LUND UNIVERSITY DEPARTMENT OF ENERGY SCIENCES
AND THE UNIVERSITY OF QUEENSLAND

Preliminary Design for a Mobile Ammonia Genset for Use with Electric Mining Excavators

Final Report

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ABSTRACT

Given global temperatures are expected to rise past the Paris Agreement's 2°C limit, Liebherr Mining aims to develop products that progress their Zero Emission Mining strategy. This project therefore selected the major components required by a mobile ammonia-fuelled genset under certain operating conditions and assessed the proposed design against existing solutions.

The project was built on findings from a business pre-study and the Liebherr Mining Zero Emission Mining Concept Definition. A further literature review covered excavator operation, genset design, ammonia combustion, and existing solutions.

A use case defined the operating conditions, and the resulting requirements were validated with industry through a Voice of the Customer survey. Key genset components were then selected to meet the design requirements. It was proposed that a partner company should manufacture the final product. Several potential partners were short-listed, ranked, and met with, and a final recommendation was made. To validate the design, it was compared to market competition using the design requirements as comparison metrics.

The proposed design included a Liebherr A9912 ammonia engine, a Stamford S7L1D alternator, and a Deep Sea controller mounted on a wheeled trailer, with an expected output of 1163 kW to 1932 kW. Fuel would be supplied by a 20 m^3 on-board NH_3 fuel tank and cracker. BGG was recommended to manufacture the product. The market comparison ranked the design higher than all other examined solutions.

Given the successful project completion and approval by stakeholders, the design is planned to be further developed and commercialised.

Keywords: *Ammonia internal combustion engine, Alternative fuel generator set, Electric hydraulic excavators, Zero emission mining solutions*

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I would additionally like to thank my supervisor at The University of Queensland, Professor Paul Meehan; his advice helped me to produce work which I am genuinely proud of.

Finally, I would like to thank Professor Martin Tunér, my supervisor at Lund University, whose guidance and support were invaluable throughout the project.

PROJECT DETAILS

Title: Preliminary Design for a Mobile Ammonia Genset for Use with Electric Mining Excavators

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LIST OF ABBREVIATIONS

Below is the list of abbreviations which were used throughout this thesis, listed in alphabetical order:

Abbreviation	Definition
AC	Alternating Current
ASC	Ammonia Slip Catalyst
BGG	Bruno Generators Group
CAPEX	Capital Expenditure
CI	Compression Ignition
DC	Direct Current
E-HEX	Electric Hydraulic Excavator
EPA	U.S. Environmental Protection Agency
HEX	Hydraulic Excavator
HV	High Voltage
ICE	Internal Combustion Engine.
LTH	Lund Tekniska Högskola at Lund University
LHV	Lower Heating Value
LV	Low Voltage
MV	Medium Voltage
N/A	Not Applicable
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OPEX	Operating Expenditure
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SWOT	Strengths, Weaknesses, Opportunities, and Threats
T4f	EPA Tier 4 Final
TCO	Total Cost of Ownership
TWC	Three-Way Catalyst
UQ	The University of Queensland
VoC	Voice of the Customer
WHR	Waste Heat Recovery
ZEM	Zero Emission Mining

1 INTRODUCTION

Section 1 defines the background, goals, constraints, assumptions, and deliverables for the project.

1.1 CONTEXT AND MOTIVATION

The Paris Agreement required that the 195 signing countries limit global temperatures from rising more than 2°C above pre-industrial temperatures (UNFCCC, 2015). Despite this agreement, global temperatures are predicted to exceed the 2°C threshold by 2050 (Yerlikaya et al., 2020), largely because of greenhouse gas emissions. Of these emissions, the mining industry produces around 4% to 7% globally (Delevingne et al., 2020). Liebherr Mining therefore aims to develop products and technology that further their progress towards their Zero Emission Mining (ZEM) strategy.

As a division of the Liebherr Group, Liebherr Mining produces three types of equipment for the international mining industry, as well as various auxiliary products and support services (Liebherr Mining, n.d.). Each equipment type has a dedicated manufacturing facility: hydraulic excavators in Colmar, France; off-highway trucks in Newport News, USA, and crawler dozers in Telfs, Austria.

The Liebherr Mining hydraulic excavator range consists of nine different models, ranging in size from 113 t to 810 t. Of these, seven are offered in an electric configuration (Liebherr-International Deutschland GmbH, n.d.). The Liebherr Mining electric hydraulic excavators (E-HEXs) are powered by a cable that runs from the machine to a field switch, which is powered by the mine's electrical network. As such, there is a need for a way to increase the mobility of the Liebherr E-HEXs.

Additionally, Liebherr Mining aims to develop products in line with their ZEM strategy. This strategy involves three objectives, the first of which was to offer low-carbon solutions for all hydraulic excavators and off-highway trucks by 2022. This objective has been achieved. The second objective is to offer fossil fuel-free solutions by 2030 with the intention of achieving zero well-to-wheel greenhouse gas (GHG) emissions. The final objective is to achieve cradle-to-grave carbon neutrality across the business. The target date for the final objective will be determined in 2024 (Schuh, 2024).

Considering these business goals, Liebherr Mining aims to develop a preliminary design for a mobile ammonia-fuelled genset that can supply power to their E-HEXs and move with the powered machine as needed. This concept is intended to increase machine mobility and provide a fossil fuel-free solution for hydraulic excavator operation. It has the added benefit of reducing machine downtime which results from adjusting the power cable, as well as bringing innovation to a saturated market.

1.2 PROJECT SCOPE

The scope of the project is defined through two research questions which aim to be answered by achieving five goals. Relevant constraints, assumptions, opportunities, and deliverables further define the project scope.

1.2.1 Research Questions

To guide the project goals, the following research questions are proposed:

- Under given operating conditions, which components of which size and manufacturer should be included in a mobile ammonia genset intended to power an E-HEX?

- How does the proposed design perform compared to similar designs with respect to the intended application?

1.2.2 Project Goals

To answer the proposed research questions, the following objectives should be met:

Aim 1 – Complete a thorough literature review to understand the required technology as well as existing market solutions. This review should cover:

- Any completed prior work which is relevant to the project assumptions,
- An evaluation of existing design methodologies to justify the project format,
- The components and typical operation of the excavators which will be powered,
- Relevant regulations surrounding ammonia and generator sets,
- Key components and design considerations for gensets,
- Information required to understand ammonia and how it is used as a fuel,
- A review of prevalent design evaluation tools as well as examples of existing mobile gensets,
- And any additional topics that become relevant through the course of the project.

Aim 2 – Define the expected use cases for a proposed genset based on industry expectations. The use case definitions should describe:

- The system under discussion,
- The actors which exhibit a behaviour when interacting with the system,
- The goal of the interaction between system and actors,
- Any preconditions for the interaction,
- And the scenario that is expected to occur during the interaction.

Aim 3 – Define the required design specifications under a given set of operating conditions. The design specifications should prescribe:

- The general design requirements, including the duty cycle, hours of operation, maximum permissible emissions, and level of modularity,
- The electrical design requirements, including the continuous and peak power output and the output frequency, voltage, and/or current,

- The interface requirements between the genset and both the E-HEX cable and the potential mobility method, as well as between different gensets as required for synchronisation,
- The maintenance requirements, including life expectancy, overhaul intervals, and spare parts,
- And any additional requirements that become apparent through the course of the project.

Aim 4 – Produce a design for the proposed genset to meet the defined design specifications. The design should be presented in the form of:

- A high-level list which identifies the manufacturer and specific part number of key components,
- A flow chart demonstrating the interaction between the key components,
- An estimate of the total system weight,
- And any other deliverables which may be required as the project progresses.

Aim 5 – Evaluate the proposed design's expected performance for the desired use case with respect to market competition. The evaluation metrics should include:

- The expected solution costs,
- The run time of the genset on a single fuel tank,
- The rated power of the genset,
- The predicted emissions from the solution,
- And any additional metrics that may be identified through the course of the project.

1.2.3 Constraints and Assumptions

The primary constraint on the scope of this project is that the design should be preliminary, rather than final. As such, the design or development of individual components (such as configuring the ammonia engine) is considered out of scope. For the same reason, this project does not consider exact component quotes, specific production or manufacturing plans, or prototype development. Also, the decision to investigate ammonia over another alternative fuel such as hydrogen or methane was made at a Liebherr Group level, and the decision is therefore considered out of scope.

In addition to these constraints, the project scope is restricted due to several assumptions. The two primary assumptions regarding this project are as follows:

- The companies listed as potential partners in a previous Liebherr study are the most viable options and others should not be actively searched for.
- The Liebherr ammonia engines will be developed and will perform as expected.

1.2.4 Deliverables

Given that this project was conducted in collaboration with multiple organisations, there were many deliverables. These deliverables are therefore described in Table 2 below.

Table 2: Project Deliverables for All Organisations

Task	**Organisation**	**Description**
Goals Document	LTH	The goals document presented the project background and objectives, disciplinary foundation, and initial methodology.
Project Proposal/Plan	UQ & LTH	The project proposal outlined the purpose and goals of the project. It also assessed risks to the completion of the project.
Interim Reports	UQ & LTH	The interim reports review the project progress, including an updated risk assessment, and any achieved results.
Workplace Feedback and Reflections	UQ	The workplace reflections will require feedback from supervisors and a personal reflection on the project's progress.
Oral Presentations	UQ & LTH	The oral presentations will explain the completed work to peers, academics, and company stakeholders.
Design Flow Chart and Specifications	Liebherr Mining	The flow chart and specifications will define the specific components recommended and their specifications.
Final Report	UQ, LTH & Liebherr Mining	The final report will present the methodology and findings of the project, and any recommendations and future work.

1.2.5 Opportunities for Stakeholders

The key stakeholders in this project are Liebherr Mining, their customers, and the power generation and mining industries. This project is expected to positively contribute to the Liebherr Mining ZEM strategy by easing the development of a zero-emission power solution for their existing equipment. It could also positively impact Liebherr Mining customers by contributing to the development of a product which reduces down-time and safety concerns currently associated with Liebherr E-HEX operations, as well as potentially leading to a means of producing emission-free energy on site. Finally, the power generation and mining industries could benefit from the reduced barriers to implementation of zero emission technology based on the conclusions drawn in this report.

2 TECHNICAL BACKGROUND

This section defines the disciplinary foundation on which the progress towards each aim was based.

2.1 PRIOR WORK

The degree project was built on the findings of a business pre-study completed by a previous student at Liebherr Mining, as well as the Liebherr Mining ZEM Concept Definition Feasibility Study. The ZEM Feasibility Study concluded that the implementation of ammonia internal combustion engines (ICEs) is feasible, but further details about the contents remain confidential.

The pre-study by Ivan Alejandro Banda Gallegos (2023) developed a business proposal for a potential Liebherr mobile and stationary genset product line. The author performed benchmarking on market gensets with a prime power over 100 kW at 1800 RPM, including both diesel and alternative fuel gensets. Ten diesel genset original equipment manufacturers (OEMs) were examined to identify trends and opportunities for collaboration. One trend noted was that large competitors often use third-party components with their gensets. MTU, for example, uses Leroy-Somer and Marathon alternators, combined with Deif or Basler Electric control modules and their own engines. Similarly, Cummins use their own engines and control modules with Stamford alternators. The study also described a trend where most market options lie within the 100 kW to 800 kW range, with only one competitor offering gensets of greater than 4000 kW.

To investigate alternative fuel options, a similar study was completed by the author for natural gas engines, and very similar results were found: most models were within the 100 kW to 800 kW range, with only one manufacturer offering a genset with over 4000 kW prime power. The natural gas study also revealed that of the sample analysed, 17% were able to blend natural gas with hydrogen, of which 62% described hydrogen blending at 10% and 38% described hydrogen blending up to 25%.

Finally, ammonia and hydrogen-fuelled gensets were studied. Competitors that offer 100% hydrogen ICE gensets such as 2G were identified, as were competitors that offer hydrogen fuel cell gensets such as Ballard. Notably, there was no evidence of an existing ammonia-fuelled genset; however, competitors such as MAN were identified as actively developing ammonia ICEs.

The paper then proceeded to identify potential companies through which Liebherr could outsource genset manufacturing, including the alternator, engine, and control module OEMs that these potential partners have previously used. This investigation included only manufacturers which do not produce their own engines, to avoid considering direct competition as an option for partnership. The results described the product line depth of 26 OEMs across Asia, Europe, North America, and South America but did not conclude by recommending any one OEM.

2.2 DESIGN METHODS

There are many design methods that are used throughout industry and academia, so it was considered necessary to investigate and evaluate various methodologies prior to completing this project.

The first example of a considered design method was Axiomatic Design. This methodology involves systematically transforming customer needs into functional requirements, design parameters, and process variables using matrices. The methodology is governed by two axioms: independence, meaning that each functional requirement is independent of the others; and information, which specifies that the information content of the design should be minimal (Benavides, 2012). This method was rejected because it does not leave enough room to consider the nuance of customer requirements, whereas this project is intended to be broad.

The second design method example was Metric Design which focusses on low cost and predictable performance under the understanding that minimal noise and cost imply an optimal product. It is again governed by two principles: a decrease in quality implies economic loss, and variability implies worse quality (Benavides, 2012). This methodology was again rejected because the new technology required for this project causes high costs and a significant number of unknown operating factors, which makes it difficult to design for reliability and cost.

Following this, the Iterative Design process was considered. This design methodology is based on the repetition of the design loop (planning, implementation, testing, and evaluation) until the optimal design is reached (Ramachandran et al., 1992). This methodology was also rejected because the short project time frame caused prototyping and testing to be out of scope.

The final example of a design method was the Waterfall Design process. In this process, each phase is completed before the next phase such that the design process is linear and sequential (Udesh S Senarath, 2021). This project used the Waterfall Design methodology because each phase of the project was dependent on the previous, so the process most aligned with the project requirements.

2.3 REVIEW OF HYDRAULIC EXCAVATORS – AIM 2

2.3.1 Liebherr Hydraulic Mining Excavators

2.3.1.1 Excavator Structure

Hydraulic excavators (HEXs), particularly those designed for mining, are primary loading tools meaning that they take material from the ground and load it into another piece of equipment (typically an off-road truck). HEXs can be split into three main subsystems:

- The upper carriage, which consists of the hydraulic reservoir, the powerpack (either electric or diesel), the ballast weight, the distributer assembly, the fuel tank (for diesel excavators), the slewing gear, and the cabin,
- The undercarriage, which consists of the rotary union, tracks, track frames, and central connecting piece,

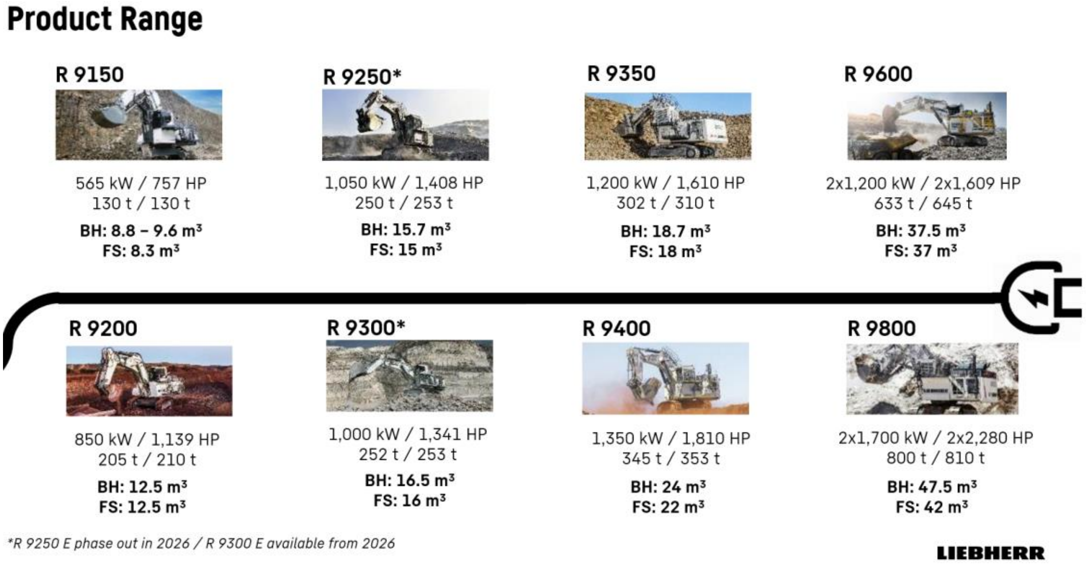
- And, the attachment, which consists of the boom, the arm, the bucket, and the cylinders. The attachment can be in either the face shovel or the backhoe configuration (Wang et al., 2022), as shown in Figure 1 and Figure 2 below.

Figure 1: Backhoe Equipment Configuration (Liebherr-International Deutschland GmbH, n.d.)

Figure 2: Face Shovel Equipment Configuration (Liebherr-International Deutschland GmbH, n.d.)

2.3.1.2 Electric Power Solution

Liebherr E-HEXs have a 70% commonality with Liebherr diesel hydraulic excavators. The primary difference is that rather than using a diesel ICE and associated subsystems, Liebherr E-HEXs run using asynchronous electric induction motors which typically have a power factor of approximately 0.88 (Rambert, 2024). The electric motor power for each Liebherr machine is presented in Figure 3.



Product Range

R 9150
565 kW / 757 HP
130 t / 130 t
BH: 8.8 – 9.6 m³
FS: 8.3 m³

R 9250*
1,050 kW / 1,408 HP
250 t / 253 t
BH: 15.7 m³
FS: 15 m³

R 9350
1,200 kW / 1,610 HP
302 t / 310 t
BH: 18.7 m³
FS: 18 m³

R 9600
2x1,200 kW / 2x1,609 HP
633 t / 645 t
BH: 37.5 m³
FS: 37 m³

R 9200
850 kW / 1,139 HP
205 t / 210 t
BH: 12.5 m³
FS: 12.5 m³

R 9300*
1,000 kW / 1,341 HP
252 t / 253 t
BH: 16.5 m³
FS: 16 m³

R 9400
1,350 kW / 1,810 HP
345 t / 353 t
BH: 24 m³
FS: 22 m³

R 9800
2x1,700 kW / 2x2,280 HP
800 t / 810 t
BH: 47.5 m³
FS: 42 m³

**R 9250 E phase out in 2026 / R 9300 E available from 2026*

LIEBHERR

Figure 3: Liebherr E-HEX Product Range (Rambert, 2024)

These motors are in turn powered by an electric cable that connects the E-HEX to a field transformer, and then to the grid. The cable may either trail behind the E-HEX to a maximum length of 500 m or be mounted on the machine using an automatic cable reel, which increases the manoeuvrability of the machine but decreases the cable length to 300 m (Rambert, 2024). Figure 4 shows this connection for a machine with a cable reel. The standard supply voltage for the Liebherr E-HEX range is 6 or 6.6 kV at 50 Hz, however other options such as 7.2 kV at 60 Hz are also available. The E-HEXs have 12 kV insulation as a standard, allowing the machine to function at up to 2800 m of elevation, however there is also the option to use

17.5 kV insulation, which increases the operating altitude to 4800 m. The machines are also capable of running at temperatures between -40°C and 50°C (Rambert, 2024).

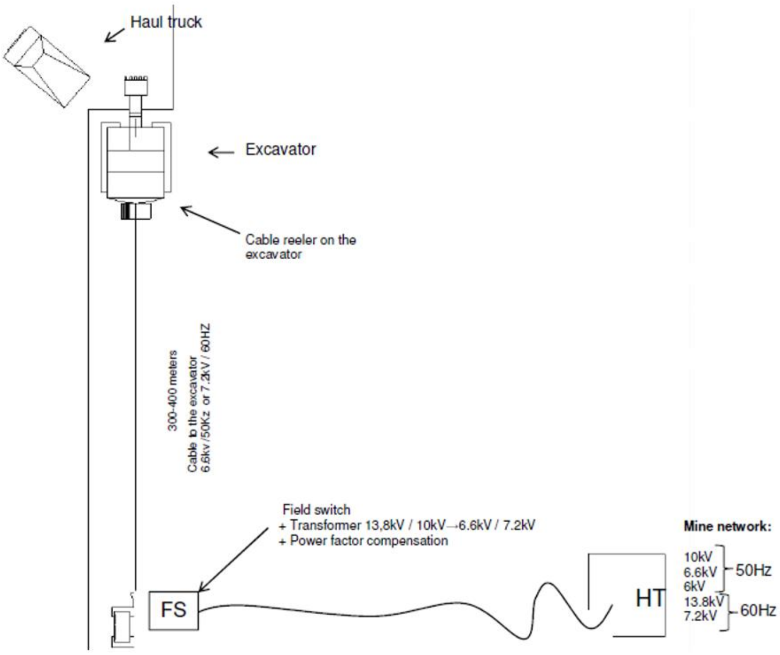


Figure 4: E-HEX Power Supply with Cable Reel (Rambert, 2024)

2.3.2 Hydraulic Excavator Operation in Industry

The operation of HEXs in industry is heavily dependent on both the specific machine as well as the mine site. For example, if the machine is in the backhoe configuration, the HEX typically sits on a bench at the same height as the top of an off-highway truck and digs downward. The machine starts at one end of the bench then moves across it before returning in the other direction. This is repeated until the desired bench depth has been dug. On the other hand, a HEX in the face shovel configuration sits on the mine floor at the truck wheel level and digs forward. It moves along the face of the wall in the same manner as a backhoe machine. In both cases, the digging and loading cycle is as shown in Figure 5 (Molaei et al., 2023).

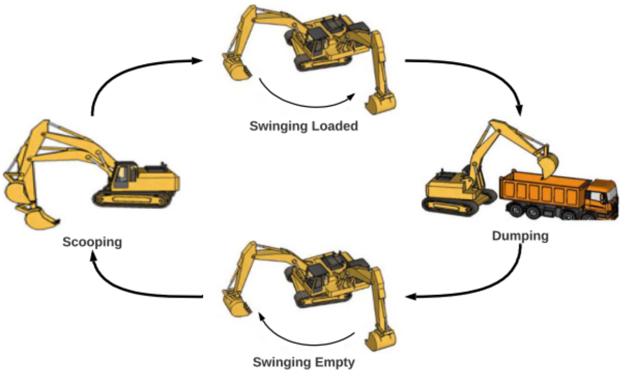


Figure 5: Excavator Loading Cycle (Molaei et al., 2023)

The distance travelled by the HEX during digging is determined by the bench length, which is defined during the mine planning phase. The bench length is dependent on the site weather and geological details as well as the physical material properties and the strike-length of the deposit available for benching (Gandhi, 1964). HEXs are also regularly moved between different benches, typically once every 3 to 7 days though this also varies between mine sites and between machines with different bucket sizes. The distance between benches is again mine plan dependent but is typically in the range of 250 m and 2 to 3 km.

A HEX is primarily stopped to allow for operator change overs, as well as for refuelling and maintenance. There are two main techniques which define how frequently this occurs. The first is used on mines without hot seating, where the machine must be stopped during shift changes and at crib break (the mid-shift break). The stop time varies depending on which works need to occur.

The second method is for mines which have hot seating for operators, meaning the next operator climbs into the machine immediately as the previous operator leaves (Walker, 2011). This technique allows the machine to only stop when it needs to be refuelled, typically once per day. During this stop, the machine is refuelled, the oil is replenished, a mechanical inspection is completed, and the old and new operators swap over. The time taken by this process depends on the machine size and the fuel flow rate. For example, for an R9600 it takes approximately 25 mins whereas for an R9800, it typically takes between 30 and 35 mins.

2.4 REVIEW OF REGULATIONS – AIM 3

Ensuring a proposed product meets all required regulations and standards is a key part of the technical design process. However, given this project aimed to produce a preliminary design, it was considered out of scope to investigate all relevant standards and regulations in all regions of operation for Liebherr Mining customers. It was therefore decided to focus on international, European, and North American standards and requirements with the understanding that slight design modifications may be necessary to comply with, for example, Standards Australia.

2.4.1 Genset Regulations

The following are standards defined by international organisations regarding the design, manufacturing, installation, operation, and maintenance of gensets:

- ISO 3046: Reciprocating internal combustion engines
- ISO 8528: Reciprocating internal combustion engine driven alternating current generating sets
- ISO 9001: Quality management systems
- SAE International J1349: Certified Power

The regulations largely cover requirements for the declaration of power, fuel consumption and testing of ICEs and generator sets. Further specifications published by European and North American organisations may be found in Appendix B.

2.4.2 Ammonia Regulations

The following are standards defined by international organisations regarding the use and storage of ammonia:

- International Chemical Safety Cards (ICSC) 0414 – Ammonia (anhydrous)

- IACS URH1 - Control of Ammonia Releases on Ammonia Fuelled Vessels
- IEC 60079: Explosive atmospheres
- ISO 5771: Rubber hoses and hose assemblies for transferring anhydrous ammonia

Some key points which are covered by these regulations include exposure limits, requirements in case of leak, storage requirements, PPE requirements, and emission limits. Further specifications published by European and North American organisations may be found in Appendix C.

2.4.3 Hydrogen Regulations

The following are standards defined by international organisations regarding the use and storage of hydrogen:

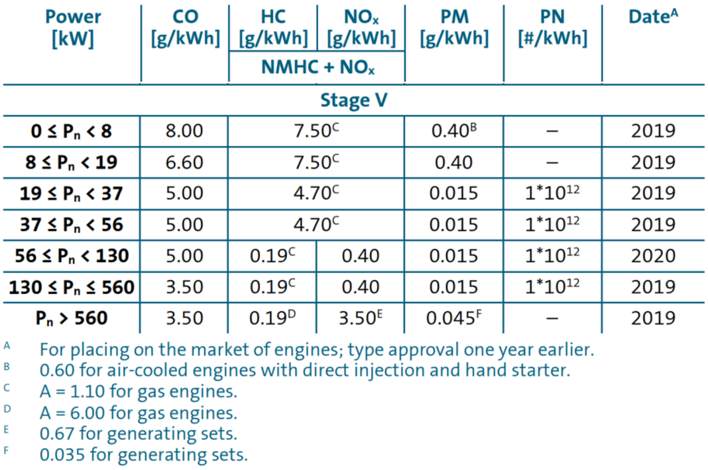
- ISO/TS 19870: Hydrogen technologies
- ISO/TR 15916: Basic considerations for the safety of hydrogen systems
- IEC 60079: Explosive atmospheres
- ISO 14687: Hydrogen fuel quality

The standards primarily discuss the minimum safety requirements when using hydrogen. European and North American standards may be found in Appendix D.

2.4.4 Emission Regulations

Given the genset is intended to be both mobile and operational off-road, it's emissions would be covered by any non-road mobile machinery directives for the region in which it operates. While the described emission limits can vary between regions, regulations from the EU and North America are equivalent in most cases. EU Regulation 2016/1628 is therefore presented in Table 3 below and regulations from the USA may be found in Appendix E. Note that N_2O and NH_3 emissions are limited to 133 mg/kWh and 10 ppm respectively (Mendoza-Villafuerte et al., 2017). The limits are defined for diesel engines unless otherwise noted but were used as a basis for defining emissions limits within this project.

Table 3: EU Non-Road Mobile Machinery Emissions Regulations (Regulation 2016/1628, 2022)



Power [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PM [g/kWh]	PN [#/kWh]	Date[A]
		NMHC + NO_x				
			Stage V			
$0 \leq P_n < 8$	8.00	7.50[C]		0.40[B]	–	2019
$8 \leq P_n < 19$	6.60	7.50[C]		0.40	–	2019
$19 \leq P_n < 37$	5.00	4.70[C]		0.015	$1*10^{12}$	2019
$37 \leq P_n < 56$	5.00	4.70[C]		0.015	$1*10^{12}$	2019
$56 \leq P_n < 130$	5.00	0.19[C]	0.40	0.015	$1*10^{12}$	2020
$130 \leq P_n \leq 560$	3.50	0.19[C]	0.40	0.015	$1*10^{12}$	2019
$P_n > 560$	3.50	0.19[D]	3.50[E]	0.045[F]	–	2019

[A] For placing on the market of engines; type approval one year earlier.
[B] 0.60 for air-cooled engines with direct injection and hand starter.
[C] A = 1.10 for gas engines.
[D] A = 6.00 for gas engines.
[E] 0.67 for generating sets.
[F] 0.035 for generating sets.

HC limits for gas engines: If an A-factor is defined, the HC limit values result from the formula HC = 0.19 + (1.5 x A x GER), but may not exceed HC = 0.19 + A. For combined HC + NOx limit value, the combined limit value is reduced by 0.19 g/kWh and applies only to NOx. GER (Gas Energy Ratio) is the average gas to energy ratio during the respective test cycle.

2.5 REVIEW OF GENSETS AND AMMONIA – AIM 4

2.5.1 Genset Components and Design

2.5.1.1 Components

The typical components in a genset are as follows (Eriksson & Lexander, 2022):

- **Frame:** Reduces vibrations and grounds the system. It can also be used to increase mobility, sound attenuation, and thermal insulation.
- **Engine:** Converts the chemical energy from fuel to mechanical energy. The engine also requires an appropriate exhaust and after treatment system as well as a lubrication system.
- **Alternator:** Converts the mechanical energy produced by the engine to electrical energy. The alternator consists of two main parts – the stator which remains stationary and the rotor which is spun by the mechanical energy from the engine. There is a magnetic field between the rotor and stator, so when the rotor is spun the stator experiences a voltage due to electromagnetic induction. When connected to a load, this voltage difference causes current to flow.
- **Battery:** Starts the engine. Genset batteries are typically lead acid.
- **Cooling system:** Prevents overheating of the genset. It typically includes a radiator and a coolant subsystem.
- **Control panel:** Regulates the operation of all other components using a Control Module software program.
- **Fuel system:** Receives, stores and supplies fuel to the ICE.
- **Voltage regulator:** Controls the voltage quantity and transforms the current from direct current (DC) to alternating current (AC). Voltage regulators are typically automatic.
- **Transformer:** Optionally used to increase or decrease the voltage by a larger amount than possible through the voltage regulator.

2.5.1.2 Design Parameters

The following parameters should be considered when designing a genset (Iverson, 2007):

- **Power output:** Equal to or higher than the expected load.
- **Operating hours and maintenance frequency:** Ideally aligned with existing site schedules.
- **Expected minimum load:** Typically, should not be less than 30% of the rated load to prevent engine damage.
- **Maximum allowable step voltage dip:** Step voltage dip is a sudden decrease in voltage due to a sudden increase in load. This typically occurs during the startup of a generator or connected machine. If a smaller dip is needed, then a larger generator is needed.

- **Maximum allowable step frequency dip:** As above.
- **Operating conditions:** Specifically, the expected ambient temperature and pressure. If either is outside the genset's specified range, then the genset is derated and will produce less power.
- **Phase:** Either single or three-phase to match the connecting equipment.
- **Frequency:** Should also match the load. Typically, the frequency is 50 Hz, 60 Hz, or 400 Hz.
- **Voltage:** Depends on both the frequency and the desired supply voltage. It was noted that different voltages correspond to different power ratings.
- **Duty Cycle:** This is defined by ISO 8528-1 (International Organization for Standardization, 2018) and ANSI/NEMQ MG1 (American National Standards Institute & National Electrical Manufacturers Association, 2021) as either Standby, Prime, or Continuous power.
    - Standby power limits operation hours to 200 hours per year.
    - Continuous power implies constant power delivery at a constant load with unlimited operational hours.
    - Prime power implies constant power delivery with a variable load over an unlimited number of operational hours. The average power output over 24 hours must be limited to 70% of the prime power rate, however an overload of up to 10% is permitted for short periods.

2.5.1.3 Synchronisation

If the expected load is too large for a singular genset or if there is a significant peak load compared to the normal operating load, then it is possible to share the load between multiple gensets. To achieve this, the voltage, frequency, and phase angle of all gensets must be synchronised to avoid overload or instability. When operating synchronised gensets, there are two control modes: droop control and isochronous control (Torres et al., 2020).

Droop control is when each genset is controlled to maintain a constant voltage, which means that it operates at a lower frequency as the load increases. This ensures that each genset can share the load evenly thereby improving reliability, but the response is typically slow, and in some applications, frequency variance can be damaging (Torres et al., 2020).

Isochronous control is when each genset is controlled to maintain a constant frequency by adjusting the generator speed as the load varies. Generators can compensate for each other by increasing their outputs in varying amounts to maintain the desired frequency. This method is beneficial in frequency-sensitive applications or when a fast load response is required but the required precision is difficult to achieve and can lead to instability (Torres et al., 2020).

2.5.2 Ammonia Production and Storage

The physical properties and health effects of ammonia are listed in Appendices F and G respectively.

2.5.2.1 Ammonia Production

Ammonia is a compound which already has significant production levels and is used across a range of industries. In 2020, annual global ammonia production was approximately 176 million tonnes (David et al., 2020) and it was used, for example, in fertiliser, as a stabiliser during rubber production, as a whitener during paper production, and as a base for the chemical synthesis of plastics, synthetic fibres, and explosives (Tornatore et al., 2022).

The primary production process for ammonia is the Haber-Bosch process, where nitrogen from the air and hydrogen from another source are combined in the presence of a catalyst at high temperature and pressure, creating the following reaction: $3H_2 + N_2 \rightarrow 2NH_3$ (Humphreys et al., 2021).

The hydrogen used in this process is sourced through several means, though data from 2020 indicated that 72% was sourced through natural gas steam reforming, 26% from coal gasification, and 1% from oil products (Tornatore et al., 2022). Figure 6 shows a high-level summary of the Haber-Bosch process when ammonia is produced using hydrogen which was produced from natural gas.

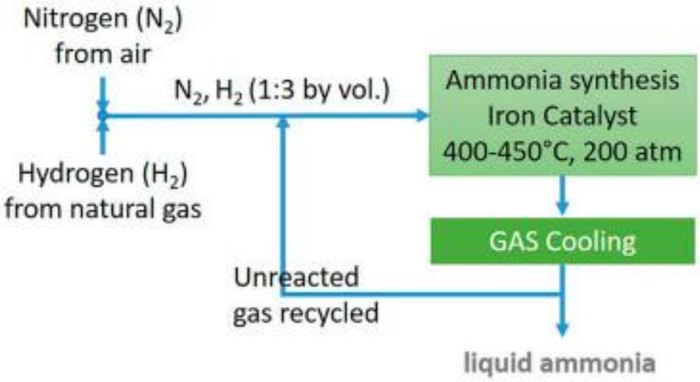


Figure 6: Grey Ammonia Haber-Bosch Process Example (Tornatore et al., 2022)

When the hydrogen is sourced from fossil fuels, as in the previous examples, the resulting ammonia is considered grey ammonia. Green ammonia describes ammonia that was synthesised from fully renewable energy sources. Several methods to produce green ammonia are currently being investigated, including using renewably sourced hydrogen to feed the Haber-Bosch process, or by electrochemical ammonia synthesis. While using renewable hydrogen for the Haber-Bosch process is arguably the simpler solution as it is more established, electrochemical ammonia synthesis theoretically has greater potential, if the process can be sufficiently scaled-up (Nayak-Luke & Bañares-Alcántara, 2020). An example of green ammonia production is shown in Figure 7.

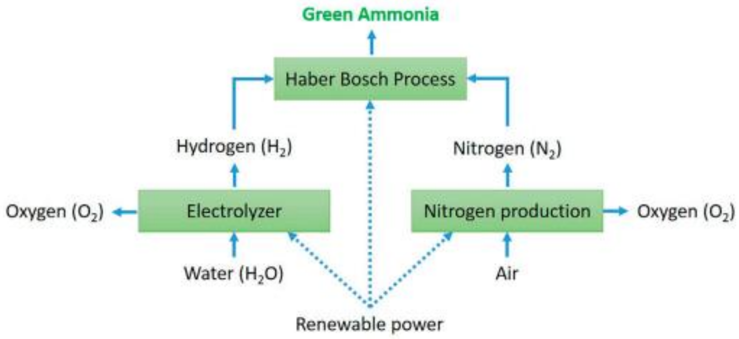


Figure 7: Green Ammonia Haber-Bosch Process Example (Tornatore et al., 2022)

2.5.2.2 Ammonia Storage

Ammonia is predominantly stored as a liquid by either being slightly compressed to approximately 1MPa or slightly cooled to approximately -33°C at atmospheric pressure. Ammonia has a narrow flammability range of approximately 15% to 28% and a high auto-ignition temp of 650°C and is therefore considered non-flammable during transport and storage. It has, however, a high apparent toxicity which means that leaks must be carefully managed (Aziz et al., 2020). As such, the key concerns when storing ammonia are preventing leaks and maintaining the correct pressure or temperature.

On a large-scale, ammonia is stored in refrigerated tanks as there is reduced cost and increased safety without pressurised tanks. On smaller-scales however, for example during local transport or at the end-user-level, pressurised tanks are typically used due to the smaller footprint and reduced number of auxiliary systems. It was noted that the maximum allowable fill point of an ammonia tank is 85% volumetrically to allow the liquid to expand during temperature fluctuations (Elishav et al., 2021).

2.5.3 Ammonia Internal Combustion Engines

2.5.3.1 Ammonia Combustion in Engines

It is possible to combust ammonia in an ICE through compression ignition (CI) or spark ignition (SI) in a manner similar to that used with fossil fuels. The 4-stroke CI cycle compresses air before injecting the fuel into the combustion chamber. The elevated temperature and pressure in the chamber cause the fuel to auto-ignite, which pushes the piston down to generate power. The 4-stroke SI cycle, on the other hand, pre-mixes the fuel and air before it is compressed. The compressed mixture is then ignited with a spark causing it to expand and generate power (Khajepour et al., 2014).

In general, CI for ammonia is more challenging than for diesel due to its high self-ignition temperature and comparatively low heating value (Chiong et al., 2021). SI for ammonia is again harder than gasoline SI because while it is theoretically possible to ignite pure anhydrous (containing no water) ammonia, if the air-fuel ratio varies outside the narrow acceptable limits, the engine will cease to function correctly (Dinesh & Kumar, 2022). It was also noted that there is currently no commercialised system that provides enough energy for the ignition of ammonia.

2.5.3.2 Dual Fuels

It is possible to reduce the problems associated with ammonia combustion by mixing ammonia with another fuel. For a CI engine, ammonia can be combined with diesel, to improve the ability to ignite the fuel mixture. This, however, only reduces carbon emissions rather than completely removing them (Tornatore et al., 2022).

Similarly, for an SI engine, ammonia can be paired with hydrogen or natural gas, to improve the ability to ignite the fuel mixture. Again, natural gas pairing would only reduce carbon emissions rather than completely removing them. Hydrogen pairing, on the other hand, would not introduce any carbon to the system, meaning that the tank-to-wheel carbon emissions would remain at zero. If green hydrogen and ammonia are used, the fuel could be fully carbon free (Tornatore et al., 2022).

Most existing literature quotes the required hydrogen energy ratio to be between 5% and 20% with Li et al. (2023), for example, finding that the optimal ratio for SI combustion is 7.5% hydrogen.

2.5.3.3 Emissions

There are three primary emissions from an ammonia engine: ammonia slip (NH_3), nitrous oxide (N_2O) and nitrogen oxides (NO_x). The relationship between ammonia slip quantity and NO_x emissions is similar to that between NO_x and soot in diesel engines, where the quantities are inversely proportional (Qi et al., 2023). Figure 22 in Appendix H shows this relationship.

Emissions are typically managed with an aftertreatment system. There are several types of aftertreatment systems that can be used individually or in various combinations. Currently, the most effective methods for removing NO_x are the three-way catalytic (TWC) converter and the selective catalytic reduction (SCR) converter. Typically, a TWC would be used in cases where the air-fuel ratio is stoichiometric, meaning that the ratio of air and fuel is exactly that required for the reaction. On the other hand, an SCR would likely be used in engines which are running lean, meaning there is excess air compared to the amount of fuel (Qi et al., 2023).

In the case of ammonia combustion, Qi et al. (2023) discussed the fact that when hydrogen is used as a combustion enhancer in ammonia engines, the best efficiency results are typically achieved under slightly lean conditions. This implies that an SCR is likely the more suitable technology to remove NO_x for ammonia ICEs. The authors also noted that SCR converters use ammonia as their reducing agent implying that ammonia engines could use the unburned exhaust ammonia for this, supplemented by the stored ammonia as required.

For unburned ammonia, the currently accepted method for aftertreatment is the use of an ammonia slip catalyst (ASC), which oxidises the remaining NH_3 to N_2. There are several mechanisms by which an ASC may function, however research into the reaction path and rate-determination under real and complex conditions is ongoing (Qi et al., 2023).

The final emission, N_2O, is not only an emission from the ICE but also a by-product of SCR and TWC converters. It has a greenhouse gas effect that is approximately 300 times stronger than that of CO_2 and, unfortunately, has the fewest established aftertreatment options (Westlye et al., 2013). The current most feasible option is an N_2O decomposition catalyst (NDC), which converts N_2O directly to nitrogen and oxygen; however, current commercially available examples are used for stationary plants that have a lower N_2O output (Qi et al., 2023). Further research into the area is therefore required as emission regulations become stricter.

2.5.4 Ammonia to Hydrogen Crackers

The consideration of dual fuels lead to the consideration of fuel supply systems. For diesel and natural gas, the system would involve two separate fuel supply and storage systems, one for the ammonia and one for the secondary fuel. For hydrogen this is also a possibility, however it is also possible to reform ammonia to hydrogen using an on-board cracker (also known as a reformer or dissociator).

2.5.4.1 Function

A cracker takes external energy to decompose ammonia into nitrogen and hydrogen through the endothermic reaction $2NH_3 (g) \rightarrow N_2 (g) + 3H_2 (g)$. This reaction requires 45.9 kJ per mole and the vaporisation of liquid ammonia into gaseous ammonia requires 23.4 kJ per mole (Ashcroft & Goddin, 2022). The energy required to complete this reaction could be provided in multiple ways, for example through an external electrical supply or from the cooling or exhaust systems of the engine. Ammonia decomposition is an equilibrium limited reaction so there is a lower operating temperature limit. At atmospheric pressure, the lowest feasible temperature is 250°C. Figure 8 shows how much ammonia is converted at various temperatures under atmospheric pressure (Asif et al., 2023).

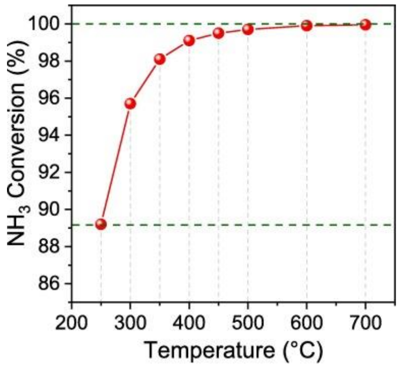


Figure 8: Thermodynamic Decomposition of NH_3 at Various Temperatures (Asif et al., 2023)

There are typically four stages in a cracker (Yousefi Rizi & Shin, 2022):

1. The liquid ammonia is vaporised and preheated to the required operating temperature.
2. The gaseous ammonia enters the catalyst bed that is heated by an external energy source and the decomposition reaction occurs.
3. The cracked gas is separated by adsorbers such that the nitrogen and any remaining ammonia are removed, and the hydrogen is of the required purity.
4. The tails gases are exhausted, and the pure hydrogen is compressed as required.

2.5.4.2 Existing Crackers

Current commercially available ammonia crackers are large and typically built with the intention of producing hydrogen on a large-scale, with a production capacity ranging from 1 to 2 MTPD (Makhloufi & Kezibri, 2021). Some examples of companies producing ammonia crackers include KBR, Topsoe, Johnson Matthey, H2Site, AFC, and Amogy. Of these, Amogy is the only company to propose a small-scale product and has previously demonstrated a functioning cracker used to supply hydrogen to fuel cells on board a tractor as well as an on-road truck.

While industrial-scale ammonia crackers are unsuitable for the context of this project, some progress has been made into small-scale crackers. Qi et al. (2023), for example, discussed the need for efficient low-temperature ammonia decomposition, and therefore summarised some existing research into on-board crackers. The authors found that most catalysts used in research were ruthenium-based, and consequently reached the same conclusion as Bell & Torrente-Murciano (2016): that the use of ruthenium causes a significant increase in cracker costs as it is a noble metal, and that further research into high-performance non-noble metal catalysts is required. Despite the current high costs, Liebherr predicts that on-board crackers will be a viable option for this project. It was therefore noted that on-board crackers can achieve between 85% and 97% conversion of ammonia to hydrogen (Yousefi Rizi & Shin, 2022).

2.5.5 Liebherr Ammonia Combustion Engines

To date, Liebherr has only run tests on the smallest available ammonia engine, the A964. The hydrogen energy ratio was measured during the A964 tests at various engine operating points. These tests concluded that the engine needs around 3% H_2 at full load, 5 to 10% at moderate load, but up to 40% at very low load and high speed. Note that this is with ammonia supplied at approximately 15 bar and hydrogen injected at 4-5 bar from a cracker. This cracker is estimated to have an energy efficiency of 80%, which is in-line with literature, including findings by Cha et al. (2021).

Measured fuel consumption data was available for all diesel engines. Table 4 shows the relevant average fuel consumption values, as well as the average engine efficiencies, published by Liebherr in their data sheets.

Table 4: Fuel Consumption of Relevant Liebherr Engines

Liebherr Engine	Maximum Available Power [kW]	Fuel Consumption	Efficiency
D964	300	72 L/h Diesel	44.7% [1]
D9812	2000	482 L/h Diesel	42% [2]
D9816	2700	735 L/h Diesel	42% [2]

[1] *Measured value at full load*

[2] *Average value*

2.6 REVIEW OF EVALUATION METHODS AND EXISTING SOLUTIONS – AIM 5

2.6.1 Evaluation Methods

The evaluation of a design can be either qualitative or quantitative, however in a technical context the evaluation is largely quantitative. Several evaluation methods were investigated, three of which are presented below.

- **Pass-Fail:** The simplest evaluation method. Criteria that can either be passed or failed are defined, and the design attributes are compared to these criteria. If most of the criteria are met, the design is acceptable. The criteria can be either quantitative or qualitative.
- **SWOT Analysis:** SWOT stands for strengths, weaknesses, opportunities, and threats and is a more complicated method. While it can be completed quantitatively, it is

typically a qualitative method that uses questions to evaluate the potential success of a design in the market (Benzaghta et al., 2021).

- **Evaluation Matrices:** This method is typically the most quantitative, although it can be completed qualitatively. There are several types of evaluation matrices (for example the Pugh matrix) however, they largely follow the same method. A set of criteria is defined, and each criterion is given a score range that describes how successful the design is in that criterion. The design is then compared to each criterion and either the average or the total score is found (Joshi et al., 2019). This method also allows multiple designs to be easily compared.

2.6.2 Existing Mobile Gensets

Some examples of OEMs with existing mobile diesel gensets in use in the mining industry include Caterpillar, Cummins, and Kohler. Figure 9, Figure 10, and Figure 11 show images of these examples. The product details are presented in Table 5. It was noted during the literature review that Liebherr has previously used two Cummins C2000D6RG gensets in combination with a 2500 kVA transformer to power an R9400 electric excavator for MINExpo.

Table 5: Existing Mobile Genset Specifications

OEM	Model	Rated Power [kW]	Frequency [Hz]	Voltage [V]	Weight* [kg]
Cummins [1]	C2000D6RG	1825	60	480	29158
CAT [2]	XC2280	1825	60	480	37195
Kohler [3]	175REOZT4	139	60	480	3621

* *Including lubricant, excluding chassis and fuel*

[1] *(Cummins Power Generation Inc., 2012)*

[2] *(Caterpillar, 2023)*

[3] *(175REOZT4, 60 Hz, Diesel, Tier 4 | Industrial Mobile Generators | Kohler, n.d.)*

Figure 9: Cummins Mobile Genset (Cummins Power Generation Inc., 2012)

Figure 10: CAT Mobile Genset (Caterpillar, 2023)

Figure 11: Kohler Mobile Genset (175REOZT4, 60 Hz, Diesel, Tier 4 | Industrial Mobile Generators | Kohler, n.d.)

In addition to the above diesel solutions, existing low-emission solutions are presented in Table 6.

Table 6: Examples of Existing Low-Emission Mobile Solutions

Power Source	OEM	Model	Rated Power [kW]
Fuel Cell	Hitachi	HyFlex	1000
	EFOY	H2Genset	28
	EODev	GEH2	88
Battery	Moxion	MP-75	40
	Alfen	TheBattery Mobile X	270
	Power Edison	TerraCharge	3000

2.6.3 Existing Stationary Gensets

Existing stationary solutions for both mobile and stationary applications are presented in Table 7.

Table 7: Examples of Existing Stationary *Power Solutions*

Power Source	**OEM**	**Model**	**Rated Power [kW]**
Diesel ICE	Kohler	KD4000	3640
	CAT	C280-8	2420
	MTU	20V4000 DS3600	2712
Fuel Cell	CAT	CAT PGS	1500
	Erenewable Innovations	EmPower	1760
	Nuvera	G-470	470
Battery	Symtech Solar	MEGATRON	1000
	Alfen	TheBattery Elements	1000
	Exide	Solition Mega	1000
H2 ICE	Geniwatt	H150-ICE	120
	CAT	G3516	1000
	CMB.TECH	N/A	160

Based on the investigation which produced these examples, fuel cell gensets appear to be increasingly common, especially for large-scale stationary applications, though the overwhelming majority are for low-power applications. Additionally, it several OEMs are discussing the development of H_2 ICE gensets including Cummins, Mitsubishi, and MTU. There are also several existing products, though no mobile solutions have been identified. Similarly, no NH_3 gensets could be identified, though several examples exist which convert NH_3 to H_2 to supply fuel cells.

3 METHODOLOGY

This section describes the methodology which will be followed to complete the project.

3.1 PERFORM A REVIEW OF LITERATURE – AIM 1

A literature review will be performed to establish the anticipated required knowledge. First, prior work completed at Liebherr Mining will be understood and summarised, which will allow confirmation that predicted topics are relevant and provide a baseline level of understanding of the project. Following this, appropriate sources for information will be identified. Then, the project aims will be systematically investigated such that the required knowledge for each is identified and summarised to a level sufficient for the completion of the project. In cases where the review of a particular topic reveals a previously unconsidered topic, opportunity, or technology, the new topic will be briefly investigated to ensure relevance before more in-depth research is completed.

3.2 DEFINE THE EXPECTED USE CASES – AIM 2

To specify the use case for the design, the system being discussed will first be identified. Following this, all potential primary and secondary actors which may interact with system in various situations will also be identified. Actors are defined as anything which exhibits a behaviour when interacting with the system, including other systems, organisations, and single users, where primary actors initiate interactions with the system and secondary actors are triggered by another actor to interact with the system. The goal of the system will be defined, followed by any possible preconditions, including ambient conditions for example. Finally, scenarios will be written which describe the interactions between the actors and the system under select preconditions. Each individual collection of system, actors, goal, preconditions, and situation will be defined as a use case, and one use case will be selected for this report.

3.3 DEFINE THE DESIGN SPECIFICATIONS – AIM 3

Design requirements will be defined based on the selected use case. The requirements will be quantified based on existing Liebherr standards, international and regional regulations and standards, and the E-HEX power supply data. At minimum, the following requirements will be specified:

- General requirements including:
    - The duty cycle,
    - The frequency and length of equipment stops,
    - And the permissible level of emissions,
- Electrical requirements including:
    - The continuous power output,
    - The output frequency and voltage,
    - And the maximum allowable frequency and voltage dips,
- Maintenance requirements including:

    - The procedure regarding critical and breakable components,
    - The procedure regarding spare parts,
    - And the life expectancy and overhaul interval,
- Safety requirements,
- Materials requirements,
- And all interface requirements between the E-HEX, mobility method, and other gensets.

To validate the requirements, a Voice of the Customer (VoC) survey will be created which aims to investigate how Liebherr customers currently use gensets on their sites, as well as to gather information about their attitudes towards alternative fuels and genset pricing. The survey will be sent to one test customer and will then be distributed to five customers operating in various locations. The results will be rationalised and cross-checked against the defined requirements. Any discrepancies will be corrected in the requirements to closely reflect real use.

3.4 SELECT AND SIZE THE COMPONENTS – AIM 4

Based on past work completed at Liebherr Mining, which defined some potential partners for genset manufacturing, a short-list of eight to ten partners will be chosen by calculating which organisations could supply components that meet the design requirements and are likely to favourably consider a partnership with Liebherr. The short-listed companies will be contacted and met with.

To limit the amount of time spent without progress, the physical properties of the most likely alternator choices will be collected while the results of the VoC are pending. The most likely alternators will be chosen based on the alternator brands that the short-listed partner companies have previously used.

The expected physical properties of all Liebherr ammonia engines will also be collected. Then, the feasibility of combining each alternator with each engine will be investigated based on the allowable power ranges of the alternators. The theoretical minimum and maximum power output of the feasible combinations will be compared to the power requirements of the Liebherr E-HEXs to demonstrate which combination would be sufficient for powering each E-HEX. The potential combination that is most suitable for the chosen use case will then be identified.

For the selected combination, the fuel consumption will be calculated to determine the fuel tank size. To achieve this, an appropriate energy ratio of ammonia to hydrogen will be selected based on values validated by literature and testing. It will also be assumed that both the efficiency and the output mechanical energy of the theoretical Liebherr ammonia engines will be equal to their equivalent diesel engines. This assumption is considered valid as it is in-line with tests run on the A964 and D964, and it is necessary as no tests have been run for larger engines yet.

Using the chosen energy ratio, several options for the secondary fuel will be compared to assess which is most suitable. To achieve this comparison, the volumetric fuel consumption values for the relevant diesel engines will be converted to gravimetric values. The output mechanical energy of the engine will then be calculated using the lower heating value (LHV) of diesel as follows. All relevant density and LHV values may be found in Appendix I.

$$E_{Out,\ Diesel}\ [kW] = FC_{Diesel,\ grav} \times LHV_{Diesel} \times \eta_{Diesel} \tag{1}$$

Using this value, the gravimetric flow rates of NH_3 and H_2 into the equivalent ammonia engine will be calculated, as shown in Equation 2 and 3 respectively. Note that $R_x = Energy\ Ratio\ of\ Fuel\ x.$

$$FC_{NH3}\ [kg/h] = \frac{E_{Out,\ Diesel} \times R_{NH3}}{\eta_{Diesel} \times LHV_{NH3}} \tag{2}$$

$$FC_{H2}\ [kg/h] = \frac{E_{Out,\ Diesel} \times R_{H2}}{\eta_{Diesel} \times LHV_{H2}} \tag{3}$$

Finally, the expected volumetric fuel consumption of both fuels, for all engines and secondary fuel options will be calculated using the appropriate fluid density.

It is expected that an on-board cracker will be one of the secondary fuel options. In this case, it will be necessary to determine the equivalent extra NH_3 which would be converted into the required H_2. Given that crackers can output H_2 at various pressures, it is assumed that an on-board cracker will supply H_2 at 5 bar, to remain in-line with current Liebherr tests. The extra NH_3 quantity will be calculated using the volumetric fuel consumption of H_2 for each engine. This project assumed a 90% NH_3 to H_2 conversion rate, in-line with literature predictions. The calculation would be as follows:

$$FC_{NH3,\ extra}\ [L/h] = FC_{H2,\ 5bar} \times \frac{\rho_{H2,\ 5bar}}{\rho_{NH3,\ 15bar}} \times \frac{2M_{NH3}}{3M_{H2}} \times \frac{1}{CR_{NH3\rightarrow H2}} \tag{4}$$

The required power to convert this amount of ammonia to hydrogen will also be calculated. Equation 5 will be used for each engine, using an 80% cracker efficiency to align with test equipment:

$$P_{NH3\rightarrow H2}\ [kW] = FC_{H2,\ 5bar} \times \Delta H_{NH3\rightarrow H2} \times \frac{2\rho_{H2,\ 5bar}}{3M_{H2}} \times \frac{1}{\eta_{cracker}} \times \frac{1}{3600} \tag{5}$$

Finally, the fuel tank volumes will be calculated based on the equipment stop frequency defined in the use case. The calculation will account for the 85% ammonia fuel fill limit.

Following meetings with the potential partner companies, the most suitable partnership will be recommended. The proposed engine and alternator pairing will then be cross-checked against the company's capabilities and modified as required. Additional required components will be selected, including those required to control the genset and those required to provide mobility, noise attenuation, vibration protection, as well as the LV to HV transformer, and any other components as required. This will be achieved by creating a list of solutions for each unmet design requirement and comparing different possibilities to find the most effective solution.

Once the components are selected, they will be collected into a flow chart and a total weight estimate will be calculated using OEM data. An estimated cost is expected to be unobtainable.

3.5 EVALUATE THE DESIGN – AIM 5

Once the design proposal is complete, it will be compared to existing solutions to validate the decisions made and allow the design to progress to the next stage of development. Based on the findings in Section 2.6.1, the design will be validated using an evaluation matrix. To achieve this, the evaluation metrics will first be defined based on the design requirements. The metrics will be specific and quantifiable, and if necessary, each will be given a weighting which represents the importance of the metric to key stakeholders. Existing alternative solutions will then be selected for comparison with the proposed design based on the findings in Section 2.6. The design and the alternative solutions will be scored against each criterion and the weighted scores will be compared. Based on this comparison, recommendations for further work will be produced.

4 RESULTS, ANALYSIS, AND DISCUSSIONS

The section as follows presents the results to date for the project, as well as the expected outcomes for the remainder of the project and any predicted risks to the completion of the project.

4.1 LITERATURE REVIEW – AIM 1

It was identified that *Scopus* and *Google Scholar* are useful databases for finding relevant and recent research papers. The software *Connected Papers* was also used to identify relevant papers that didn't appear in initial search results. The results relevant to Aim 1 may be found in Section 2 of this report.

4.2 USE CASES – AIM 2

The use case selected for this project is defined below. The list of potential options on which this use case was built may be found in Appendix J.

System: Proposed mobile genset.

Actors:
Primary: R9400E, mine schedule, unknown mobility method
Secondary: Mine plan/layout, fuel truck, operator

Goal: Provide continuously available power to the connected E-HEX

Preconditions:

- The average mine altitude is 500 m above sea level.
- The average mine ambient temperature is 37°C.
- No extreme weather conditions are typical for the site.
- The site does not use hot seating, so equipment stops occur every 12 hours for 30 minutes.
- The maximum distance between benches is 3 km.
- The mine does not operate with double benching.
- The excavator is in the backhoe configuration.
- The excavator is an R9400E model and therefore has a continuous electrical load of 1455 kW and can move at up to 2.7 km/h.
- The excavator operates at 50 Hz and 6.6 kV.

Scenario:
The power cable from the E-HEX is connected manually to the genset. A start-up procedure checks that the connection was successful and the genset starts, followed by the E-HEX. The genset remains out of the pit while the E-HEX moves backwards along the bench and digs down in front of it, maintaining a secure connection and a safe distance between the equipment. After

12 hours of operation, the E-HEX and genset are switched off. A fuel truck refuels the genset within the 30-minute break, and the operating process begins again.

This use case was selected as it covers the conditions which are most often experienced on mine sites and designs for a mid-sized excavator. It is therefore expected to cover a wide range of customers and serve as a base design which can be easily modified to suit other contexts. This could include changing the insulation such that it runs in hotter or colder climates, changing the alternator and engine such that it can power a different excavator, or changing the alternator and transformer such that it can supply power at a different frequency and voltage.

4.3 DESIGN REQUIREMENTS – AIM 3

Presented in Table 8, Table 9, and Table 10 are the defined general, electrical, and maintenance requirements respectively. The VoC survey questions which were be distributed to confirm these requirements are presented in Appendix K.

Table 8: General Design Requirements

Requirement	Value
Duty Cycle	Prime Power
Frequency of Equipment Stop	Every 12 hours
Length of Equipment Stop	35 minutes
Permissible NO_X Emissions	0.40 g/kWh
Permissible PM Emissions	0.015 g/kWh
Permissible PN Emissions	1×10^{12} per kWh
Permissible N_2O Emissions	133 mg/kWh
Permissible NH_3 Emissions	10 ppm
NH_3-Contacting Component Material	Black, mild, or stainless steel NOT: Galvanized metals
H_2-Contacting Component Material	Austenitic stainless steels, aluminium alloys, copper, and copper alloys NOT: nickel or nickel alloys, grey, ductile, or malleable cast irons

Table 9: Electrical Design Requirements

Requirement	Value
Continuous Power Output	At least 1455 kW
In-Rush Current Peak to Withstand	1.9 to 2.4 times the nominal current (depending on machine setup) for 1 second
Frequency	50 Hz
Voltage	6.6 kV
Power Factor	0.8
Maximum Frequency Dip	5%
Maximum Voltage Dip	10%

Table 10: Maintenance Design Requirements

Requirement	Value
Critical and Breakable Components	Breakable components shall be easily accessible and removable to minimise downtime due to maintenance. Breakable and critical parts shall be clearly identifiable using appropriate documentation.
Spare Parts	Spare parts for each component within the genset shall be available on stand-by for a minimum of 10 years after the end of the serial delivery of the genset.
Life Expectancy	36 000 hours
Overhaul Interval	18 000 hours

The aim of these requirements was to define as clearly as possible the minimum satisfactory operation of the design. While it was not possible to define an exact weight or cost requirement, some limits were defined. For example, it was defined that the system should have the lowest possible weight to reduce fuel consumption and cost and increase ease of mobility, without compromising the other key operating requirements. It was also defined that the system costing, including capital and operating expenditure (CAPEX and OPEX), should be minimal while meeting the other design requirements. This may be achieved for example by:

- Minimising the quantity of high voltage (HV) and medium voltage (MV) components.
- Utilising the concept of downsizing by using the smallest feasible ICE for a given power.
- Using peak shaving concepts to reduce the initial power draw on the system.

The results from the VoC confirmed that these requirements are valid and realistic. The survey responses also indicated that competitive costing is a significant requirement and that, while genset pricing varies depending on power and duty cycle, competitor’s prices are known to range from approximately USD 99 000 to USD 1 100 000. Further key factors included safety, reliability, and mobility.

With regards to cost, the VoC results also indicated that fuel prices contribute significantly to OPEX for a genset. This is a significant limitation of the proposed system as ammonia is inherently more expensive than diesel: NH_3 ICEs require approximately three times more fuel volumetrically than diesel ICEs, NH_3 infrastructure for fuel supply is currently limited, and if H_2 is used as a secondary fuel, these issues are exacerbated.

Another system limitation identified through the VoC results was that clients typically prefer to run genset for at least 24 hours, rather than following the equipment operating hours. This runtime is unfeasible for an ammonia-based system as storing enough fuel on a mobile unit is unrealistic. It was therefore considered reasonable to align the genset refuel time as closely as possible to the equipment, rather than aiming for 24-hour operation.

Despite the conclusions drawn from the VoC, it was acknowledged that only responses from three of Liebherr's major customers were considered due to the restricted timeline. This could have caused nuances between different clients and locations to be missed, which may reduce the validity of the design requirements. It is therefore recommended to increase the quantity of responses and re-evaluate the design requirements.

4.4 PROPOSED DESIGN – AIM 4

4.4.1 Potential Partner Investigation

Table 11 shows the shortlist of potential partners. These companies were shortlisted as they each have a broad customer network, experience in mining, proven collaboration interests with several engine manufacturers, and strong testing, after-sales, and service offerings.

Table 11: Shortlisted Potential Genset Partners

Name	**Number of Employees**	**Location**
Genesal Energy	43	Spain
GFE Power Products	Unpublished	UK
Himoinsa	>1000	Spain
Inmesol	108	Spain
Pramac	1100	Italy
Modasa	1000 - 5000	Peru
ABZ	52	Germany
Bruno Generators Group (BGG)	350	Italy

From the shortlist of potential partners, three were initially interested in a partnership for the project: Inmesol, BGG, and ABZ. Meetings were therefore organised with each company to discuss project goals, capabilities, and next steps, as well as to assess the extent to which the company cultures complimented each other. Based on conversations held during these meetings, the three companies were compared, as shown in Table 12. For each metric, the companies were ranked from 1 to 3, with 3 indicating the most compliance with the metric, and 1 indicating the least. The results are visualised in Figure 12.

Table 12: Comparison of Preferred Partners

Comparison Metric	**Inmesol**	**ABZ**	**BGG**
Production Capabilities (including typical project timeline, number of production plants, and capacity)	1	2	3
Size of Global Customer Network	3	2	1
Experience in Mining	2	1	3
After Sales and Service Offerings	1	2	3
Testing Capabilities	1	3	2
Experience with Alternative Fuels	2	1	3
Flexibility	1	3	2
Perceived Interest in Project	1	2	3
AVERAGE	**1.6**	**1.9**	**2.5**

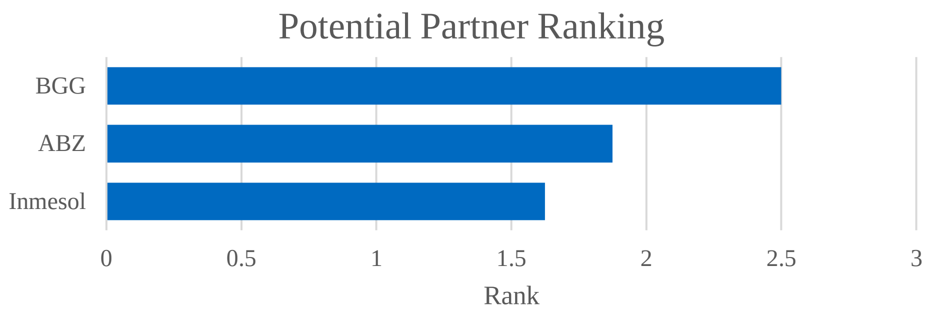


Figure 12: Comparison of Potential Partners

At that point in the process, however, Inmesol indicated that they were no longer able to progress with the project as they were unable to devote sufficient resources to it. On the other hand, Modasa indicated that an initial interest, though further progress was not made in this relationship prior to the completion of this thesis project.

In accordance with the above findings, it is recommended that Liebherr Mining should partner with BGG to produce the prototype and product line of ammonia gensets, as they scored highly in most metrics. BGG has previously collaborated with several major alternator OEMs, so this recommendation did not restrict the selection of the alternator. It is acknowledged, however, that conversations with Modasa may alter this recommendation. Also, additional companies may express interest if direct contact can be made therefore a further contact round should be completed to prevent the accidental exclusion of a strong candidate.

4.4.2 Engine and Alternator Selection

To limit the selection pool for alternators, the alternator OEMs which each of the shortlisted partners collaborated with was analysed to find trends. Figure 13 shows the alternator OEMs used by the shortlisted partners, as well as how many partners used each OEM.

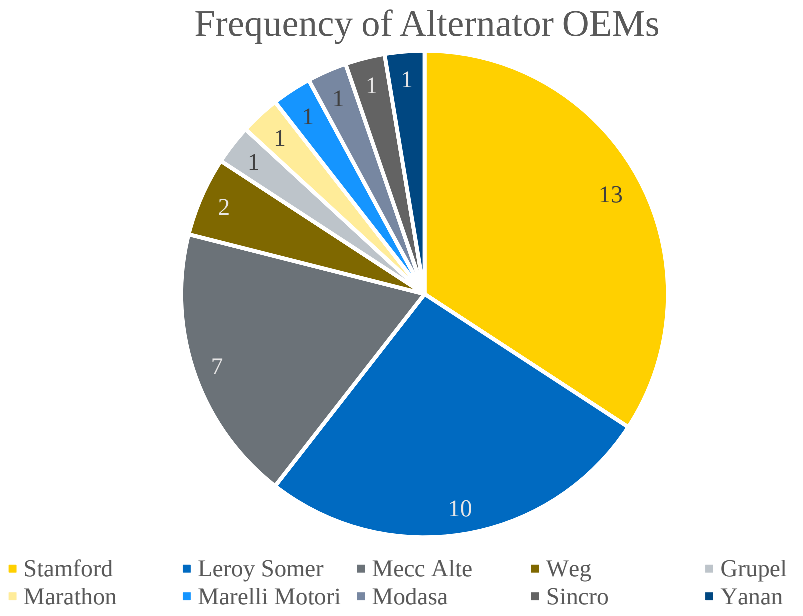


Figure 13: Frequency of Alternator OEMs Across Potential Partners

Across the shortlisted companies, the most common alternator OEMs were Leroy Somer, Stamford, and Mecc Alte. Each standard alternator offered by these companies in the power range relevant to this project was compared to the Liebherr ammonia engines. The comparison revealed that all three alternator OEMs offered equipment which would be possible to combine with every Liebherr engine. Full results are presented in Appendix L.

Further to this, the maximum and minimum available power of each feasible alternator-engine pairing was compared to the Liebherr E-HEX power requirements for both 50 Hz and 60 Hz applications. This revealed that Stamford alternators can cover the widest range of Liebherr E-HEXs across their alternators, however mid-power Leroy Somer alternators individually had a broader power range than the other OEMs. The full table of coverage is in Appendix M.

Based on the comparisons made between alternators, it was proposed that either the Liebherr A9912 or A9916 engines be used for the genset line, as they were compatible with the broadest range of alternators and could supply sufficient power to all the Liebherr E-HEXs between them. For the specific use case considered in this report, it was proposed that the A9912 engine be used in combination with the Stamford S7L1D alternator. Table 13 presents the theoretical maximum and minimum power which the pairing could supply, for both 50 Hz and 60 Hz applications. The paring would be suitable for both the 50Hz R9350E and R9400E, as well as the 60 Hz R9400E.

Table 13: Theoretical Maximum and Minimum Power of Proposed Alternator-Engine Pairing

Frequency [Hz]	Rated Maximum Power [kW]	Rated Minimum Power [kW]
50	1932	1163
60	2314	1316

It was noted during the investigation that a low voltage (LV) alternator would be preferable to an MV or HV alternator. The equipment is applying an MV load, so using an MV alternator which can directly supply the required voltage would reduce the required number of components. However, MV alternators have several disadvantages. Firstly, they are more expensive due to the additionally required in-built protective systems. They are also less common than LV alternators, so there is less testing and spare parts availability, implying longer lead times. Finally, MV systems require specific safety procedures and training for maintenance and operation.

The Stamford S7L1D was specifically chosen as it is an LV alternator with a broader power range than other similar options. Stamford is also an existing partner with BGG and another six of the eight shortlisted partners, implying that it would highly likely be available through the chosen company. Finally, it would be able to supply both frequency options for the desired equipment, reducing the complexity of the solution.

While investigating the alternator options, it was noted that the in-rush current peak may cause the solution to be underpowered given the peak is so large (up to 2.4 times the nominal current). Upon further investigation, however, it was noted that this peak only lasts for approximately 1 second. Typically, gensets have an overload rating of 10% of the rated load for 1 hour but when the time is as short as 1 second, this rating can reach 50% overload. It was further noted that the E-HEX settings may be adjusted to reduce the in-rush peak to approximately 1.9 times the nominal current if required. As such, there was found to be no need to oversize the genset to meet the in-rush demand peak.

4.4.3 Fuel Tank Sizing

After the engine and the alternator, the component which required the most careful decision was the fuel tank. To begin sizing it, an energy ratio of 80% ammonia to 20% hydrogen was used based on the measured A964 fuel consumption. Three potential secondary fuel solutions were investigated: hydrogen at 350 bar or 700 bar, and hydrogen provided by an on-board cracker at 5 bar. The calculated fuel consumptions of ammonia and these secondary fuels are presented in Table 14.

Table 14: Proposed Genset Fuel Consumption

		A9912	**A9916**
H_2 at 350 bar	*Ammonia [L/h]*	1166	1777
	Hydrogen [L/h]	1207	1839
H_2 at 700 bar	*Ammonia [L/h]*	1166	1777
	Hydrogen [L/h]	713	1087
H_2 from cracker	*Ammonia [L/h]*	1452	2213

Figure 14 presents the fuel tank size for each solution to run for 12 hours.

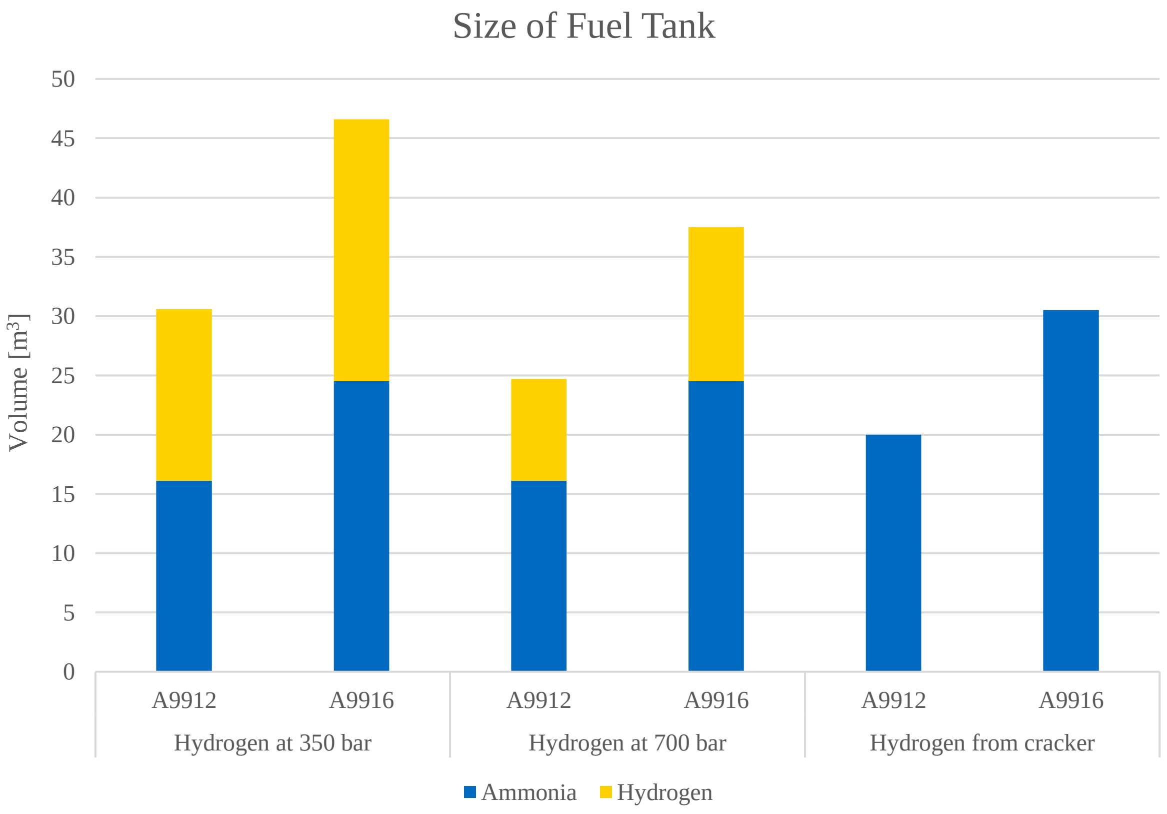


Figure 14: Proposed Genset Fuel Tank Size Options

Of the options, the hydrogen at 350 bar consumed 4.9 times more fuel volumetrically than an equivalent diesel engine, 3.9 times more for hydrogen at 700 bar, and was the lowest when using a cracker, consuming 3 times more. These findings were higher than expected from literature, which largely agrees that efficient ammonia systems use 2.5 to 3 times as much fuel as an equivalent diesel system, (Reiter & Kong, 2011; Starkman et al., 1967). These expected values, however, were measured using test engines which were up to 20% more efficient than their diesel counterpart, implying that real engines would have a higher fuel consumption. The findings were therefore considered valid for the purpose of this project.

While the findings were considered valid, it was acknowledged that they were limited by the assumptions on which they were based. For example, the assumption that the NH_3 efficiency will be equal to the equivalent diesel efficiency could significantly impact the findings. Another limitation of the results was that they only considered the average fuel consumption and did not consider variations to consumption or efficiency at different engine loads and speeds. Once engine testing has been completed, it is therefore recommended that the findings in this report are corroborated.

Despite their limitations, the results implied that using a cracker would be the best option of the three considered. A cracker would also allow for the simplification of the design by removing of the secondary fuel supply and storage system, as well as the need for both NH_3 and H_2 fuelling points and trucks, though the additional components required by a cracker introduce a different complexity.

Concerns were raised, however, about the additional energy requirements of an on-board cracker. To assess the impact of this, the power required to decompose enough hydrogen for 12 hours of operation was calculated. Assuming 80% cracker efficiency and a 90% conversion rate, to align with both literature and test equipment, a genset using an A9912 engine would require 217 kW of additional power, and an A9916 would require 330 kW. These additions constituted 10.5% and 11.9% of the engine power, respectively. While not insignificant, this energy loss would not inhibit the proposed genset from supplying sufficient to power the E-HEX in the given use case, as well as in several other test cases. It was therefore considered a reasonable loss.

In response to these energy considerations, the potential to use waste heat recovered from the ICE was identified. This could reduce the heating energy required by the cracker and therefore increase the system efficiency. In genset applications, waste heat recovery (WHR) can produce up to 10% additional power, depending on the specific heat exchanger used (Hossain & Bari, 2014). WHR could therefore almost entirely negate the energy drawn by the cracker, in an ideal case, but would also increase the system cost. It is therefore recommended that when more detailed costing is available, a cost-benefit analysis of WHR should be completed.

Additional to the energy concerns, it was noted that the predicted fuel tank sizes, especially for the A9916, were large. To add context, it was assumed that the system would be contained within a space equivalent to a standard 40 ft shipping container, which has an internal volume of 67 m^3. It was also assumed, based on the dimensions of Liebherr’s NH_3 storage tank, that the external space used by the on-board fuel tank would be 30% larger than the internal volume.

As such, for a system using an A9916 engine and an on-board cracker, the fuel tank would require 39 m^3, which is equivalent to 58% of the total system volume. Comparatively, the A9912 fuel tank would require 26 m^3, or 38% of the total volume.

Given there must be sufficient space for other parts, as well as for operators and maintenance technicians to access the components, it was recommended that gensets using the larger engine refill more frequently. If the tank was refilled every 8 hours instead of every 12 hours, it would allow the fuel tank to be the same size as that of the A9912. While this tank would still be significantly larger than for an equivalent diesel genset, sufficient room should remain for safe access to all other components.

The final consideration made regarding fuel was the fuelling time, which significantly contributes to the length of the equipment stop. This time is dependent on the fuel dispenser rate of the specific site, however there are standard options for this rate in heavy duty applications, including 200 L/min, 280 L/min, 500 L/min, ad 1000 L/min. For the A9912 fuel tank, these rates corresponded to fill times of 70 mins, 50 mins, 28 mins, and 14 mins respectively. At the higher fill rate options, the fill time was within the required time frame however it was not suitable at the lower flow rates. This rate would therefore be important to consider if more detailed designs are completed.

4.4.4 Control Module Selection

Another major component was the control module. Based on market research, three OEMs were compared. Table 15 shows the ranking system that was used, Table 16 shows how the metrics were weighted and Table 17 summarises the results of the comparison. The metrics used for comparison were selected and weighted based on conversations with internal stakeholders. Note that capital cost was excluded as quotes for large-scale production were unavailable without a non-disclosure agreement, and time did not permit. Figure 15 visually demonstrates the findings by scaling the rankings from 0 to 10 where 10 was the highest possible score.

Table 15: Comparison Rating Descriptions

Rating	Description
1	Does not provide
2	Provides a little
3	Somewhat provides
4	Provides well
5	Provides perfectly

Table 16: Control Module Metric Weightings

Metric	Weight
Synchronisation	3
Ease of Operation	1
Good User Interface	1
Support Available	3
Remote Accessibility	2

Breadth of Supply Network	2

Table 17: Comparison of Control Module OEMs

Comparison Metric	Deep Sea	DEIF	ComAp
Synchronisation	15	15	15
Ease of Operation	4	5	3
Good User Interface	4	4	5
Support Available	12	9	12
Remote Accessibility	10	10	8
Breadth of Supply Network	10	6	4
AVERAGE	**9.17**	**8.17**	**7.83**

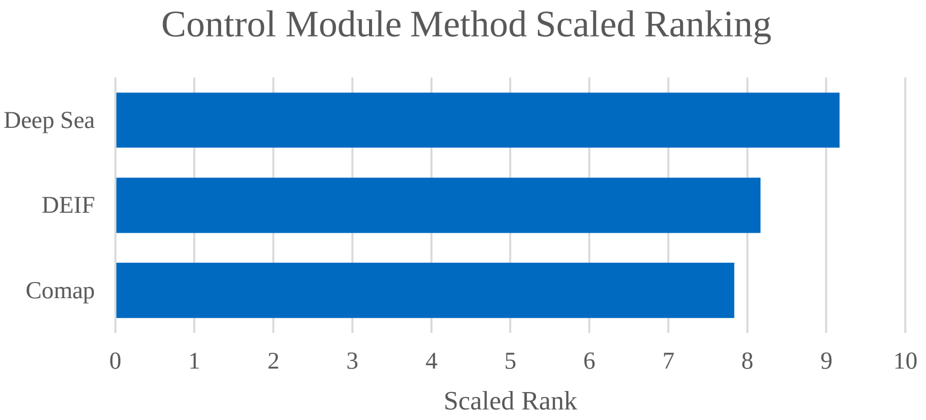


Figure 15: Scaled Comparison of Control Modules

From this comparison, it was clear that Deep Sea controllers out-perform the other options across most metrics except for the user interface. It was further noted, however, that several of the companies on the partner short-list offer their own control modules. There was limited information available about these options, but it was understood that the abilities of a partner-branded controller would be highly dependent on the selected partner. Despite these unknowns, working directly with the chosen partner, rather than using a third-party component, would likely reduce cost, increase flexibility, and allow for more readily available support. It was therefore recommended that discussions should occur between Liebherr Mining and the partner company regarding the capabilities of a partner-branded controller. If the findings are unsatisfactory, it is recommended that a Deep Sea control module be used.

4.4.5 Mobility Method

The mobility method was selected through the same process as the controller. The four options considered were combinations of two propulsion methods and two ground contact methods. The types of propulsion were trailer type, where the genset is mounted on a trailer which is then hitched to a separate cab, and self-propelled, where the engine, drivetrain, and controls are built into the genset itself. The ground contact methods were tracks or wheels. The comparison metrics were selected based on typical mine site conditions as well as the requirements defined in Section 4.3. The evaluation is presented in Table 19, with ratings as described in Table 15 weighted as shown in Table 18 based on stakeholder feedback. Figure 16 visually demonstrates the findings by scaling the rankings from 0 to 10 where 10 was the highest possible score.

Table 18: Mobility Method Metric Weightings

Metric	Weight
35° inclination	1
Up to 3km movement	1
Not damage surface	1
Ease of operation	2
Ease of maintenance	2
Low CAPEX	3
Low OPEX	3

Table 19: Comparison of Mobility Methods

Comparison Metric	Trailer Type with Tracks	Trailer Type with Wheels	Self-Propelled with Tracks	Self-Propelled with Wheels
35° inclination	3	2	5	3
Up to 3km movement	5	5	2	2
Not damage surface	2	3	2	3
Ease of operation	4	4	10	10
Ease of maintenance	6	10	4	6
Low CAPEX	9	12	3	6
Low OPEX	6	12	3	9
AVERAGE	**5.00**	**6.86**	**4.14**	**5.57**

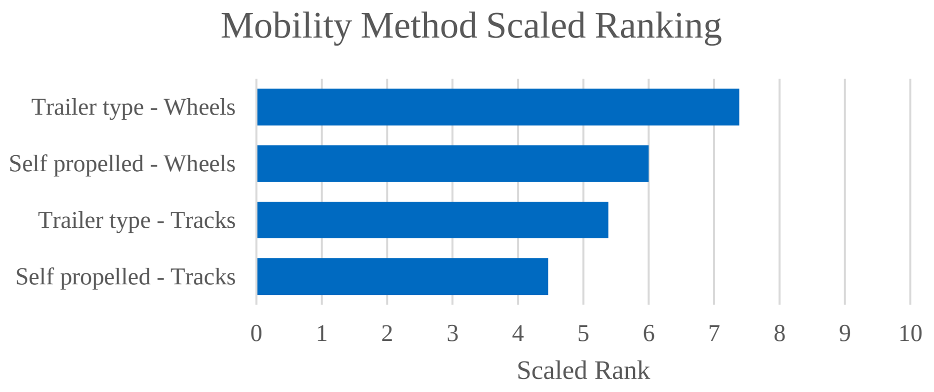


Figure 16: Scaled Comparison of Mobility Methods

During the analysis, it was noted that a self-propelled system may be easier to convert to fully zero-emissions, which was a significant quality for the design option. Despite this, the positive values of a towed system, including reduced fuel consumption, lower CAPEX, and the ability to run the genset while the truck is serviced, outweighed the benefits of a self-propelled system.

Further, careful consideration between wheels and tracks was required. Tracks, for example, would be more stable on soft or uneven surfaces, provide more traction on significant slopes, and would be more power efficient, but they would also require a large turning circle and may damage packed or sealed roads. Wheels, on the other hand, may provide better manoeuvrability, lower CAPEX and OPEX, and would be easier to maintain, although they must be replaced more frequently than tracks and have a higher likelihood of becoming stuck.

The results of these considerations therefore indicated that the most effective mobility method would be to mount the genset on a wheeled trailer, which would then be towed by a separate truck. It was recommended that the optimal number of wheels be calculated based on the final system weight, to provide sufficient traction and prevent wheels becoming stuck where possible.

4.4.6 Solution Flow Chart

To display the proposed design in a cohesive manner, a flow chart showing the individual components and their relationships was developed and is presented in Figure 17. This flow chart included the components described so far, as well as the following additional components:

- A cooling and after-treatment system as required by the engine. To be determined based on further engine testing.
- WHR to heat the cracker. To be sized based on cost-benefits analysis.
- On-board NH_3 to H_2 cracker as used on the Liebherr test bench (further information is currently unavailable).
- A 400 V to 6.6 kV transformer.
- Four 12 V 4D Li-Ion starter batteries or equivalent.
- A modified 40 ft container to provide the frame and housing.
- A connection port to match the client-specific E-HEX power cable.
- A fuel subsystem including fuel inlet, pump, supply lines, and other associated components.
- A tow hitch, wheels, axles, suspension, brakes, and lights to match relevant regional off-road trailer safety standards.

An estimate of the system weight was also developed and is presented in Table 20. Note that only purchased components were included, as no weight estimates were able to be made for manufactured components. This estimate was nevertheless a good indication of the system weight as it accounted for the heaviest components, including the fuel, the engine, the transformer, and the alternator.

Table 20: System Weight Estimate

Component	**Weight [kg]**
A9912	9300
S7L1D	3350
NH_3 Fuel	11 933
Transformer	8618
Deep Sea Controller	0.88
Deep Sea AVR	0.46
4 x Starter Battery	208
TOTAL	**37 112**

From these results, it was clear that the fuel would be the largest contributor to the system weight, followed by the power system components, which aligned with expectations based on examples of similarly powered gensets. The total system weight also aligned with these expectations; the examples considered had weights in the range of 40 000 kg to 45 000 kg. Considering the estimate did not account for the mobility or exhaust systems, the final number was predicted to fall within this range.

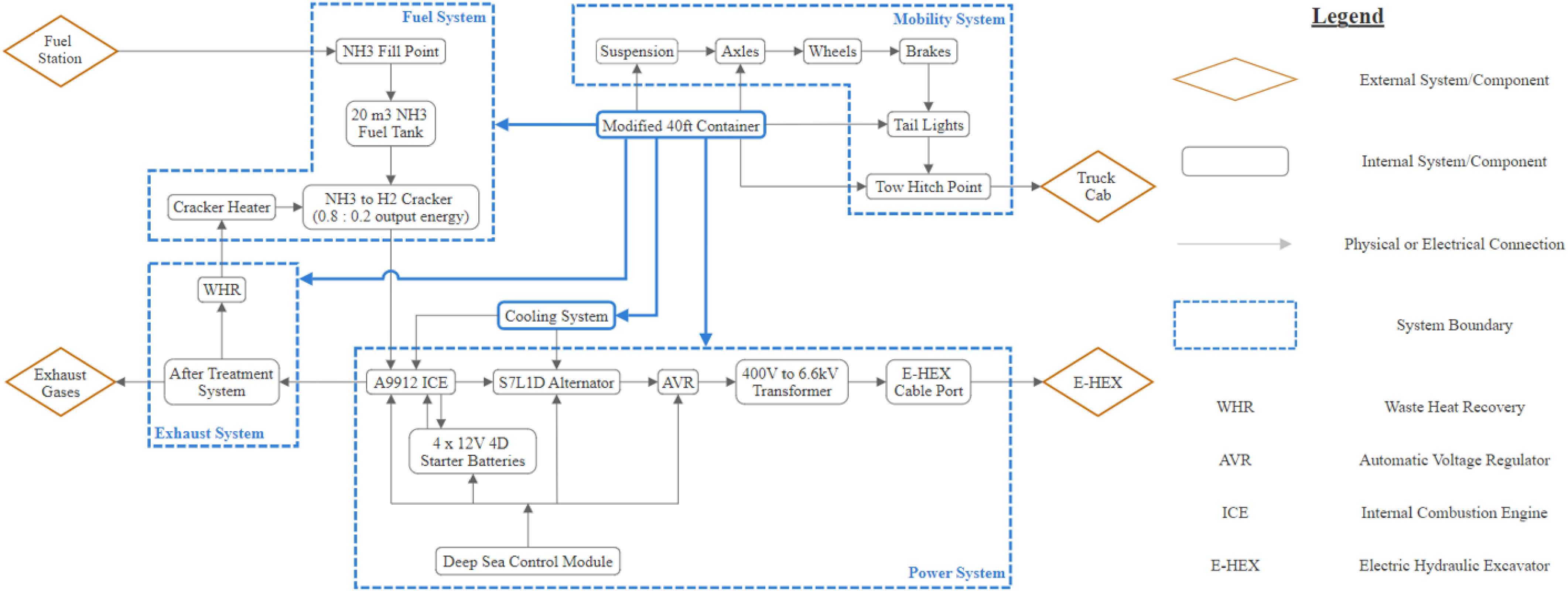


Figure 17: Proposed System Flow Chart

4.5 DESIGN EVALUATION – AIM 5

4.5.1 Ability to Meet Requirements

To assess the validity of the design, the expected design qualities were compared to the defined design requirements. The results of this comparison are shown in Table 21 and Table 22. Note that material and maintenance values were not defined in the high-level pre-design and were therefore not included in the comparison, however it is recommended that future work considers them. The comparison showed that the proposed design would be capable of meeting all identified design requirements.

Table 21: Design Ability to Meet General Requirements

Description	Requirement	Expected	Met?
Duty Cycle	Prime Power	Prime Power	Yes
Frequency of Equipment Stop	12 hours	12 hours	Yes
Length of Equipment Stop	35 mins	14, 28, 50, or 70 mins	Yes
Permissible NOx Emissions	0.40 g/kWh	CONFIDENTIAL*	Yes
Permissible PM Emissions	0.015 g/kWh	approx. 0 g/kWh	Yes
Permissible PN Emissions	1 x 1012 per kWh	approx. 0 g/kWh	Yes
Permissible N_2O Emissions	133 mg/kWh	CONFIDENTIAL*	Yes
Permissible NH_3 Emissions	10 ppm	CONFIDENTIAL*	Yes

*Measured engine values exist and are known to be below the required threshold but are unable to be published.

Table 22: Design Ability to Meet Electrical Requirements

Description	Requirement	Expected	Met?
Continuous Power Output	1455 kW	1932 kW	Yes
In-Rush Current Peak to Withstand	1.9 times nominal current for 1s (2765 kW)	50% overload capacity for 1s (2898 kW)	Yes
Frequency	50 Hz	50 Hz	Yes
Voltage	6.6 kV	6.6 kV	Yes
Power Factor	0.8	0.8	Yes
Maximum Frequency Dip	5%	< 5%	Yes
Maximum Voltage Dip	10%	1% alternator, 4% ICE	Yes

4.5.2 Comparison to Alternative Solutions

Further to confirming whether the proposed design meets the design requirements, it was validated by comparing it to alternative existing solutions. Table 23 presents the scale of metrics which were used to complete this analysis.

These metrics were based on the design requirements, and only the rated power and the emissions were considered significantly more important than the other metrics. This was because if the solution cannot provide sufficient power, it would be necessary to use several pieces of equipment, which would increase the cost and emissions and decrease the mobility. The rated power and emissions metrics were therefore weighted by 2.

Quantitative values were used for the rating scale wherever possible, as described below:

- Run time: This was based on the number of hours the solution could run without stopping the supply of power, where 24-hour operation was the best.
- Rated Prime Power: 2 MW or greater was considered the best prime power option as it would be suitable for the considered use case and provide options for other excavators.
- Emissions: This was based on the U.S. Environmental Protection Agency (EPA) Tier 3 and Tier 4 final (T4f) limits, as these are typically referenced within OEM data sheets. The ability to produce zero emissions was chosen to be the ideal rating.
- Suitability for mines: This metric was difficult to quantify as information was rarely available from OEMs. It was decided that a broad understanding of the technology for each solution should be used to assess whether the solution can withstand extreme temperatures and particulates. Any additional capabilities described by the relevant OEM were also then considered. The expected level of modifications required for the solution to withstand typical mine environments was used to determine the rating level.
- Total Cost of Ownership (TCO): The TCO was another difficult to quantify metric as standard prices of gensets are typically not published. It was therefore decided that diesel gensets should represent the industry standard of TCO, and that solutions should be rated based on their expected relative price to the industry standard. It was, however, noted that the TCO of fossil fuel solutions is expected to increase in the coming years due to the increasing cost of carbon credits globally. It is therefore recommended that quotes be requested from the selected partner, and a more detailed cost analysis accounting for the cost of carbon be completed.

The analysis which was completed using these metrics is presented in Table 24 for mobile solutions, Table 25 for stationary solutions, and Table 26 for the proposed solution. To make the comparison easier to understand, the ratings were scaled to fall in the range of 0 to 10, where 10 is the best possible score, and presented in Figure 18.

During this analysis, it was concluded that diesel solutions are the cheapest and most prevalent across both mobile and stationary applications, however the emissions were consistently the highest for diesel solutions. It was also concluded that battery systems, though common, were more expensive than other solutions and unsuitable for mine environments. By comparison, fuel cells appeared to be increasing in commonality, were more easily suited for mine sites, and were expected to decrease in price over the coming years.

The analysis results indicated that the proposed solution is expected to perform to a higher standard than all other examined solutions, which implied that the ability to meet all the design requirements would justify the increased cost compared to diesel. The results indicated that another significant advantage of the design was that it uses an ICE, which is more suitable for mine environments than other low- or zero-emission solutions.

It was noted, however, that quantified cost comparisons may affect these conclusions if the solution is found to be significantly more expensive than anticipated. It was therefore recommended to conduct a comprehensive cost analysis once a partnership has been established and a non-disclosure agreement has been signed.

Table 23: Comparison Metric Rating Scale Definition

Metric	**1**	**2**	**3**	**4**	**5**
TCO	Significantly higher than industry standard	Higher than industry standard	Higher than industry standard but expected to decrease significantly with time	In line with industry standard	Lower than industry standard
Suitability for mines	Cannot withstand extreme temperatures and dust	Can withstand extreme temperatures and dust with significant modifications	Can withstand extreme temperatures and dust with moderate modifications	Can withstand extreme temperatures and dust with minor modifications	Can withstand extreme temperatures and dust without modifications
Mobile	No	-	-	-	Yes
Run Time	6 or fewer hours	8 hours	12 hours	18 hours	24 hours
Rated Prime Power	600 kW	800 KW	1 MW	1.5 MW	2 MW or more
Emissions	EPA Tier 3 compliant or less	EPA Tier 4 final compliant	Approx. 50% Fewer emissions than EPA T4f	Approx. 75% Fewer emissions than EPA T4f	Zero Emissions

Table 24: Rating of Existing Mobile Power Solutions

	Mobile Diesel			**Mobile Fuel Cell**			**Mobile Battery**		
OEM	*CAT*	*Cummins*	*Kohler*	*Hitachi*	*EFOY*	*EODev*	*Moxion*	*Alfen*	*Power Edison*
TCO	4	4	4	3	3	3	2.5	2.5	2.5
Suitability for mines	4	5	4	3	2	2	2	2	2
Mobile	5	5	5	5	5	5	5	5	5
Run Time	2.5	3	5	5	5	4	3.5	3.5	1
Rated Prime Power	8	8	0	4	0	0	0	0	10
Emissions	4	2	2	10	10	10	10	10	10
AVERAGE	**4.58**	**4.50**	**3.33**	**5.00**	**4.17**	**4.00**	**3.83**	**3.83**	**5.08**

Table 25: Rating of Existing Stationary Power Solutions

	Stationary Diesel			**Stationary Fuel Cell**			**Stationary Battery**			**Stationary Hydrogen ICE**		
OEM	*Kohler*	*CAT*	*MTU*	*CAT*	*Renewable Innovations*	*Nuvera*	*Symtech Solar*	*Alfen*	*Exide*	*GeniWatt*	*CAT*	*CMB.TECH*
TCO	4	4	4	3	3	3	2.5	2.5	2.5	3.5	3.5	3.5
Suitability for mines	4	4	3	3	3	3	2	2	2	3	4	4
Mobile	1	1	1	1	1	1	1	1	1	1	1	1
Run Time	5	5	5	5	5	5	1	1	1	5	5	5
Rated Prime Power	10	10	10	8	8	1	6	10	6	0	6	0
Emissions	2	4	2	10	10	10	10	10	10	7	8	7
AVERAGE	**4.33**	**4.67**	**4.17**	**5.00**	**5.00**	**3.83**	**3.75**	**4.42**	**3.75**	**3.25**	**4.58**	**3.42**

Table 26: Rating of Proposed Solution Against Existing Solutions

	Mobile NH_3 ICE
	Proposed Design
TCO	3
Suitability for mines	4
Mobile	5
Run Time	3
Rated Prime Power	8
Emissions	8
AVERAGE	**5.17**

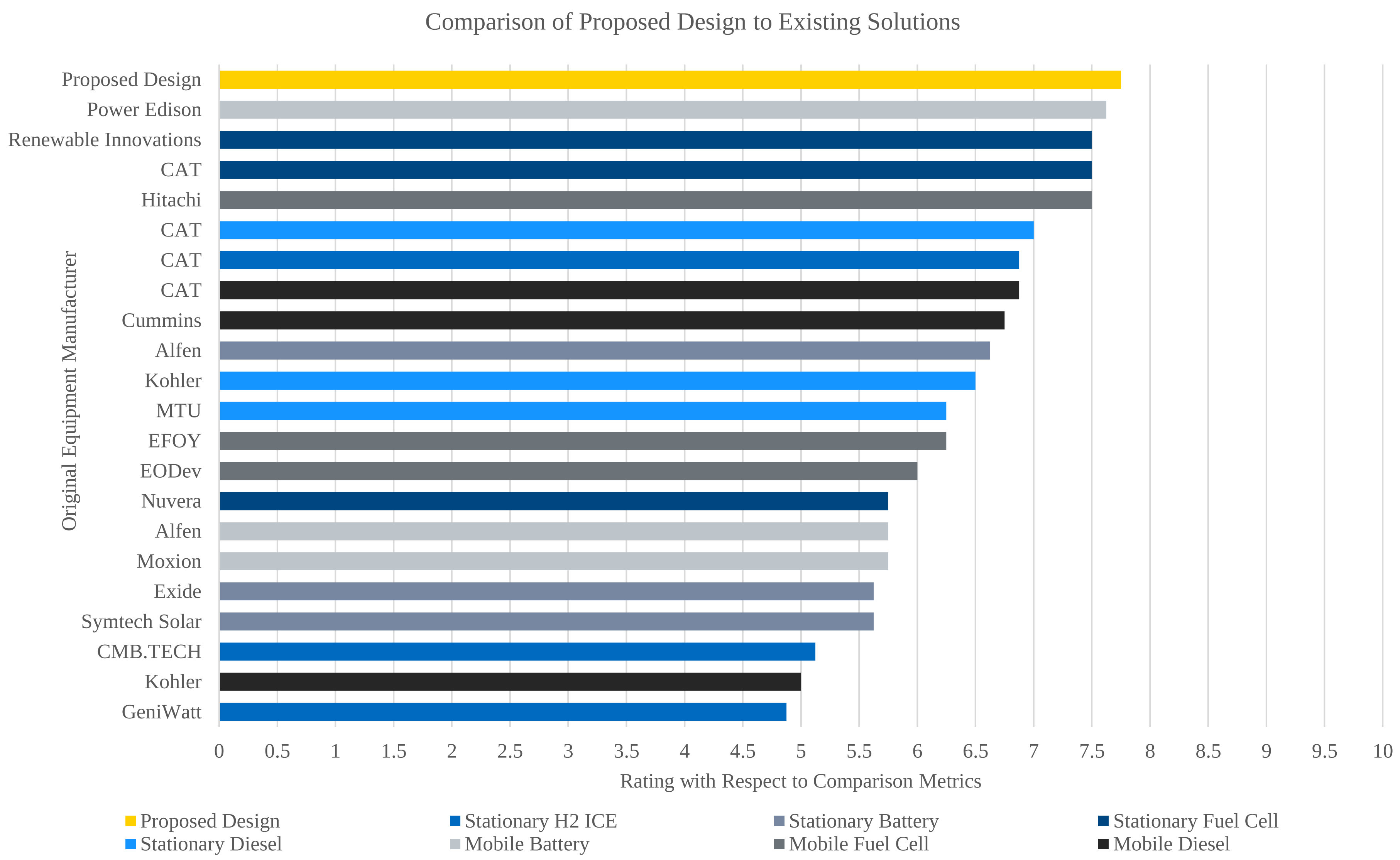


Figure 18: Scaled Visualisation of Design Evaluation

5 CONCLUSIONS

Given that global temperatures are expected to rise past the limit defined in the Paris Agreement (Yerlikaya et al., 2020), Liebherr Mining aims to develop products and technology that further their progress towards their Zero-Emission Mining strategy. One such product is their electric excavator line which currently experience mobility challenges due to their power cables which connect to the grid. Liebherr Mining therefore proposed the development of a zero-emission genset that can supply power to their electric excavators and move with the powered machine as needed.

This project defined and sized the components required by a mobile ammonia-fuelled genset under given operating conditions and compared the proposed design to existing solutions to assess its expected performance. This work was split into five aims. To achieve the first aim, a literature review was completed covering the technical background required for the project, including relevant prior work, a review of design methods, a review of hydraulic excavator operation, a review of relevant ammonia, genset, hydrogen, and emissions regulations, a review of genset design and ammonia combustion, and an investigation into existing solutions.

Following this, the second aim defined operating conditions in the form of a use case. The selected use case required the genset to provide 1455 kW of power to an R9400E excavator at 50 Hz for up to 12 hours on a site located 500 m above sea level at 37°C ambient. Within Aim 3, design requirements were defined based on the use case and were cross-checked with industry through a Voice of the Customer survey. The survey concluded that the requirements were realistic and to the appropriate standard for industry.

The fourth aim was to produce a design proposal for the genset. During the completion of this aim, it was proposed that a partner company manufacture the product to maximise the breadth of experience and customer network. After short-listing, ranking, and meeting several potential partners, it was recommended that Liebherr Mining partners with BGG due to their production and testing capabilities, experience in mining and alternative fuels, and strong perceived interest in the project.

Following this recommendation, a design was produced which demonstrated how the proposed genset could meet the specified requirements. The design included a Liebherr A9912 ammonia engine paired with a Stamford S7L1D alternator with an expected output of between 1163 kW and 1932 kW of continuous power. To supply sufficient fuel, an on-board cracker was included to split NH_3 into H_2, suppling fuel with an 80:20 energy ratio between NH_3 and H_2 to the engine. The cracker would require 217 kW of heat to correctly function, though this may be reduced using waste heat recovery, and would receive ammonia from a 20 m^3 on-board fuel tank.

A Deep Sea control module was chosen for the system to allow load control, synchronisation, and remote access, although it was recommended that a controller supplied by the selected partner also be considered. To allow system mobility, it was recommended that the genset be mounted on a wheeled trailer, which may be towed by a separate truck. Using these recommendations, the total weight of purchased components was estimated to be at least

37 000 kg. Accounting for the manufactured components that were excluded from this estimate, the proposed solution was predicted to have an equivalent weight to the considered existing diesel gensets.

The final aim assessed the validity of the design by comparing the expected design qualities to the defined design requirements. The comparison showed that the proposed design would be capable of meeting all identified design requirements. To further validate the design, a comparison of the proposed design to market competition was completed. The results indicated that the proposed solution is expected to perform to a higher standard than all other examined solutions, which justified the increased cost of ownership compared to diesel. The results also implied that the use of an ICE within the design increased its suitability for mine environments than other low- or zero-emission solutions.

The results of the project were considered to be reasonable and within the expected outcomes, based on existing mobile gensets. Additionally, the project goals were completed to a high standard and were approved by key stakeholders. The design is therefore planned to be further developed and commercialised.

6 RECOMMENDATIONS AND FUTURE WORK

Despite the positive outcome of the project, significant further work is required to develop a product based on the outcomes of the project. As such, several recommendations for further work were made. Firstly, it was recommended that the Voice of the Customer survey be completed by more customers to ensure the design is suitable for all Liebherr clients. It is understood that by contacting their top 40 clients, Liebherr Mining may gain insight into how 80% of its equipment is used.

Regarding the potential manufacturing partner, it was noted that additional short-listed companies may be interested in the project if contacted again. It is therefore recommended that further attempts be made to contact these companies, to prevent the accidental exclusion of a strong candidate. It is further recommended that during this expanded contact round, non-disclosure agreements may be used to gain quotes regarding genset development and sales costs, which would allow more valid and relevant comparison between the partner options. This recommendation is also applicable to specific components, including the transformer, engine aftertreatment system, cracker, and waste heat recovery.

Once the final partner is selected, it is recommended that discussions should occur between Liebherr Mining and the partner company regarding the capabilities of a partner-branded controller, which may reduce cost, increase flexibility, and allow for more readily available support.

The final note made during this project was that while this pre-design was as accurate and relevant as possible, it is significantly dependent on the true capabilities of the Liebherr ammonia engines. It is therefore recommended that the A9912 and A9916 are finalised and tested fully, and that the conclusions made in this report are corroborated with the test results.

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APPENDIX A: PROJECT PLAN

This appendix presents the updated and initial planning for the project, including a description of the original project timeline, a completed risk assessment and opportunities which were identified at the beginning of the project. The original timeline is presented in the form of a Gantt chart in Figure 19.

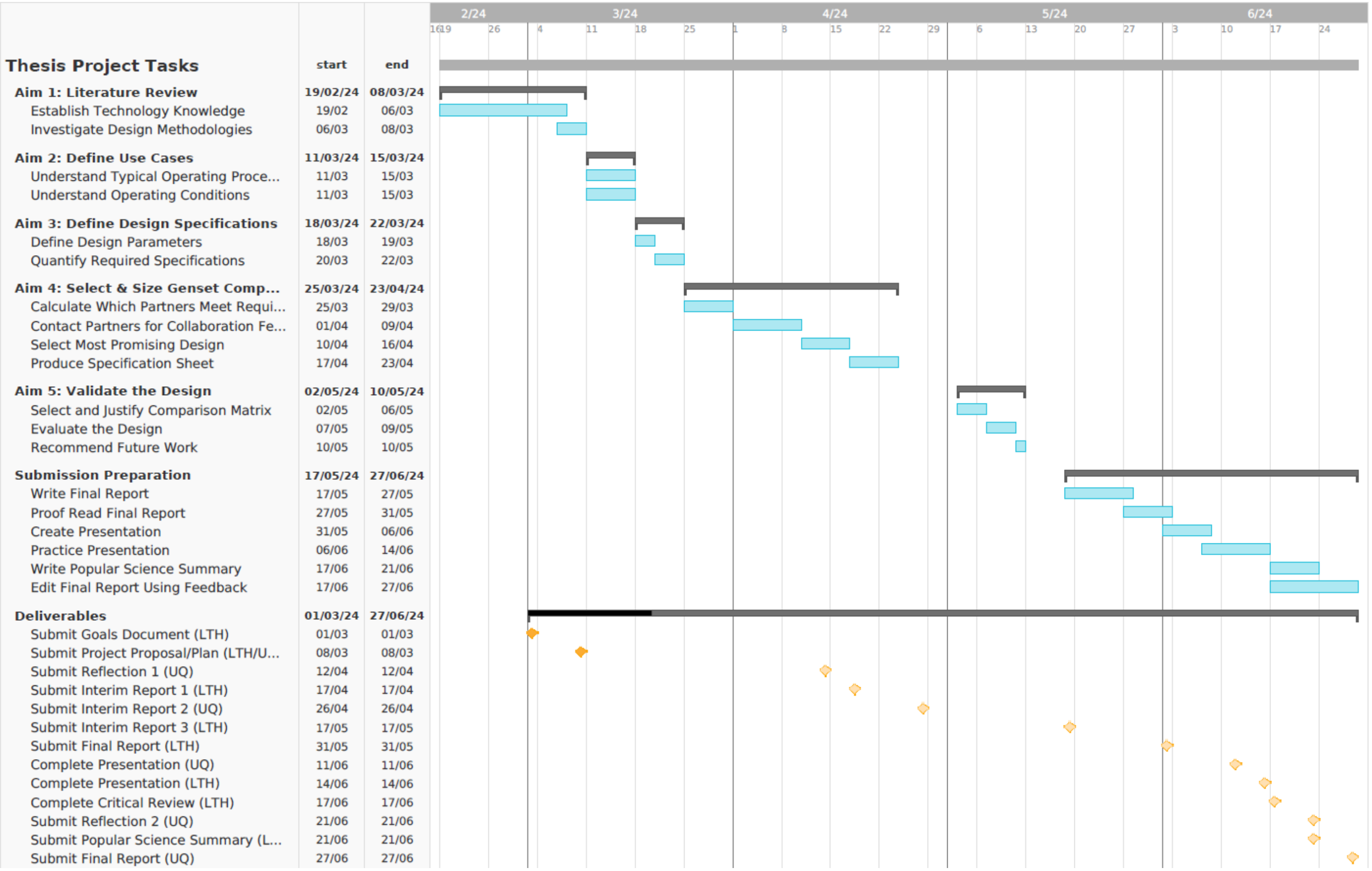
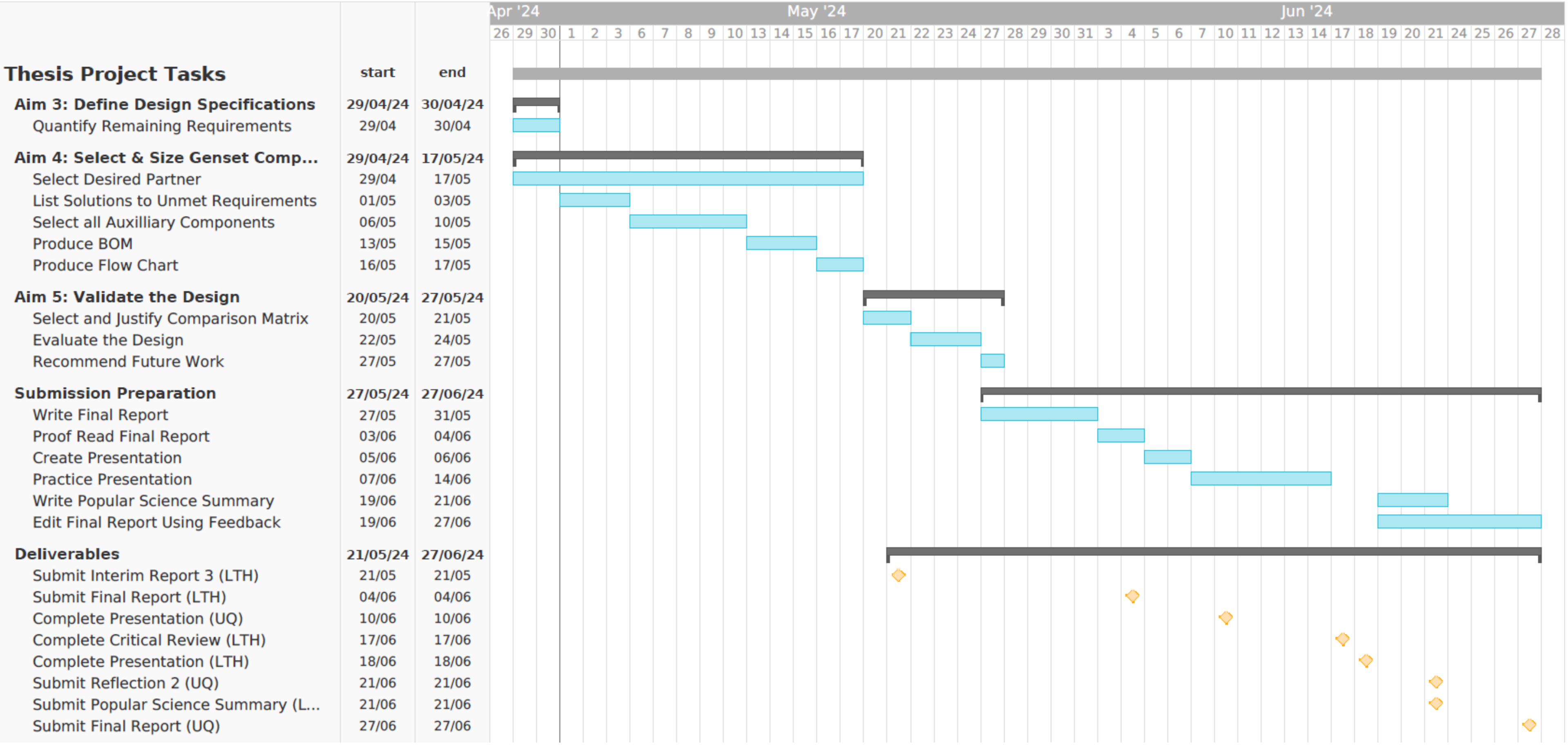


Figure 19: Gantt Chart Displaying Original Predicted Timeline

The update project timeline is presented in the form of a Gantt chart in Figure 20.



Thesis Project Tasks	start	end
Aim 3: Define Design Specifications	**29/04/24**	**30/04/24**
Quantify Remaining Requirements	29/04	30/04
Aim 4: Select & Size Genset Comp...	**29/04/24**	**17/05/24**
Select Desired Partner	29/04	17/05
List Solutions to Unmet Requirements	01/05	03/05
Select all Auxilliary Components	06/05	10/05
Produce BOM	13/05	15/05
Produce Flow Chart	16/05	17/05
Aim 5: Validate the Design	**20/05/24**	**27/05/24**
Select and Justify Comparison Matrix	20/05	21/05
Evaluate the Design	22/05	24/05
Recommend Future Work	27/05	27/05
Submission Preparation	**27/05/24**	**27/06/24**
Write Final Report	27/05	31/05
Proof Read Final Report	03/06	04/06
Create Presentation	05/06	06/06
Practice Presentation	07/06	14/06
Write Popular Science Summary	19/06	21/06
Edit Final Report Using Feedback	19/06	27/06
Deliverables	**21/05/24**	**27/06/24**
Submit Interim Report 3 (LTH)	21/05	21/05
Submit Final Report (LTH)	04/06	04/06
Complete Presentation (UQ)	10/06	10/06
Complete Critical Review (LTH)	17/06	17/06
Complete Presentation (LTH)	18/06	18/06
Submit Reflection 2 (UQ)	21/06	21/06
Submit Popular Science Summary (L...	21/06	21/06
Submit Final Report (UQ)	27/06	27/06

Figure 20: Gantt Chart Displaying Predicted Timeline for Project Completion

It was considered that unexpected opportunities may have arisen during the project which could have improved the outcome of the results. These opportunities could have included the design and evaluation being completed ahead of schedule, which would allow for the project scope to be expanded. Another potential opportunity would have been if the project goals were completed successfully and stakeholders were happy with the results, which could have resulted in the design being fully developed and potentially commercialised. While the project was not completed ahead of schedule, the project goals were completed to a high standard and were approved by key stakeholders. The design is planned to be further developed and commercialised.

Given that this project involved only design work, no safety risks were predicted during the project. However, several scheduling risks were identified. Table 27 presents the matrix used to assess the expected risks. Table 28 defines the potential hazards, describes an appropriate hazard control method, and assigns a residual risk level as completed at the start of the project. Table 29 lists further risks which were identified in the first Interim Report.

Table 27: Risk Matrix

			Consequences				
			Negligible	Minor	Moderate	Significant	Catastrophic
		Definition	Insignificant delay	Minor delay causing no lasting impact	Delays requiring effort to recover	Significant delays which reduce project scope	Severe delays causing project suspension
Likelihood	Almost Certain	Once per week	M (11)	H (16)	H (20)	E (23)	E (25)
	Likely	Once per month	M (7)	M (12)	H (17)	E (21)	E (24)
	Possible	Once every 6 months	L (4)	M (8)	M (13)	H (18)	E (22)
	Unlikely	Once per year	L (2)	L (5)	M (9)	H (14)	H (19)
	Rare	Once per decade	L (1)	L (3)	L (6)	M (10)	H (15)

Residual Risk Level			
1-6	7-13	14-20	21+
Low	Moderate	High	Extreme

Table 28: Scheduling Risks

Hazard	**Consequence**	**Hazard Control**	**Residual Risk**
Delays receiving information from customers about use cases	Design is delayed or incomplete	Contact customers with sufficient time; Send follow up messages	Moderate

Delays receiving information from potential partners about components	Design is delayed or incomplete	Contact partners with sufficient time; Send follow up messages	Moderate
Delays receiving information from internal sources about Liebherr components	Design is delayed or incomplete	Contact sources with sufficient time; Send follow up messages	Moderate
Working files become corrupted or lost	Work will need to be repeated	Save a new document version after each major change; Backup to an external drive once per week	Low
Personal illness	Delays in work completion	Notify all supervisors of illness; Dedicate float time in schedule to allow catch-up	Low
A supervisor is unavailable	Meetings may be delayed; unable to discuss issues	Schedule regular meetings in advance	Low
Delays or other problems regarding French visa	The project may be delayed or completed online	Begin visa process early; Correctly complete all requirements; Maintain open information channel with human resources and supervisors	Moderate

Table 29: Additional Scheduling Risks

Hazard	**Consequence**	**Hazard Control**	**Residual Risk**
External companies don’t reply	Shortlist of partners is reduced	Attempt contact with company through multiple methods and send follow-up messages	Low
Travel delays or restrictions prevent the ability to meet with potential partners	Information is delayed or never received	Ensure an alternative online meeting is possible whenever organising an in-person meeting	Low
The desired partner is unsuitable or unwilling to collaborate	Project is no longer feasible	Maximise the number of components which can be supplied by several partners	Low

APPENDIX B: ADDITIONAL GENSET STANDARDS

The following are standards defined by European organisations regarding the design, manufacturing, installation, operation, and maintenance of gensets:

- DIN 6271: Reciprocating internal combustion engines
- BS 5514: Reciprocating internal combustion engines
- European Commission: Restriction of Hazardous Substances in Electrical and Electronic Equipment
- ECHA REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals

The following are standards defined by North American organisations regarding the design, manufacturing, installation, operation, and maintenance of gensets:

- NEMA MG1: Motors and Generators
- NEMA ICS1: Industrial Control and Systems: General Requirements
- NEMA ICS10: Industrial Control and Systems
- NEMA 250: Enclosure Ingress Protection Testing
- NEMA ICS6: Industrial Control and Systems: Enclosures
- NEMA AB1: Molded-Case Circuit Breakers, Molded Case Switches, and Circuit-Breaker Enclosures
- ANSI/IEE C62.41: Recommended Practice for Surge Voltages in Low-Voltage AC Power Circuits
- NFPA 37: Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines
- NFPA 70: National Electrical Code
- NFPA 110: Standard for Emergency and Standby Power Systems
- CSA C22.2: General requirements — Canadian Electrical Code, Part II
- UL 2200: Stationary Engine Generator Assemblies
- UL 508: Industrial Control Equipment
- UL 489: Molded-Case Circuit Breakers, Molded Case Switches, and Circuit-Breaker Enclosures
- NEC 700: Emergency Systems
- NEC 701: Legally Required Standby Systems
- NEC 702: Optional Standby Systems
- NEC 708: Critical Operations Power Systems

APPENDIX C: ADDITIONAL AMMONIA STANDARDS

The following are standards defined by European organisations regarding the use and storage of ammonia:

- Directive 2014/68/EU: The pressure equipment directive
- ATEX 114 Directive 2014/34/EU: Equipment and protective systems intended for use in potentially explosive atmospheres
- ATEX Directive 99/92/EC: Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.

The following are standards defined by North American organisations regarding the use and storage of ammonia:

- API 620 Design and Construction of Large, Welded, Low-Pressure Storage Tanks
- API 625 Tank Systems for Refrigerated Liquefied Gas Storage
- ANSI CGA G-2.1: Requirements for The Storage and Handling of Anhydrous Ammonia
- C.R.C., c. 1146: Anhydrous Ammonia Bulk Storage Regulations
- ASME Boiler and Pressure Vessel Code
- OSHA 29 CFR 1910.111: Storage and handling of anhydrous ammonia
- US-Dept. of Transportation 49 CFR Parts 171-180: Transportation of Hazardous Materials
- US-EPA EPCRA: Emergency Community Right-to-know Act
- US-EPA RMP: Risk Management Plan
- US-EPA SNAP: Significant New Alternatives Policy

APPENDIX D: ADDITIONAL HYDROGEN STANDARDS

The following are standards defined by European organisations regarding the use and storage of hydrogen:

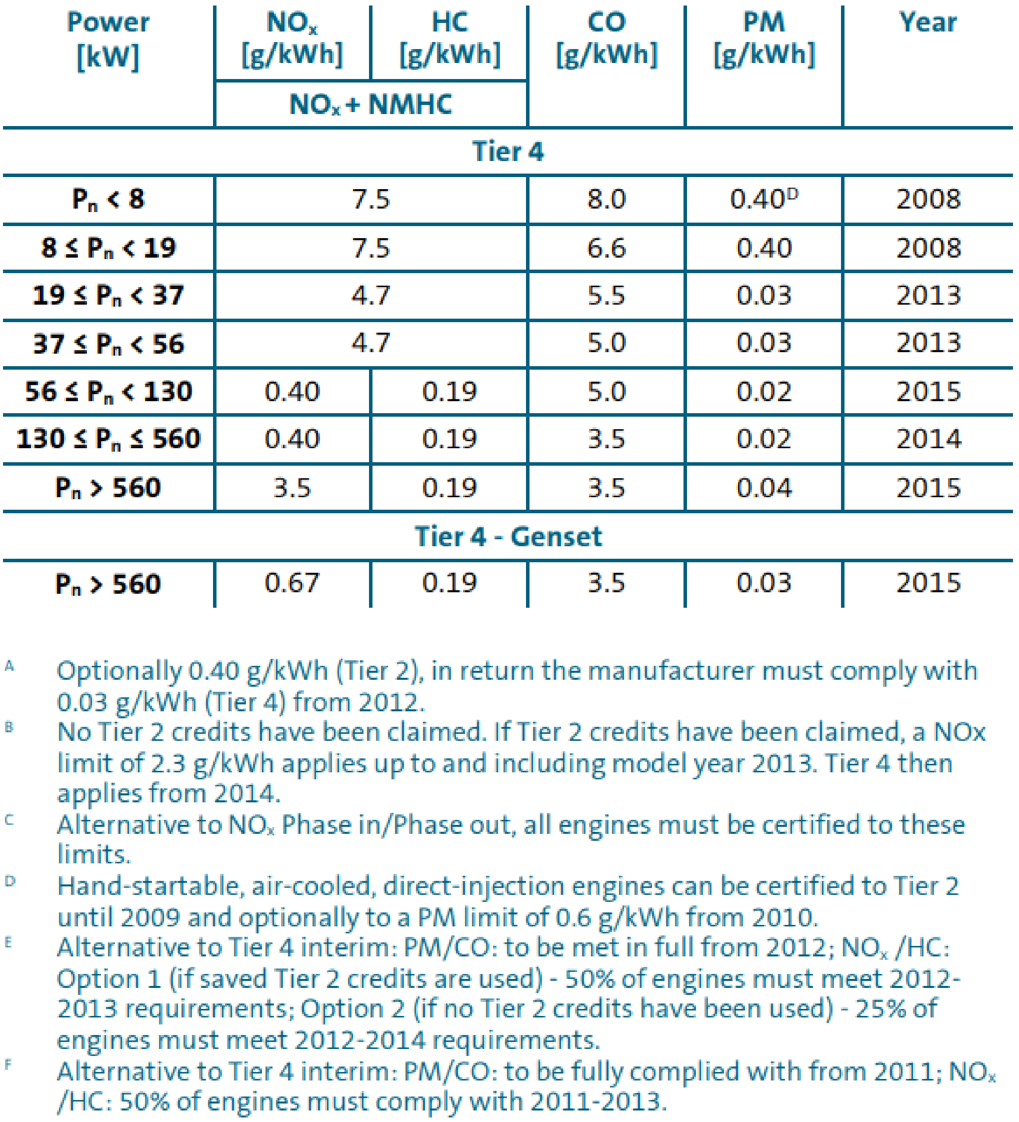
- EU 2021/535 LHSS and CHSS Storage systems
- Directive 2014/68/EU: The pressure equipment directive
- ATEX 114 Directive 2014/34/EU: Equipment and protective systems intended for use in potentially explosive atmospheres
- ATEX Directive 99/92/EC: Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.

The following are standards defined by North American organisations regarding the use and storage of hydrogen:

- NFPA 55: Compressed Gases and Cryogenic Fluids Code
- NFPA 497: Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas
- ASME Boiler and Pressure Vessel Code
- US-Dept. of Transportation 49 CFR Parts 171-180: Transportation of Hazardous Materials
- US-EPA EPCRA: Emergency Community Right-to-know Act
- US-EPA RMP: Risk Management Plan
- US-EPA SNAP: Significant New Alternatives Policy
- OSHA 29 CFR 1910.103: Hydrogen

APPENDIX E: USA EMISSIONS REGULATIONS

Table 30: USA Non-Road Mobile Machinery Emissions Regulations



Power [kW]	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]	Year
	NO_x + NMHC				
Tier 4					
$P_n < 8$	7.5		8.0	0.40[D]	2008
$8 \leq P_n < 19$	7.5		6.6	0.40	2008
$19 \leq P_n < 37$	4.7		5.5	0.03	2013
$37 \leq P_n < 56$	4.7		5.0	0.03	2013
$56 \leq P_n < 130$	0.40	0.19	5.0	0.02	2015
$130 \leq P_n \leq 560$	0.40	0.19	3.5	0.02	2014
$P_n > 560$	3.5	0.19	3.5	0.04	2015
Tier 4 - Genset					
$P_n > 560$	0.67	0.19	3.5	0.03	2015

[A] Optionally 0.40 g/kWh (Tier 2), in return the manufacturer must comply with 0.03 g/kWh (Tier 4) from 2012.

[B] No Tier 2 credits have been claimed. If Tier 2 credits have been claimed, a NOx limit of 2.3 g/kWh applies up to and including model year 2013. Tier 4 then applies from 2014.

[C] Alternative to NO_x Phase in/Phase out, all engines must be certified to these limits.

[D] Hand-startable, air-cooled, direct-injection engines can be certified to Tier 2 until 2009 and optionally to a PM limit of 0.6 g/kWh from 2010.

[E] Alternative to Tier 4 interim: PM/CO: to be met in full from 2012; NO_x /HC: Option 1 (if saved Tier 2 credits are used) - 50% of engines must meet 2012-2013 requirements; Option 2 (if no Tier 2 credits have been used) - 25% of engines must meet 2012-2014 requirements.

[F] Alternative to Tier 4 interim: PM/CO: to be fully complied with from 2011; NO_x /HC: 50% of engines must comply with 2011-2013.

Note that in addition to the particulate measurement, a transient smoke test is required; from Tier 4 onwards, this only applies to particulate emissions above 0.07 g/kWh; engines with constant-speed operation are generally exempt.

APPENDIX F: AMMONIA PHYSICAL PROPERTIES

The following properties were sourced from (Agency for Toxic Substances and Disease Registry, 2011) unless otherwise indicated.

State at STP (20°C, 1.013 bar): Gaseous.

Boiling Temperature: -33.4°C

Minimum Ignition Energy: In the range of 8MJ and 680MJ but varies with data source and stoichiometric ratio (Essmann et al., 2024).

Solubility in water:

Table 31: Solubility of Ammonia in Water

Temperature [°C]	Weight Percentage Concentration [w/w]
0	42.8 – 47
15	~38
20	33.1 – 34
25	31 – 34
30	~28
50	~18

Auto-ignition temperature: 650°C

Flash point: 132°C

Explosive limits in air: 15% vol to 28% vol

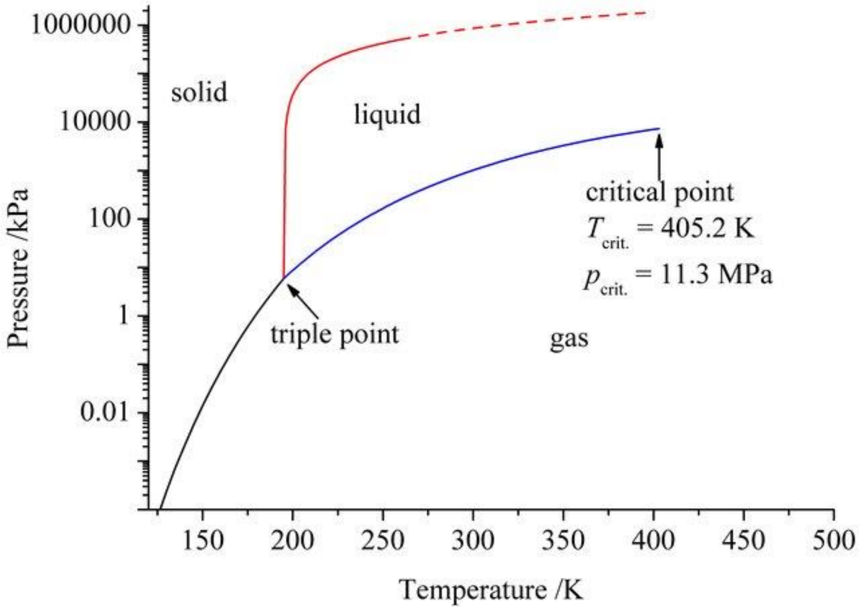


Figure 21: Ammonia Temperature-Pressure Phase Diagram (Richter & Niewa, 2014)

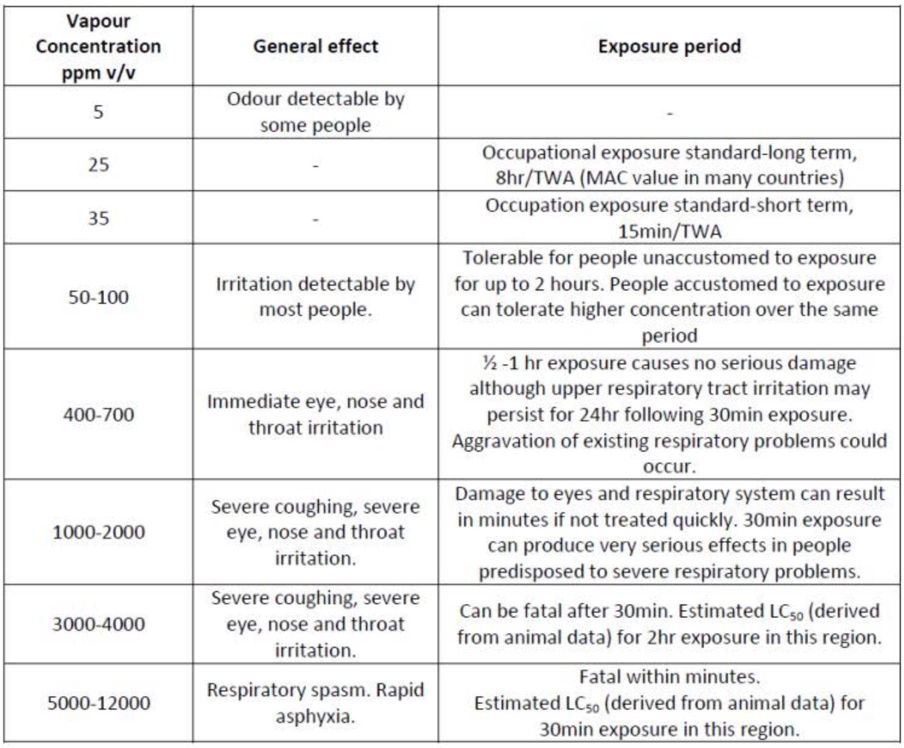
APPENDIX G: AMMONIA HEALTH EFFECTS

Exposure to high levels of ammonia in air may cause the following (National Center for Environmental Health, 2023):

- Burns
- Coughing
- Lung irritation
- Throat irritation
- Eye irritation
- Skin irritation

Table 32 presents specific exposure consequences for different quantities of ammonia.

Table 32: Effects of Ammonia Exposure (Fertilizers Europe, 2012)



Vapour Concentration ppm v/v	**General effect**	**Exposure period**
5	Odour detectable by some people	-
25	-	Occupational exposure standard-long term, 8hr/TWA (MAC value in many countries)
35	-	Occupation exposure standard-short term, 15min/TWA
50-100	Irritation detectable by most people.	Tolerable for people unaccustomed to exposure for up to 2 hours. People accustomed to exposure can tolerate higher concentration over the same period
400-700	Immediate eye, nose and throat irritation	½ -1 hr exposure causes no serious damage although upper respiratory tract irritation may persist for 24hr following 30min exposure. Aggravation of existing respiratory problems could occur.
1000-2000	Severe coughing, severe eye, nose and throat irritation.	Damage to eyes and respiratory system can result in minutes if not treated quickly. 30min exposure can produce very serious effects in people predisposed to severe respiratory problems.
3000-4000	Severe coughing, severe eye, nose and throat irritation.	Can be fatal after 30min. Estimated LC_{50} (derived from animal data) for 2hr exposure in this region.
5000-12000	Respiratory spasm. Rapid asphyxia.	Fatal within minutes. Estimated LC_{50} (derived from animal data) for 30min exposure in this region.

APPENDIX H: RELATION BETWEEN NO_X AND NH_3

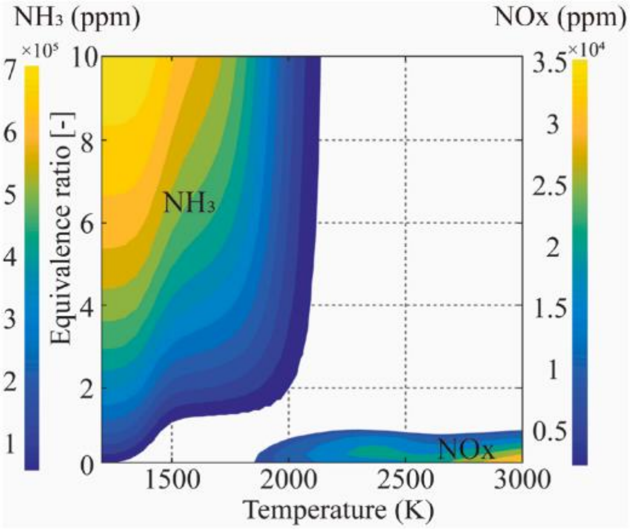


Figure 22: Equivalence Ratio-Temperature Diagram of NH_3 vs NO_x for an NH_3 ICE (Qi et al., 2023)

APPENDIX I: RELEVANT FUEL DENSITIES AND LOWER HEATING VALUES

The following density values were used for all relevant calculations:

- Ammonia at 37°C and 15 bar: 595.55 kg/m3 (Ichihara & Uematsu, 1994)
- Hydrogen density at 37°C and 5bar: 0.3898 kg/m3 (Lemmon et al., 2023)
- Hydrogen density at 37°C and 350bar: 22.55 kg/m3 (Lemmon et al., 2023)
- Hydrogen density at 37°C and 700bar: 38.14 kg/m3 (Lemmon et al., 2023)

The following lower heating values were used for all relevant calculations:

- Diesel: 42.5 MJ/kg (Billerot et al., 2023)
- Ammonia: 18.8 MJ/kg (Lhuillier et al., 2019)
- Hydrogen: 119.96 MJ/kg (Lemmon et al., 2023)

APPENDIX J: POTENTIAL OPTIONS FOR USE CASES

System:
Proposed mobile genset

Potential Actors:
Primary: E-HEX (7 options), mine schedule, mobility method
Secondary: Mine plan/layout, fuel truck, operator

Goal:
Provide continuously available power to the connected E-HEX

Possible Preconditions:

- The altitude of the mine is typically in one of two situations: greater than 1000 m above sea level, or less than or equal to 1000 m above sea level
- The ambient temperature of the mine is typically in one of three situations: less than -30°C, between -30°C and 40°C, and greater than 40°C
- Weather conditions which may affect the operation of the system include: strong winds, heavy rain, high humidity, or snow and ice.
- The operators may either use or not use hot seating for shift changes. If hot seating is used, system stops will occur every 24 hours for up to an hour. If hot seating is not used, system stops will occur every 8 or 12 hours for 20 to 35 minutes.
- The distance over which the excavator moves can be up to 3km when moving between benches, depending on the mine plan/layout.
- The mine operations may use either double or single benching.
- The excavator may either be in the face shovel or backhoe configuration.
- The excavator may operate at 6 or 6.6 kV at 50 Hz, or 7.2 kV at 60 Hz
- The excavator selected will require a certain power supply and will have a certain speed:

Table 33: Liebherr E-HEX Load and Travel Speed

Liebherr E-HEX Class	Continuous Load [kW]	Movement Speed [km/h]
R9150E	623	2.9
R9200E	924	2.8
R9250E	1139	2.7
R9350E	1297	3.3
R9400E	1455	2.7
R9600E	2560	2.2
R9800E	3618	1.7

APPENDIX K: VOICE OF THE CUSTOMER SURVEY

“As a mining OEM, Liebherr is constantly looking for ways to improve our products and services to better meet the needs of our customers. Stationary and mobile gensets play a critical role in the mining industry but low and zero emission solutions are needed to meet OEM and customer climate goals, and Liebherr is committed to providing the best solutions possible.

Your feedback is extremely valuable to us and will help us continue providing innovative and effective solutions for your mining operations - thank you for your collaboration.

- Do you currently use gensets in your operations? If yes, can you provide more details? For example:
  - What are your typical use cases? (e.g. emergency power, mobile power generation for equipment, back-up power to cover gaps in renewable energy supply)
  - How many gensets do you typically have per site?
  - What power ranges are they most frequently rated for?
  - Do you have a standard voltage and frequency for gensets across your sites?
- Based on your experience, what would be an expected cost per kWh for a diesel genset? What factors would influence this number?
- What price difference would you expect between a zero emission and a diesel genset? What factors would influence this figure?
- What do you value the most when it comes to gensets? Examples include reliability/availability, emissions, ease of installation, cost-effectiveness, etc.
- Are there any fuels or energy sources that you would not consider when purchasing a genset and why?
- Would you be more likely to consider purchasing a mobile or a stationary genset? What factors would influence this decision?
- What specific performance or operational requirements would you like from a genset? Including, for example:
  - What duty cycle and power would your equipment require?
  - Do you have any space or size restrictions?
  - Do you have any specific operating conditions (e.g. cold temperatures, high altitude)?
  - Are there any specific legal requirements to be considered in your operation?
- What lifetime and major overhaul interval would you expect from a genset? How many hours of operation would expect from one refuelling?
- Do you have any recommendations or further comments for us?

APPENDIX L: ALTERNATOR-ENGINE COMBINATION FEASIBILITY

Table 34: Feasibility of Leroy Somer Alternators Interfacing with Liebherr Engines

		Alternator	TAL 0463	TAL 0463	TAL 0473	TAL 0473	TAL 049	TAL 049	LSA 47.3	LSA 47.3	LSA 49.3	LSA 49.3	LSA 50.2
		Cont. Power Min [kW]	184	230	328	408	584	732	328	410	528	660	880
		Cont. Power Max [kW]	292	350	528	660	800	1000	528	660	800	1000	1312
		Max Efficiency [%]	94.1	94.1	95.6	95.4	95.9	95.8	95.7	95.6	95.8	95.7	96
No.	Max	Min											
A964	299.97	89.991	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A966	449.955	134.9865	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
A976	599.94	179.982	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE
A9612	899.91	269.973	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9612+	999.9	299.97	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9616	1199.88	359.964	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9616+	1333.2	399.96	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9620	1499.85	449.955	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9912	2066.46	619.938	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE
A9916	2766.39	829.917	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE
A9920	3432.99	1029.897	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE

		Alternator	LSA 50.2	LSA 52.3	LSA 52.3	LSA 53.2	LSA 53.2	LSA 54.2	LSA 54.2
		Cont. Power Min [kW]	1000	1488	1786	2120	2520	2448	2880
		Cont. Power Max [kW]	1600	2200	2720	2640	3120	2664	2918
		Max Efficiency [%]	95.8	96.6	96.6	96.6	96.6	96.8	96.8
No.	Max	Min							

A964	299.97	89.991	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A966	449.955	134.9865	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A976	599.94	179.982	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9612	899.91	269.973	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9612+	999.9	299.97	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9616	1199.88	359.964	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9616+	1333.2	399.96	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9620	1499.85	449.955	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
A9912	2066.46	619.938	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
A9916	2766.39	829.917	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE
A9920	3432.99	1029.897	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE

Table 35: Feasibility of Stamford Alternators Interfacing with Liebherr Engines

		Alternator	HC4E	HC4F	S4L1D	S4L1D	S4L1S	HC5C	HC5C	HC5D	HC5D	HC5E	HC5E
		Cont. Power Min [kW]	308	364	288	364	230	340	400	400	460	448	540
		Cont. Power Max [kW]	352	400	360	450	400	400	475	400	515	488	600
		Max Efficiency [%]	93.9	94.3	93.5	93.6	94.3	94.6	94.6	94.9	94.8	95.2	95.1
No.	Max	Min											
A964	299.97	89.991	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A966	449.955	134.9865	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	TRUE	FALSE
A976	599.94	179.982	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9612	899.91	269.973	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9612+	999.9	299.97	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9616	1199.88	359.964	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9616+	1333.2	399.96	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9620	1499.85	449.955	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE
A9912	2066.46	619.938	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9916	2766.39	829.917	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

A9920	3432.99	1029.897	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

		Alternator	HC5F	HC5F	S5L1D	S5L1D	S5L1S	S5L1S	S6L1D	S6L1D	S7H1D	S7L1D	S7L1D
		Cont. Power Min [kW]	520	590	400	475	340	400	640	700	752	1204	1365
		Cont. Power Max [kW]	536	660	600	750	536	660	1120	1355	1300	2000	2400
		Max Efficiency [%]	95.3	95.2	95	95.1	95.3	95.2	95.8	95.8	95.6	96.6	96.4
No.	Max	Min											
A964	299.97	89.991	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A966	449.955	134.9865	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
A976	599.94	179.982	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE
A9612	899.91	269.973	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
A9612+	999.9	299.97	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
A9616	1199.88	359.964	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
A9616+	1333.2	399.96	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE
A9620	1499.85	449.955	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9912	2066.46	619.938	FALSE	TRUE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9916	2766.39	829.917	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE
A9920	3432.99	1029.897	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE

		Alternator	P80HV	P80HV	P80MV	P80MV	P80LV	P80LV
		Cont. Power Min [kW]	1718	1920	2120	2520	1812	2080
		Cont. Power Max [kW]	3100	3800	3402	4152	3129	3571
		Max Efficiency [%]	96.8	96.7	96.8	96.8	96.9	96.5
No.	Max	Min						
A964	299.97	89.991	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A966	449.955	134.9865	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

A976	599.94	179.982	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9612	899.91	269.973	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9612+	999.9	299.97	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9616	1199.88	359.964	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9616+	1333.2	399.96	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9620	1499.85	449.955	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9912	2066.46	619.938	TRUE	TRUE	FALSE	FALSE	TRUE	FALSE
A9916	2766.39	829.917	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9920	3432.99	1029.897	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE

		Alternator	S9H1D	S9H1D	S9M1D	S9M1D	S9L1D	S9L1D
		Cont. Power Min [kW]	1222	1229	1440	1840	2096	2320
		Cont. Power Max [kW]	3748	4200	3450	4200	3400	4080
		Max Efficiency [%]	97.3	97.2	97.2	97.3	97.1	96.8
No.	Max	Min						
A964	299.97	89.991	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A966	449.955	134.9865	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A976	599.94	179.982	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9612	899.91	269.973	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9612+	999.9	299.97	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9616	1199.88	359.964	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A9616+	1333.2	399.96	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
A9620	1499.85	449.955	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE
A9912	2066.46	619.938	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
A9916	2766.39	829.917	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9920	3432.99	1029.897	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE

Table 36: Feasibility of Mecc Alte Alternators Interfacing with Liebherr Engines

		Alternator	ECO40 4 C	ECO40 4 C	ECO43 4 A	ECO43 4 A	ECO46 4 A	ECO46 4 A
		Cont. Power Min [kW]	320	384	656	788	1200	1440
		Cont. Power Max [kW]	600	720	1120	1360	2240	2728
		Max Efficiency [%]	95.3	96.8	96.4	96.7	97.1	97.3
No.	Max	Min						
A964	299.97	89.991	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
A966	449.955	134.9865	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
A976	599.94	179.982	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
A9612	899.91	269.973	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
A9612+	999.9	299.97	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
A9616	1199.88	359.964	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
A9616+	1333.2	399.96	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE
A9620	1499.85	449.955	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
A9912	2066.46	619.938	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE
A9916	2766.39	829.917	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
A9920	3432.99	1029.897	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE

APPENDIX M: ALTERNATOR COVERAGE OF LIEBHERR E-HEXS

Note that blue and yellow rows indicate 50 Hz and 60 Hz applications respectively. Red lines indicate MV or HV alternators, which were excluded from consideration.

Table 37: Coverage of Liebherr E-HEXs by Potential Alternator-Engine Pairings

	A9912							**A9916**							
	9150	**9200**	**9250**	**9350**	**9400**	**9600**	**9800**	**9150**	**9200**	**9250**	**9350**	**9400**	**9600**	**9800**	Count
TAL 0473	Y														1
TAL 049	Y														1
TAL 049		Y							Y						2
LSA 47.3	Y														1
LSA 49.3	Y														1
LSA 49.3		Y							Y						2
LSA 50.2		Y	Y						Y	Y					4
LSA 50.2			Y	Y	Y					Y	Y	Y			6
LSA 52.3					Y							Y			2
LSA 52.3													Y		1
LSA 53.2													Y		1
LSA 54.2													Y		1
HC5F	Y														1
S5L1D	Y														1
S5L1S	Y														1
S6L1D	Y	Y							Y						3
S6L1D		Y	Y	Y					Y	Y	Y				6
S7H1D		Y	Y						Y	Y					4
S7L1D				Y	Y						Y	Y			4
S7L1D					Y							Y			2
P80HV													Y		1
P80HV													Y		1
P80MV													Y		1
P80MV													Y		1
P80LV													Y		1
P80LV													Y		1
S9H1D				Y	Y						Y	Y	Y		5
S9H1D				Y	Y						Y	Y	Y		5
S9M1D					Y							Y	Y		3
S9M1D													Y		1
S9L1D													Y		1
S9L1D													Y		1
ECO40 4 C	Y														1

ECO43 4 A		Y							Y						2
ECO43 4 A		Y	Y	Y					Y	Y	Y				6
ECO46 4 A				Y	Y						Y	Y			4
ECO46 4 A					Y							Y	Y		3