Carbon economy. Suiso has developed a breakthrough microwave-energy based process for the low cost on-site or distributed production of Hydrogen from Natural Gas or Bio Gas with very low CO_2 emissions. The Suiso process combines microwave energy with a low cost Reaction Initiator (RI) to crack the feed gas into Hydrogen and solid Carbon. CO_2 emissions from the process is estimated at less than 5% that of Steam Methane Reforming (SMR) while electrical usage will be less than 20% that of Electrolysis. The produced Carbon is a stable solid that permanently sequesters the Carbon, unlike gaseous CO_2 storage, and can be sold as Carbon Black generating additional income to lower Hydrogen costs.

The objective of this Phase I project was to mature the pre-Phase I concept into an FEL-2 level engineering design and assess the technical and economic feasibility of the developed design. Additional lab-scale experiments were conducted which resulted in a significant technical innovation. A detailed Phase II plan for pilot-scale demonstration and a commercialization strategy were developed. Key outcomes are:

1. **Suiso technology is technically feasible**
   - A reactor concept was developed and a feasibility assessment concluded that the required balance of plant process operations are readily available.
   - New RI was developed showing 95%+ conversion enabling a simpler system.
   - Safety assessment of the system concluded that it can be safely operated but metallurgy, dust control and other areas must be further assessed.

2. **Suiso technology is economically feasible**
   - Levelized Cost of Hydrogen Production (LCOH) for the Suiso technology (£125/MWh-H_2 LHV) is lower than that of a 1MW (£211/MWh-H_2LHV) and 10MW PEM electrolyser (£160/MWh-H_2 LHV).
   - When CO_2 from electrical generation is included, Suiso emits less CO2 than electrolysis (3kg vs. 17kg CO_2 /kg-H_2) and can yield a net reduction of 17kg CO_2/kg-H_2 from avoided emissions.
   - Suiso requires almost no infrastructure improvements and can scale production to match demand, eliminating oversized upfront investments and lowering operating costs leading to faster availability of Hydrogen.

3. **Commercial market entry is possible in 3 years and will make an impact**
   - Suiso plans to sell its first commercial systems in 2025 and by 2032 it expects to have sold systems with a combined production capacity of over 6.7 TWhr-H_2 LHV/year resulting in a potential reduction over 3M tonnes CO_2 /year.

4. **Phase II will represent the last development step prior to commercialization**
   - Phase II will see the field demonstration of a large pilot system to validate the technology at a relevant scale. Suiso has assembled a world-class project team and identified a potential site for the field demonstration.

5. **Substantial Dissemination Efforts Made**
   - Over 50 outreaches were made during Phase I to industry participants, academics, investors, governmental and industry bodies and others.

2. Glossary

B	Billion
BEIS	Department for Business, Energy & Industrial Strategy
BOP	Balance of Plant
CAPEX	Capital Expenditure
CCUS	Carbon capture, utilisation and storage
CHA	CHA Corporation
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPI	Centre for Process Innovation
EBITDA	Earnings Before Tax, Depreciation and Amortization
FEL-1	Front End Loading 1
FEL-2	Front End Loading 2
H_2	Hydrogen
Hr	Hour
HS1	Health and Safety Review 1
HS2	Health and Safety Review 2
IEA	International Energy Organization
IRR	Internal Rate of Return
Kg-H_2	Kilogram Hydrogen
Kg/hr	Kilogram per Hour
Kw-Hr	Kilowatt Hour
LCOH	Levelized Cost of Hydrogen Production
LHV	Lower Heating Value
LOC	Limiting Oxygen Concentration
M	Million
M^3	Cubic Meter
MHz	Mega Hertz
MWHr	Megawatt Hour
MWHr-H_2	Megawatt Hour Hydrogen
OPEX	Operating Expense
P&ID	Process & Instrumentation Diagram
PPA	Power Purchase Agreement
PEM	Proton Exchange Membrane
RI	Reaction Initiator
SMR	Steam Methane Reformation
T&S	Transport and Storage
Therm	British thermal unit
TWhr	Trillion Watt Hour
VAT	Value Added Tax

3. Phase I Overview

3.1 Introduction

Suiso has developed a breakthrough microwave-energy based process for the low cost on-site or distributed production of Hydrogen from Natural Gas or Bio Gas with very low CO_2 emissions. The Suiso process combines microwave energy with a low cost Reaction Initiator to crack the feed gas into Hydrogen and solid Carbon.

CO_2 emissions from the process is estimated at less than 5% that of Steam Methane Reforming (SMR), which is the most common means of producing Hydrogen today. Electrical usage will be less than 20% that of Electrolysis, making the Suiso process very cost effective. The produced Carbon is a stable solid that permanently sequesters the carbon, unlike gaseous CO_2 storage, and can be sold as Carbon Black or into other higher value uses generating additional income to lower Hydrogen costs.

Suiso is optimizing its technology for smaller-scale distributed generation with a focus on efficient stop/start-cyclical operations to minimize the need for expensive storage facilities. It is not reliant on new large-scale infrastructure investments and can be installed into almost any location that has available Natural or Bio Gas and electricity thereby accelerating widespread availability of Hydrogen and the development of a Hydrogen economy across the UK and world-wide.

The objective of the proposed Phase I project was to complete Front End Loading (FEL-1 and FEL-2) engineering studies of Suiso's microwave technology and assess the technical and economic feasibility of the resultant system design. Further objectives for Phase I were to develop a detailed Phase II plan for pilot-scale demonstration of the technology and a commercialization strategy following completion of Phase II.

3.2 Distributed Hydrogen Generation

Hydrogen is the most abundant element in the universe and is widely used in the chemical processing industry. It is poised to play a key role in the coming low Carbon economy as a medium for energy generation, storage and transfer. One of the earliest sectors expected to adopt Hydrogen as a fuel will be the transport industry, especially in commercial vehicles (Hydrogen Insights, Hydrogen Council & McKinsey 2021) which will require a widespread network of Hydrogen fuelling stations.

The primary production methods of Hydrogen are currently large-scale SMR, Methane Pyrolysis, and increasingly Electrolysis, which produce large quantities of Hydrogen in centralized complexes near the end user, usually a refinery or steel mill. However, to use these assets to feed a dispersed fuelling network will require costly investments for Hydrogen pipelines, storage tanks, and dispensing infrastructure. The magnitude of the capital and operating costs for this infrastructure represents one of the primary barriers to Hydrogen adoption. While this infrastructure will ultimately come into place and will deliver the lowest cost Hydrogen, it may take decades before it can be justified by actual demand.

On-site distributed Hydrogen production can avoid these barriers. Hydrogen is produced with smaller, low cost production systems at or near the point of usage which eliminates the need for expensive pipeline distribution networks and substantially lowers the need for expensive storage facilities. Additional capacity can be easily added as demand grows; no need for costly upfront investments into large oversized plants years before actual market need. As the market matures, these production assets may ultimately be displaced by pipelines but given the massive breath of the current fuelling network, this may take decades and it is likely that distributed generation will continue to occupy a significant market niche into the foreseeable future in areas where pipeline Hydrogen is not economically competitive.

3.3 Suiso Technology Summary

The Suiso process is shown in Figure 1 below. A gas feed, either natural gas or biogas, is heated to approximately 500-600ºC then introduced into a microwave reactor which contains a Reaction Initiator. When microwave energy is applied, the RI quickly heats and the gas feed pyrolyzes into Hydrogen and Carbon as it contacts

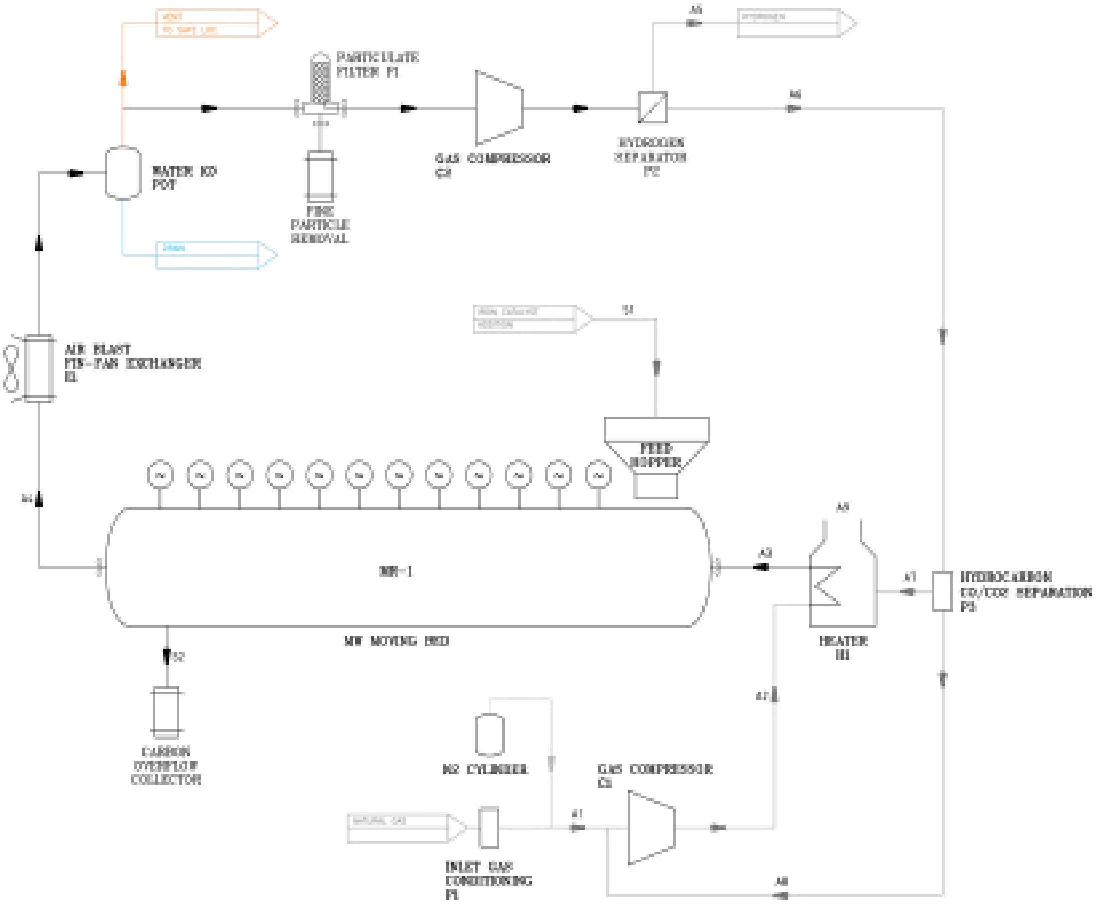

Figure 1 Suiso Overall Process Flow Diagram

the RI. The Hydrogen is purified to over 99.9% purity and the Carbon is sold as a product. A detailed description of the process is presented in Section 5.

Pyrolysis is a highly endothermic process and thus requires significant energy. Approximately 20% of the process energy is used to heat the feed gas to the reaction temperature and 80% of the energy is used by the pyrolysis reaction. In conventional pyrolysis, reaction temperature is typically over 1,000°C and all of the process energy is provided by combustion which leads to high CO_2 emissions. In the Suiso process, the heat of reaction is provided by microwave energy and CO_2 is only produced by the gas fired preheater which heats the incoming feed gas to just 600°C. As a result, Suiso believes direct CO_2 emissions from its process are at least 80% lower than that of conventional pyrolysis and 95% lower than that of SMR, where all carbon is converted into CO_2.

Suiso believes that a key advantage of its technology is that it is well suited to the stop/start-cyclical nature of onsite production. Microwaves are amongst the most efficient and fastest means of heating solid materials and as a result, reactor start-up is very fast and the system can also 'throttle' production up or down without suffering significant loss of efficiency. This process flexibility will substantially reduce the amount of Hydrogen that must be stored as "bridge H_2" to ensure continuous supply, thereby reducing expensive storage costs.

3.4 Phase I Objectives & Approach

Specific deliverables for the Phase I project are:

- FEL-2 design study of a 500 kg-H_2/day Suiso system.
- Technical and Economic Feasibility Studies of the developed system.
- Commercialization Plan to bring Suiso technology to market.
- Phase II project plan and impact assessment.
- Engineering design of a 120 kg-H_2/day pilot unit for Phase II

The overall strategy to meet the Phase I objectives was to conduct FEL-1 engineering evaluation of potential system configurations, select the optimal configuration and develop a FEL-2 engineering design study of the selected concept. This resultant design served as the basis for the economic feasibility assessment, development of a detailed Phase II plan and development of a commercialization plan to bring the technology to market after the completion of Phase II.

Additional lab-scale process data was collected during the technical evaluation stage to ensure the FEL-2 design efforts were based on a strong experimental foundation. Product Carbon samples were produced and evaluated by a potential customer to confirm marketability of the end products.

4. Technical Feasibility Assessment

4.1 Microwave Reactor Feasibility Assessment

Two potential conceptual microwave reactor designs were developed and assessed, a vertical reactor configuration and a horizontal reactor configuration.

The horizontal bed concept was assessed to be superior to the vertical configuration and a horizontal reactor configuration was developed in the FEL-2 design study. In this configuration, microwave energy is injected into the top of the reactor through quartz windows and slotted waveguides, both of which are mature technologies. A bed of reaction initiator is located underneath the quartz and serves as the primary pyrolysis reaction zone. The reactor dimensions to enable the target gas residence time in the RI bed appear acceptable and the gas velocity through the RI bed can be kept below the limit to minimise Carbon entrainment in the product gas. The biggest challenge of the horizontal system is the solids handling system which must feed fresh RI into the reactor while removing the product Carbon. The RI must be of a shape and size that it can flow through the reactor with minimal mechanical assistance.

4.2 System Feasibility Assessment

A system feasibility assessment was conducted by Centre for Process Innovation (CPI) who reviewed the overall process and balance-of-plant (BOP) requirements to determine if technologies already exist that can be deployed to affect the desired physical and/or chemical changes needed for the system to operate.

The study concluded that the required process operations do exist and are either readily available or can be obtained with reasonable levels of customization. A summary of the results is shown in Table 1 below.

Table 1 CPI BOP Feasibility Assessment

Process Step	Comments	Conclusion
Gas Filtration/Prep	• Well understand and characterized process • Wide availability of suitable equipment	**Technically Feasible**
Gas Preheat	• Well understand and characterized process • May need to consider custom solution given size and service conditions	**Technically Feasible**
Compressor	• Well understand and characterized process • Wide availability of suitable equipment but may have to oversize due to minimum size requirements	**Technically Feasible**
Product Gas Heat Exchange	• Well understand and characterized process • May need to consider custom solution given size and service conditions	**Technically Feasible**
Gas-Gas Separator	• Pressure Swing Adsorption looks the most promising/feasible, • Integration with system should be considered carefully	**Technically Feasible**

4.3 Reaction Initiator Development

A four-month study was conducted to develop a solid particle form RI material which can drive efficient microwave pyrolysis of Methane while still being able to flow through a horizontal reactor. Multiple candidate particulate materials were tested and a new material was found to be the most effective RI material. Testing of this new RI material demonstrated that a **single pass conversion of 95% may be attainable** and product gas recycle may not be required.

A sample test result is shown in Figure 2 where the new RI material achieved 95%+ conversion of Methane into Hydrogen and Carbon over a period of nearly three hours before slowly declining. Also shown is a test result from the original CHA study with powder form RI (the best performing RI in the study) showing the new particle RI performs nearly as well as the powder form RI. **This is a significant advancement in the technology.**

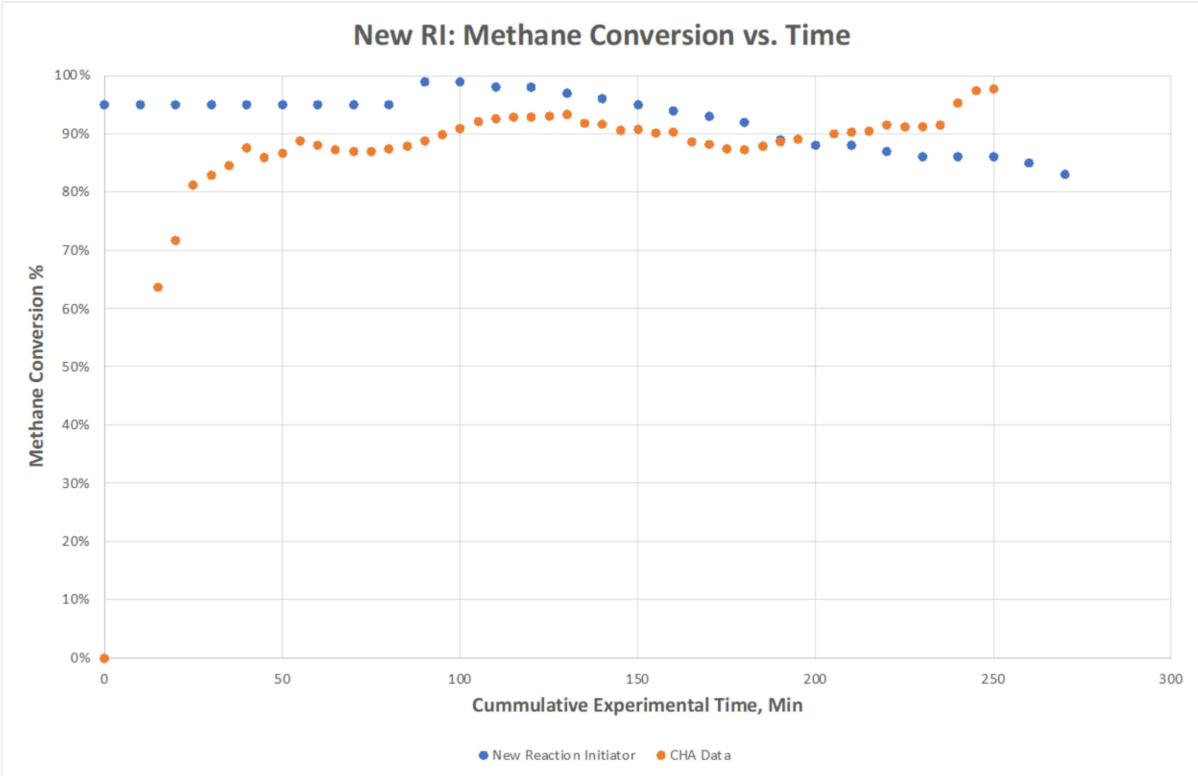

Figure 2 Methane Conversion Test with New Reaction Initiator

4.4 Product Carbon Assessment

Kilogram-scale Product Carbon samples were produced and sent to a potential customer for evaluation. A photo of the collected sample is shown in Figure 3.

The customer indicated that with some upgrading, the Carbon could be sold as a carbon black replacement. Currently they receive about £1.0/kg for recycled tyre Carbon Black and believe the Suiso Carbon can receive this price or better.

Suiso believes future process tuning can improve the characteristics of the Carbon even further and open higher value applications.

Figure 3 Product Carbon Sample

5. Conceptual Engineering Design Study

5.1 Design Basis

The basis for the FEL-2 study was a 500 kg-H_2/day capacity system.

5.2 System Material Balance System

The system mass balance was developed based on 95% single pass conversion of the feed gas into Hydrogen. Tests with the new RI developed in the Phase I program (see Section 4) confirmed the feasibility of this conversion efficiency.

This single pass conversion is higher than the original concept presented in the Phase I application of 80% but with a higher overall conversion of 98% with recycle of unconverted Hydrocarbons. The new assumption allows the removal of the recycle step making the overall system simpler to operate but results in a slightly higher CO_2 generation of 0.83 kg-CO_2/ kg-H_2 from the new system concept versus 0.56 kg-CO_2/ kg-H_2 from the original concept.

The system material balance is shown below in Table 2.

Table 2 500 kg/Day Material Balance

Component	Inlet (kg/hr)	Outlet (kg/hr)
Methane	76.4	3.8*
Ethane	15.9	0.8*
Hydrogen		21.3
Carbon		65.1
Carbon Monoxide		3.1*
Iron Oxide	5.9	
Iron		4.1
Totals	**98.2**	**98.2**

*CO and unconverted Methane, ethane are combusted for process heat which produces CO_2 at the rate of 17.7 kg-CO_2/hr. No additional fuel gas is needed.

5.3 System P&ID

The Suiso Process & Instrumentation Diagram (P&ID) for a 500 kg-H_2/day system is shown in Appendix 1 500 Kg-H_2/Day System P&ID. Feed gas enters the system and water and other liquids are removed in knock-out vessel V-001 before being compressed by compressor C-001 and fed into a second vessel V-002 to remove any liquids that may have formed during compression. The compressed feed gas is passed through a gas-fired heater H-001 and heated before entering the microwave reactor. The selected design is a shell and tube heat exchanger with a gas fired burner.

The feed gas is fed into the microwave reactor R-001 where it pyrolyzes into Hydrogen and solid Carbon. The product gas exits the microwave reactor and is first cooled by air cooled heat exchanger E-001 then passes through a filtration system V-003A where entrained solids are removed. The filtration is by a cyclone with a bag filter. The product gas is then compressed by compressors C-002 and C-003 before entering into a Pressure-Swing-Adsorption system where Hydrogen is separated from the other gases. Target purity for the Hydrogen system is 99.9% or higher.

5.4 Microwave Reactor Design

A microwave reactor concept was developed and refined to FEL-2 level.

The reactor is comprised of a cylindrical housing with solids inlet and outlet sections at opposite ends of the reactor tube. Microwave energy is produced by microwave generators and injected into the reactor. A perforated solids containment tray is located inside the reactor and runs the total length. Reaction Initiator is fed into the entry chamber of the reactor from a Nitrogen purged feed lock hopper, falls onto the containment tray and is distributed down the length of the reactor.

Feed gas enters at the bottom of the reactor then flows upward through the excited RI bed where it pyrolyzes into Hydrogen and Carbon. The product gas exits the top of the reactor for cooling and Hydrogen separation. A small quantity of Carbon can be entrained in the gas which must be removed from the gas before separation. The product Carbon remains in the reactor and from time to time, the product Carbon is removed from the reactor and into a containment vessel.

5.5 HS1, HS-2 Safety Assessment

A safety assessment, Health & Safety Level 1(HS-1) and Health & Safety Level 2 (HS-2), of the system design concept was conducted as part of the FEL-2 study. A team of experts from CPI and Suiso reviewed each process step; identified the major process hazards and where possible proposed mitigation strategies to control them to a broadly acceptable level of residual risk. If this was not possible, then further analysis was recommended to demonstrate the reduction of the risk is managed to an acceptable level. Review and detailed design of the proposed mitigations will be conducted in later stages of design engineering. The overall conclusion of the assessment is that the system can be safely operated but specific areas, including metallurgy selection, dust handling, and oxygen ingress prevention, must be further developed and assessed.

6. Economic Feasibility Assessment

6.1 Lifecycle Cost Analysis

The lifecycle costs of a 500kg H_2 per day Suiso system were assessed.

The input assumptions into the lifecycle cost analysis are shown in Table 3 below. The cost figures for electricity and natural gas prices are lower than current levels but were selected to match the values used in a 2021 BEIS analysis (BEIS, 2021) to allow for use of the electrolysis and SMR LCOH calculated by BEIS in the benchmarking analysis.

Table 3 LCOH Analysis Inputs

Parameter	Value
Feedstock Hydrocarbon Conversion	95%
Uptime & Availability	90%
Operating Weeks/Year	47
Natural gas	£0.57/therm
Electricity	£0.09/kw-hr

The costed Suiso system was based on the detailed mass & energy balances and P&IDs developed by Suiso and CPI. The reactor costs were provided by CHA Corp. while the BOP subsystems costs were estimated by Suiso with vendor inputs. Commonly accepted engineering factors were used to calculate piping, integration and automation, and site preparation costs. Total annual operating costs for a 500kg H_2/day system include costs for feedstocks, electricity, RI materials, maintenance and other operating items. End of life of the system is assumed after 15 years. The company expects that the system can be refurbished for resale or reuse by Suiso. End of life costs for returning the site to original conditions are assumed as the same as the site prep costs.

6.2 LCOH Benchmarking

The lifecycle costs were used to calculate the Levelized Cost of Hydrogen production for the Suiso system. The analysis utilized the calculation method outlined in the BEIS analysis (BEIS, 2021).

The Suiso LCOH cost was benchmarked against large (10MW) and small (1MW) Proton-Exchange Membrane (PEM) electrolysis and SMR with Carbon capture, utilisation and storage (CCUS). The data for the large scale PEM and SMR with CCUS was obtained from the BEIS document for the year 2025 (BEIS, 2021). The figures for the small scale PEM electrolyser were calculated by Suiso from the BEIS data. The comparison of LCOH for each generation method is shown in Table 4 below.

Table 4 LCOH (£/MWh H_2 LHV)

	Suiso	**PEM Electrolysis (10MW)**	**PEM Electrolysis (1MW)**	**SMR with CCUS**
Design Capacity	0.5 tons/day	4.5 tons/day	0.5 tons/day	180 tons/day
CAPEX	28	12	14	12
Fixed OPEX	19	5	4	4
Variable OPEX	20	4	5	0
Electricity cost	24	140	189	0
Fuel cost	33	0	0	35
CO_2 T&S cost	0	0	0	7
Carbon cost	1	0	0	2
Total LCOH	**125**	**160**	**211**	**60**

Based on the BEIS methodology, the LCOH for the Suiso technology is lower than the LCOH for a 10MW and 1MW PEM electrolyser. This is due primarily to the lower electricity usage in the Suiso process which is less than 1/5 that of electrolysis. The Suiso LCOH is higher than the forecasted 2025 LCOH for SMR with CCUS. However, the SMR LCOH does not include costs for distributing the Hydrogen to the point of usage and when these costs are added, which have been estimated at £70/MWh-H_2 LHV (European Commission, 2021), the SMR LCOH is higher than that of the Suiso system.

One factor that can skew the analysis is the assumed price of natural gas. To determine if Suiso is competitive in a high natural gas price environment, the Suiso LCOH was recalculated using a natural gas price of £1.00/therm which increased the total LCOH to £152/MWh-H_2 which is still below electrolysis costs. Therefore even in a high gas price environment, Suiso LCOH is lower than electrolysis and potentially lower than large-scale SMR once transport and distribution costs are included.

This analysis did not include the cost of local compression and storage prior to dispensing. The Suiso process will deliver Hydrogen at approximately 5-10 bar while PEM electrolysis can deliver Hydrogen at 30 bar or higher. Typical Hydrogen dispensing pressures are about 300 bar. However, these costs are expected to fall and not expected to increase the LCOH materially in the long term (BEIS, 2021).

6.3 Commercial Benchmarking

A second analysis was conducted to benchmark the commercial attractiveness of the Suiso system against competing technologies. This analysis included factors such as capital intensity and total revenues to assess the commercial competitiveness of Suiso's technology to the technologies listed below in Table 5.

Table 5 List of Benchmark Technologies

Technology	Large, centralized scale	Small, distributed scale	Example Company
PEM electrolysis (Polymer electrolyte membrane)	Yes	Yes	NEL
Methane pyrolysis (thermo-catalytic)	Yes	No	Hazer Group
Microwave plasma	No	Yes	HiiRoc Ltd.
Steam methane reforming (SMR)	Yes	No	Generic process (e.g. BASF)

A list of input assumptions into the benchmarking analysis and a description of each competing technology with data sources are presented in Appendix 2 Benchmarking Assumptions.

For each technology the following parameters were calculated:

- Capital cost to install a plant (CAPEX).
- Total operating cost including maintenance, fuel, electrical power, transportation and other costs (OPEX)..
- CO_2 emissions
- Revenue generation – Total revenues from Hydrogen and by-products.
- Electrical usage
- Natural gas usage

An Internal Rate of Return (IRR) was then calculated for each technology based on the CAPEX and OPEX costs. All calculated metrics were normalized to a per kilogram unit of Hydrogen produced basis to allow for direct comparison. The results are shown in Table 6.

The results of the commercial benchmarking analysis show that the Suiso technology is potentially commercially superior to the alternative technologies. For small-scale distributed production, the Suiso process is the only process that can generate a positive IRR at a Hydrogen price of £3.0/kg because of the added carbon sales (Carbon price assumed at £0.9/kg). Microwave plasma is near breakeven at this price due to the assumed sales of CO_2 (price assumed at £0.7/kg) from the process. However, plasma processes have traditionally suffered from low single-pass efficiency and selectivity and require high levels of power resulting in high operating costs (Bailey, Nov. 2020).

Table 6 Commercial Benchmarking Results

	Distributed Production Technology			Central Production Technology		
	Suiso	Electrolysis (Small)	MW Plasma	Thermo-Catalytic	Electrolysis (Large)	SMR
Hydrogen Production (Tons/day)	0.5	0.5	1.0	200	300	200
By-product Production (Tons/day)	Carbon 1.5	N/A	CO_2 1.25	Carbon 590	Oxygen 3	N/A
Rev. (£/ kg-H_2)	5.33	3.00	4.68	5.43	6.03	3.00
CO_2 Emission (Kg-CO_2/kg-H_2)	0.83	0	0	2.0	0	9.3
CAPEX (£/kg-H_2)	7.10	5.20	7.44	3.05	5.40	4.23
OPEX (£/kg-H_2)	3.63	6.00	4.76	2.63	5.71	2.96
Electricity (£/kg-H_2)	0.62	4.2	1.26	0.14	3.64	0.03
Natural Gas (£/kg-H_2)	1.51	N/A	2.12	2.22	N/A	2.55
Breakeven H_2 Price, (£/kg-H_2)	1.5	6.00	3.08	0.20	2.69	2.96
IRR based on H_2 Price £3.0/kg-H_2	27%	N/A	N/A	50%	4%	-6%

The Suiso process also appears very competitive to the large-scale technologies. Thermo-catalytic is the lowest cost means of production and when revenues from Carbon sales are included, the breakeven price of Hydrogen is £0.20/kg-H_2. However, large-scale technologies like thermo-catalytic require transportation and storage of the Hydrogen at the point of use which is estimated to cost from £1-3/kg-H_2, depending on the distance and method of transport (European Commission, 2021). When these costs are included, the Suiso process becomes commercially competitive to Thermo-catalytic.

Large scale electrolysis benefits from the sale of Oxygen (price assumed at £0.4/kg) but IRR is very low (5%) at the baseline electrical cost. Under the conditions of this analysis, SMR even without CCUS does not appear economically attractive. While the LCOH analysis showed a cost equivalent to £2.0/kg-H_2, when adjusted for the higher gas price in the benchmarking, this increases to £2.6/kg-H_2. The remaining difference between the LCOH and the calculated breakeven price £2.9/kg-H_2 is due to assumptions on capital and operating cost. This is substantially higher than Suiso's breakeven price which is lowered by Carbon sales.

6.4 Energy Usage and CO_2 Emissions

Suiso has the lowest electricity usage amongst the small-scale distributed technologies (8 kw-hr/kg-H_2). Electrolysis is the highest (60 kw-hr/kg-H_2) followed by microwave plasma (18 kw-hr/kg-H_2). An average of 290 g CO_2 is emitted per kw-hr of electricity used from conventional generation (BEIS, 2021). When this CO_2 is included, the Suiso process emits less CO_2 (3kg CO_2/kg-H_2) than electrolysis (17kg CO_2/kg-H_2) or plasma (23kg CO_2/kg-H_2). A net reduction of up to 17kg CO_2/kg-H_2 is possible when avoided emissions from displacing Hydrocarbon fuel (11kg CO_2/kg-H_2) and conventional Carbon Black (~9kg CO_2/kg-H_2 (Abdallas Chikri, 2020)) is factored in.

6.5 Low Cost Hydrogen Scenario

A number of scenarios were examined to find a commercially viable path to a Hydrogen price of £1/kg utilizing gas and electricity price assumptions from the benchmarking analysis. Under these conditions, Suiso can generate a 20% IRR provided it reduces CAPEX costs by 30% and increases Carbon pricing to £1.2/kg. If natural gas prices remain at current high levels (£1.00/therm), the £1/kg Hydrogen price is achievable if product Carbon price increases to £1.35/kg.

Suiso believes CAPEX costs can fall by 30% or more over the next 10 years. The technology is still at an early stage and costs should naturally fall as production volumes increase though increased purchasing power over suppliers, more efficient system designs, and efficiencies gained through experience. Suiso also believes that higher Carbon prices are achievable. Since Carbon Black price is tied to the price of natural gas, current Carbon Black prices are 20-30% above long-term average (Waverly Carbon, Private Analysis, June 2022). The availability of Carbon credits to the product Carbon could also bring Carbon price to the target level.

7. Commercialization Strategy

7.1 Suiso Business Description

Suiso's business is the design, production, marketing & sales and service of proprietary systems for the production of Hydrogen and Carbon from Natural gas or Bio gas. Suiso systems will be sited at or near the point of use and generate Hydrogen 'on-demand', minimizing the need for expensive Hydrogen distribution and storage. A depiction of a Suiso installation is shown in Figure 4 below.

At the start of commercialization where Hydrogen demand is emerging, Suiso will sell systems and Reaction Initiator materials (RI) to customers who are likely to be in the fuelling station business. Suiso will also offer Carbon collection and processing services to system operators. As Hydrogen demand grows, especially in commercial transport applications, Suiso will offer Hydrogen production services to customers who require Hydrogen but do not wish to own and operate a system. In this model Suiso will install and operate a production system at a customer site and sell Hydrogen to the user.

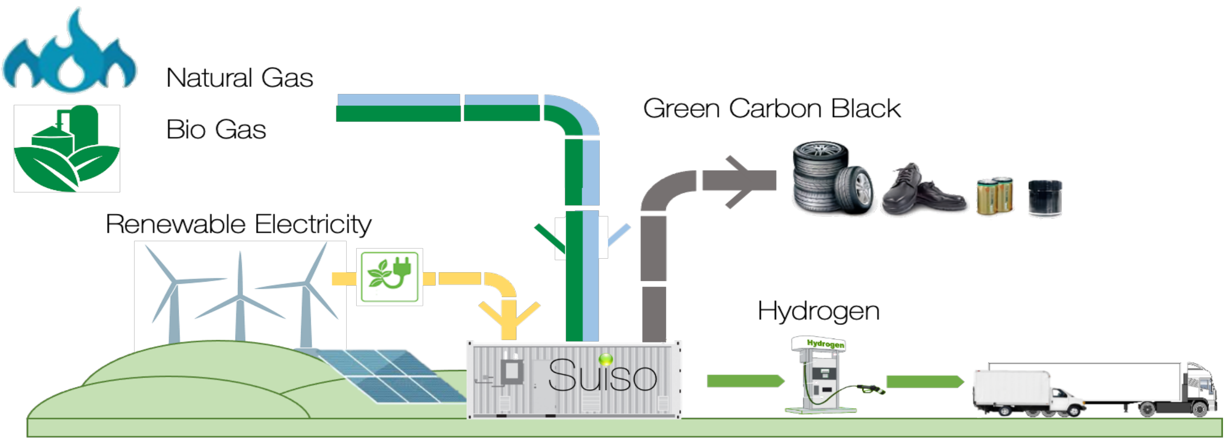

Figure 4 Suiso Installation Concept

7.2 Target Customers

Suiso target customers for its Hydrogen production systems are Hydrogen fuelling station operators. The number of Hydrogen fuelling stations is projected to grow rapidly from about 700 stations worldwide ([IEA, 2020]) in 2022 to over 10,000 by 2030 ([McKinsey 2021]). Suiso estimates that Hydrogen fuelling stations targeting commercial transportation, which are often remote, could be as high as 30% of the total station population. This creates a market for Suiso of potentially 3,000 sites by 2030.

Suiso target customers for its Hydrogen production service are large fleet operators who must fuel large numbers of vehicles but do not wish to operate Hydrogen production systems. By using Carbon sales to lower Hydrogen prices, the customer receives lower cost Hydrogen while reducing capital expense and avoiding complex system operations. Suiso believes these customers will begin to emerge in the mid-2020s and grow rapidly as governments enforce tighter CO_2 reduction policies.

7.3 Route to Market

Suiso will market, sell and deliver its systems and Hydrogen production services directly to potential customers. Installation and startup support will be provided by Suiso engineers. Post-sales support will be provided directly by Suiso in the UK while third parties may be contracted to provide after sales service outside the UK. Suiso will operate systems for on-site merchant supply of Hydrogen. RI materials will be sold and shipped directly from Suiso to the system operator. Suiso may market the product Carbon directly to Carbon Black customers or use third party distributors.

7.4 Production Strategy

Suiso's core production activity is the design and fabrication of Hydrogen production systems. The microwave reactor is a core intellectual property asset of Suiso and its design and assembly will be kept inhouse. Balance-of-plant sub-systems (e.g. heaters, gas separators, and heat exchangers) will be purchased from external suppliers and integrated with the reactor into the final system at Suiso's facilities. Suiso will also control RI production and supply. Suiso will utilize qualified contract manufacturers to produce the RI materials who will ship the RI in bulk to Suiso where it will be packaged in moisture-proof containers before sending to system operators.

7.5 Commercialization Roadmap

Suiso has developed a 3 year plan to commercialize its technology after Phase I.

2023-25 Pilot Demonstration: Suiso will build and demonstrate a 120 kg-H_2/day pilot unit and begin initial marketing of systems to prospective customers.

2025 System Production & Sales: Suiso will accelerate marketing to potential customers from mid-2024. First system deliveries are targeted for Q4 2025.

2027 Hydrogen Production Services: Following launch of the system business, Suiso will begin marketing on-site merchant production services globally to fleet operators with first customer installations targeted for 2027.

With the lower CAPEX and OPEX costs of the Suiso system and by nearly eliminating the need for large-scale infrastructure investments, Suiso expects to have sold systems with a combined production capacity of over 200,000 tonnes H_2/year (6.7 TWhr-H_2 LVH per year) by 2032.

7.6 Business Feasibility

A 10-year financial model was built based on the commercialization roadmap. The model shows that Suiso can create an attractive business with and IRR of close to 40%.

8. Phase II Demonstration Project

Suiso has developed a detailed Phase II plan which will see Suiso and its partners design, build and field demonstrate a large pilot system to validate the performance, operability and economic viability of its technology at a relevant scale. Phase II will represent the last major technology development step prior to commercialization.

8.1 Phase II Objectives and Approach

The project objectives for Phase II are:

- Design and build a 120 kg-H_2/day pilot system (approximately 50% scale of first commercial system).
- Field demonstrate the pilot system to prove operability and performance.
- Collect data to inform design of the first commercial scale system.
- Confirm market value of the Hydrogen and Carbon products.

To achieve the Phase II project objectives, Suiso has developed a program comprised of 11 work packages which will last a total of 22 months. The project will include a 6 month field demonstration. The deliverables from the Phase II project are (1) Detailed engineering design of a 120 kg-H_2/day Hydrogen production system (2) Operational 120 kg-H_2/day pilot system that meets performance targets (3) 6 month demonstration program and (4) Final report containing:

- Operating performance summary (e.g. uptime, conversion, energy efficiency, CO_2 emissions).
- Updated process economics based on actual field performance data.
- Customer evaluation of product Hydrogen and Carbon.
- Safety assessment of the pilot system.
- Scale-up and commercialization plan to launch business.

8.2 Phase II System Design

The mass balance for a 120 kg-H_2/day system is shown below in Table 7.

Table 7 Pilot System Material Balance

Component	Inlet (kg/hr)	Outlet (kg/hr)
Methane	17.9	0.9*
Ethane	3.7	0.2*
Hydrogen	-	5.0
Carbon	-	15.3
Iron Oxide (RI)	1.4	-
Iron	-	0.9
Carbon Monoxide	-	0.7*
Total	**23.0**	**23.0**

*CO and unconverted Methane, ethane are combusted for process heat which produces CO_2 at the rate of 4.2 kg-CO_2/hr. No additional fuel gas is needed.

The pilot system will be comprised of a microwave reactor and all BOP process steps found in a full commercial system. The P&ID scheme for the pilot unit is identical to that of the 500 kg H_2/day system shown in Appendix 1 500 Kg-H_2/Day System P&ID. However, the pilot system will not be a strict scale-down of the larger system but is oversized in sections to allow for more flexibility during the development phase, or in some instances where subsystems are below the size at which "off-the-shelf" units are available, larger available units have been selected to avoid the long lead time and cost of customized equipment.

Prior to the detailed design and build of the pilot system a 60 kg/H_2 per day pre-pilot test unit (PPT) system will be built and tested to validate the design concepts. The results of the PPT test program will be used to optimize the pilot system design.

8.3 Phase II Schedule

In total, the project will require 22 months to complete, with the final report delivered to BEIS in month 23. The proposed start date for the work on 01/02/2023 with an end date before 01/02/2025.

8.4 Phase II Partners

Suiso has assembled a world-class project team who together have all key capabilities required to successfully execute Phase II including gas supply, Hydrogen system integration, Carbon Black processing and distribution as well as taker for all H_2 produced during the pilot. Suiso has agreed a Letter of Intent with the Gas network partner and received confirmation of interest in the pilot from the other partners.

8.5 Phase II Site

Suiso has identified a potential site for the Phase II field demonstration located at Dunfermline, Scotland. Located approximately 1 mile South of the city, the site is over 6 acres in size, and is used as a depot for maintenance operations. A satellite image of the site is shown in Figure 5 Phase II Dunfermline Site.

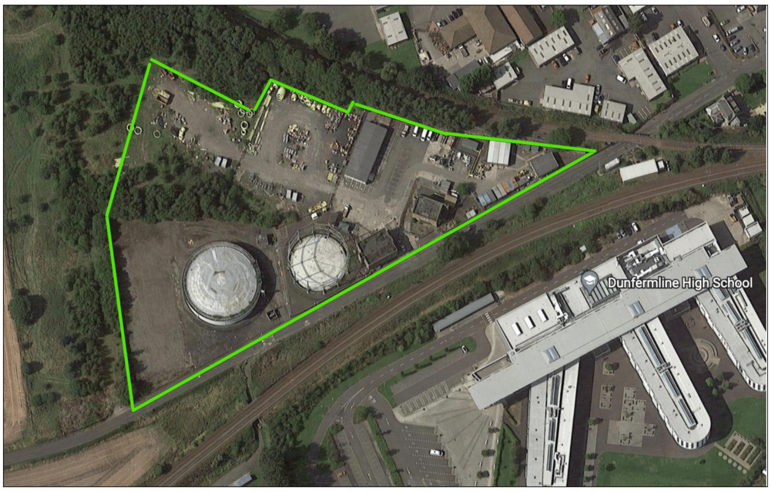

Figure 5 Phase II Dunfermline Site

8.6 Phase II Impact

The Phase II project is an essential step towards commercial deployment of Suiso's technology and will accelerate development of a Hydrogen economy by demonstrating that Suiso's low cost distributed Hydrogen production technology is ready for commercial use. The Phase II project will provide hands-on experience with a fully integrated system to enable development of standard operating procedures for start-up, operations, shutdown and maintenance. It will enable a full-scale HAZOP study to identify potential safety and operational risks.

Phase II will also enable engagement with potential customers. The pilot demonstration will provide large-scale performance data to further refine economic models and demonstrate to customers and other stakeholders that the technology is ready for commercial deployment. Potential customers of the product Carbon will receive large quantities of samples to validate its commercial value.

9. Benefits of Successful Commercialization & Barriers

Benefit 1 Suiso can deliver the lowest cost production of Hydrogen. The analysis presented in Section 4 shows that the Suiso process will have a LCOH lower than small or large scale electrolysis. The Suiso LCOH is higher than large-scale SMR with CCUS but if distribution costs to the point of usage are included, SMR is more expensive than the Suiso system. Beyond LCOH, Suiso systems can deliver Hydrogen at the point of usage without costly infrastructure investments and can scale production to match demand leading to faster deployment and lower costs.

Benefit 2 Rapid growth of Hydrogen production capacity where it is needed. The UK's current focus is to create Hydrogen clusters in just six major areas (Element Energy, 2021) which will potentially leave substantial parts of the country without access to Hydrogen. Given the cost advantages discussed above, Suiso will make Hydrogen economically viable in these areas and accelerate deployment of a widespread fuelling network essential to commercial transport.

Benefit 3 Substantial CO_2 emissions reductions. By 2032 Suiso expects to have sold systems with a combined production capacity of over 200,000 tonnes H_2/year (6.7 TWhr-H_2 LVH per year). Every kg of Hydrogen produced by a Suiso generator reduces CO_2 emissions by just over 17kg CO_2 for a total reduction over 3M tonnes CO_2 /year by 2032.

Benefit 4 Pathway to de-carbonise Bio Gas production. Approximately 3% of UK gas production comes from Bio Gas. As pipelines transition to Hydrogen, producers will seek technology to convert Bio Gas to Hydrogen which could deliver approximately 200 tonnes H_2/day. Suiso technology is ideal for these smaller often remote sites and will protect these renewable assets from obsolescence.

Barrier 1 Real but manageable technical engineering challenges. Suiso's scale-up strategy will seek to minimise the complexity of each scale-up step by making incremental changes to the sizes of the reactor and balance-of-plant subsystems. The Phase II project is a key enabler in this strategy.

Barrier 2 Green Carbon Black Incentives in the UK and Worldwide are needed. Carbon Black production generates 15-20B kg of CO_2 year (Abdallas Chikri, 2020). Suiso is unaware of any existing or pending scheme to incentivize the industry to reduce its CO_2 emissions. Any scheme that increases the demand for Suiso's green Carbon Black will significantly lower the price of Hydrogen.

Barrier 3 Need to modify the RTFO scheme to recognize validity of Power Purchase Agreements (PPAs) for Bio Gas supplied via the gas grid. The UK Government revised requirements in 2021 to allow green Hydrogen producers use PPAs as evidence that producers have purchased renewable energy. Suiso would like a similar arrangement to allow the purchase of Bio Gas from a producer which is then shipped to the usage site by pipeline. Suiso believes this modification will potentially accelerate the transition of Bio Gas industry to Bio Hydrogen production.

10. Dissemination

Suiso has undertaken substantial dissemination efforts during the Phase I feasibility project to introduce Suiso's novel microwave driven methane pyrolysis technology and its potential to accelerate the development of the Hydrogen economy to a wide range of audiences spanning private companies, government agencies, leading academic entities and financial institutions. Additional outreaches are planned to follow the completion of Phase I.

In summary, 19 outreaches were made to Industry Participants, e.g. potential customers, suppliers and partners; 8 direct contacts were made to academic institutions in the UK and abroad; 22 outreaches were made to financial entities and potential investors; 3 engagements with governmental bodies; and further 3 were made to industry bodies and trade organizations.

In addition, Suiso has augmented this focussed approach with ad-hoc opportunities to communicate to wider groups. It has participated in Hydrogen focused conferences regarding investment in the sector, H_2 supply broking, H_2 supply chain development and it will be an exhibitor at the London Climate Tech Conference in early October.

These dissemination efforts have already yielded positive results, securing significant for the Phase II project. Potential investors have also been identified as well as early expressions of interest from potential university development partners for further research and development of Suiso's input and output materials.

After completion of Phase I, Suiso has a number of outreaches planned including:

- Press release announcing completion of Phase I
- Exhibitor at the London Climate Tech Conference in early October.
- Additional corporate interactions
- Investor presentations
- Presentations to additional Academic institutions.

Finally, Suiso has used its website as a wide area communication vehicle. While available content is limited due to the confidential nature of the current development phase, it does set out basic descriptions of the company's mission, technology and participation in the BEIS Low Carbon Hydrogen Supply Program. Suiso will add substantially more content after the completion of Phase I which will further extend its dissemination reach.

11. Conclusions

Suiso technology is technically feasible.

- A horizontal microwave reactor concept was developed that can meet the key process requirements, e.g. residence time, gas velocity.
- A new Reaction Initiator was developed which showed 95%+ conversion and appears suitable for use in Suio's reactor.
- A safety assessment of the system concept concluded that the system can be safely operated but specific areas must be further developed and assessed.

Suiso technology is economically feasible.

- The LCOH for the Suiso technology (£125/MWh-H_2 LHV) is lower than that of a 1MW (£211/MWh-H_2 LHV) and 10MW PEM electrolyser (£160/MWh-H_2 LHV).
- It is higher than SMR with CCUS but when distribution costs are included the SMR LCOH is slightly higher than that of the Suiso system.
- When CO_2 from electrical power generation is factored in, the Suiso process emits less CO_2 (3kg CO_2/kg-H_2) than electrolysis (17kg CO_2/kg-H_2).
- A net reduction of up to 17kg CO_2/kg-H_2 is possible when avoided emissions from displacing Hydrocarbon fuel (11kg CO_2/kg-H_2) and conventional carbon black (~9kg CO_2/kg-H_2 (Abdallas Chikri, 2020)) is factored in.

Commercial market entry is possible in 3 year and will make an impact.

- Suiso's business is the design, production, marketing & sales and service of systems for the production of Hydrogen and Carbon from Natural gas or Bio gas.
- Suiso allows capacity growth paced to demand growth, eliminating the need for large upfront investments into production plants oversized to market demand, ultimately enabling faster Hydrogen deployment at significantly lower costs.
- Commercialization is possible in 3 years and a 10-year model shows that Suiso will deliver an IRR of nearly 40%.
- By 2032 Suiso expects to have sold systems with a combined production capacity of over 200,000 tonnes H_2/year (6.7 TWhr-H_2 LVH per year) resulting in a potential annual reduction over 3M tonnes CO_2 /year.

Phase II will represent the last development step prior to commercialization.

- Phase II will see the design, build and field demonstration of a pilot system to validate the performance, operability and economic viability of its technology at a relevant scale.
- Suiso has assembled a world-class project team who together have all key capabilities required to successfully execute Phase II and identified a potential site for the Phase II field demonstration located at Dunfermline, Scotland.

Government policy can help Suiso and others enter the market faster

- Green Carbon Black Incentives in the UK and Worldwide are needed. Any scheme that increases the demand for Suiso's green Carbon Black will significantly lower the price of Hydrogen while decreasing CO_2 emissions.

- Allowing Suiso and other Hydrogen producers to use PPAs as evidence that they have purchased renewable Bio Gas and claim credits under the RTFO scheme will accelerate the transition of the Bio Gas industry to Bio Hydrogen production.

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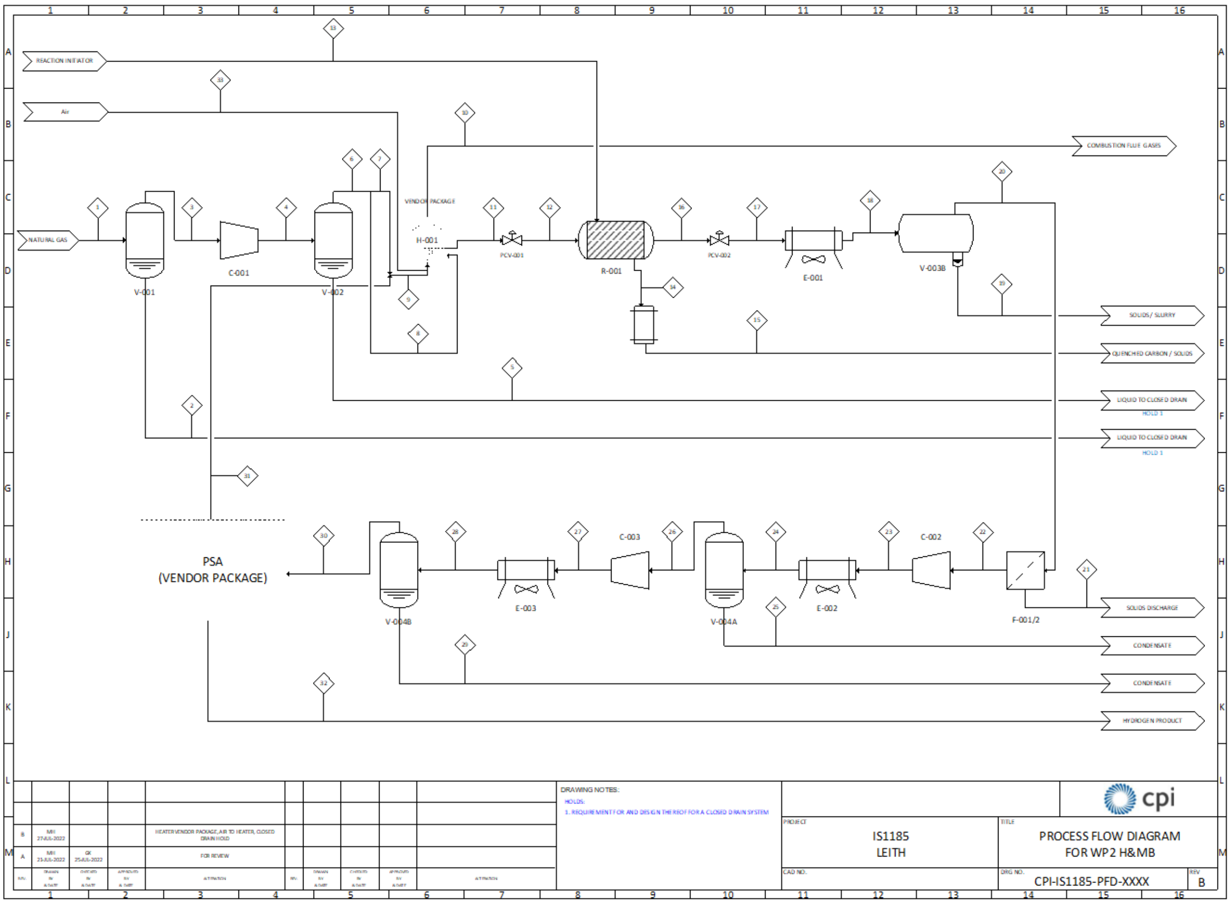
Appendix 1 500 Kg-H_2/Day System P&ID



P&ID Tag	Description
V-001, V-002, V-003b, V-004a, V-004b	Liquid knock-out vessels
C-001, C-002, C-003	Gas compressors
H-001	Gas preheater
R-001	Microwave Reactor
E-001	Air-cooled fin-fan gas heat exchanger
F-001	Particulate removal sub-system
E-002, E-003	Interstage compressor coolers
PSA	Pressure Swing Adsorption sub-system

Appendix 2 Benchmarking Assumptions

These assumptions used in the competitive benchmarking are shown below:

Assumption	Value	Units
GBP/EUR conversion rate	0.8391	GBP/EUR
GBP/USD conversion rate	0.8223	GBP/USD
Electrical price	7.00	p/KW.hr
Natural gas price	77.00	p/Therm
Hydrogen selling price	£ 3.00	GBP(EXVAT)/Kg
Carbon product selling price	£ 0.9	GBP(EXVAT)/Kg
Oxygen selling price	£0.4	GBP(EXVAT)/Kg
Carbon Dioxide selling price	£0.7	GBP(EXVAT)/Kg

Benchmarked technologies and data references are presented below:

Large-Scale Electrolysis is based on figures from NEL (SØRENG, 2022) for a proposed 800MW electrolyzer plant.

Small-Scale Electrolysis is based on a system modelled by Lee, et al., (Science Direct, 2018) describing the economics of PEM electrolysis for distributed hydrogen refuelling stations.

SMR CAPEX was derived from figures in the work Hydrogen Production Using Methane: Techno economics of decarbonizing fuels and chemicals (Parkinson, et al., 2017). OPEX figures were largely based on a separate work (Parkinson, et al., 2018) which included utility, catalyst, adsorbent costs, etc.

Thermal Catalytic pyrolysis for hydrogen production has been based on a published technoeconomic analysis (Jarrett, et al., 2021). This work studied a large (216 tonne H_2/day) plant and provided total OPEX and OPEX breakdown figures for capital, methane, catalyst and utility costs.

Microwave Plasma analysis was based on a small distributed processing concept from a United States Department of Energy presentation Hydrogen shot summit event (Gupta, 2021). A per unit CAPEX for microwave plasma sizing was then used to calculate the total microwave cost (de la Fuente, Kiss, Radoiu, & Stefanidis, 2017).

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