CALIX ZESTY TECHNOLOGY
ZERO EMISSIONS IRON AND STEEL

PRE-FEED REPORT DEMO PLANT H-DRI 30,000 TPA

G4-V30902-0001

Version	2
Submitted By	Tom Dufty
Reviewed By:	Matthew Gill
Document Approved:	Matthew Gill
Date Approved	10/05/2023
Document Distribution Approval:	☐Internal Only ☐Confidential ☒External ☒ Public
Document Type	Pre-FEED Project Report
Managed By	Engineering

Rev	***Prepared***	***Review***	***Approved***	***Date***	***Reason For Revision***
0	AA	AO,TD,MBH,MG	MG	05/10/2023	Released for Issue
1	TD		MG	10/08/2023	Revised format to respond to ARENA comments
2	MG		MG	19/09/2023	ARENA disclaimer added

DISCLAIMER

This report has been prepared for Australian Renewable Energy Agency (ARENA) by Calix Ltd (Calix) as an independent consultant and is based in part on information furnished by ARENA and in part on information not within the control of either ARENA or Calix. While it is believed that the information, conclusions, and recommendations will be reliable under the conditions and subject to the limitations set forward herein, Calix does not guarantee their accuracy. The use of this report and the information contained herein shall be at the user's sole risk, regardless of any fault or negligence of Calix.

This project received funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program.

The views expressed herein are not necessarily the views of the Australian Government. The Australian Government does not accept responsibility for any information or advice contained within this document.

TABLE OF CONTENTS

DEFINITIONS

BoD	-	Basis of Design
BF	-	Blast Furnace
BOF	-	Basic Oxygen Furnace
Calciner	-	Calix Flash Calciner Reactor, or CFC Reactor
CAPEX	-	Capital Expenditure
CCUS	-	Carbon Capture Utilisation and Storage
CFC	-	Calix Flash Calciner
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
DR	-	Direct Reduction
DRI	-	Direct Reduced Iron
EAF	-	Electric Arc Furnace
e-CFC	-	Electric Calix Flash Calciner
EPCM	-	Engineering, Procurement, and Construction Management
FEED	-	Front-End Engineering Design
H_2	-	Hydrogen
H_2O	-	Steam or Water
H-DRI	-	Hydrogen DRI
HBI	-	Hot Briquetted Iron
HHBI	-	Hydrogen HBI
HX	-	Heat Exchanger
HYBRIT	-	Hydrogen Breakthrough Ironmaking Technology
LEILAC™	-	Low Emissions Lime and Cement
MEL	-	Mechanical Equipment List
MOU	-	Memorandum of Understanding
MS	-	Milestone
OPEX	-	Operational Expenditure
Pre-FEED	-	Preliminary Front-End Engineering Design
PDC	-	Process Design Criteria
LKAB	-	Luossavaara-Kiirunavaara Aktiebolag
IEA	-	International Energy Agency
PSD	-	Particle Size Distribution
SAF	-	Submerged Arc Furnace
SSAB	-	Svenskt Stål AB
TPD	-	Tonnes Per Day
TPA	-	Tonnes Per Annum
ZESTY	-	Zero Emissions Steel Technology

TABLES LIST

FIGURES LIST

ATTACHMENTS

V30901 – Commissioning Report

1 EXECUTIVE SUMMARY

The Pre-FEED study into a demonstration scale plant with a nominal output of 30,000 TPA DRI using the Calix ZESTY process technology has been undertaken. This study aims to propose an initial Basis of Design (BoD) for a ZESTY plant whilst also considering possible Australian locations for a plant.

Potential sites upon which a demonstration scale plant could be located where examined and compared on eleven different criteria with the results captured in Table 3 - Plant Site Selection Criteria for ZESTY Demo Plant H-DRI 30,000 TPA (page 15). The resultant analysis provided three leading candidates being: Port Hedland in Western Australia, Port Kembla in New South Wales and Port Augusta/Whyalla in South Australia. All three options will be further examined in the future FEED study. The pre-FEED study also considered potential process flowsheets for Haematite/Goethite and Magnetite fine ores with the primary difference between the two flowsheets being a pre-oxidation step to activate the magnetite prior to reduction. The requirement for a pre-oxidation step is being tested as part of the pilot test work program. A preliminary Basis of Design has been prepared and is summarised in the Table 1 below:

Plant Battery Limits and components are discussed including the following areas:

- Feed Storage and Handling
- Pre-processing of Ores
- ZESTY Reactor
- Furnace System
- Reactor Discharge System
- Off-gas Handling and Cooling
- Product Handling
- Ancillary Plant Services

2 BACKGROUND AND INTRODUCTION

The iron and steelmaking process involves the processing of iron ore into steel. Ironmaking is the first stage, which involves reducing iron ore into molten iron in a Blast Furnace (BF). The conventional ironmaking process uses coal as a reducing agent to produce molten iron. During the process, the coal reacts with iron ore, producing CO and CO_2. The CO then reacts with iron oxide, producing molten iron. The steelmaking process requires large amounts of energy, mainly in the form of electricity, to melt the molten iron and refine it into steel. The conventional ironmaking route using BF involves several chemical reactions that take place at 2000^{o}C:

- Charging: The raw materials, including pelletised haematite ore, coke (fuel), and limestone (flux), are charged into the top of the blast furnace.
- Reduction: The coke is burned to produce carbon monoxide (CO), which then reacts with the iron ore to produce molten iron and carbon dioxide (CO2).

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

- Combustion: The coke also provides the heat needed to maintain the high temperature in the furnace, and it burns with oxygen (O2) from the hot air that is blown into the furnace.

$$C + O_2 \rightarrow CO_2$$

- Fluxing: The limestone helps to remove impurities from the iron ore and also reacts with the silica in the ore to form a slag that floats on top of the molten iron.

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$$

The conventional ironmaking route is associated with a significant environmental concern due to the high level of CO_2 emissions. CO_2 is produced during the combustion of coke and is also released as a by-product during the reduction of iron ore.

These conventional iron and steelmaking processes generate substantial CO_2 emissions, contributing to climate change. According to the International Energy Agency (IEA), the global iron and steel industry is responsible for approximately 7% of global CO_2 emissions. Within the industry, the ironmaking process is responsible for approximately 2.3 gigatons (Gt) of CO_2 emissions annually, whereas the steelmaking process contributes to around 1.3 Gt CO_2 emissions annually; with approximately 64% of global CO_2 emissions in the iron and steel industry attributed to the ironmaking process, and the steelmaking process responsible for around 36% of emissions.

Efforts to reduce CO_2 emissions from the iron and steelmaking process have focused on alternative reducing agents and carbon capture technologies. The most common approach has been to replace coal with alternative reducing agents such as natural gas or hydrogen. These reducing agents have a lower carbon footprint than coal and result in lower CO_2 emissions. However, their adoption is limited by factors such as availability, cost, and technological readiness.

Carbon capture technologies have also been explored as a means of reducing CO_2 emissions from the iron and steelmaking process. Carbon capture involves capturing CO_2 emissions and storing them underground, preventing them from entering the atmosphere. The IEA estimates that carbon capture technologies could reduce the iron and steel industry's CO_2 emissions by up to 1.7 Gt annually by 2050.

One example of a carbon capture project in the iron and steel industry is the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project, which aims to produce fossil-free steel using hydrogen as a reducing agent and capturing the CO_2 emissions produced during the steelmaking process. The project is a joint venture between Swedish steelmaker Svenskt Stål AB (SSAB), mining company Luossavaara-Kiirunavaara Aktiebolag (LKAB), and Swedish energy company Vattenfall. The project aims to reduce CO_2 emissions by up to 10 million tonnes annually, representing a significant reduction in the iron and steel industry's CO_2 emissions. The iron and steel industry must continue to explore new technologies and approaches to reduce its CO_2 emissions and contribute to the global effort to address climate change.

Calix has been awarded a $947,035 grant by the Australian Renewable Energy Agency (ARENA) to help fund an eleven-month study for a Zero Emissions Steel TechnologY (ZESTY) iron demonstration plant. The study will include the Basis of Design (BoD) and pre-Front-End Engineering and Design (pre-FEED) for a renewably powered 30,000 TPA demonstration plant for ZESTY iron. The program includes undertaken a pilot plant upgrade and further testing of iron ores at pilot scale R&D plant located at our manufacturing site in Bacchus Marsh, Victoria, Australia.

3 PROJECT OVERVIEW AND PRE-FEED STUDY OBJECTIVES

3.1 Scope

The ZESTY ARENA project is structured around distinct engineering and development phases and milestones to ensure that the project proceeds with the endorsement and support of Australian iron ore and steel producers for a demonstration plant. Calix will complete a pre-FEED and FEED study for a 30,000 TPA H-DRI commercial demonstration plant using Calix's ZESTY process. The project will also include further pilot-scale testing of multiple ores.

3.2 Timelines

The development of the ZESTY process technology can be broken down into 4 phases.

- **Phase 1:** Lab study (complete)
- **Phase 2:** Pilot plant Underway
- **Phase 3:** Pre-FEED & FEED study ZESTY ARENA Project (current)
    - Milestone 1: Completion report by 28 April 2022 (Pilot Plant Upgrades & Pre-FEED/BoD Report)
    - Milestone 2: Completion of Pilot Plant Report by 31 July 2023
    - Milestone 3: Final report and completion of FEED Study 30 November 2023
    - Milestone 4: Financial report by 29 February 2024
- **Phase 4:** Demonstration Plant

Phase 1 - during Phase 1, Calix, in partnership with Swinburne University of Technology (SUT), conducted a laboratory study to establish the theoretical validity of their flash reduction concept. This four-month investigation focused on testing three distinct ores in a lab-scale reactor, which enabled the measurement of reduction kinetics and yielded valuable insights into the modifications required for the existing electric calciner (e-CFC) Pilot calcining in Australia.

Phase 2 - in this phase, Calix proceeded to modify the existing e-CFC at its Bacchus Marsh Pilot plant in Victoria. The upgraded facility was utilised to perform proof of concept trials of the ZESTY process, utilizing a variety of different ores to produce H-DRI. Several further improvements to the pilot plant were identified, these improvements have been implemented with the support of the current ARENA grant and more detailed pilot testing of the process is to commence shortly.

Phase 3 - this phase is currently underway and represents the ongoing development of the ZESTY development pathway. This phase involves a pre-FEED and FEED study for an H-DRI Demonstration Plant based on the innovative e-CFC technology. The study encompasses a comprehensive analysis of technical, commercial, and regulatory workstreams, and deliverables aimed at developing an optimized and feasible plan for the Demonstration Plant. The FEED study will provide a budget estimate of ± 25% capital costs for the Demonstration Plant, giving stakeholders a clearer idea of the financial resources required for the project. The project's outcomes will provide valuable insights that will inform the recipient's decision-making process.

Phase 4 – in this phase, the Final Investment Decision (FID) will be made to determine whether or not to proceed with the project. This critical stage involves carefully evaluating the risks, rewards, and feasibility of the project, considering the technical, financial, and regulatory factors identified in the earlier phases. Ultimately, the decision made in Phase 4 will be pivotal in determining the project's success, and thorough analysis and consideration of all factors will be crucial in making an informed and well-reasoned decision. Outlined below are the Pre-FEED/BoD development work packages and key activities integral to the ZESTY ARENA Project.

Table 1 - Pre-FEED/Basis of Design Development Work

Work Package	Key Activities
Phase 3 Pre-FEED / BoD development	• Review design criteria and screen design options • Finalise design configuration considering optimum feedstock and process requirements. • Process a range of iron ore feedstocks through the upgraded Pilot plant in accordance with the Testing Plan and commence analysis of the e-CFC pilot trials and feed stock or product and process data. • Identify design parameters and process requirements including scale of Demonstration Plant required to achieve testing outcomes. • Define site and boundary conditions for the Project. • Develop BoD for selected sites.

4 PROCESS DESCRIPTION

4.1 Preliminary Basis of Design

The following is the expected plant data and preliminary material and energy consumption figure for ZESTY demonstration plant for 30,000 TPA

Table 2 - Consumption Figure for Demo Plant 30,000 TPA

Process Material Product	Product	Hydrogen Direct Reduced Iron (H-DRI)		
Production Rate	Target	30,000 metric tonnes H-DRI per annum or 4.0 t/h		
Expected Processing Temperature and PSD	Testwork	850- 950°C 100-500 μm		
Expected Reaction Energy	Aspen Modelling Calculation	Reduction of Haematite to H-DRI @4.0t/h: 1265 kW Reduction of Goethite to H-DRI @4.0t/h: 2195 kW Roasting Magnetite and Reduction to H-DRI @4.0t/h: (-236.2kW) + 1061.3 kW = 825.1 kW		
Reactor Atmosphere	Aspen Modelling/ Testwork Data	Predominantly hydrogen during operation. Excess hydrogen with water vapours (or steam as product) are the off-gas composition		
Plant Availability	Target	Targeting 91% plant availability (or 8000 hr/year)		
Feed Ore/Concentrate	Aspen Modelling Calculation	Haematite Fe_2O_3	Goethite FeO(OH)	Magnetite Fe_3O_4
		5644 kg/h Or 45,152 TPA	6280 kg/h Or 50,240 TPA	5455 kg/hr Or 43,640 TPA
Hydrogen Consumption	Aspen Modelling Calculation	218 kg/h or 54.1 kg/tons of DRI		
Product Quality	Industry standard International Iron Metallics Association (IIMA)	General product specifications for DRI Fines (% by weight), based on 65.5-68.0% Fe: • Metallisation: 95.0-96.0% • Fe (Total): 86.1-93.5% • Fe (Metallic): 81.0-87.9% • Carbon content: 1.0-4.5% • Sulphur content: 0.001-0.03% • Phosphorus content: 0.005-0.09% • Gangue*: 3.9-8.4%		

		• Average bulk density: 1.6-1.9t/m^3 General product specifications for HBI (% by weight): • Metallisation: 94.0-95.0% • Fe (Total): 86.1-93.5% • Fe (Metallic): 81.0-87.9% • Carbon content: 0.5-1.6% • Sulphur content: 0.001-0.03% • Phosphorus content: 0.005-0.09% • Gangue*: 3.9-8.4% • Fines and chips: ≤5.0% • Size (typical): (90-140) x (48-58) x (32-34)mm • Average bulk density: 2.5-3.3t/m^3 **gangue: residual unreduced oxides mainly SiO_2 and Al_2O_3, CaO, MgO, MnO*

4.2 Process Configuration

4.2.1 Haematite/Goethite ZESTY Flowsheet

Calix's technology centres around the grinding of iron ore to the target grind size in haematite Fe_2O_3 or goethite FeO(OH) flowsheets. The mined ores undergo a grinding process to achieve a particle size between 100 to 500 µm, ensuring optimal efficiency in subsequent processing steps. Once ground, the ores are rapidly subjected to "flash" heating in an externally electrically heated reactor, under a hydrogen-rich atmosphere at temperatures up to 950°C releasing only water vapours or steam.

Hydrogen Direct Reduction reactions in ZESTY reactor producing H-DRI:

Haematite: $Fe_2O_{3(s)} + 3\ H_{2(g)} = 2\ Fe_{(s)} + 3\ H_2O_{(g)}$

Goethite: $2FeO(OH)_{(s)} + 3\ H_{2(g)} = 2\ Fe_{(s)} + 4\ H_2O_{(g)}$

The H-DRI fine powder exhibits significant reactivity, which requires passivation or carburisation techniques. These measures result in the formation of cementite, a suitable raw material for the production of hot briquetted iron (HBI) through briquetting or low-carbon liquid steel via smelting in a SAF or EAF.

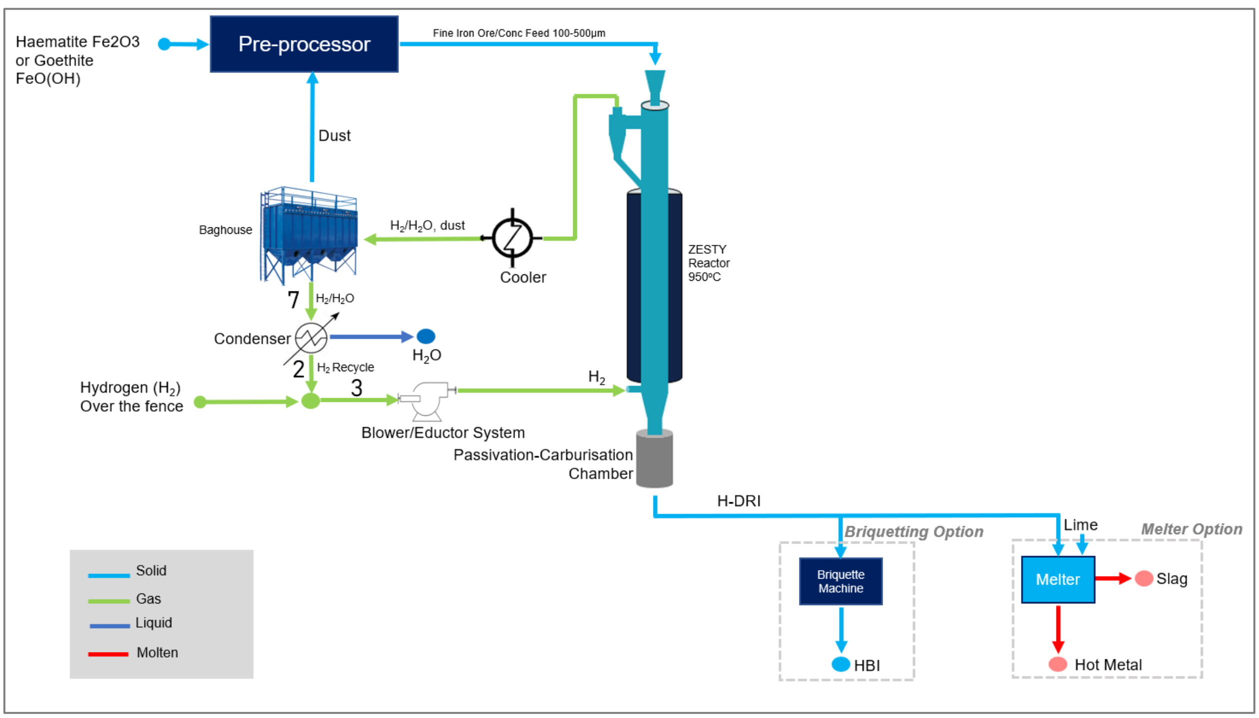

Figure 1 - Haematite / Goethite ZESTY Flowsheet

4.2.2 Magnetite ZESTY Flowsheet

In hydrogen-induced direct reduction, magnetite-based iron ore exhibits a high affinity for sticking and a poor ability to reduce within the reactor due to its dense structure. To improve its reduction behaviour, a pre-oxidation treatment may be required. This involves grinding the magnetite ore or concentrate to a particle size which is expected to be in the range of 100 to 500 µm, which ensures optimal efficiency in subsequent pre-oxidation steps.

Pre-oxidation/pre-calcination of magnetite to haematite followed by its direct reduction in pure hydrogen:

Pre-oxidation Magnetite: $4\ Fe_3O_{4(s)} + O_{2(g)} = 6\ Fe_2O_{3(s)}$
H_2 Direct Reduction: $Fe_2O_{3(s)} + 3\ H_{2(g)} = 2\ Fe_{(s)} + 3\ H_2O_{(g))}$

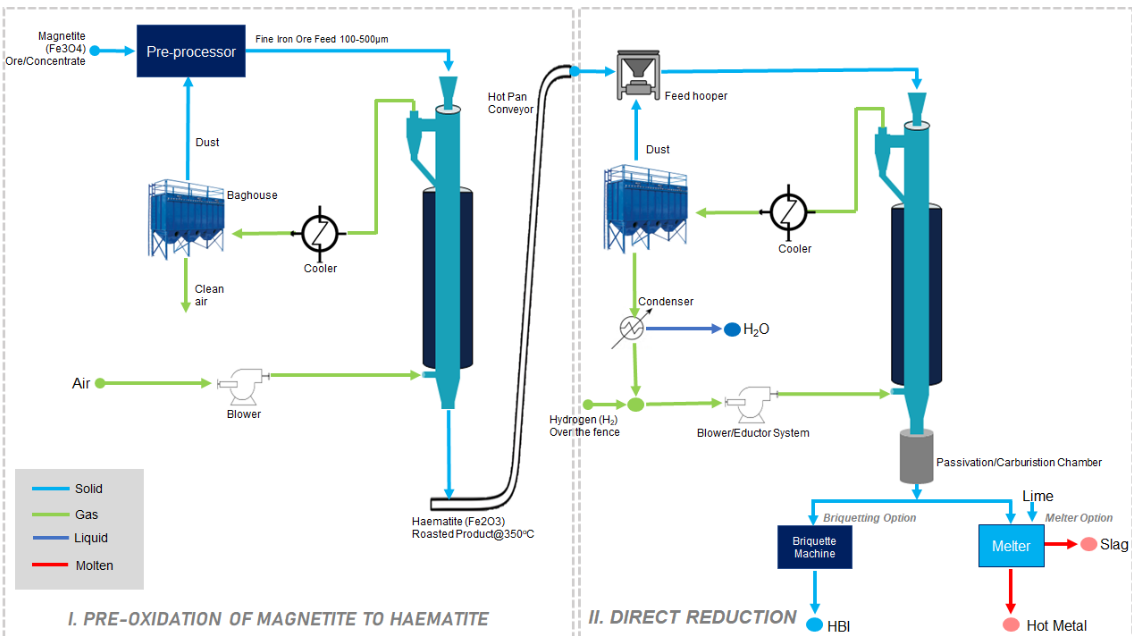

Figure 2 - Magnetite Flowsheet ZESTY Flowsheet (Pre-oxidation and H2 Direct Reduction)

The ground ore is then rapidly pre-oxidised in an externally electrically heated reactor under an air-rich atmosphere at temperatures of up to 950°C, which converts the magnetite to haematite. The resulting pre-oxidised product is then conveyed via hot pan conveyor to an electric flash calciner for reduction in another stage, which produces hydrogen-direct reduced iron (H-DRI) with a metallisation of 95%. The H-DRI product can then be passivated or carburised, and subsequently briquetted or sent to the Melter unit to produce liquid steel.

Based on recent laboratory testwork conducted in collaboration with Swinburne University of Technology, ongoing investigations are being carried out to further optimise the ZESTY direct reduction process of magnetite. This involves a focus on key process parameters such as ore particle size distribution, retention time, and reaction temperature, with the aim of achieving greater process efficiency and product quality.

Of particular interest is the development of a direct reduction process that eliminates the need for a pre-oxidation stage, which has the potential to significantly reduce both capital and operating costs while also improving environmental sustainability.

4.2.3 General Reactor Layout

Initial plant layout and sizing has been conducted based on the initial equipment sizing. Key aspects of the plant including the main furnace and reactor are largely flexible and aspects such as transport routes and topography will influence final layout.

Plant layout will be further developed once site selection is firmed up during the FEED study.

The figures below shows an initial general arrangement, birds eye layout and approximate dimensions.

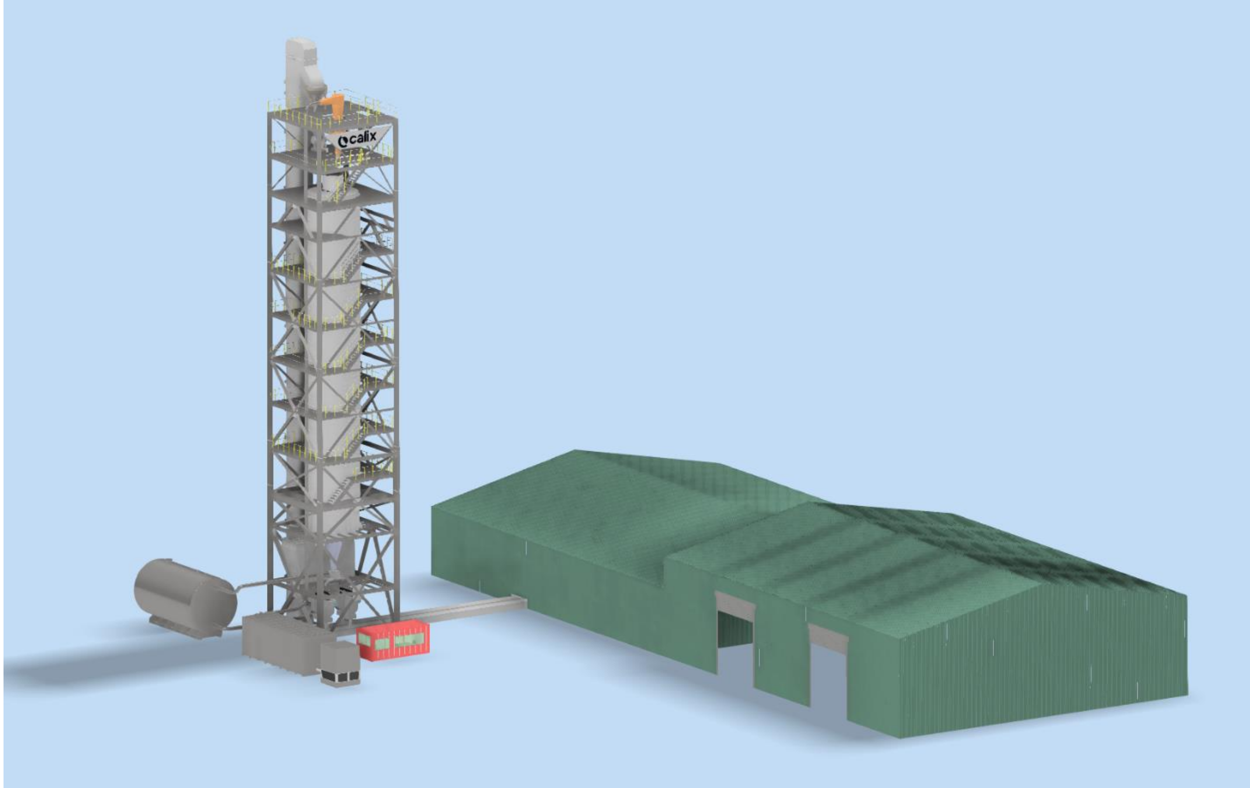

Figure 3 - Plant layout

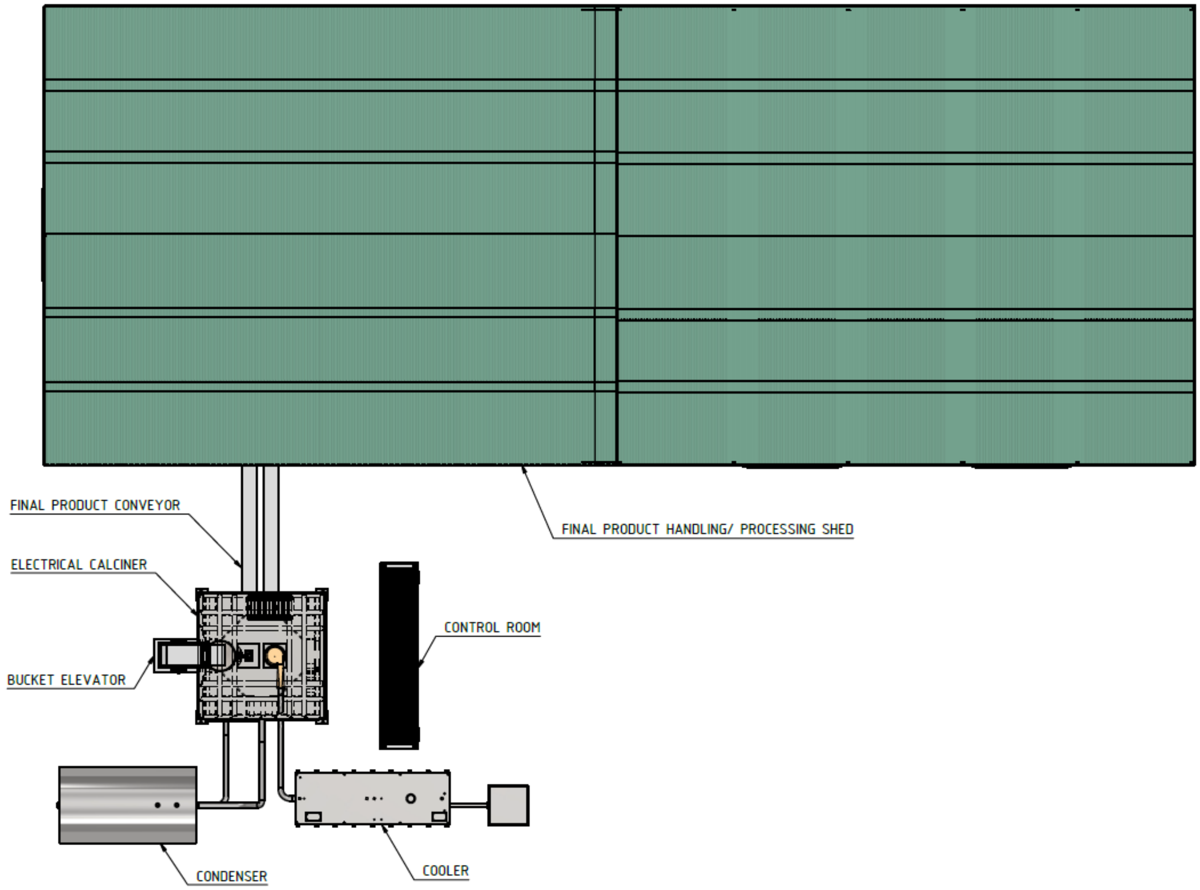

Figure 4 - Initial plant layout

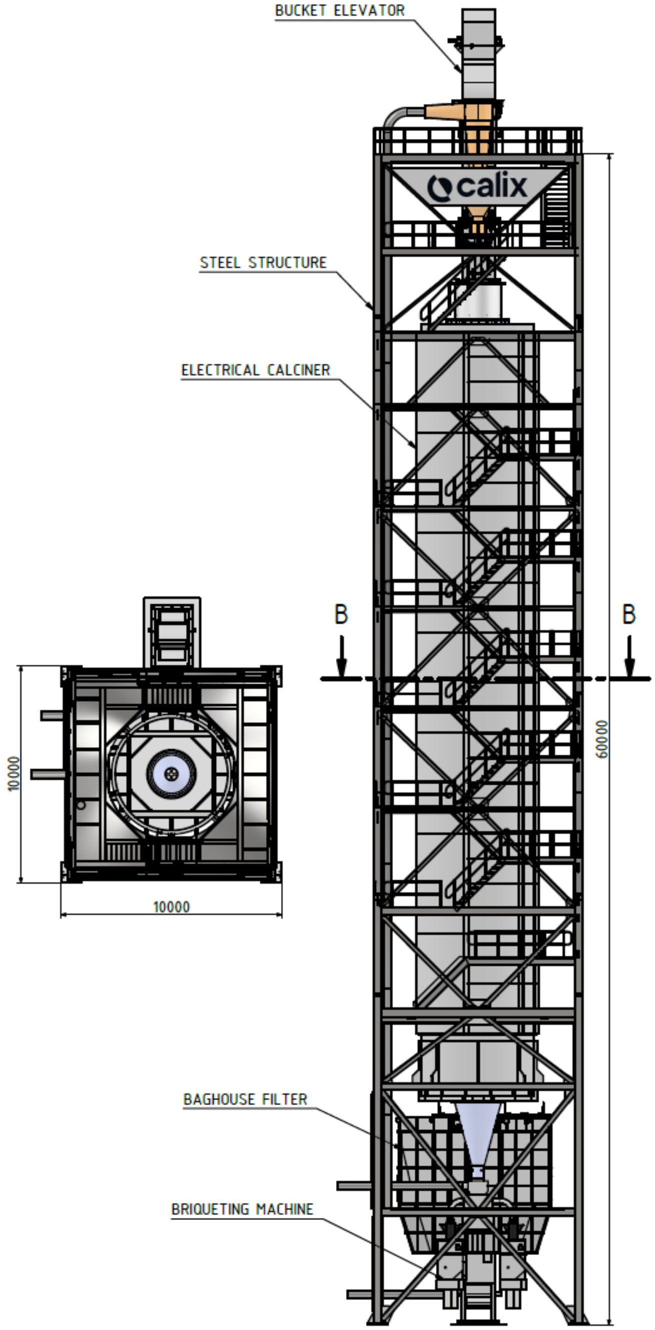

Figure 5 - Initial furnace layout

4.2.4 Hydrogen Sourcing Options

The sourcing of Hydrogen for the project is a key aspect of its viability and economics. Hydrogen can be sourced from a variety of options and are given colour codes based on their origin source for example green, grey or blue hydrogen.

Given the fundamental purpose of the ZESTY process is to eliminate emissions, sources of blue or preferably green hydrogen are considered.

The following sources of hydrogen could potentially provide for the project:

Table 3 - Hydrogen sources

Source	Type	Pros	Cons
Electrolyser on site	Green*	• Can be 100% renewable • High degree of flexibility	• Capital Heavy • Requires additional water treatment • Large Footprint
Electrolyser over the fence	Green*	• Split capital outlay • Can be 100% renewable • High degree of flexibility	• Requires additional water treatment • Large Footprint
Industrial Gas supplier	Grey/blue/Green	• Currently available • Cost lower • No water recycle requirement	• Batch supply only • Frequent vehicle deliveries • Higher emissions footprint
H2 Hub Pipeline	Grey/blue/Green	• Minimal integration • Low capex • No water recycle requirement • Minimal site footprint	• Site Constrained to a handful of locations • Infrastructure still in development

*Green H2 assumes H2 is generated from renewable electricity

4.2.5 Sponge Iron Handling - Post-processing of ZESTY H-DRI Fine Product

To produce a commercially desirable product with added value, post-processing of H-DRI fine product to produce high-quality HBI or liquid steel could be required.

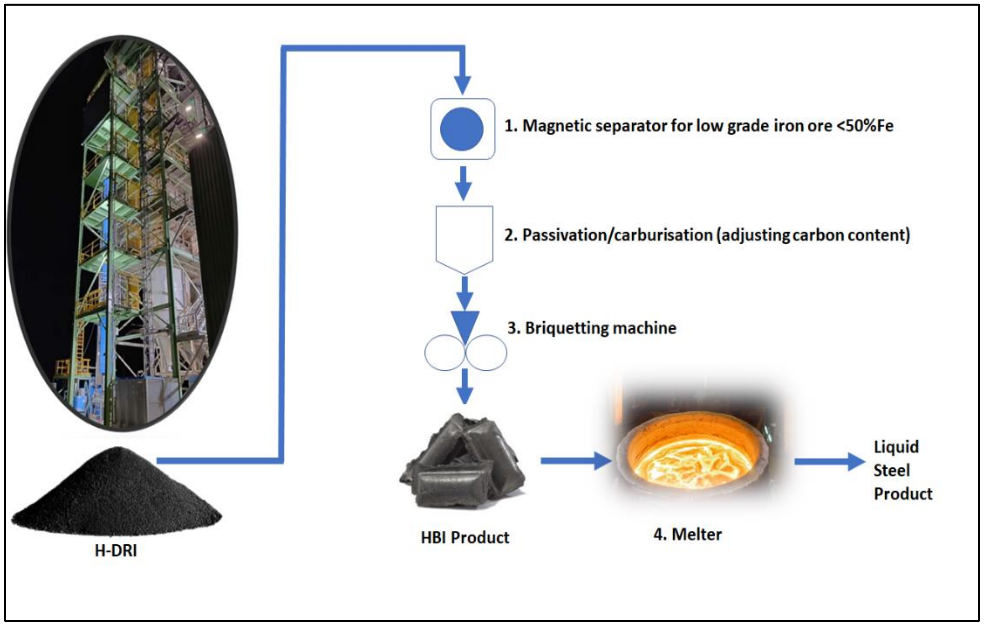

Figure 6 - Post-processing of ZESTY H-DRI

Several pathways can be used for ZESTY H-DRI post-processing, which are envisages as follows:

1. **Magnetic separation process** can be utilised to enhance low-grade iron ore by extracting gangue materials that contribute to the basicity of the slag. This step can also help to reduce waste slag volume and energy consumption during the smelting process, making it a suitable for ZESTY to treat a low-grade iron ore (<50%Fe).
2. **Passivation/carburisation process** involves the use of carbonaceous gas (CO/CO_2) or biomass to passivate H-DRI and forming cementite. This step adjusts the carbon content in H-DRI, which is desirable for smelter operation as it lowers the liquidus temperature and electric consumption.
3. **Hot briquetting process** of ZESTY H-DRI involves pressing fine powder at 600-800°C into pillow-shaped briquettes, which are then cooled in a cooling chamber and separated from the gases. This process helps to improve the handling and transportation of DRI, as the briquettes have higher density and are less susceptible to breakage or combustion. The hot briquetting machine is a crucial part of the HBI production process and is used by iron and steelmakers to improve the efficiency of their operations.
4. **Smelting process** may demonstrate that Calix's HBI briquettes is suitable in EAF/SAF for steelmaking. It is worth noting that ZESTY Iron will exclusively prioritise HBI manufacturing operations, while ZESTY Steel will produce liquid steel in conjunction with the LEILAC furnace, which can also scrub excess CO_2 as well as other pollutants from the exhaust gases. The post-processing of the ZESTY H-DRI product will be further optimised during the FEED study.

4.2.6 Integration Considerations

The process flow sheet for a full DRI plant has a number of integration considerations upstream, downstream and for operation of the DRI plant itself. The key considerations when looking into site selection and opportunities for integration with existing infrastructure include:

- Access to utilities including:
  - Power
  - Hydrogen
  - Waste Water treatment
- Integration with upstream material processing including:
  - Shipping facilities for receival of ore
  - Storage and buffering of raw materials
  - Milling
  - Drying
  - Beneficiation
- Integration with Downstream processing
  - Shipping facilities for dispatch of product
  - Storage of product
  - Direct integration with downstream processing for immediate use of hot product

Due to the flexible nature of the ZESTY DRI plant, several other options exist for integration including

- Tying in with existing gas streams such as BF top gas
- Integration with other forms of heat of gas for drying of material or production of steam for heat integration
- Co-sourcing electrolyser for providing O2 for BOF

The options are conceptual only will not be considered at a pre-FEED stage.

4.2.7 Plant Sites Selection

The decision to build a hydrogen-based iron ore reduction demonstration plant in Australia would depend on several factors, such as the availability of raw materials, labour force, energy costs, proximity to customers, government incentives, and availability of hydrogen-hub & electricity infrastructure. Based on these general considerations, here are five potential sites that could be considered for building a demonstration plant in Australia:

- **Port Augusta/Whyalla, South Australia:** Whyalla is already home to an iron and steelmaking plant, and its location near major iron ore deposits in the Middleback Ranges of South Australia makes it an ideal location for a demonstration plant.

- **Kwinana, Western Australia:** Kwinana has an existing heavy industry sector, with access to raw materials such as iron ore and electricity. It is also well connected to transportation infrastructure and has a skilled labour force.

- **Port Hedland, Western Australia:** Pilbara region is known for its rich iron ore deposits and a major source of iron ore exports to China and other Asian markets, which makes it an attractive location for a demonstration plant due to the availability of raw materials, a well-developed infrastructure and transportation network, including a deepwater port and rail connections. The town has access to a skilled labour force, and WA government has identified the Port Hedland as a priority area for investment and economic development for green steel and hydrogen projects.

- **Gladstone, Queensland:** Gladstone has an established heavy industry sector and access to iron ore, hydrogen, and renewable electricity. It also has a deepwater port and is well connected to transportation infrastructure.

- **Port Kembla, New South Wales:** Port Kembla is located near major iron ore deposits and has an existing steelmaking industry. It also has a deepwater port and is well connected to transportation infrastructure.

Table 3 outlines the plant site selection criteria for ZESTY Demo Plant H-DRI 30,000 TPA, with the top three preferred site locations at:

- **Port Hedland, Western Australia**
- **Port Augusta/Whyalla, South Australia**
- **Port Kembla, New South Wales**

The location of Port Hedland within the proximal vicinity of the iron ore reserves of the Pilbara region provides an advantageous position with respect to access to essential raw materials. Moreover, the region benefits from a well-developed port and rail infrastructure, offering seamless transportation of finished products. Furthermore, the Western Australia Government has reserved land for various heavy industrial undertakings, thus furnishing the prospect of collaboration and synergy with other industries.

Conversely, Port Kembla and Whyalla harbors a well-established steel industry, including the prestigious Liberty/GFG Whyalla and Bluescope Steelworks, sites that boasts an illustrious history and a highly skilled workforce with existing Blast Furnaces. A new steel plant in Whyalla could capitalise on this pre-existing infrastructure and expertise, resulting in the generation of fresh employment opportunities and providing an economic impetus to the local community.

Figure 7 - ZESTY ARENA Preferred Site Location for Demonstration Plant H-DRI 30,000 TPA

Table 4 - Plant Site Selection Criteria for ZESTY Demo Plant H-DRI 30,000 TPA

Plant Site Selection Criteria	Site 1 Port Augusta Whyalla SA	Site 2 Kwinana WA	Site 3 Port Hedland WA	Site 4 Gladstone QLD	Site 5 Port Kembla NSW
Access to raw materials: Choose a location that is close to the source of raw materials to minimize transportation costs and ensure a steady supply of materials.	✓	✓	✓	✗	✓
Transportation infrastructure: Consider the availability of transportation options, including highways, rail lines, and ports, to ensure that the finished products can be shipped to markets efficiently.	✓	✗	✓	✓	✓
Labor force:A location with a strong & skilled labor force that can provide the necessary skills & expertise to operate steelmaking plant.	✓	✗	✓	✗	✓
Regulatory environment: Be aware of the regulations and permits required to operate a processing plant in Australia, including environmental regulations, health and safety regulations, and zoning laws.	✓	✓	✓	✓	✓
Proximity to customers: Consider the location of potential customers to ensure that the finished products can be delivered efficiently and cost-effectively.	✓	✓	✓	✓	✓
Availability of hydrogen-hub & electricity infrastructure	✓	✓	✓	✓	✓
Cost of land: Choose a location that offers a competitive cost of land, as this will affect the capital costs of building and operating the processing plant.	A$50-100/$m^2$	A$250-350/$m^2$	A$400-600/$m^2$	A$200-400/$m^2$	A$300-500/$m^2$
Economic incentives: Consider any economic incentives or tax breaks offered by the state or local government to encourage investment in the region.	SA government for new infrastructure & equipment	WA gov. Industrial Lands Authority offers land for industrial development at competitive price; also Regional Economic Development (RED) that supports job creation & economic growth regional areas.	A$70bn from WA gov. for the allocation of land for 7projects for hydrogen-related projects to companies including BP, South Korean steelmaker POSCO and FMG	QLD gov. Jobs and Regional Growth Fund provides funding for businesses looking to create new jobs and expand operations in the state	NSW gov Regional Investment Attraction Fund for businesses looking to invest in regional areas, inc. support for infrastructure dev & job creation. The Australian government's Manufacturing Modernisation Fund provides grants for businesses in the manufacturing sector looking to modernise their operations & increase their competitiveness. Existing Blast Furnace Operation
Energy availability and costs: Consider the availability and cost of energy, including electricity, gas, and other fuel sources, as this will have a significant impact on the operational costs of the processing plant.	Electricity: 29.1¢/kWh Gas: 3.3¢/MJ	Electricity: 20.4¢/kWh Gas: 3.6¢/MJ	Electricity: 20.4¢/kWh Gas: 3.6¢/MJ	Electricity: 16.2¢/kWh Gas: 3.3¢/MJ	Electricity: 19.1¢/kWh Gas: 3.4¢/MJ
Current steel production	1.2 MT (Liberty)	0.0	0.0	0.0	3.0 MT (Bluescope)
Iron ore/steel company producer	Liberty/GFG, SIMEC Mining, OneSteel	Bluescope, BHP, Rio Tinto, CITIC, Mineral Resource	BHP, Rio Tinto, FMG, Roy Hill, Mineral Resource	No iron ore/steel producer but exisiting plant for aluminium smelters (RT,QAL), Gladstone Pacific Nickel,Cement Australia, Queensland Resource Energy	Bluescope, Liberty/GFG, Infrabuild, Bisalloy Steel

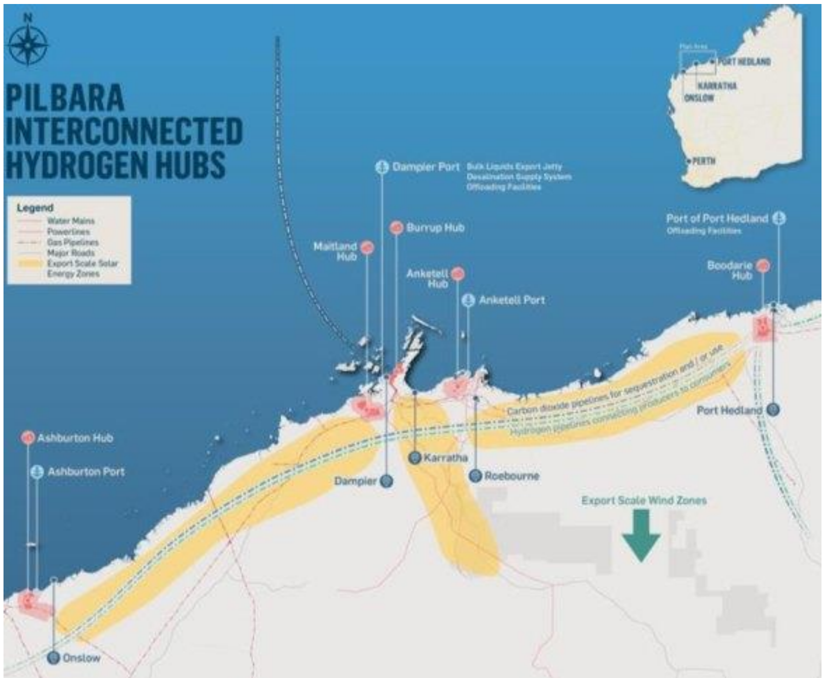

Figure 8 - Pilbara H2 Hub

Figure 9 - NSW H2 plan

5 PRELIMINARY SCOPE OF SUPPLY

5.1 Battery Limits

Calix Battery Limits listed below in 5.3 Equipment Supply.

5.2 Material of Construction

The best-suited material for a H-DRI demonstration plant operating at high temperatures would be stainless steel (SS) that has high-temperature resistance and excellent corrosion resistance properties. Specifically, austenitic stainless steel with higher chromium and nickel content such as 310S, 253MA, or Alloy 800H are commonly used for high-temperature applications in hydrogen gas plants. These SS alloys exhibit excellent resistance to oxidation, sulfidation, and carburisation, and can withstand temperatures ranging from 800°C to 1200°C, which makes them ideal for use in high-temperature H-DRI demo plant.

5.3 Equipment Supply

Calix will provide the following mechanical equipment:

5.3.1 Feed Storage and Handling

The feed system will be required to transfer iron ore/concentrate from the outlet of the dryer to top of the structure and consistently discharge the material into the reactor. The system will be designed to contain enough material to provide an adequate buffer for short term repairs. The system will nominally be comprised of the following equipment:

Table 5 - Haematite/Goethite Flowsheet Feed System

Equipment Number	Type	Capacity	MOC
111-HP-001	LIW Feed Hopper	3.5 m^3	Stainless Steel
111-CN-001	Feed Transfer Screw	1.0-6.3 t/h	Stainless Steel
111-ER-001	Feed Transfer Ejector	6.3 t/h	Stainless Steel
111-BL-001	Feed Transfer Blower	450 m^3/h	Stainless Steel
111-RV-001	Feed Rotary Valve	1.0-6.3 t/h	Stainless Steel

Table 6 - Magnetite Flowsheet Feed System

Equipment Number	Type	Capacity	MOC
111-HP-001	LIW Feed Hopper	3.5 m^3	Stainless Steel
111-CN-001	Feed Transfer Screw	1.0-6.3 t/h	Stainless Steel
111-ER-001	Feed Transfer Ejector	6.3 t/h	Stainless Steel
111-BL-001	Feed Transfer Blower	450 m^3/h	Stainless Steel
111-RV-001	Feed Rotary Valve	1.0-6.3 t/h	Stainless Steel
111-CN-002	Hot Pan Conveyor	1.0-6.3 t/h	Stainless Steel
111-HP-002	LIW Feed Hopper	4.0m^3	Stainless Steel
111-CN-003	Feed Transfer Screw	1.0-6.3 t/h	Stainless Steel
111-RV-002	Feed Rotary Valve	1.0-6.3 t/h	Stainless Steel

5.3.2 Pre-processing Feed Fine Ores (Haematite, Goethite, Magnetite)

To achieve H-DRI quality with a metallisation degree of 95% or higher, an optimised particle size distribution (PSD) feed must be obtained through pre-processing of iron ore. The processing techniques required for haematite, goethite, and magnetite, the primary iron ores, vary significantly. High-grade haematite/goethite iron ores can be satisfactorily sized through crushing and screening. However, low-grade haematite ores necessitate additional beneficiation to attain the required iron content, which usually involves crushing and screening with low energy requirements. Conversely, fine-grained magnetite ores necessitate fine grinding, often below 30 µm, to liberate magnetite from the silica matrix, leading to higher energy consumption and costs. The precise pre-processing feed ore requirements will be further specified after completion of the Zesty Campaign Trial II testwork.

5.3.3 ZESTY Reactor System

The reactor will be comprised of a metallic alloy reactor based on Calix Technology. The reactor is proposed to be 253MA Alloy Stainless Steel with other options assessed during the value engineering stage. The reactor will be sized to provide adequate heat transfer from the furnace into the process stream. The reactor will include ancillary equipment required to seal the reactor to the outside environment, compensate for thermal expansion and control the pressure and atmosphere within the reactor.

Table 7 - Haematite/Magnetite Reactor System

Equipment Number	Type	Capacity	MOC
112-SD-001	Preheater Cyclone	3.0 t/h	Stainless Steel
120-RE-001	Reactor	6.0 t/h	Stainless Steel
122-EF-001	Electric Furnace	2.5MW	TBA

Table 8 - Magnetite Reactor System

Equipment Number	Type	Capacity	MOC
112-SD-001	Preheater Cyclone (Pre-oxidation)	3.0 t/h	Stainless Steel
112-SD-002	Preheater Cyclone (Reduction)	3.0 t/h	Stainless Steel
120-RE-001	Reactor with (Pre-oxidation)	6.0 t/h	Stainless Steel
120-RE-002	Reactor (Reduction)	6.0 t/h	Stainless Steel
122-EF-001	Electric Furnace (Pre-oxidation)	0.5MW	TBA
122-EF-002	Electric Furnace (Reduction)	2.5MW	TBA

The reactor will have the following interfaces:

Table 9 - ZESTY Reactor Interface System

Interface	Location	Type	Description
Process Temperatures	Thyristor Housing	Instrument Connection	Terminal Box/ Modbus
Process Pressures	Thyristor Housing	Instrument Connection	Terminal Box / Modbus
Valve Controls	Thyristor Housing	Digital 24V Connection	Terminal Box / Modbus
Elongation Sensors	Thyristor Housing	Instrument Connection	Terminal Box / Modbus

5.3.4 ZESTY Furnace System

The furnace system will be comprised of a steel casing lined with ceramic fibre insulation. The electrical elements will line the anulus evenly surrounding the reactor tube in the centre. The furnace structure will be designed such that the casing is adequately stiff and feeds all loads into the structure. The system will be sized in such a way as to trade off the additional capital cost of a larger furnace with lower surface temperatures and heat loss. The installed power of the furnace and surface load of the elements will be designed to provide adequate margins and life for the elements. The furnace system consists of the following equipment:

Table 10 - ZESTY Furnace System

Equipment Number	Type	Capacity	MOC
122-EF-001(Reduction) 122-EF002(Pre-oxidation)	Electric Furnace	0.5MW (Pre-oxidation) 2.5 MW (Reduction)	Carbon Steel – Ceramic Fibre
122-EF-001/002	Thyristor Housing	TBD	N/A

The battery limits for the furnace system are:

Table 11 - ZESTY Battery Limits for the Furnace System

Interface	Location	Type	Description
Electrical Power Input	Thyristor Housing	Electrical Connection	Terminals for main Incomer
Furnace Controller	Thyristor Housing	Control Connection	Modbus

5.3.5 Reactor Discharge System

The product discharge system is required to collect the fine powder H-DRI as it exits the heated section of the reactor and discharge it into the product handling and cooling system. The system is required to isolate the atmosphere in the reactor from the downstream process. The discharge system comprises of the following equipment.

Table 12 - ZESTY Haemsatite/Goethite Discharge System

Equipment Number	Type	Capacity	MOC
131-RV-001	Outlet Rotary Valve	4.0 t/h	Stainless Steel

Table 13 - ZESTY Magnetite Discharge System

Equipment Number	Type	Capacity	MOC
131-RV-001	Outlet Rotary Valve (from Pre-oxidation Furnace)	5.3 t/h	Stainless Steel
131-RV-002	Outlet Rotary Valve (from Reduction Furnace)	4.0 t/h	Stainless Steel

5.3.6 Off-Gas Handling and Cooling System

In order to maintain optimal operational conditions, the off gas must undergo cooling via a dedicated system to extract the contained heat before entering the bag house at a temperature inlet of 220°C. In addition, further cooling is necessary to condense the water vapour, which can then be reused as plant water. Moreover, the recovered hydrogen can be reintroduced into the ZESTY Reactor.

The proposed solution is to utilise dry coolers or air-cooled heat exchangers before the baghouse and air-cooled condensers to condense water from the hydrogen off-gas. The entrained flow containing the product will be carried through the internal pipe. An air-cooled heat exchanger employs ambient air to cool down fluids like water or process gas. The process gas is cooled by exchanging heat with the air flowing over the fins of the dry cooler. The heated air is then released into the atmosphere. It is recommended that a more compact cooling method be investigated during the value engineering phase. The cooling system is comprised of the following equipment.

Table 14 - ZESTY Haematite/Goethite Cooling System

Equipment Number	Type	Capacity	MOC
126-HE-001	Air cooled off gas cooler (to bag house)	0.7-1.0 MW	Stainless Steel
126-HE-002	Air cooled condenser (to condense H2O)	0.3-0.5 MW	Stainless Steel

Table 15 - ZESTY Magnetite Cooling System

Equipment Number	Type	Capacity	MOC
126-HE-001	Air cooled off gas cooler (to bag house pre-oxidation)	0.1-0.2 MW	Stainless Steel
126-HE-002	Air cooled off gas cooler (to bag house – reduction)	0.7-1.0 MW	Stainless Steel
126-HE-003	Air cooled condenser (to condense H_2O)	0.3-0.5 MW	Stainless Steel

5.3.7 Product Handling System

The handling system for the H-DRI fine product will transfer it from the reactor exit to downstream processing equipment. The proposed system for handling the product is a lean-phase pneumatic conveying system and in the case of magnetite, Aumund Hot Pan Conveyor.

The system will be sized to provide sufficient air flow for consistent transfer and enough pressure capability to overcome the pressure drop across the line, including the product cooler section. The discharge baghouse filter will have sufficient hopper volume to allow for a buffer zone for upstream maintenance activities.

The product handling system includes the following equipment.

Table 16 - ZESTY Haematite/Goethite Cooling System

Equipment Number	Type	Capacity	MOC
126-FN-001	Off gas exhaust fan	TBA	Stainless steel
126-FL-001	Bag House Filter	0.3 t/h	Stainless steel
131-RV-001	Rotary Valve	4.0 t/h	Stainless Steel

Table 17 - ZESTY Magnetite Cooling System

Equipment Number	Type	Capacity	MOC
126-FN-001	Off gas exhaust fan	TBA	Stainless steel
126-FL-001	Bag House Filter	0.3 t/h	Stainless Steel
131-RV-001	Rotary Valve	5.3 t/h	Stainless Steel
126-FN-002	Off gas exhaust fan	TBA	Stainless Steel
126-FL-002	Bag House Filter	0.3 t/h	Stainless Steel
131-RV-001	Rotary Valve	4.0 t/h	Stainless Steel

5.4 Control and Instrumentation Specification

Control and instrumentation specification will be developed during FEED study.

5.5 Hydrogen, Plant and Instrument Air Supply

5.5.1 Hydrogen Supply

For the basis of pre-FEED , Hydrogen gas will be assumed as supplied by others over the fence. The current design utilises a consumption rate of 54.1 kg/tons of DRI, which will be refined further based on test work trials.

5.5.2 Plant Air

Plant air is required for roasting magnetite and approximately 500-600 Nm3/hr.
Plant air is within Calix's scope and Point of connection between Calix's equipment and the plant air supply will be determined during FEED study.

5.5.3 Plant Inert Gas

The Reduction Furnace demands high-purity nitrogen gas with a minimum concentration of 99.998% for both pre- and post- purging procedures. During plant startup, the reduction reactor tube is thoroughly flushed with high-purity nitrogen gas to eliminate any traces of moisture and air. Similarly, during plant shutdown, nitrogen gas is employed to expel all hydrogen from the reduction reactor tube, ensuring plant and personnel safety. The H-DRI collection vessel necessitates high-purity argon gas with a minimum concentration of 99.998% to prevent reoxidation resulting from moisture or air. Plant inert gases are within Calix's scope and point of connection between Calix's equipment and the plant inert gas will be determined during FEED study.

5.5.4 Instrument Air

Instrument air will be in Calix scope for a standalone plant and point of connection between Calix's equipment and the Instrument air supply will be determined during FEED study. Calix estimates its equipment has an instrument air duty of 36-40 m3/hr at 10 bar.

5.5.5 Inert Instrument Gas

Inert Instrument Gas is typically used in a plant to prevent the oxidation or contamination of sensitive equipment or instruments. This type of gas is usually a high-purity form of nitrogen, argon, with concentrations above 99.998%. The Inert Instrument Gas is utilised to purge any air or moisture that may be present in the system and displace them with the inert gas, thus maintaining a dry and inert environment. This prevents the formation of unwanted by-products that may interfere with the proper functioning of the equipment. Inert Instrument Gas is employed in various off-gas analytical applications, such as gas chromatography/mass spectrometry, to ensure accurate and reliable measurements.

5.6 Support and Access Structure

The primary objective of the Support and Access Structure Section is to ensure that all plant equipment is supported and accessed safely and efficiently, which provides detailed information on the type, layout, and design of the various support and access structures required for the plant equipment. These structures include foundations, platforms, stairways, ladders, and handrails, among others.

Support and access structure will be further developed during pre-FEED study.

6 PROJECT RISK AND MITIGATION

The following aspects have been considered when assessing risk to the project:

- Client Risk
- Commercial
- Financial
- Project management
- OHS
- Technical

Separate in depth risk assessments are conducted on the OHS risks associated with the operation of the pilot plant. These are not covered in this report.

The following table provides a summary of the key risks identified and high-level mitigations:

Table 18 - Summary of high-level risks and mitigations

Risk	Mitigation
Budget Overrun	Regular progress reviews and planning amendment to ensure project objectives are met
Supply Chain issues/ Difficulty providing accurate project costs	Procurement of standard equipment is continuously ongoing in parallel projects. The cost base for various equipment and raw materials will be updated frequently throughout the project.
Limited access to required information	A close relationship will be developed with industry partners and universities to ensure free flowing information where possible.
Inability to select appropriate site	Multiple appropriate sites will be considered as part of the study.
Inability to find appropriate H2 source	Close linkages to the supply of electrolysers for green hydrogen production.
Insufficient safety considerations included in design stages	Ensure design, procurement and fabrication of components are reviewed and completed by suitably qualified person(s) and are of verifiable standard and quality
Pilot plant trials unable to deliver required results	Test plan to be comprehensive enough to allow for adequate data collection
Pilot plant trials do not perform as well as expected	Wide Window of operations to be tested e.g. PSD sizes, H2 flow rates to understand possible alternatives and equipment modifications to improve performance.

7 CONCLUSIONS AND NEXT STEPS

At the conclusion of pre-FEED the following has been completed to provide input into further FEED work.

- Preliminary flow sheet options for different ores
- Preliminary options for material handling and product processing
- Preliminary sizing for the required equipment
- Preliminary assessment of H2 sourcing options

The initial work demonstrates the large optionality associated with the various options for pre-treatment, post-treatment, H2 sourcing and plant integration. A successful demonstrator will need to find a balance of demonstrating the core technology whilst allowing exploration of variations to the upstream and downstream flow sheets.

The report recommends the following next steps which will be undertaken as part of FEED:

- Investigation on post-processing of H-DRI products includes upgrading the low-grade iron ore using magnetic separators, carburisation and passivation, briquetting, and conducting smelting test work.
- Conducting operation tests using a broader Australian iron ore feed grades to ascertain the ideal Particle Size Distribution (PSD) and maximum throughput per tube while ensuring an acceptable H-DRI product quality. Performing additional investigations into the pre-processing requirements for magnetite, including a pre-oxidation stage, to further enhance the reduction of magnetite ore.
- Finalise design of DRI plant, hot briquetted iron plant, instrument and control system and electrical system with complete Process Flow Diagram (PFD) and energy and mass balance and Piping and Instrumentation Diagrams (P&IDs), equipment list, electrical load list and single line diagrams as in FEED study.
- Establish broad base design to allow for flexibility with incoming ore and outgoing post-processing requirements.

8 REFERENCES

1. Li, M., Li, J., Li, J., Li, L., Wang, D., & Li, J. (2019). Hydrogen as a reducing agent for ironmaking: A review. Journal of Cleaner Production, 231, 1298-1311.
2. Luitel, H. K., & Kazmi, S. H. A. (2017). Carbon capture and storage in iron and steel production: Problems and opportunities. Journal of Cleaner Production, 162, 112-131.
3. HYBRIT. (n.d.). The HYBRIT Project. Retrieved from https://www.hybritdevelopment.com/
4. Australian Renewable Energy Agency. (2022, March 17). Grant supports development of zero-emissions steel production. Retrieved from https://arena.gov.au/news/grant-supports-development-of-zero-emissions-steel-production/
5. Australian steel industry: A snapshot, by the Australian Industry Group. Retrieved from: https://cdn.aigroup.com.au/Reports/2019/190926_Steel_Snapshot.pdf
6. Australian steel: State of the nation 2020, by the Australian Steel Institute. Retrieved from: https://www.steel.org.au/getmedia/b311c2ad-9fc0-4db3-82c0-e898bacbfa66/ASI-Whitepaper-Ensuring-a-Sustainable-Australian-Steel-Industry-V3-pdf(10-11-20).pdf
7. Resources and Energy Quarterly by the Department of Industry, Science, Energy and Resources. Retrieved from: https://www.industry.gov.au/data-and-publications/resources-and-energy-quarterly
8. Western Australia Land Pricing. Retrieved from: https://www.landgate.wa.gov.au/
9. Iron ore, oil and steel giants line up to develop $70bn of green industrial projects in Pilbara. Retrieved from: https://reneweconomy.com.au/iron-ore-oil-and-steel-giants-line-up-to-develop-70bn-of-green-industrial-projects-in-pilbara/
10. Bureau of Meteorology Australia (BOM). Retrieved from: http://www.bom.gov.au.
11. DRI and HBI Quality – International Iron Metallics (IIMA) https://www.metallics.org/
12. International Energy Agency. (2018). Energy Technology Perspectives 2018: IEA Input to the Clean Energy Ministerial. Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2018
13. International Energy Agency. (2019). Energy Technology Perspectives 2019. Paris, France: OECD/IEA. Retrieved from https://www.iea.org/reports/world-energy-outlook-2019
14. SSAB, LKAB and Vattenfall. (2021). HYBRIT: Towards fossil-free steel. Retrieved from: https://www.hybritdevelopment.com/.
15. Midrex Technologies, Inc. (2021). Midrex H2: Clean, affordable, hydrogen-based DRI. Retrieved from https://www.midrex.com/products-services/midrex-h2.
16. Energiron Tenova & Danieli (2021). Green steel production through Hydrogen-based Energiron DRI process. Retrieved from https://www.energiron.com/wp-content/uploads/2021/12/SEAISI_2021_Energiron.pdf
17. Sohn, H. Y. (2021). Flash Ironmaking. Routledge.
18. Metso. (2021). Circored® hydrogen-based reduction. Retrieved from https://www.metso.com/portfolio/circored-hydrogen-based-reduction/P
19. Primetals Technologies. (2021). HYFOR hydrogen-based fine-ore reduction. Retrieved from https://www.mhi.co.jp/technology/review/pdf/e592/e592070.pdf
20. Posco. (2019). HYREX: Hydrogen-based Reduction of Iron Ore. Retrieved from: https://newsroom.posco.com/en/special-project-for-great-conversion-to-low-carbon-eco-friendly-steelmaking-process-%E2%91%A0-hyrex/