Industrial fuel switching with novel high temperature heat pump technology.

Techno-commercial feasibility report.

30th September 2022

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1. Executive Summary

According to the IEA, 70% of all industrial energy use globally is for the production of process heat - the vast majority of which is generated by fossil fuels on site - meaning decarbonising industry's heat is essential to achieving net-zero carbon emissions. Within this, heat requirements of between 100°C and 200°C alone result in more carbon emissions than the entire aviation industry. These relatively low, sub-combustion temperatures can technically be met using electrification technology in the form of high temperature heat pumps, but the techno-economic barriers of working at higher temperatures and the historically low price of gas has meant this has not been commercially feasible.

Futraheat is a high temperature heat pump (HTHP) technology developer with a novel compressor technology (TurboClaw), the benefits of which yield lower manufacturing and maintenance costs. Futraheat conducted this feasibility study in partnership with Projective Ltd, a sustainable energy consultancy and engineering services provider to industry, in order to evaluate the feasibility for the widespread application of its novel HTHP technology in industry.

A core element of the study were client consultations and site visits, which concluded that a HTHP delivering steam up to 3barg (143°C) and capable of operating with heat sources down to 60°C would serve the majority of industry's low-pressure steam driven processes, and all those encountered as part of this study.

Furthermore, the client consultations found that net-zero is no longer optional for industry, to the extent that process heat users are now comparing the cost of alternative low-carbon heating technologies against the cost of direct-electrode heating, rather than the gas-boiler status quo. On this basis it becomes economically feasible to recover lower temperature heat with a conventional heat pump, either from waste streams or the environment, and then utilise a HTHP to generate low-pressure process steam.

A parametric analysis of TurboClaw established that with two-stages of compression on a single shaft it could deliver 300kWt of low-pressure steam at 3barg (143°C) from source heat as low as 80°C. It also found that although turndown is limited to about 25% for a single compressor, where multiple compressors are used to deliver the more commonly found higher capacities of around 1MWt, turndown of around 75% is achievable.

The engineering feasibility aspects of the study looked at design simplification and the implications of operating at higher temperatures. The ambition of simplifying the architecture of Futraheat's current compressor design by adopting an oil-free bearing technology and combining the motor and compressor (reducing parts count) was found to be feasible through the use of [redacted]. Achieving up to 150°C heat output rather than the 130°C possible with the current compressor design was found to be feasible through a review of the wider HTHP bill-of-materials, which identified those areas where the existing specification fell short and proposed alternative solutions.

A wider cost study quantified the cost benefits of adopting oil-free bearing technology and reducing the parts count, and also established how production costs would reduce with volumes. This concluded that an installed cost to the customer of £400/kWt was achievable under nominal conditions.

The feasibility evaluation culminated with a proposed concept design for a steam generating HTHP, 'Greensteam' product, and a comprehensive techno-economic analysis illustrated how a HTHP technology with Greensteam's target performance would provide the lowest lifetime cost, and lowest lifetime cost of carbon abated vs fossil fuels and other low-carbon alternatives.

The culminating output from the study was a business plan for the commercialisation of Futraheat's HTHP technology.

2. Contents

Tables

Figures

3. Understanding the needs of industry

3.1. Introduction

An integral part of the project was to gain first hand understanding of industry's process heat needs and evaluate the feasibility of these being met through the use of high temperature heat pump products such as Futraheat's. Project partner Projective - with its established industrial customer base and intimate knowledge of likely target processes – led delivery of the work package.

Following the IFS Phase 1 contract award, Projective developed a project plan to ensure delivery and manage stakeholder engagement at each of the partner manufacturing companies targeted to be engaged in the study.

The project plan is included in this report together with a description of each project process step and the expected outcomes from each step.

In total six application case studies were completed across six sites and four clients. Each client has additional applications for High Temperature Heat Pumps (HTHP), however the six selected represented a good range of applications and were also within areas where clients' IP and confidentiality was least impinged allowing greater access to information.

Each client has publicly announced their Net Zero ambitions with dates for full Net Zero operations between 2030 and 2050, and recognises the decarbonising of the high temperature heat demands at their facilities to be their largest challenge to this ambition. Current available technology is limited and the electrification (using renewable power) of this high temperature heat utilising electrode type heaters with a 98% efficiency is practically the only option available at this time. Many sites do not have the electrical infrastructure to support this large scale deployment of electrode heaters and the commercial impact of the price increase of the fuel switch is financially challenging to the cost of goods. Each client, once informed, recognised the ability to utilise HTHPs to achieve the same process conditions at efficiencies of >200% represents an ideal solution that meets all their environmental goals and commercial needs.

3.2. Project process and programme

Projective formed a project team to carry out the extensive works required to complete the project. Projective's senior project manager developed the programme and process to meet the deliverables in the timescale require. A significant part and subsequent challenge to the project was working with external stakeholders at clients' sites. With site access still restricted and stakeholder staff numbers at site reduced due to Covid related absence, the timely turnaround of key information and the co-ordination of travel, Covid clearances all proved a major challenge. We thank all involved in making this study possible in these sensitive times.

During the initial discussions with external stakeholders, it was clear their knowledge of heat pumps and in particular high temperature heat pumps was limited, and they would need, and requested, more details before providing access and information from their processes. This knowledge help form the following ten programme steps.

1. Understanding the process limits of the Futraheat heat pump
2. Internal review to select external stakeholders/clients to approach
3. Customer introduction meetings
4. Customer training & familiarisation sessions
5. Shortlisting processes to be reviewed
6. Data collection
7. Site visits, including process and buildability review
8. Basic concept Engineering
9. Economic review
10. Report creation

A detailed explanation of each stage is given below to provide the reader with an indication of the output and purpose of each step.

<u>Step 1 – Kick off meetings and process limits</u>

Meeting with the Futraheat team, Projective was able to determine the operational range of temperatures and energy flow to target when identifying the initial processes at the clients site. Key areas considered Included the following – agreed results are also shown in italics.

- Maximum outlet temperature
    - *130°C based on single compressor stage, 150°C based on refrigerant – (future opportunity to cascade to a steam compressor at temperatures over 150°C)*
- Minimum inlet temperature
    - *60°C. Where waste heat source is lower than 60°C a conventional heat pump can be used to provide a 60°C+ heat source*
- Evaporator and Condenser approach temperatures
    - *2°C allowed. Practically this could be reduced but at a cost and physical size penalty*
- Temperature lift per stage
    - *Typically 30°C including approach temperatures per stage. Multiple stages in series can be used for higher temperatures*
- Output Heat flow
    - *300kWt per compressor, Parallel machines can be used for higher flows*
- System turndown limits & ability to modulate heat output
    - *Typical turndown is 30% ie. 70-100% Output. Thermal stores can be used to provide further modulation.*
- Typical COP at a given temperature lift
    - Expected COP of 3 – 7 depending upon temperature lift. Futraheat to provide more details as project progresses.

- Physical size
    - *Unit size dominated by the heat exchanger sizes. Typical HTHP size at 300kWt would be 2m wide x 2m long x 2m high.*
- Maintenance requirements
    - *Quarterly oil maintenance and routine refrigerant lead detection is all that is expected.*

<u>Step 2 – Target client and case study identification</u>

With the process limits determined in step one, Projective was able to identify potential stakeholders and potential processes to approach for support. A number of stakeholders had expressed an interest in the project prior to the award, however given the current health restrictions and the relatively short programme, Projective wanted to ensure the best selection was made.

When determine stakeholders to approach, the following was considered:

- Stakeholders with a strong commitment to carbon reduction
- Stakeholders interest in high temperature heat pumps & percentage of heat demand the client has at high temperature
- Number of high temperature processes the stakeholder has across each site and their entire site portfolio
- Stakeholders whose processes are similar to others inside and outside their industry
- Stakeholders who have influence and presence in an industry
- Stakeholders whom Projective have current health clearance to visit sites
- Stakeholders with sites in UK or Ireland to limit travel costs/restrictions

Following the review 4 stakeholders were shortlisted covering the following industry sectors and processes:

<u>Industry sectors</u>

- Food & Beverage

The food and beverage industry is one of the largest globally, with demand for its products being a basic human need. The industry is known to be highly competitive with costs of goods and market presence a major factor to success. With consumers becoming more environmentally aware, the marketing benefits of a Net Zero product are becoming significant and the need to achieve this at the lowest operating cost is an essential part of success for any company in this sector.

- Pharmaceutical

Again, the pharmaceutical industry provides essential life-saving medicines to benefit mankind globally. The industry has a high profile and is a strong culture in supporting innovation. The industry ethos is to make people achieve longer lives and to live better. Environmental protection is a foundation of this and therefore these industries have a strong environmental policy.

- Fast Moving Consumer Goods (FMCG)

Like the food industry, consumers have choice in which FMCG products they purchase - such has deodorant, washing powder, etc. - and therefore with acute awareness of environmental protection, consumers are demanding much better environmental stewardship from companies they *choose* to purchase from.

Industry Processes

- Drying

The removal of moisture or a solvent is a common process in virtually all process industries. These processes universally utilise heat for the evaporation phase. To reduce the size of the process equipment and heat exchange surface, higher temperature source-heat is normally utilised to drive the moisture from the product. Energy contained in the vapours leaving the drying process equals the energy needed to produce the source heat, however these saturated vapour temperatures are often lower than the source heat. This represents an ideal opportunity for a heat pump to recover the vapour energy and amplify its temperature to create the processes source heat.

- Cleaning and Sanitisation

All hygienic processes have a cleaning process, and many aseptic processes will also have a sanitation stage. Typically, industry uses two methods to achieve these results, chemical cleaning/sanitisation or thermal cleaning/sanitisation. Previous years have seen many processes move to chemical solutions however with increasing reluctance to use man-made chemicals and their environmental impact, the focus now is moving to thermal treatments. Due to the nature of the industry, the pharmaceutical industry has been using thermal sanitisation as a standard with clean temperatures at 80°C or above and sanitisation temperatures of over 121°C.

- Distillation

The separation of multiple fractions from liquors through distillation is a common process in many beverage, chemical, oil/gas and process industries. Similar to the drying processes mentioned above, the energy available for recovery at lower temperatures equals the energy needed to drive the distillation reboiler/kettle. Distillation often has much closer vapour and reboiler temperatures and provides an excellent process to be driven by a heat pump.

- Process Reactor Heating

Many industrial processes utilise reactor vessels in which controlled chemical or biological reactions are supported. To achieve peak reaction performance the temperature of the product inside the reactor is controlled by a combination of reactor vessel jackets or internal/external heat exchangers.

The service side of these reactor jackets and heat exchangers are filled with a pumped thermal fluid which is heated and cooled to meet the processes needs. With multiple reactions taking place in multiple reactors at differing stages (heating and cooling), there is an opportunity to recover the heat removed from the cooling stages and use a heat pump to raise its temperature to meet the process reactor's high temperature needs.

Step 3 – Client engagement

With steps 1 and 2 complete, Projective approached each client through its senior sustainability manager to discuss the programme aims, likely commitment needed from them, and the benefits they would gain from taking part. As all clients had worked extensively in the past with Projective in previous commercial sustainability projects, these introductions were simple to set up.

Key points discussed during introductory meetings were:

- Client confidentiality

Projective were working under a very comprehensive NDA with each participant and it was insisted and agreed that no sensitive process information would be made public and no customers names or sites would be mentioned throughout the report.

- Site access

Project would be required to utilise existing staff on this project that had security and health and safety clearance at each site. For some sites, each visit would require senior management approval due to the COVID status at the facility.

- Process Data

The study would not share process data above that which is required to complete the study. This would be limited to the heat energy flow profile, operating hours, heat pump temperature at the inlet or outlet.

- Energy Cost Data

The study would utilise a standard energy cost model which is representative of all the participants' energy costs (see p17).

Step 4 – Client Education

All participants requested additional information on heat pumps and in particular Futraheat's HTHP technology. Two larger international customers requested a more formal training of their Global Energy Managers on this new innovative technology as part of agreeing to supporting the process in full. Projective developed a training pack for these clients and undertook a number of training sessions on heat pump technology, with a special emphasis on high temperature heat pumps. The sessions were delivered via MS Teams to over 40 engineers and energy managers in total.

The training contained the following elements:

1. Introduction to heat pumps – A technical introduction
2. Environmental & Commercial benefits of heat pumps – How to calculate a ROI
3. Identifying where heat pumps can be deployed in an organisation – Completing a simple pinch study
4. How to install heat pumps – How to connect into an existing process & the use of thermal stores and batteries
5. High temperature heat pumps – Market development and the Futraheat solution
6. Potential process examples of deploying high temperature heat pumps

Step 5 - Agreeing the processes to be covered at the site

With stakeholders onboard, we worked with them to agree the most appropriate sites to visit at which the target processes could be found. Each client has a global footprint, but in the interests of time and cost, site in the following locations were agreed:

- South Coast of England – 2 Sites
- West Scotland – 1 site
- Southern Ireland – 2 sites
- Central Eastern Europe – 1 Site

Step 6 – Preliminary data collection

With sites and processes agreed, Projective was introduced to the process owners at each site. Projective had reasonable prior knowledge of each site and the processes from previous works, however the following data was requested

- Process P&ID
- Hours run a year
- Similar processes in the network
- Control system screen dump when process in operation
- Utilities system temperatures and pressures
- Energy Costs

Not all sites were able to provide all the information provided, in which case Projective agreed to collect this data manually when at site. During the collection of data phase, Projective held periodic MS Teams calls with the process owners to discuss the data as it was coming through. The collection of data was the hardest part of the project as many of the systems do not record the data needed and site priorities often meant the collection of data or sending of drawings was not prioritised.

Step 7 - Site visits

Each of the 6 sites was visited towards the end of the data collection phase. Where possible, Projective completed this with locally based Projective engineers to reduce costs and limit Covid travel risks. The purpose of the site visits was to collect the remaining data from site, and also to assess the "buildability" of each solution.

Crucially, the client consultations and site visits highlighted the challenge to the economics of retrofitting high temperature heat pumps to existing installations. Whilst the heat pump footprint and capital cost is relatively small compared to the process equipment it is being installed upon, each application is unique to a greater or lesser degree and the distances from the waste heat source and location of the heat demand can be up to 100m. Both this bespoke nature and potential need for new infrastructure was seen as a cost driver to be addressed.

For 'new build' factory process plant these retrofit challenges would not apply; designs would ensure heat sources and sinks are located optimally and heat recovery capability would be integrated into the process plant itself. This is why in future, Futraheat expects its core business to be the supply of its compressors into third-party process equipment suppliers and integrators. But the work conducted under this feasibility study confirmed that in the short to medium term industry needs cost-effective retrofit solutions to decarbonising its assets for the remainder of their life.

Step 8 – Concept engineering

The cost challenges to retrofit HTHP solutions identified in step 7 above supported the concept of 'steam generating' HTHP products. The vast majority of industry's process heat, including that for all the processes evaluated in this study, is delivered to the point of use in the form of steam, generated by a central fossil fuel boiler. Taking this approach has the following benefits, all of which reduce cost:

- Allows for standard products (power, capacity, steam pressure)
- New infrastructure is limited through being able to locate the HTHP close to the heat source and integrating its steam output directly into the existing steam infrastructure
- Allows processes to use existing heat exchangers etc, avoiding the need to make significant, costly changes to capital equipment.

- Limits the time for installation.
- Leaves existing infrastructure intact for redundancy – likely very important to gaining confidence from industry for the adoption of new technology.

Other key design requirements highlighted at the site visits and deemed essential for any next-stage pilot/demonstration were:

1. Failure of the heat pump should not stop the process from operating
2. The function of the heat pump should not affect the process operation
3. The heat pump and installation must meet all corporate and statutory standards
4. The heat pump must be integrated into the site control system such that operation and performance is visible to the site operators within control rooms and locally at the plant

The following solutions were developed for each site to ensure the above conditions are met based on the requests above.

1. The heat pump should be installed prior to the existing heat exchanger or in parallel to existing steam demand. The heat pump will in affect "economise" the existing system reducing or removing demand on the existing fossil fuelled heat source. Should the heat pump fail to meet demand, the existing fossil fuelled heat source will engage to ensure the process conditions are maintained.
2. Installing the heat pump as described above secures operation of the process and also allows for start-up and shut down conditions or in conditions where the heat pump capacity is not sufficient. Heat pump sizing in these initial installations shall be selected for a base load duty and where demand is variable, a heat store will be installed to allow the heat stored to be modulated within its limits and start and stop as required ensuring enough heat is stored to meet the process needs.
3. Projective are an experienced global supplier of utilities equipment and designs to all these clients engaged in this report and as such have ensured all designs include sufficient costs to meet all standards local and national standards.
4. The heat pump is controlled by an industrial standard Logic controller from the Schneider Eco-Struxture family. This is compatible with the majority of industrial Control systems and provides communications to most industrial SCADA and historian systems. Costs have been allowed in the project multiplier to connect the heat pump to the sites existing control system and provide industrial standard control functionality.

Step 9 – Economic Review

All manufacturers engaged in this report were utilising gas as their primary fuel and steam as their onsite process heat supply. All companies have made commitments under the Science Based Targets (SBT) and Re100 to reduce carbon emissions from their operations and have, or are in the process of, supplying their facility with approved certified carbon free electricity by

2025. For the study, all companies insisted we should consider electricity at zero carbon emissions, as all would be in this situation by the time any equipment would practically be installed and fully commissioned.

All the companies engaged with in this study reported differing actual energy costs. Some of this was because many have hedged the energy market and purchased large volumes of energy at low rates which were available during 2020/21 Covid years and all reported large geographical variations with higher current costs for both renewable electricity and gas in the EU and Asia than in the US regions. The global nature of client operations and the purchasing strategies of these global companies makes it impossible to take a "point in time" assessment of actual market prices that is representative.

During this study time of this project, the economics and viability of heat pumps and especially high temperature heat pumps has changed significantly. Manufacturing customers worked with during the study are now making public statements towards a net zero ambitions and this is driving many manufactures away from the use of fossil fuels for heating and towards alternative fuels such as zero carbon electricity, green hydrogen and green biofuels. Limitation in supply, the financial economics and the practical logistics of green hydrogen and green biofuels have favoured the electrification of heat at many sites. The key limiting factor to limit the amount of electrification of heat is sites' electrical infrastructure and grid connection size. Direct electrification through electrode boilers or electrode heaters, whilst this presents a simple technical answer, is not viable due to the amount of power needed at site and the high operating costs. This has led to a realisation that heat pumps' inherent efficiency (i.e. high coefficient of performance - kilowatt of electricity used per kilowatt of heat delivered) – which delivers electrification, but without the capacity and OPEX costs of direct electrode heating - makes their deployment an essential part of any manufacturing plant's drive to Net Zero.

The war in Ukraine has also highlighted to many global manufacturers the risks of utilising gas as a primary fuel. Whilst for many years this fuel has been seen as a cheap and secure in supply, the situation has changed dramatically, with gas restrictions expected to hit industry in the winter of 2022/23, and with the situation expected to worsen in future years. This economics and business continuity driver is also pushing clients to favour electrically driven heat pumps for their thermal demands.

In previous years, the low cost of gas vs electricity has been a blocker to the deployment heat pumps and other electrification technology within industry. Furthermore, despite a dramatic increase in the generation of renewable electricity, electricity prices have largely been linked to that of the gas still responsible for much of its generation. However, as renewable electricity generation begins to dominate, and gas prices soar, this situation is set to change. Predictions are that over the next 5 to 10 years gas and electricity prices will disconnect: Gas prices are expected to remain at exceptionally elevated levels whilst the existing supply and security issues exist and then continue to increase in the long term due to carbon taxation, whereas electricity prices will stabilise and reflect their increasingly economical costs of production.

In summary, with the stabilisation of electrical prices in coming years and the predicted increases in gas prices, the future for heat pumps and high temperature heat pumps to meet the higher temperature industrial demands look strong and economically viable. In addition to this, the desire for carbon neutral manufacturing provides a long-term future for the technology.

Taking into account all of the above, it was agreed that a uniform primary energy cost should be used in this report. Whilst some regions or procurement strategies may cause local short-term variations, the global trends are similar.

Primary fuel costs to be used in this report were agreed at:

- Renewable electricity commodity cost: £160/MWh
- Gas commodity cost, including carbon taxation: £60/MWh

It was further agreed a steam boiler efficiency of 84% and steam distribution efficiency of 95% would be used, giving a cost of heat delivered at the user of £75/MWh.

3.3. Case Studies

3.3.1. Case study 1

Sector	Food and Beverage
Client	International food casing manufacturer
Sites Globally	6
Process	Drying

Situation

This client produces food casings from a biological process, these final food casing are formed wet and then are required to be dried on a former to develop the required shape and texture. The drying process is similar of all six sites globally.

The drying process is by passing the former through a drying tunnel being supplied with 80°C hot dry air. The process for generating the existing hot dry air is first to use a desiccant wheel dehumidifier to dry the air before heating it to the required 80°C

This dry hot air absorbs the moisture from the casing and is finally vented to atmosphere.

Several drying tunnels exist on each site and are operated continuously 24/7, with short stoppages for operational and maintenance purposes. Average tunnel operating hours is 7,200 hrs per year.

Each drier has a typical process air flow of 10.5 kg/s with an average air on temperature to the steam heater of 40°C. The steam average heat demand is 423kW. Heat is also required to heat the regeneration section of the desiccant dehumidifier. This required heated ambient air to 75°C and also absorbs 116kW of heat from the steam system. The total energy demand from the system is 539kW of heat. Given current site boiler and steam system efficiency estimates from site this requires 675kw of gas to produce (84% boiler efficiency and 95% steam distribution efficiency)

Opportunity

There is an opportunity to capture the lower temperature sensible and latent heat energy in the two vents from the dryer and the dehumidifier. Utilising a high temperature heat pump this heat could be raised to a temperature required to heat the inlet air to the dryer and dehumidifier regeneration section.

Target Project

It is estimated that the combine vents would have a saturation temperature around 70°C therefore operating the heat pump refrigerant suction pressure of 68°C saturated would allow for the majority of the air energy to be captured. Allowing the heat pump discharge to 112°C would allow for a smaller heat exchanger which is essential for site as space and pressure drop on the supply air side is a premium. If this temperature could be lowered in detailed design, then savings would be greater.

Economics

The high run hours and moderate temperature lift in this application would result in very good saving, even vs gas, facilitating rapid payback for the customer.

ΔT (°C)	COP	Load (kW)	Run Hours	Gas (£/yr)	Elec (£/yr)	HTHP (£/yr)	£ saved vs Gas	£ saved vs Elec
44	4.5	539	7,200	279,418	620,928	137,984	141,434	482,944

3.3.2. Case study 2

Sector	Pharmaceutical
Client	Internationals pharmaceutical manufacturer
Sites Globally	30 – with this application
Process	Water heating, Cleaning and Sanitation

Situation

This client utilises pure water and ultra-pure water systems within their manufacturing process. This water is required to be kept at temperatures over 80°C and kept moving at all times. Periodically, the storage and distribution system requires sterilisation at higher temperature (120°C) by flowing high temperature water through the system.

Heating of the water is currently achieved utilising industrial steam at 3-9barG (dependant on site), generated by natural gas. There is a requirement under the company's Net Zero Carbon ambition to remove the use of fossil fuels from its facilities.

Typical flowrates for these systems are between 2.0 m^3/h and 20.0 m^3/h. The system reviewed operated at 3.0 m^3/h (0.83kg/s)

Operating hours for this plant are 24/7, however the loads are subject to peaks as process vessels are filled. Typical heat pump operating hours are estimated at 5,376hrs per year for this site.

Opportunity

As previously mentioned, the client is intending to remove the use of fossil fuels from their manufacturing processes and is looking to electrify the heating system onsite. Approximately 70% of heat onsite is used at low temperatures of less than 60°C for HVAC, and a further 15% is used for the heating and sanitation of water systems at the temperatures above. The client facility does not have the electrical infrastructure and grid connection to directly replace the gas steam boilers with electric electrode boilers, therefore is looking for alternative solutions.

Although the 80°C demand in this application could be met by commercially available medium-temperature heat pumps, the periodic 120°C demand for sterilisation cannot and requires a HTHP to efficiently electrify this heat's production. By meeting both these demands with one HTHP solution, capital expenditure is minimised and space constraints met.

Target Project

It is proposed that a conventional heat pump is used to produce hot water at temperatures of 60°C to service the HVAC demands and provide a source of heat for a high temperature heat pump to produce heating at 85°C for operational heating and 120°C for cleaning and sanitation. The source heat for the conventional heat pump will be industrial waste heat from chiller condensers, air compressors, waste-water, together with renewable resources such as ground and air sources.

Due to the peak demand on the process system, it is recommended that a phase change thermal store or simple water stratification tank is installed to allow the high temperature heat pump to operate efficiency across the full demand range.

Economics

The very low temperature lift and good run-hours of the 80°C demand deliver strong savings, and although delivering the higher sterilisation temperatures for limited durations does not, together as a one-fit solution the proposal is cost-effective.

ΔT (°C)	COP	Load (kW)	Run Hours	Gas (£/yr)	Elec (£/yr)	HTHP (£/yr)	£ saved vs Gas	£ saved vs Elec
15	6.5	400	5,376	154,829	344,064	52,933	101,896	291,131
60	3.0	400	1,824	52,531	116,736	38,912	13,619	77,824

3.3.3. Case study 3

Sector	Pharmaceutical
Client	Internationals pharmaceutical manufacturer
Sites Globally	12 – with this application
Process	Tablet Film Coating

Situation

Many tablets are now coated with a product to aid digestion and provide a controlled release of the drug within the patient. The process of coating the tablet is similar to the process used by food manufacturers to coat a sweet, such as a Smartie.

A batch of tablets is placed into a rotating drum and sprayed with the coating product, simultaneously, hot dry air is passed through the drum to ensure the coating sticks and dries to the tablet.

The contaminated hot air leaves the coating drum and is then finely filtered to remove any traces of product before being vented to atmosphere. The temperature of the air leaving the system after filtration is remains very high at between 60°C and 70°C dependant on the air flow rate, tablet size and coating material

The temperature of the final supply air varies with product again, and is between 110°C and 120°C typically. The airflow rate observed was 4,500m³/h (1.38kg/s).

A single film coater would operate at approximately 50% duty cycle due to the time taken to load, unload and clean the machine. Between 3 and 8 film coaters are installed at sites and these are run in batch sequence to allow the operators to be coating one batch whilst unloading and preparing the next.

Opportunity

This represents a good opportunity for a high temperature heat pump. Recovering the waste heat from the film coaters exhaust.

A high temperature heat pump can then be used to increase the temperature from the recovery temperature to the maximum 120°C required.

Target Project

Based on this single heat exchanger, and to provide continuous use, two film coating machines can be considered demanding heat at any one time. This sizes the high temperature heat pump at 235kW thermal output at max 120°C continuously for 7,200 hours per year.

Economics

This high-lift application presents more challenging economics, yet still provides OPEX savings vs gas and a clear advantage over direct electrification. This is an attractive solution for the client, which is primarily concerned with decarbonising the process as cost effectively as possible.

ΔT (°C)	COP	Load (kW)	Run Hours	Gas (£/yr)	Elec (£/yr)	HTHP (£/yr)	£ saved vs Gas	£ saved vs Elec
60	3.0	235	7,200	121,824	270,720	90,240	31,584	180,480

3.3.4. Case study 4

Sector	Pharmaceutical
Client	Internationals pharmaceutical manufacturer
Sites Globally	4 – with this application
Process	Solvent recovery through distillation

Situation

In the process of manufacturing active pharmaceutical ingredients, solvents are used throughout the process to separate the individual process ingredients and for cleaning. At the end of the process these solvents are reprocessed for future use rather than destroyed. The reprocessing process effectively is to distil the solvents, removing all the water and other aqueous wastes as well as any impurities. The final cleaning solvent is then re-used in the process once again. The process of distillation is similar to that used in the beverage industry and oil/gas industry. Essentially these are a large vertical column where the temperature up the column separates the various fractions. At the bottom of the column there is a re boiler and at the top of the column, and at various levels in the column, there are condensers where the various elements that are separated are condensed into liquid form and recovered into their various recovery streams. Reboiler temperatures vary, but for the common used solvents a temperature of 105-110°C is typical, condensing temperatures also vary with solvent but between 65-80°C is common.

Typical operating hours for a common solvent column is 7200 hrs per year with a reboiler steam flowrate of 1,000kg/hr

Opportunity

The energy released at the condensers is equal to the energy required in the reboiler and therefore recovering this energy represents an ideal opportunity for a high temperature heat pump. Installation of a recovery system on the distillation columns for the most commonly used solvents would reduce energy demands significantly, whereas recovery on the smaller, less frequency used columns is unlikely to be cost effective.

Target Project

The target project is to install a HTHP to recover heat at the condensing temperatures down to 65°C. This can then be raised up to 120°C and used in a steam generator loop to provide low pressure steam from the existing reboiler, preventing the need to purchase a second parallel reboiler – something the client is keen to avoid due to the significant cleaning and space requirements.

Economics

This modest-lift, high run-time, and relatively high load application presents a very attractive application case, which would readily pay for itself within 3 years with savings made vs gas, and in less than a year with savings made vs direct electrode heating.

ΔT (°C)	COP	Load (kW)	Run Hours	Gas (£/yr)	Elec (£/yr)	HTHP (£/yr)	£ saved vs Gas	£ saved vs Elec
45	4.4	700	7,200	362,880	806,400	183,273	179,607	623,127

3.3.5. Case study 5

Sector	Pharmaceutical
Client	Internationals pharmaceutical manufacturer
Sites Globally	8 – with this application
Process	Process Thermal Fluid Heating

Situation

In the process of manufacturing active pharmaceutical ingredients, process reactors are used to create the chemical reactions needed. These process reactors and cooled and heated several times within the process cycle. Heating and cooling is provided via the reactor jacket, this jacket contains a thermal fluid (Syltherm), this thermal fluid is heated to temperatures of 120°C and cooled to temperatures of -5°C degrees dependent on the reactor cycle.

The site has several reactors all at various stages in each cycle so there is a continuous need for the production of hot and cold thermal fluid.

Thermal demand is continuous, and the system has a large thermal store installed to allow for peaks in demand. Currently heating is provided by 4 barg steam via a gas fired steam boiler.

Typical heating demand is 518kW.

Opportunity

Utilising a high temperature heat pump to generate the 120°C thermal fluid represents a good opportunity to reduce carbon emissions and to also capture the waste heat being released by the cooling system that is cooling the same thermal fluid.

The site already has plans to electrify all its 60-80°C hot water and heating needs using conventional heat pumps, which will recover waste heat from the cooling system.

The existing thermal store is excellent to provide a continuous steady heating load for the heat pump and the installation of a second heat exchanger in the system does not represent a process concern to the client.

Target Project

Waste heat is available at 30°C from the cooling system. This will be improved utilising a conventional heat pump to 60-80°C, The 80°C heat can then supply a high temperature heat pump to deliver 120°C heat to the high temperature thermal fluid. Installing a separate heat exchanger is possible in the thermal fluid circuit, therefore the installation can be self-contained, leaving the existing system as a back-up.

Economics

Having already made the decision to electrify its lower temperature heat needs, and with a plentiful source of waste heat from the cooling system, the remaining modest lift to 120°C, high run-hours and reasonable load make a HTHP installation a clear choice.

ΔT (°C)	COP	Load (kW)	Run Hours	Gas (£/yr)	Elec (£/yr)	HTHP (£/yr)	£ saved vs Gas	£ saved vs Elec
40	4.7	518	8,760	326,713	726,029	154,474	172,239	571,555

3.3.6. Case study 6

Sector	Fast moving Consumer Goods – Personal Care
Client	Internationals FCMG manufacturer
Sites Globally	3 – with this application
Process	Effluent Dewatering

Situation

The client is disposing of 5,300 tonnes of waste product a year through road transport offsite @ £360,000/yr. The product was 70% water and disposal costs were increasing as road transport costs increased. The product was a mixture of chemicals which formed soaps. The site is currently using a belt press to achieve the percentage solids above prior to shipping off site.

Opportunity

Utilising thermal evaporation of the water from the product the percentage water could be significantly reduced and reduce the volume of product being sent for off-site disposal. Given the nature of the product, client trials showed that retaining a percentage water (70% down to 30%) was desirable to prevent burning on any heat exchanger surface.

Target Project

Futraheat recommended a forced flow evaporator to prevent burning and reduce cleaning cycles. The evaporator would include a high temperature heat pump recovering heat from the condensing of the clean water evaporated from the product and improving its temperature to provide the heat of evaporation at the evaporator via a heat exchanger.

This simple heat recovery evaporator scheme would operate at very high efficiency and due to the low temperature rise needed (90°C - 110°C). Utilising the existing site storage tanks, the evaporator size could be reduced to operate continuously. The solution would aim to reduce the overall 5,300t of waste product by 40%.

Economics

In this case, savings are made through reducing the volume and therefore cost of off-site waste disposal. Reducing the 5,300t of waste by 40% using the HTHP costs only £32,615 per year due to the low-temperature lift and high run hours. Whereas it saves £144,000 in reduced disposal cost. The net effect is a £111,385 annual saving.

ΔT (°C)	COP	Load (kW)	Run Hours	Gas (£/yr)	Elec (£/yr)	HTHP (£/yr)	£ saved vs Gas	£ saved vs Elec
20	6.5	151	8,760	NA	NA	32,615	NA	NA

3.4. Conclusions

- A HTHP delivering steam up to 3barg (143°C) and capable of operating with heat sources down to 60°C would serve the majority of industry's low-pressure steam driven processes, and all those encountered during the site consultations and visits.
- Net-zero is no longer optional for industry, to the extent that process heat users are now comparing the cost of alternative low-carbon heating technologies against the cost of direct-electrode heating, rather than the gas-boiler status quo.
- On this basis it becomes economically feasible to recover lower temperature heat with a conventional heat pump, either from waste streams or the environment, and then utilise a HTHP to generate low-pressure process steam.

4. TurboClaw HTHP compressor parametric analysis

4.1. Aim

The purpose of conducting a parametric analysis of Futraheat's TurboClaw HTHP compressor technology was to determine its operational envelope when constrained by the relevant technical and commercial factors, namely:

1. Using Solstice R1233zd HFO refrigerant gas (max working temperature of 164°C). This gas had already been chosen as the most compatible with TurboClaw due to its thermodynamic and environmental properties (ultra-low global warming potential).
2. Limiting the number of compression stages to a maximum of 2. Further compression stages would require multiple machines and become uneconomical.
3. Delivery of 300kW of heat across the full range of discharge temperatures up to 143°C (required to generate 3barg steam) and source temperatures down to 80°C.
4. Max motor speed of 20,000rpm – as governed by limitations of the magnetic coupling between the motor and compressor.

The specific outputs targeted were:

- Compressor maps for single and multi-machine HTHPs
- Turndown (in kW heat delivered) achievable
- Efficiency (CoP) achievable

4.2. Methodology

The process to generate compressor performance maps starts by taking test data gathered on TurboClaw, and scaling the performance based on the size of the required compressor and the properties of the new gas at the required operating conditions. This required adjustments to be made based on the relative densities, speed of sound and geometry. This process outputs the performance of a single stage compressor, in terms of capacity vs temperature lift, and CoP. To add an additional stage, each point on the map that was calculated becomes the inlet condition for the next compressor stage. The output from all these calculations can then be added together to produce a multi-stage compressor map.

Compressor mapping is conducted using Matlab and Ansys software tools, but still requires an iterative, trial and error approach, which is lengthy and only possible with considerable experience. For these reasons a well-informed baseline data-set is highly preferential, which for this study was the existing HTHP demonstrator design, which was sized to deliver 300kW of heat at a 30°C temperature lift at a nominal discharge temperature of 120°C.

4.3. Results

The first aim of the analysis was to establish what the existing compressor design (150mm impeller) could achieve as either the first or second stage of a two-stage machine. Figure 1 below illustrates that neither combination could deliver the desired capacity (300kWt) over the full temperature range of 80°C to 143°C.

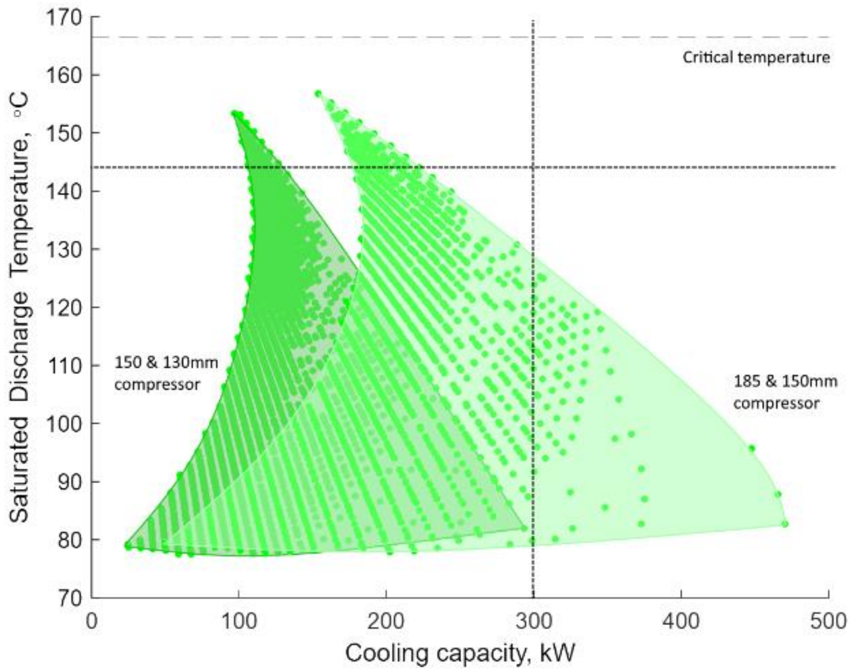


Figure 1. A comparison of the two, two-stage compressor maps containing the existing HTHP demonstrator's 150mm impeller.

The next phase of analysis consisted of systematically evaluating ever refined combinations of TurboClaw sizing to establish an optimal geometry that could generate the required pressure ratio and mass flow rate to meet the outlet temperature and capacity requirements. This resulted in a 158.6mm and 153.1mm impeller diameters combination operating at 20,000rpm. Figure 2 below shows the resulting compressor map.

Turndown – the extent to which the compressor can deliver the full temperature lift at reduced capacities – was shown to be possible down to 225kW.

The CoP of the system was shown to range from 3 at the maximum temperature lift, to 7 at a temperature lift of 25C.

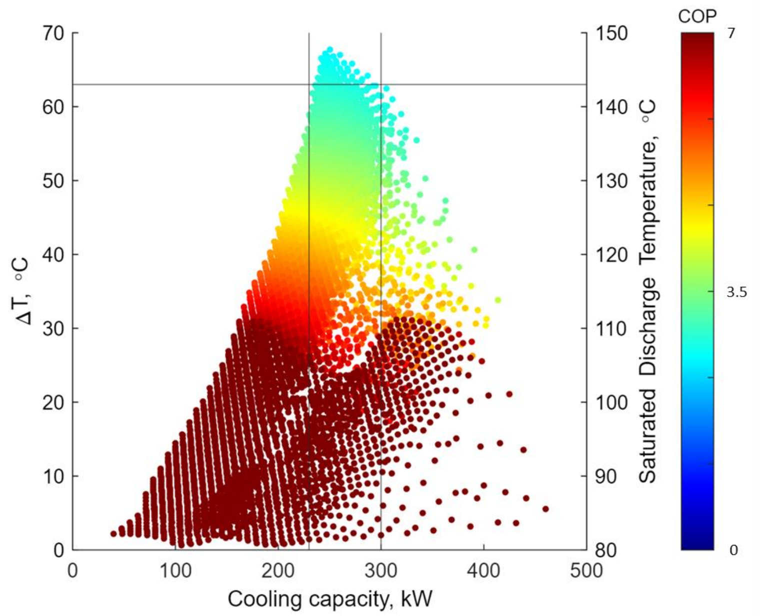


Figure 2. Optimised 2-stage compressor map delivering the maximum required temperature lift between 225kW and 300kW.

The final phase of the analysis sought to establish the operational map for a 1MWt capacity HTHP. To avoid repeating many tens of hours of analysis with slightly larger machine capacities (i.e. 3x 333kWt compressors), it was considered acceptable to approximate from the results of 3x 300kWt compressors.

Figure 3 below shows the expected performance map if 3x 300kWt compressors were operated in parallel. The full range of the three-compressor heat pump would be from 225kWt to 900kWt when outputting heat at the required level of 143°C. There are areas between the operational islands where the heat pump would need to use hot gas bypass to operate, but this scenario would cover more of the map than a single 900kWt compressor, providing significantly more turndown.

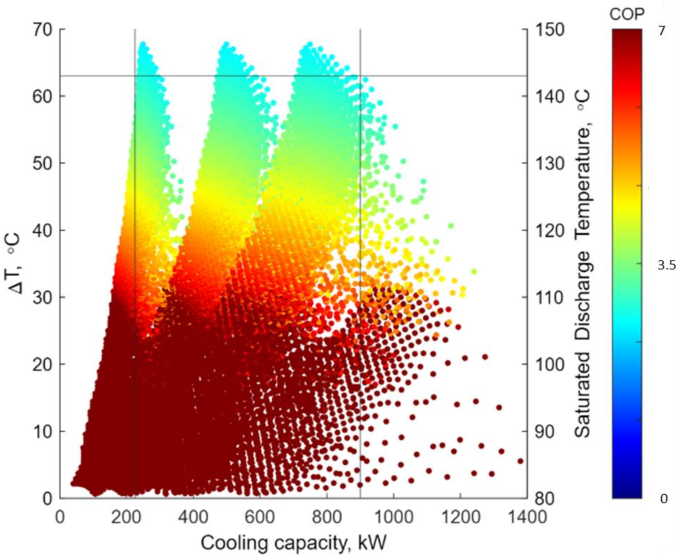


Figure 3. 1MWt, 3-stage compressor map

4.4. Outputs

The main outputs from the parametric analysis were:

- Confirmation that a two stage TurboClaw HTHP compressor delivering its maximum pressure lift could generate 3barg steam from an 80°C heat source
- Turndown for a single compressor is limited at this maximum temperature lift to about 25% (225kWt to 300kWt)
- Turndown for a 1MWt HTHP product would be approximately 75%
- CoP performance supports business case economics even at maximum temperature lifts
- The key specification elements of speed, impeller size and geometry and shaft power needed to proceed with concept design and design optimisation for cost and performance

5. Engineering feasibility: design for performance and cost reduction

Having established target end-user requirements and gained a parametric understanding of TurboClaw's performance capabilities in meeting these, (in sections 3 and 4 respectively), this section 5 reports on the engineering feasibility of developing a viable commercial product, optimised for performance and cost-effectiveness.

5.1. Current vs target specifications

The foundation of the engineering feasibility assessment is Futraheat's current HTHP demonstrator design specification. This is given in the table 1 below:

No.	Requirement	Value	Units	Comments
1.1	Gas	R1233zd	n/a	
1.2	Evaporator saturation temp (nominal)	90	°C	
1.3	Condenser saturation temp (nominal)	120	°C	
1.4	Suction pressure	8.33	bara	
1.5	Discharge pressure	15.75	bara	
1.6	Mass flow rate	2.07	kg/s	
1.7	Design capacity*	315	kWt	Max at 30°C ΔT
1.8	Shaft power at design capacity	55	kW	26 Nm
1.9	Speed at design capacity	20,000	rpm	
1.10	Impeller mass (single stage)	0.800	kg	OD of Ø150 mm
1.11	Estimated motor shaft mass	6.7 kg	kg	Max Ø74 mm (PM rotor OD)
1.12	Magnetic rotor sleeve inner diameter	55	mm	
1.13	Gas temp in motor bearing housing	95	°C	
1.14	Gas pressure in motor bearing housing	8.83	bara	0.5 bara above suction pressure
1.15	Impeller end load	841	N	Max. at 8.83 bara housing pressure

1.16	Balancing grade	G2.5	n/a
1.17	Radial load due to imbalance	31.0	N

Table 1. Current Heat Pump Specification

The end-user analysis in section 3 identified multiple, widespread, and highly scalable applications for HTHPs that could achieve temperature lifts in excess of 50°C. As anticipated, this increased duty is beyond the demonstrator's design specification, but the parametric analysis detailed in section 4 illustrated that such applications could be addressed by a two-stage TurboClaw solution, which could deliver more than a 63°C lift. Assuming a maximum temperature of 150°C – which provides a comfortable safety margin to the maximum expected 143°C required to generate 3barg steam – the maximum-duty requirements specification to consider for the purposes of engineering feasibility analysis and concept design was defined as follows:

No.	Requirement	Value	Units	Comments
2.1	Gas	R1233zd	n/a	
2.2	Evaporator saturation temp (minimum)	60	°C	
2.3	Condenser saturation temp (maximum)	150	°C	
2.4	Maximum temperature lift	63.6	°C	
2.5	Number of stages	2	n/a	
2.6	Min suction pressure	5.1	bara	
2.7	Max discharge pressure	27.4	bara	
2.8	Mass flow rate*	2.86	kg/s	
2.9	Design capacity	314	kWt	Max at 63.6°C ΔT

Table 2. Two Stage Compressor Specification

5.2. Current architecture and optimisation opportunities

Futraheat's existing HTHP design utilises a TurboClaw compressor with an architecture designed to best evaluate its performance against the requirements as per the specification in section 5.1, whilst also demonstrating oil-free gas compression.

To do this it was deemed optimal to entirely segregate the prime mover (electric motor), from the compressor itself. This removed a number of variables and 'unknowns' associated with operation of the motor at elevated temperatures and pressures, and instead allowed an, off-the-shelf motor and electronics to be used.

Segregation of the motor and compressor is achieved using a magnetic coupling, and only made possible thanks to the relatively low-rotational speed of the compressor, as such couplings are speed-limited.

Oil-free compression is achieved using a shaft seal, which contains the bearings' lubricating oil within a bearing cartridge. Again, such shaft-seals are speed limited and this arrangement is only possible due to TurboClaw's uniquely low-speed operation. The seal requires a small amount of refrigerant gas to 'bleed' through into the oil to operate correctly. The refrigerant is then separated from the oil and returned to the compressor circuit.

An annotated cut-away image and schematic diagram of the current compressor architecture are shown in Figures 4 and 5 below.

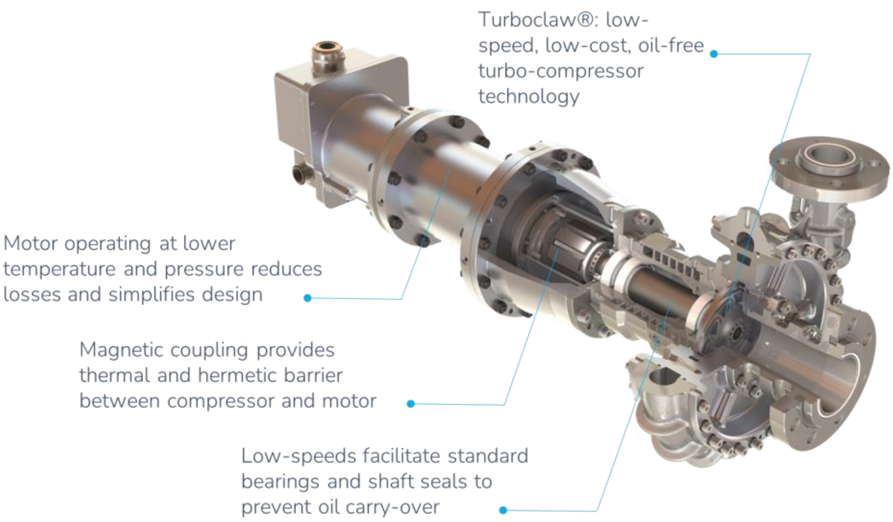


Figure 4. Current compressor render with 1/4 cut away

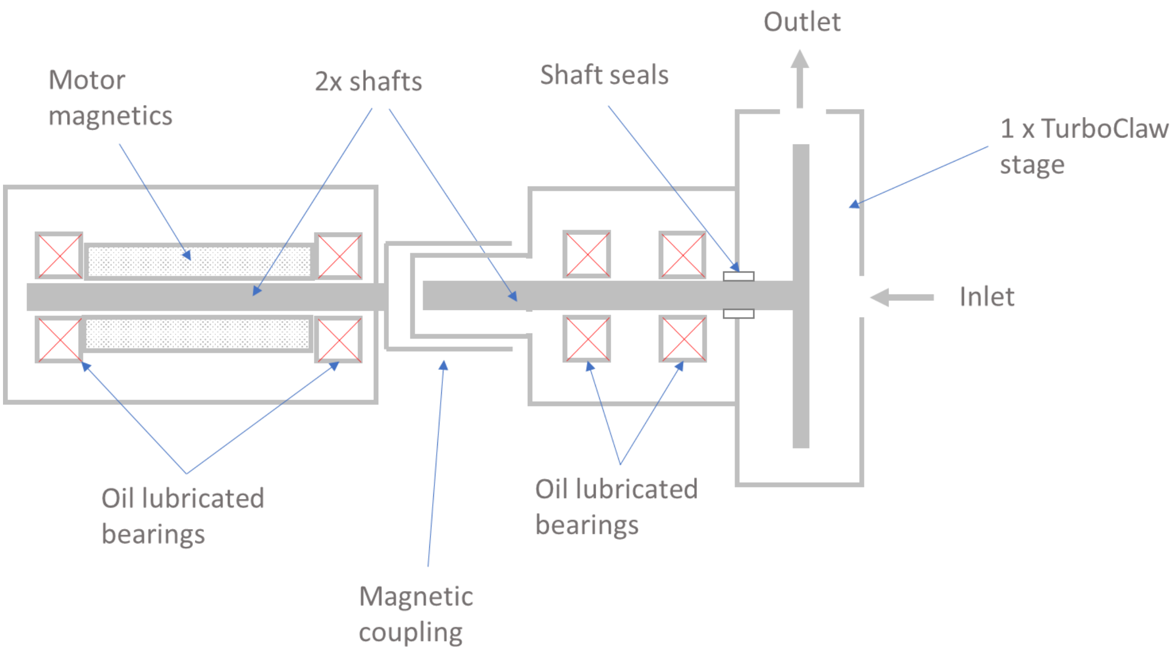


Figure 5. Current compressor schematic

Whilst this arrangement was essential to the development and proving of the compressor, it is not optimal from a production cost perspective. A preferred architecture combines the motor, bearings and compressor into one hermetically sealed arrangement, (see figure 6) removing the need for the magnetic coupling, a second shaft and set of bearings, contact-shaft seals, the oil-refrigerant separation system, and the motor oil lubrication system - the last two of these are themselves relatively complex and costly sub-systems (see figure 7).

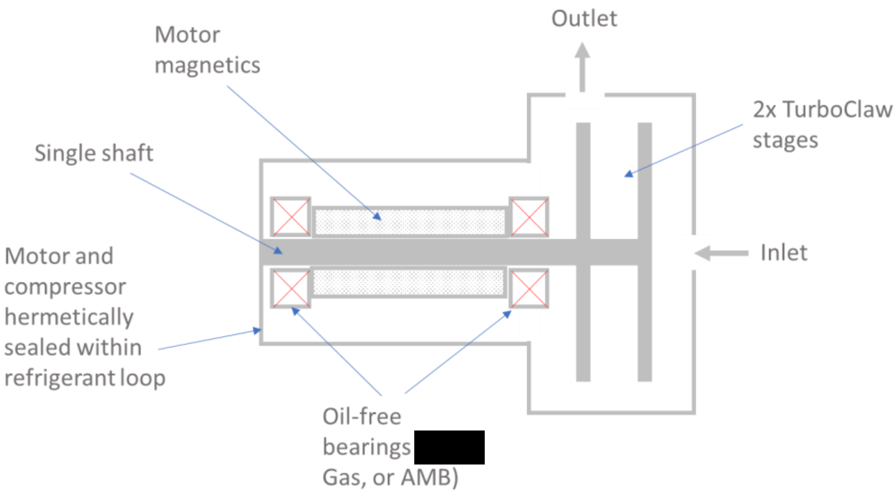


Figure 6. Proposed compressor schematic

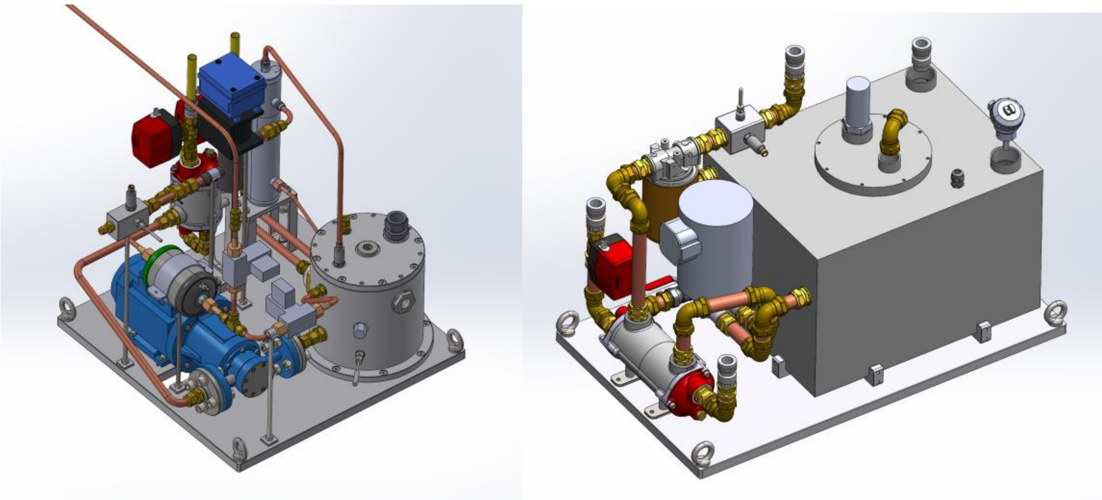


Figure 7. Compressor oil system, left, and motor oil system, right

The feasibility of this preferred architecture is determined by whether a technically viable and cost effective, oil-free bearing solution is possible. The next section describes the approach therefore taken to evaluate the options available.

5.3. Technology research and solutions identification

The current HTHP compressor utilises oil lubricated rolling element bearings. This limits the product offering where an oil-free machine is highly desirable, and as discussed in the preceding section introduces costs associated with oil/refrigerant management. This section reports on our investigations into alternative bearing solutions.

5.3.1. Approach

An initial search was undertaken of the bearing technology landscape to establish the state-of-the-art in oil-free solutions and identify those warranting deeper investigation. Preliminary contact was then made with a number of developers/suppliers to determine what information they required in order to make an assessment of feasibility with respect to a HTHP application.

We then prepared a specification document against which developers/suppliers were asked to make a costed solution proposal. The proposals were then evaluated based upon their technical and commercial merits, and compared. The most promising solutions were then considered within the concept design.

5.3.2. Oil-free bearing technologies

Industrial research and commercial enquiries identified several different types of high-speed and oil-free bearing technology solutions potentially applicable to the HTHP compressor. These bearing types categorised into three main types are listed below and described in detail in the following sections:

- Rolling element (ball) bearings
  - Grease lubricated
  - [redacted]
- Gas or liquid bearings (otherwise known as air or fluid film bearings)
  - Hydrostatic
  - Hydrodynamic
  - Hybrid – a combination of both hydrostatic and hydrodynamic
- Active magnetic bearings
  - With or without passive assistance

5.3.3. Rolling Element (Ball) Bearings

Rolling element ball bearings are a traditional and conventional technology used across a wide range of industries for many years. There are varying forms, super-precision angular contact hybrid ball bearings are the type most suited to the high-speed and load demands of turbomachinery applications. Angular contact ball bearings can withstand moderate to high rotational speeds, but at these speeds the bearings still require frequent maintenance and are responsible for most of all machine failures despite being a well understood technology.

Critical for all ball bearings to operate at elevated speeds (even low speeds) is a continuous supply of lubricant (typically oil) circulation through the bearing elements. The bearings are lubricated by actively by injecting or spraying lubricant or lubricant-air mixture directly inside of the bearing. The lubricant acts to create a thin layer (elasto-hydrodynamic lubrication) between the points of contact (balls and bearing races) this reduces friction and prevents wear. Relatively small amounts are required to lubricate the bearing, but a steady flow of lubricant is needed to remove excess heat generated by the contacts. The faster the bearing rotates the greater the heat generation and hence an increased demand for cooling flow.

Hybrid bearings refer to balls made from ceramic to improve durability and reduce the rotational weight of the bearing. Typically, the bearing races are manufactured from specialist through hardening steels such as 100Cr6 for high fatigue applications. More advanced materials and coatings can be used for further mitigating friction. Super-precision bearings are manufactured to tighter tolerances.

In the vast majority of applications oil is used as the lubricant in ball bearings. Greased bearings might be seen as being virtually oil-free as the intention is to contain the grease withing the bearing race, but they still carry the risk of contamination into the process fluid and are not suited to higher temperature applications due to the propensity for the grease to breakdown and its inability to provide cooling.

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

5.3.4. Gas or Liquid (Fluid Film) Bearings

A bearing is a machine element that permits relative motion between two constrained surfaces with minimal friction. For the case of a gas or liquid (fluid film) bearing, the relative motion between the two surfaces is a sliding motion on a shear of lubricant (the gas or liquid). There is no moving contact of the metallic rotating shaft and static housing components except during start-up or shutdown, and even this is avoided in a purely hydrostatic bearing. This separating shear of lubricant is a thin film, typically such as oil, air or water, but the process fluid (e.g. refrigerant) can also be used if it exhibits the required properties. There are two major types of fluid film bearing, one is hydrodynamic and the other is hydrostatic, both can be subdivided with further permutations. A hybrid fluid film bearing is simply a combination of both hydrodynamic and hydrostatic variants (see figure 9 below).

In hydrodynamic gas or liquid bearings, the film pressure that separates the surfaces is created by the relative motion (rotation) of the surfaces as the fluid is pulled into a converging geometry between the surfaces. Whereas in hydrostatic bearings the film pressure is generated externally by a pump, fluid is pumped in through an orifice or through a porous material. For this reason, a hydrostatic bearing rotor can start (and stop) without rubbing component contact if the bearing chamber is pressurised beforehand, a primary advantage. A combination hybrid fluid film bearing for a compressor application has a few options:

It should be noted that typically hydrostatic bearings utilise either liquid or gas whereas in hydrodynamic bearings the fluid is a gas (liquid ingress can damage the lift elements). In fluid bearing operation since there is no contact between the moving parts, there is no sliding friction, resulting in higher mechanical efficiencies, lower (near-zero) wear, and vibration compared to conventional ball bearings. The major difference between rolling element and fluid bearings is life expectancy. For given operating conditions rolling element bearings have a predictable life based upon the proven L10 calculation method. However correctly designed and maintained fluid film bearings can achieve 'infinite' life operation.

The primary roles of bearings are to control the shaft position, balance forces on the system, and provide damping. The geometry of angular contact ball bearings can support both radial and axial forces, but for a fluid bearing to achieve the same two elements are required. Journal bearings support radial loads which act perpendicular to the axis of rotation. Thrust bearings support axial loads which act along the axis of rotation. Design of the journal and thrust bearings are unique to the application in question, rarely can a particular fluid film bearing be applied successfully to varying processes unlike ball bearings.

The journal bearing design is less sensitive in hydrostatic applications compared to hydrodynamic ones. For dynamic journal bearings the converging geometry is provided by slight differences in diameters of the shaft and housing bore. A defined profile is machined into the journal bearing to develop the proper film. If stability is an issue journal tilt pads are often used which allow performance optimisation. In thrust bearings the converging geometry is either machined into the face of a fixed plate or provided by the tilting action of tilt pad thrust bearings.

A fixed geometry is designed for a specific condition, so tilt pad bearings are often used to accommodate variable conditions. Fixed profile bearing designs are usually used for lightly loaded applications and advanced tilting pad solutions for demanding conditions. Foil bearings are a hydrodynamic type where the rotor is supported by a compliant, spring-loaded foil journal lining. With enough speed the working fluid pushes the foil away from the shaft, so no contact occurs. Latest generation foil bearings using advanced coatings can survive hundreds of thousand start/stop cycles.

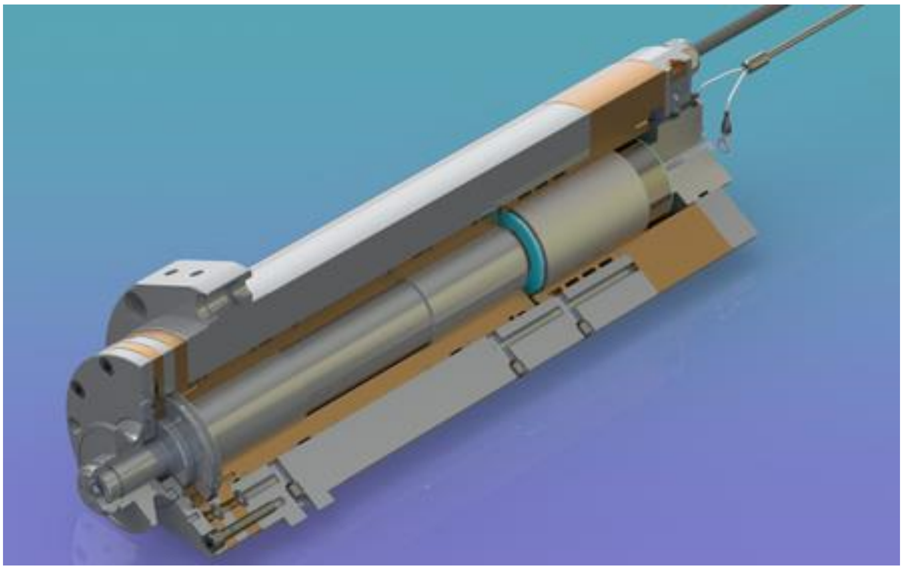


Figure 9. Illustration of hybrid gas bearing arrangement

5.3.5. Active Magnetic Bearings

Active Magnetic Bearings (AMB) use electromagnets to levitate the rotational shaft allowing it to rotate without contact between the rotating and stationary housing components (see figure 10 below). The absence of metal-to-metal bearing contacts means that the machine mechanical efficiency can see significant increases compared to conventional bearing technologies. Vibration - and nearly friction-free performance results enable low noise and quiet operation. AMBs can function without conventional lubrication requirements and independently of the process fluid, therefore AMBs present a solution that can enable completely oil-free operation.

Unlike rolling element or fluid-film bearings however, AMBs require an advanced control system to actively monitor shaft position and continuously adjust the current in the bearing coils to maintain stable shaft position. Associated electrical inefficiencies can be a trade-off against AMB's mechanical efficiencies, particularly where mechanical imbalances exist through design or manufacture.

AMBs were first developed in the 1980s as a specialist and premium oil-free bearing solution. Advances in control capability and electronics manufacturing has reduced the relative cost of the technology, which is now found widely in industry and has multiple suppliers to the market, but its cost remains relatively high, particularly for lower kW applications.

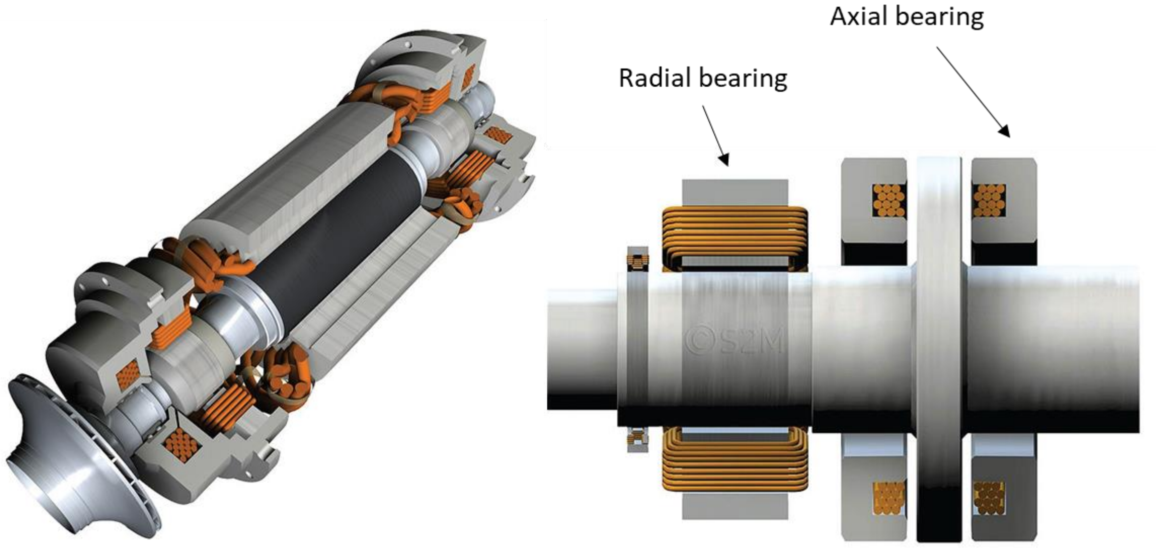


Figure 10. Illustration of an AMB arrangement

5.3.6. Supplier consultation

After the preliminary research phase and consultation with a handful of bearing suppliers, a specification document, based upon the outline two-stage compressor specification in table 3 above, was prepared and send to the comprehensive list of suppliers shown by technology type below:

<u>AMB suppliers contacted</u>

- SpinDrive, Finland
- Mecos AG, Switzerland
- Schaeffler Technologies, Germany
- Waukesha Magnetic Bearings Ltd, UK
- KEBA Industrial Automation, Germany
- S2M, France
- Siemens AG, Germany
- Calnetix Technologies, US
- Synchrony, US
- Celeroton AG, Switzerland
- Maruwa Electronic Inc., Japan
- FG-AMB Foshan Genesis, China
- SKF Magnetic Bearings, Canada

- L.A. Turbine, US
- Nortek Air Solutions, US

Gas/Liquid (fluid film) bearing suppliers contacted

- Venus Systems Ltd, UK
- Ultra Precision Motion Ltd, UK
- Waukesha Bearings Corporation, UK
- Miba Industrial Bearings, Germany
- 3M Hydrodynamic Thrust Bearings, US
- Kingsbury, US
- HYPROSTATIK Schonfeld, Germany
- Pioneer Motor Bearing Co., US
- Bently Bearings, US
- High Temp Bearings, US
- Fluid Film Devices Ltd, UK
- Omega Dot Ltd, UK
- C2 Technology, UK
- New Way Air Bearings, US
- Oil-Free Machinery, US
- OFTTech Ltd, UK
- Zollern, Germany
- IBS Precision Engineering, Netherlands
- OAV Air Bearings, USA
- Mohawk Innovative Technology, US
- Loadpoint Bearings, UK
- Celera Motion, US
- Spieth-Maschinenelemente, Germany
- Celeroton AG, Switzerland

[redacted]

- Boca Bearing Company, US
- SKF, UK
- Carter Bearings, UK
- GRW Bearings, Germany
- Cerobear, UK
- Timken, US

The majority of the suppliers contacted responded. Some were unable to assist due to the particular requirements of the HTHP application, but the majority were able to propose a solution. The information gathered from the proposals, and more than a dozen follow-up consultation video calls, allowed for a detailed comparison to be made between the different bearing types with respect to specific technical or commercial considerations. A summary of the relative benefits of each can be seen in table 3 below:

Technical/commercial consideration	[redacted]	Gas	AMB
NRE development cost	[redacted]	Moderate The costs incurred will be external to the designer, and the development will be completely custom to the application. A third-party consultant should be used to verify the final design. The properties of the refrigerant gas are critical to the bearing design.	Moderate to high The costs incurred will be external to the designer. If pre-existing designs can be used, then the costs can be kept moderate. The control element involved does still generate a higher NRE development cost than the other bearing types. The refrigerant gas does not impact the bearing design. The machine will be able to operate independently of the working fluid choice.
NRE development timescale	[redacted]	Moderate to high Development timescale is dependent on the working relationship with the bearing supplier because the bearings heavily impact the electrical machine design.	Moderate Development timescale is dependent on the working relationship with the bearing supplier. If the AMB supplier is also capable of providing the electrical machine, then the timescale could be significantly reduced.
Prototype cost	[redacted]	Low to moderate	Moderate to high

	[redacted]	The final cost will depend upon the number of bearing iterations required to achieve a working machine. Typically, this could be two to four sets. Each set is moderately priced but would have a far greater impact on the lead time. Cost is marginally higher than PEEK caged ball bearings.	Most of the cost is held within the controller and optional UPS (power supply). The magnetic bearings are expensive in direct comparison to the other types due to the use of more exotic materials and manufacturing techniques, as well as programming control labour.
Prototype lead time	[redacted]	Low to moderate The lead time is not dictated by material availability but rather the sequence of manufacturing steps required. Machining, assembly, coating and grinding steps combined are expected to take three to four months. The lead time of the complete machine is still likely to be determined by the electromagnetic motor components rather than the bearings.	Moderate to high Due to the availability of magnetic materials and electrical components, and the manufacturing processes required the lead time is long at approximately six months. However it is still equivalent to the lead time of the electromagnetic motor components so should not change the overall machine delivery date.
Internal resource demand	[redacted]	Moderate to high We would need to work closely with the gas bearing provider on the design to integrate the bearings into the electric machine. Engineering analysis effort would be shared to verify results. It is yet	Low The AMBs are the dominant constituent part of the electric machine so the responsibility would lie heavily with the supplier to integrate the design. Rotordynamics would be

	[redacted]	to be determined who would take responsibility for the manufacture and the overheads of project management.	performed by the bearing supplier. Internal effort would be required to manage the interface with the compressor and any sealing. Commissioning and testing would be supervised and supported by the bearing provider. Project management overheads are to be carried by the AMB supplier.
Internal expertise requirements	[redacted]	Low to moderate The internal team require the following expertise: • Specification determination • Compressor sizing • Concept design (full) • Detailed design (part) • Engineering analysis (part) • Technical drawing (part) • Manufacturing (full) • Assembly (full) • Commissioning (full) • Testing (full) Team should have the full suite of expertise to deliver the entire project.	Low The internal team require the following expertise: • Specification determination • Compressor sizing • Concept design (part) • Detailed design (part) • Engineering analysis (part) • Technical drawing (part) • Manufacturing (part) • Assembly (part) • Commissioning (part) • Testing (part) Team only really requires the expertise related to the provision of the compressor section.
Efficiency (losses, windage etc.)	[redacted]	High (depending on loads) Windage is likely to dominate the efficiency, and this is heavily	High (depending on loads) Windage is likely to dominate the efficiency, and this is heavily

	[redacted]	dependent on the size of the thrust bearing required to handle the axial load. Gas bearings have minimal losses other than windage. High axial loads will require a large diameter thrust bearing and hence generate undesirable windage which could render the gas bearing with the lowest efficiency. Low friction losses due to being a non-contacting solution	dependent on the size of the thrust bearing required to handle the axial load. It should be smaller than the gas bearing loss as a passive component can negate most of the load. Electrical losses in the controller are likely to be minimal due to the advances in electrical component efficiency. If the machine is subject to external vibration and as a result requires more active control, then the losses through the controller will increase as it has to work harder correcting the shaft position. A well balanced and isolated machine should generate minimal losses comparable to ball bearings. Non-contacting design so there are no friction losses.
Life	[redacted] [redacted]	Moderate/high to infinite Once running due to the non-contacting nature of the gas bearing the life can be infinite. There are no wearing parts to cause failure like in a ball bearing. However, in a hydrodynamic gas bearing the foils experience rubbing contact when starting and	High to infinite Mechanically the life will be determined by component fatigue (most risk is vibrating electrical contacts or inadequate cooling), which should easily exceed the desired life of the HTHP unit. The highest risk to life is electrical component failure. Touchdown

	[redacted]	stopping and through the low-speed region before enough lift has been generated. Life can be as low as 3000 start/stop cycles but also reach 500,000 cycles design dependent. This can be mitigated by using a hybrid design with an external pressure feed for starting and stopping but this introduces pump complexities. Close to infinite life can be best achieved for continuously operating steady state applications.	events from power failure carry the highest risk of bearing failure but the probability is low and mitigated by provision of a UPS allowing s safe shutdown. The machine will be designed to survive at least ten touchdowns and unlikely to even experience one.
Speed limits	[redacted] [redacted]	Approaches burst limit Faster can be better for hydrodynamic bearings. If the speed is too low, then the foils will not be able to generate enough lift to support the shaft. The faster the rotational speed consequently the higher the bearing surface speed which enables more compact bearings to be used. In turn higher speeds lead to a smaller electric machine and hence this all aids a reduction in windage. Speed is limited to the mechanical burst limit of the shaft components. Typically gas bearings shouldn't	Approaches burst limit Magnetic bearings can run happily at any speed. Speed is limited to the mechanical burst limit of the shaft components.

		run slower than 30% of the design speed.	
Temperature limits	[redacted]	Cryogenic to high Gas bearings can withstand very high temperature operation, before impacting the bearing the high temperature will first become problematic for the electromagnetic motor rotor.	Low to high AMB bearings can withstand very high temperature operation, before impacting the bearing the high temperature will first become problematic for the electromagnetic motor rotor.
Pressure limits	[redacted]	TBC R1233zd HTHP applications suggested are ok for these bearings, but the design does need to be checked on a case-by-case basis.	None Magnetic bearings can operate in vacuums to high pressure applications.
Radial load limits	[redacted]	High, no issue for these bearings.	High, no issue for these bearings.
Axial load limits	[redacted]	Moderate Higher the axial load the larger the thrust bearing resulting in increased windage losses.	Moderate to high Can be designed to handle high loads but careful design required to minimise windage efficiency reductions.
Sealing considerations	[redacted]	Possible to affect a combined bearing and labyrinth shaft seal, position control is within the	Possible to affect a combined bearing and labyrinth shaft seal, position control is within the performance tolerances required by

		performance tolerances required by the seal.	the seal, small sizes might require higher control accuracy.
Failure modes (reliability)	[redacted]	Foil fatigue is an intrinsic problem. Liquid ingress into the bearing at high-speed could destroy the bearings.	Touchdown limits but mitigated by UPS enabling safe shutdown. Electrical component and contact failure carries the highest risk.
Control requirements	[redacted]	None Hydrodynamic gas bearings have no control requirements.	High AMB controller is critical to the function of the bearings and requires integration with the machine and further HTHP unit.
Damping	[redacted]	Excellent	Excellent
Noise	[redacted]	Quiet	Quiet
Position control	[redacted]	Fair	Fair to good
Unbalance response	[redacted]	Good	Excellent
Natural frequency control	[redacted]	Good	Excellent
Stability	[redacted]	Good	Good
Lubricant quality	[redacted]	Good	n/a
Tolerance for misalignment	[redacted]	Tolerant	Tolerant
Other concerns (integration)	[redacted]	Whirl instabilities require careful design to avoid. Only workable for the gas and single application.	Material compatibility checks need to be undertaken. A positive is that this machine could be used

	[redacted]	High shaft balance grade of G0.7 or G1 required.	independently of the process gas so has several potential applications. Shaft can run out of balance without issue but G2.5 still minimum preferred.
Commissioning considerations	[redacted]	Two or three prototype iterations are likely to be required to perfect the port sizes and foil profiles. Commissioning and testing could be a lengthy process the get the prototype machine running. Commissioning can't be performed by the supplier as they don't have access to the R1233zd HFO refrigerant.	The AMB electrical machine needs to be commissioned by the supplier but can be fully commissioned without the need to refrigerant. The machine can be provided ready to run from the supplier.
Technology maturity and risk	[redacted]	A mature technology using air but a new custom design for the HFO refrigerant so will carry a higher risk. All the risk is placed in the bearing designer performing the calculations correctly.	Maturing technology and understood, low risk to realising a working machine. Highest risk is access to expertise for supporting units once in the field.
Production (make vs. buy)	[redacted]	Make As the design is custom to the application it is recommended to manufacture the parts alongside the other parts in the machine	TBC (make and buy) The mechanical bearings parts can be manufactured alongside the other machine parts but due to the complexities of the controller this

			will need to be purchased from the AMB supplier.
Production costs	[redacted]	Low cost in volume production, for very high annual runs the cost will tend towards the price of material with minimal processing charges and become comparable to that of ball bearings.	Moderate to high cost in volume production.
IP and commercial issues	[redacted] [redacted]	TBC Design is unique to the application so purchased with exclusive rights.	TBC Design can be provided for the mechanical parts but control IP is likely to reside with the AMB bearing supplier.
Summary	[redacted]	• Low production cost solution • Mature core tech, but limited evidence of use with refrigerant which would require new design to validate • Uncertainty over touch-down resilience related to start/stop operation	• Relatively high production cost solution • Mature tech with turn-key solution providers

Table 3. Bearing technology comparison

5.3.7. Summary of findings

This part of the feasibility study set out to identify alternatives to the oil-lubricated bearing system currently employed on Futraheat's HTHP demonstrator. Through technical and market research, three alternatives were identified which could potentially meet the specific, high-speed, high-temperature requirements of the HTHP application. Following further detailed consultation with a large number of suppliers, a comparison was made and the following high-level conclusions drawn:

- Gas and [redacted] both present a low-cost solution in production.
- AMBs will always remain a relatively high-cost solution due to the materials and control system required.
- AMBs present the lowest technical risk option, with many examples of the technology being applied to turbo-compressor applications and turn-key solutions available from suppliers.

[redacted]

- Gas bearings, although widespread in industry, are not commonplace in refrigeration applications and would require a development programme to verify suitability. Furthermore, they carry technical risk associated with the number of potential 'touch-downs' experienced during operation. This number will be determined by the use cases, which are known to vary, but are not certain.

6. HTHP engineering feasibility

6.1. HTHP skid design and basic operation

Futraheat's 150°c heat pump design will be based off its existing 130°c beachhead model, comprised of the Turboclaw compressor, condenser, expansion valve, evaporator, bypass expansion valve, cooler, and all additional ancillary and data capturing devices. The skid is configured to have a bypass circuit, to prime the compressor and protect it from surging and a heat recovery circuit, to upgrade factory waste heat to usable levels.

Initially, refrigerant will exit the compressor and be directed through a 3-way valve to the bypass or heat pump circuit. Refrigerant will pass through the bypass loop, through an expansion valve to drop pressure, and cooler to drop temperature, reaching compressor inlet conditions to prime the TurboClaw compressor for heat recovery. The bypass loop also acts as a means of surge protection for the compressor, where reduced flow causes a reversal in direction causing damaging oscillations to the compressor. Refrigerant headed for the condenser can be redirected to the compressor inlet at cooler conditions to maintain flow into the compressor.

In the heat recovery circuit, refrigerant will pass from the 3-way valve to the condenser. Here, the refrigerant condenses from a superheated, gaseous state to a liquid. The energy transferred from this process is used to upgrade factory waste heat with significantly lower emissions than a comparable gas boiler. Refrigerant moves to the expansion valve where its pressure and temperature are reduced before reaching the evaporator. Factory waste heat is used to evaporate the refrigerant once again before it reaches the compressor and the cycle restarts.

The two-stage compressor will discharge refrigerant at 153.5°c, 24.25 Bara, with similarly high conditions up to the expansion valve and bypass expansion valve on the heat pump and bypass circuits. The pressure and temperature are reduced on the bypass circuit by the bypass expansion valve to 6.26 Bara and 124.45 °c, with the circuits showing conditions of around 79°c and 6.25 Bara from the expansion valve and bypass cooler. Table 4 shows a full breakdown of operating conditions at each point in the circuit and components required at these points.

Position in Circuit	Compressor Outlet to Bypass Expansion Valve and Condenser		Bypass Expansion valve to Bypass Cooler		Condenser to Expansion Valve		Expansion Valve to Evaporator		Bypass Cooler and Evaporator to Compressor	
Operating Conditions	p/BarA	T/°c	p/BarA	T/°c	p/BarA	T/°c	p/BarA	T/°c	p/BarA	T/°c
	24.25	153.52	6.26	124.45	24.25	142.46	6.26	77.65	6.26	78.65
Components	3-Way Valve Condenser Bypass Expansion Valve		Bypass Cooler		Expansion Valve		Evaporator		3-Way Valve Filter Drier Sight Glass	
Rating Required	p/BarA	T/°c	p/BarA	T/°c	p/BarA	T/°c	p/BarA	T/°c	p/BarA	T/°c
	30	160	8	140	30	160	8	100	8	100

Table 4. Operating Conditions and Required Component

A P&ID has been included to provide clarity on the heat pumps architecture. Many components from Futraheat's 130°c model can be used, although a number will not meet the higher temperatures and pressures needed for the 150°c, two stage design.

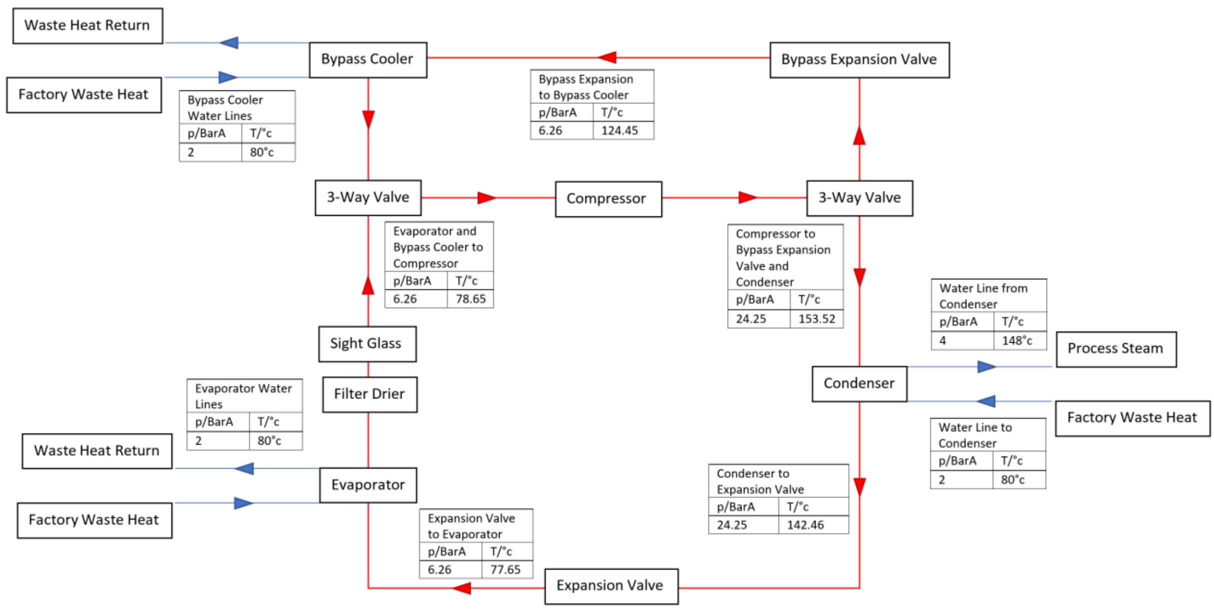


Figure 11. Heat Pump Skid P&ID

6.2. Product selections

Section 6.2 reviews each component group within the heat pump design in consideration of the higher temperature applications identified in section 3 and found achievable through the analysis detailed in section 4. Alternatives have been investigated and proposed where possible where existing component specifications fall short of the requirements of delivering heat up to 150°C.

6.2.1. Heat Exchangers

Three Heat exchangers will be used on the skid, these being the condenser, evaporator, and bypass cooler.

The condenser will be used to provide 4 Bara process steam to the factory by taking >80°c waste heat up to 150°c with the hot, high pressure refrigerant output from the compressor. Refrigerant will be heated when passing through the evaporator. Here, the 80°c waste heat from factory processes will be used to evaporate the liquid refrigerant downstream from the expansion valve ready to enter the compressor.

The bypass cooler is used to drop the temperature of refrigerant from compressor outlet conditions to inlet conditions or below depending on priming or surge control requirements.

Alfa Laval products have been selected for use on the 130°c skid, which all meet the temperature and pressure requirements of the 150°c skid. The CBH210-180AH has been selected for the condenser, with operating conditions of -196-204°c and 33 BarA. Threaded, soldered, and welded connections are available, mitigating risks of conventional sealing materials.

The ACH1000DQ has been selected for the evaporator. It, again, has a temperature range of -196-204°C, but a higher maximum pressure of 45 Bara. As with the CBH210-180AH, multiple seal options are available. CB200-40L is in use for the bypass cooler in the 130°C skid, working in a range of -196-225°C and pressure of up to 33 Bara, with the same connection options available.

Alfa Laval were contacted when selecting the heat exchangers for the 130°C skid, which were oversized for contingency. They will again be contacted to help determine the most efficient products for the higher temperature skid. As most of Alfa Laval designs work to above 200°C and 30 Bara, heat exchangers are not considered a major bottleneck to the feasibility of the project.

Heat Exchanger	Temperature Range	Pressure Range	Seal	Price
Alfa Laval CBH210-180AH	194-204°c	33 BarA	Welded/Screwed	£1,825.00
Alfa Laval ACH1000DQ	194-204°c	45BarA	Welded/Screwed	£4,495.00
Alfa Laval CB200-40L	194-225°c	33 BarA	Welded/Screwed	£3,100.00

Table 5. Heat Exchanger Selections

6.2.2. Valves

The Futraheat high temperature heat pump will operate at greater temperatures than conventional systems. Due to the small pool of commercial high temperature heat pumps, there has been little existing market to push the development of refrigerant valves designed to operate at 150°c. On top of this, R1233zd is a relatively new refrigerant. Many valves don't provide compatibility data for R1233zd, meaning many models cannot be verified for use in the heat pump, further increasing the difficulty in selecting appropriate valves.

The expansion valve is a crucial component in the heat pump cycle, necessary in dropping refrigerant pressure before entry to the evaporator. Looking through the current options available and studies of experimental high temperature heat pumps using R1233zd as their refrigerant, two options have been selected as viable. The Danfoss ETS 12.5 was used in the 2019 study "Overview on HCFO-R1233ZD(E) use for high temperature heat pump application", where condenser temperatures of 135°c were achieved. Inlet fluid temperatures are stated at a maximum of 65°c, with higher available on contacting Danfoss for bespoke products.

Siemens have produced the MVL661 range of expansion valves, used in the "CHESTER high temperature heat pump prototype" study, where temperatures of 135°c were achieved for short periods. Maximum operating conditions have been stated as -40-120°c, although short periods of operation at 140°are permissible. The MVL661 has also been selected for use in Futraheat's 130°c heat pump design.

Three-way valves will also be required to move between the bypass and heat pump circuits. Siemens also provide a 2-port proportional refrigerant valve, the M3FB, with the same operating conditions to the MVL661. Two single port, proportional valves could be installed to control flow between the circuits, although a single valve is the preferred option.

Valve	Maximum Temperature	Maximum Pressure	Seal Materials	Price
ETS 12.5	65°c, Higher on Request	45.5 BarA	Brazed Copper	Unknown as bespoke
MVL661	120°c, 140°c For No More Than Ten Minutes	45 BarA	Welded/Brazed Steel/Brass	£920
M3FB	120°c, 140°c For No More Than Ten Minutes	43 BarA	Welded/Brazed Steel/Brass	£1,650

Table 6. Expansion Valve Options

Contact has been made with Siemens, Danfoss and Parker in the effort to source a high temperature refrigerant valve.

Danfoss responded stating it was not able to provide a solution for a valve at such high temperature, with motor failure likely. Whilst their valve body was rated for higher temperatures, the motor, followed by sealing rings, were stated to be limiting factors at higher temperatures. Ironically, Danfoss later reached out to discuss the potential supply of bespoke valves for our application.

Siemens is unable to supply valves with the appropriate operating conditions. Based on the required operating conditions, the heat pumps Kv, or flow coefficient value, at the valve location is significantly higher than the maximum supplied in Siemens MVL range. A suggestion of using three in parallel was made, although this would add significant cost and complexity.

Parker has recently replied to our enquiry, with the first response from the technical team stating the sealing materials limit the pump to 116^{0}c. Further enquiry has been made to determine if the seals can be changed inhouse and if so, will other components fail at the elevated temperatures.

6.2.3. Filter drier

Filter driers are components used to filter the working fluid by removing any entrained system contaminants and water content, which can react to form acids and damage components within the skid. Initially the filter drier was planned to be installed between the condenser and expansion valve, on the liquid line, although as discussed later the temperature demands of the system has led to the decision to install a suction line filter drier at a point on the circuit with more favourable operating conditions.

Filter driers also pose an issue due to a lack of products able to meet the temperature demands of the higher temperature system. Research has been undertaken to review available products on the market and experimental high temperature heat pump set ups to determine what options exist for the 150°c Futraheat skid.

Two options stand out, although both are only rated to 100°c. Carly supply BYC filter driers which are rated at 100°c, 45 Bara. The BCY has been selected for use in Futraheat's 130°c heat pump skid and CHESTERs prototype, where its operation for short durations at 140°c has been confirmed. Further enquiries have been made to determine its performance for extended periods at 150° and 25 Bara.

Danfoss also provide the DMT filter drier rated to 100°c, 140 Bara. It is designed for use in CO_2 systems, hence the high-pressure rating. Both filter driers have brazed connections, mitigating any risks due to sealing materials. Further consultation with Danfoss is underway to assess its suitability for use in the system.

Filter Drier	Temperature Range	Pressure Range	Filtration	Seal	Price
Carly BDCY 425 S	-40-100°c	<42 BarA	150 Micron	Brazed Copper	Unstated
Danfoss DMT	-40-100°c	<140 BarA	25 Micron	Flare and Solder Options	Unstated

Table 7. Initial Filter Drier Options

Following discussion with Carly, a suction line filter drier has been decided on. The filter drier will still be able to provide the necessary contaminant control and will benefit from operating conditions being 78.65°c, 6.25 BarA. Due to the size of line required a BACY 20033 S has been recommended, with the conditions stated below.

Filter Drier	Temperature Range	Pressure Range	Filtration	Seal	Price
Carly BDACY 20033S	-40-80°c	<33 BarA	50 Micron	Brazed Copper	€915.62

Table 8. Final Filter Drier Selection

6.2.4. Pumps

The pumps found on the 130°c skid are both situated on the water side of the skid to pump waste heat from the factory into the condenser, where it is upgraded to usable steam, or evaporator, to heat the refrigerant. The pumps are controlled by variable speed drives to provide differing flows to achieve ideal heat transfer over the heat exchangers based of fluid conditions monitored using sensors.

It is likely pumps will not be necessary should the skid be moved into a factory, as waste heat lines are often pressurised making the pumps redundant. The pumps selected for the 130°c skid have been included below and as discussed, would be able to meet the operating requirements should they be necessary.

A Grundfos TPE 80-240/4 S-A-F-A-BQQE-LDA and TPE 80-250/2 S-A-F-A-BQQE-MDB have been selected for use as the condenser and evaporator pump respectively. They both operate from -25-120c and up to 16 Bara. Both come with flanged connections, although as water pumps, sealing materials do not cause a bottleneck.

Pump	Temperature Range	Pressure Range	Seal	Price
Grundfos TPE 80-240	-25-120°c	<16 Bara	Flanged	£4,701.45
Grundfos TPE 80-250	-25-120°c	<16 Bara	Flanged	£4,826.90

Table 9. Pump Selections

6.2.5. Sensors

Three types of sensors are found on the heat pump skid. Pressure, temperature, and flow sensors are required for data acquisition and control purposes. A sight glass is also included, as a visual aid to show the refrigerants condition.

Of the sensors used in the 130°c skid, only the flow sensor can meet the new requirements. The sensors will be deployed in tandem with pumps, if used, to vary flow of water supplied from the factory into the condenser and evaporator, thereby varying the water temperature output. The ABB sensor can operate in a temperature range of -55-280°c and pressure of up to 40 Bara. The sensor is flanged, mitigating issues with low temperature rated sealing O-rings, with unreactive PTFE used on seals elsewhere. As pumps may not be necessary due to the factories supplying pressurised waste heat, flow sensors would also be made redundant.

Pressure sensors will be required to monitor the operation of the skid, with large deviations from expected values showing critical issues with operation. The pressure sensors selected for

Futraheat's current project will not be suitable for use on the 150°c skid. Unfortunately, IFM do not produce high temperature pressure sensors capable of operating at 25 BarA. Several options have been found which meet the operating requirements, although sealing material, or lack of information regarding has proven to be an issue. The options have been selected in table 10 below.

Sensor	Temperature Range	Pressure Range	Seal	4-20 mA
Paine 211-37-520-01	–40 to +204 °C	0-344 Bara	Unstated, possibly used with dowty washer	mV
ESI PR3860	0 °C to +205 °C	0 – 60 Bara	FKM, alternative available as 250 possibly PTFE	Yes
Omega PX1009L0-1KAV	-54 to 343°C	0 to 68.9 Bara	Unstated, possibly used with dowty washer	mV
Keller PAA 35XHTC	<300°c	0-60 Bara	Unstated, possibly used with dowty washer	Yes

Table 10. Pressure Sensor Options

Temperature sensors will be deployed to collect operational data, as well as used to vary flow into the bypass cooler in tandem with a proportional valve. Similarly, the sensors currently used in the 130°c heat pump will not meet the temperature requirements of the 150°c system. IFM provide TA2511 sensors with a temperature range of -50-200°c and pressure rating of 160 Bara. Seal materials have not been provided on the IMF data sheet; further enquiries will be made to confirm the TA2511 shows compatibility with r1233zd.

A sight glass will be installed immediately downstream of the filter drier. Sight glasses are clear windows positioned on the refrigerant line to provides a visual indication of the condition of the fluid. The ACI 522 has been selected due to its excellent maximum temperature, 280c, and pressure, 40 Bara, operating conditions.

Sensor	Temperature Range	Pressure Range	Seal	4-20 mA	Price
ABB FSS430	-55-300°c	<40 BarA	Flanged, PTFE	Yes	Unstated

ESI PR3860	0 °C to +205 °C	0 – 60 BarA	FKM	Yes	Unstated
IFM TA2511	-50-200°c	<160 BarA	FKM	Yes	Unstated
ACI 522	<280°c	<40 BarA	BSP, Unstated Material	N/A	Unstated

Table 11. Sensor Selections

6.2.6. Refrigerant pipes

Due to the high temperature and pressure demands, pipework is relatively hard to select. Both stainless steel and copper were required for the 130°c heat pump due to issues finding suppliers able to provide copper pipes with the appropriate pressure ratings and connections. The ideal sizes of pipe have been determined, using target pipe velocities to ensure laminar flow and minimal pipe losses. Due to the short runs, under sizing pipes will not corelate to significant overall pressure losses. This allowed for pipes to be under sized on the 130°c skid, for ease of connection with components on the lines and reducing the need for expanders, with the <9% gradient required to mitigate wall separation greatly increasing the length of lines required. Once components are selected, pipes can be resized accordingly, with pipe loss calculations run to ensure the reduced size doesn't corelate to significant pressure losses. The ideal refrigerant pipe sizes have been included on table 12 below.

Position in Circuit	Compressor Outlet to Bypass Expansion Valve and Condenser	Bypass Expansion valve to Bypass Cooler	Condenser to Expansion Valve	Expansion Valve to Evaporator	Bypass Cooler and Evaporator to Compressor
Ideal Pipe Size	2 1/8"	2 1/8"	3 1/8"	4 1/8"	4 1/8"

Table 12. Pipe Sizing

Following recommendations from Daikin's AG 31-011 document, the bypass line can be undersized by "1 size" due to their short length. This has been taken to mean 3 1/8" for the 4 1/8".

Lawton have been used to supply copper tubes for the 130° skid. Their refrigeration and air conditioning tubes also meet the pressure requirements for the 150°c skid. The tubes also come capped and oxygen free nitrogen charged, ensuring excellent purity for use in the heat pump skid.

Yorkshire copper also provides tubes, with higher pressure ratings and closer diameters needed for ideal flow. They do not produce refrigerant pipes, so are not cleaned and capped. Medical tubes are produced, further enquiries will be made to determine if the necessary pipes can be supplied at the necessary cleanliness.

6.3. Cost study

6.3.1. Compressor cost modelling

Assumptions on the cost for Futraheat's two-stage, 300kW design has been based off the costs associated in producing our current, single-stage model. The design concept validated in section 4 uses one motor to power two compressors on a single shaft. Due to this, the costs needed for the current motor have been increased accordingly and costs for compressor components doubled. Additionally, options to create an oil free compressor considered in this report [redacted], Gas and AMB bearings) - removing the need for the magnetic coupling, additional shaft, and complicated oil system – have also been considered.

As [redacted] bearings would operate with a similar, yet scaled back support system to that of the existing oil-lubricated design, these costs can be approximated accurately. The cost was found to be significantly lower than the existing oil lubrication system, as the oil separator and subsequent refrigerant reintegration circuit is not needed.

Through work outlined in section 5.3 of this report, the cost and expected discounts at volume have been found for gas bearings and AMBs. These two systems are initially much more expensive than the [redacted] due to the non-recuring cost in designing the bespoke bearings. Although compressor costs are lower by around £1,200 due to these systems not using the existing bearings, the associated design costs cause air bearings to not become competitive until production scales of >20.

Magnetic bearings' consistently high costs cause them never to be the most cost-effective option. The bearing cost graduation has been displayed below, with the effect on final heat pump skids costs included later.

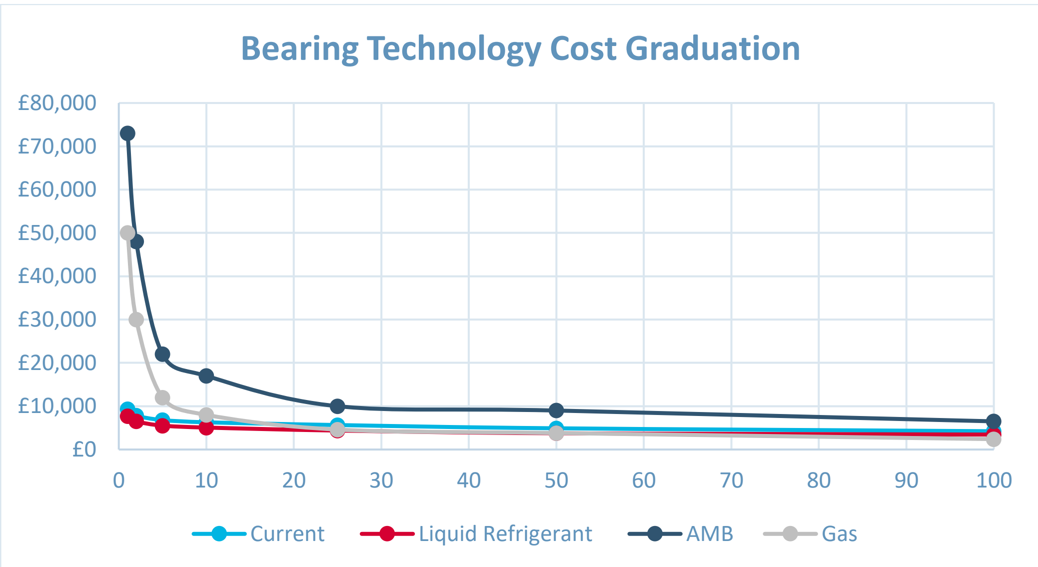


Figure 12. Bearing Technology Costs

Effort has been made to consider future design for manufacture, with the volute and diffusers being combined, improving ease of assembly and costs with less components needed to produce each compressor.

A model has been created to show the cost reductions linked to greater production volume. Based on close contact with suppliers over the production of the current test rig, historic data, and supplier and consultation specifically as part of this feasibility study, costs at 1-off to 100-off prices have been determined as a percentage of the unit cost.

Area	1-Off	2-Off BASE	3-Off	4-Off	5-Off	10-Off	25-Off	50-Off	100-Off
CNC	150 %	100%	80%	70%	60%	50%	30%	20%	15%
Motor Kit	100 %	100%	85%	85%	85%	75%	70%	65%	60%
Castings	160 %	100%	95%	85%	80%	75%	70%	60%	50%
Supplied Parts	100 %	100%	100%	100%	100%	95%	90%	80%	75%
Inverters	100 %	100%	100%	100%	100%	95%	90%	80%	75%

Table 13. Cost of Production at Volume Price Graduation

The model has been applied to form the following cost projection for the two-stage Futraheat compressor design.

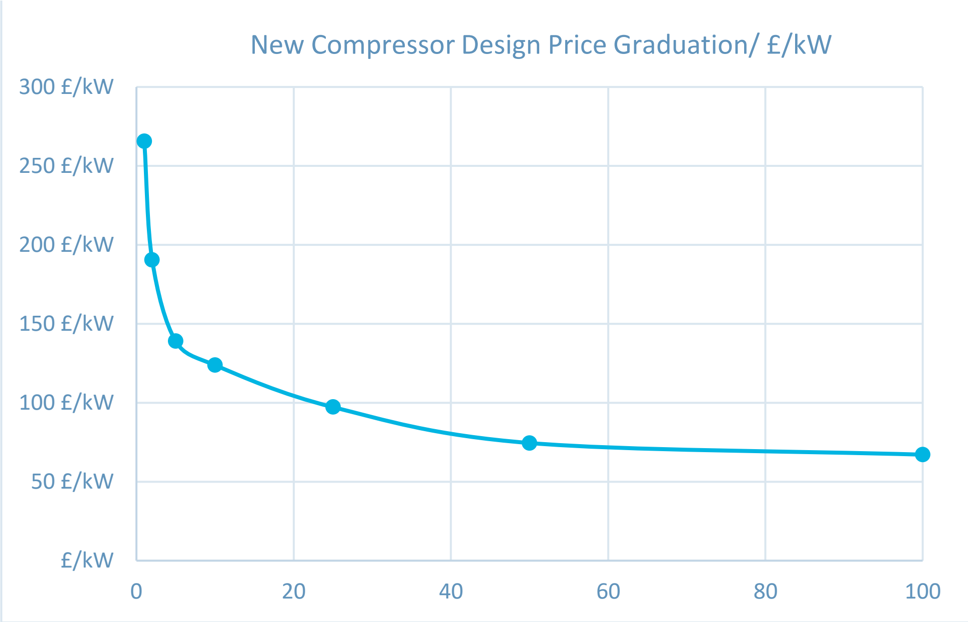


Figure 13. Compressor Production Cost Volume Graduation

1-off costs are very high, as a 1-off piece requires similar CNC programming or cast making costs as needed for all compressors in a 100-off batch, giving a much lower cost per unit at higher volumes. Many fasteners, sensors, seals, and additional supplied parts also benefit from economies of scale. Due to this the cost falls from 265 £/kW to 65 £/kW. A competitive price of 80 £/kW is reached at the production of 35 compressors.

6.3.2. HTHP cost modelling (baseline)

The costing of the wider heat pump system has been found from the price of constituent components, detailed earlier in the report, as well as assumptions on the assembly and commissioning cost. The cost of compressor has been modelled with the method outlined above, with the effects on price from bearing selection included. The costs of components confirmed by manufacturers have been used. This will provide an overestimate in the case of the heat exchangers, which were chosen with higher than necessary specifications for the contingency of planned higher powered compressor tests. The refrigerant valves and sight glass are still to be determined, therefore place holder values from similar products have been used. The cost of sensors and controls has been assumed to be £40,000. This is 30% less than the current cost on Futraheat's test rig. This is as the test rig is being used to harvest far more data than would be required in commercial operation, meaning the cost of control will undoubtedly fall. The cost of ancillaries, including pipe work, valves and supporting structure, has been set at £15,000, a similar value to the current build. As both machines are of similar sizes and capacities, a figure in the same ballpark has been assumed to be accurate. The cost of assembly and commission has initially been set at £25,000 per heat pump. This shows a 25% reduction in costs to produce the current test rig. As production volumes increase, a larger workforce and more streamlined practises will reduce costs significantly. By 100-off production the price is assumed to be £5000. Consultation with Productiv, a 'productionisation' consultancy, has supported this price graduation for an efficiently planned production process.

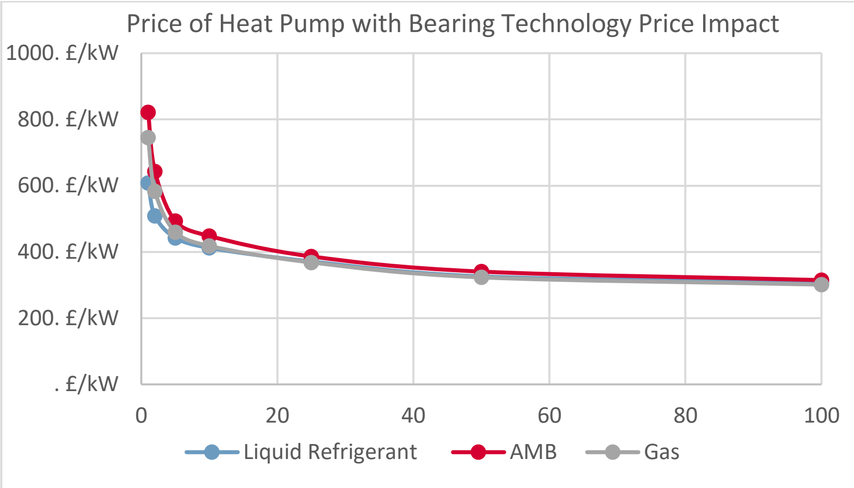


Figure 14. Price of Heat Pump at Varying Production Volumes

The cost again falls quickly from 1 to 2-off production, as of the steep decrease in manufactured parts. Prices for all options eventually fall to between 230-250 £/kW. Due to the higher low-volume costs of gas and magnetic bearings, they are not competitive until higher production runs. As gas bearings show similar, and then better, costs to [redacted], they reach similar prices by 10-off production and best option by 20-off production. Magnetic bearings are significantly more expensive than the other options at 210 £/kW more than the cheapest bearing option at 1-off to 10 £/kW more at 100-off productions.

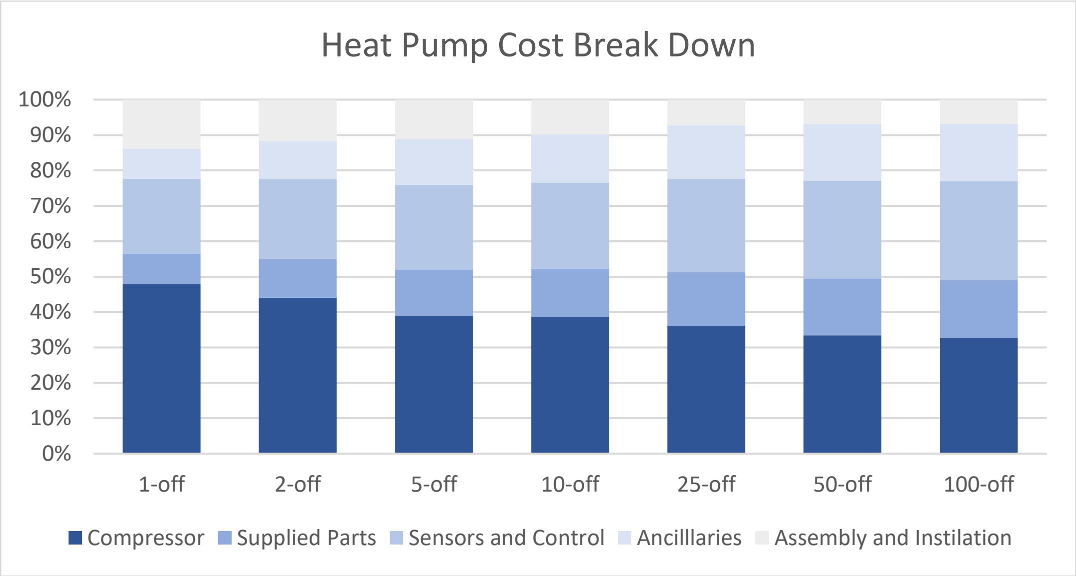


Figure 15. Cost Breakdown at Varying Production Volumes, [redacted]

As seen from the breakdown in figure 15, compressor costs dominate costs at low production volumes, making up 50% of the total outlay. This falls, with the compressors cost dropping faster than the other heat pump components at higher volumes. Compressor costs make up 30% of the final costs by 100-off production. Assembly costs are the only other cost to show a reduction in the weighting of final costs. They also show a steep decrease in price as production volumes are increased, dropping from 14% to 7% of final heat pump costs.

Sensors and control costs make up only 20% of the total heat pump cost at 1-off production but raise to be on par with the compressor as the highest items at 30% by 100-off production. As they make up a large outlay and don't not benefit as greatly from economies of scale, they become a more significant expense per heat pump as production volume is increased.

Whilst the supplied parts and ancillaries make up larger proportions of cost at each step up in production, they are consistently lower than compressor and control costs, rising from around 8% at 1-off production to 16% by 100-off.

6.3.3. HTHP cost modelling (1MW Greensteam production model)

Futraheat aims to produce a 1MW$_{th}$ heat pump by 2024 due to the large market of industrial users, including pharmaceutical, food and beverage, and paper industries, requiring heat in the 1 MW$_{th}$ region and the economies of scale the larger capacity brings, which will help early product adoption.

Cost estimations have been made for volume production runs. As three compressors will be needed, as illustrated by the analysis in section 4, the costs for the compressor and bearings have been tripled, giving an estimate of £70,000 per heat pump.

Costs of supplied parts have increased, although only slightly due to the oversizing of current components. The final estimate for the cost of supplied parts for a 1 MW_{th} heat pump is £15,750.

Due to the additional compressors, the cost allotted to sensors and control has been increased from £20,000 to £28,000. As considerable control is necessary on the compressor to maintain proper operation, leading to the 40% increase in budget. The existing control on the rest of the heat pump is assumed to remain a similar price due to the lack of change to the architecture to the system.

The ancillaries necessary, including the valves, pipework and heat pump frame, have been estimated to be a similar cost to the existing skid. A small increase due to the additional materials to connect and support the extra compressors has been factored into the cost model, with ancillaries costing £14,000 for each heat pump.

The cost of assembly has been set at £6,000 per heat pump. This assumes 25-man days for the assembly of the heat pump, with an additional 7.5 to assemble the compressors.

The Breakdown of costs, with the comparison to the planned 300 kW heat pump has been displayed below.

Heat Pump Cost Breakdown	300 kW	1 MW
Compressor	£23,583.08	£70,000.00
Supplied Parts	£11,745.00	£15,750.00
Sensors and Control	£20,088.93	£28,000.00
Ancillaries	£11,721.75	£14,000.00
Assembly and Installation	£4,869.10	£6,000.00
Total	£72,007.87	£133,750.00

Table 14. 1MW Heat Pump Cost Breakdown

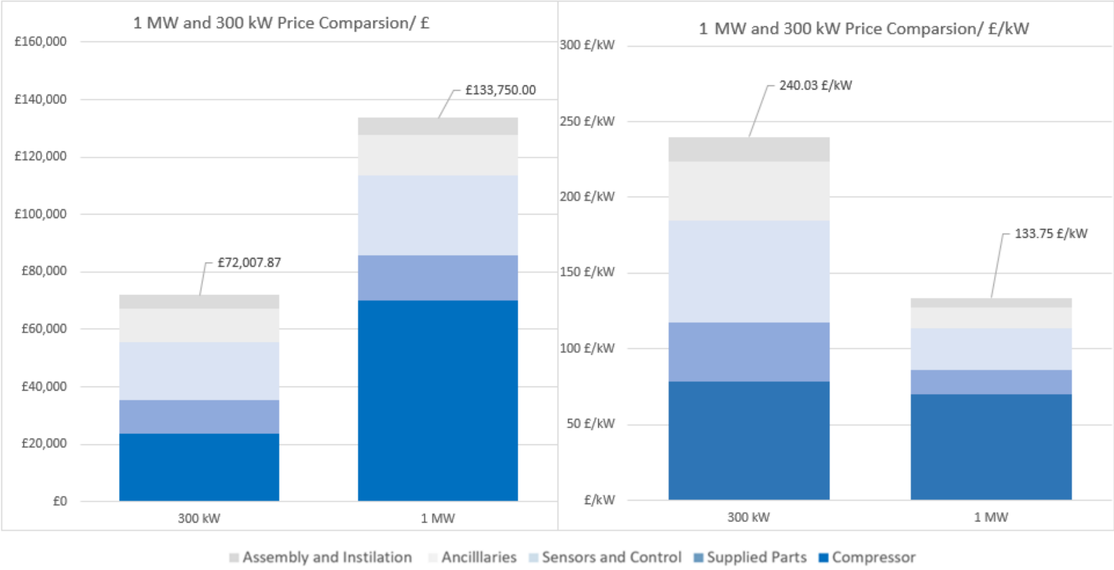


Figure 16. 300kW and 1MW Heat Pump Absolute Price Comparisons

The absolute cost and cost per kilowatt have been displayed in the graphs above. Although the 1MW heat pump costs close to double that of the 300kW heat pump, its larger capacity allows for a lower price per kilowatt of heat provided. A production cost of 135 £/kW provides an ideal final installed price point of around 400 £/kW, considering a 50% profit margin and a factor of 1.5 to install into a factory. Therefore, Futraheat's 1MW Greensteam product is expected to be able to abate 1000 tonnes of carbon per year at a price supporting the three-year pay back needed for industry to readily invest.

7. Concept design

The extensive research, analysis and evaluation carried out and reported above in sections 3 to 6 led to the concept design for an IFS phase 2 demonstrator and subsequent first commercial HTHP product. The product concept, its specification and architecture/technology choices are given below.

7.1. Product

The proposed product concept is for a steam generating HTHP, branded *Greensteam*. Greensteam HTHPs will be designed for retrofit integration into factories' existing process steam systems, to off-set or replace fossil-fuel generated heat. Greensteam will provide up to 3barg steam from source temperatures down to 60°C, and present a zero-carbon heating solution when powered by electricity from renewable sources.

Greensteam will be made available in a power range from ~300kWt to 1300kWt and measure up to 2mx2mx2m in size. The target installed price to the customer is £400/kWt, providing both the opportunity for customer return on investment and sales margin.

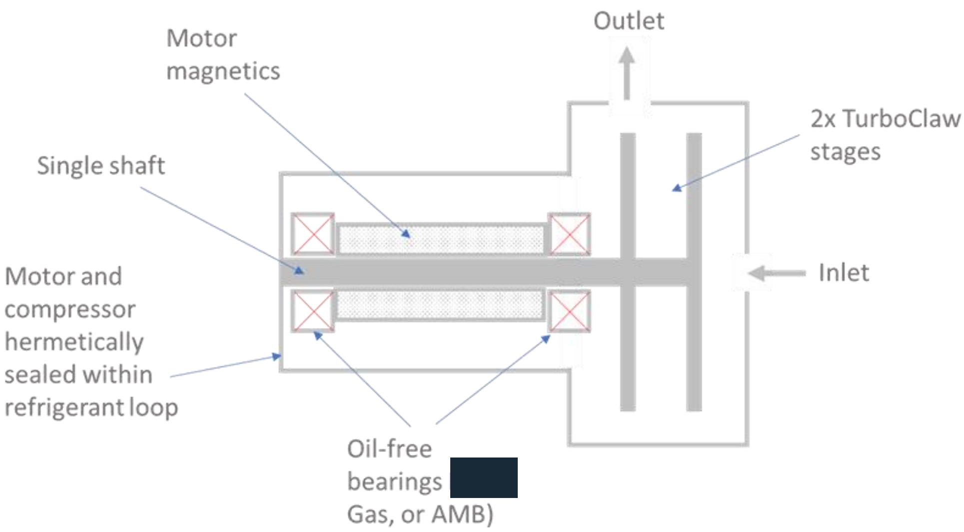
Figure 17. An illustration of Futraheat's Greensteam HTHP product

7.2. Architecture and bearing technology choice

The TurboClaw performance analysis and Engineering feasibility analysis conducted in sections 4 and 5 respectively led to the compressor architecture and bearing technology choice shown in the figure 18 below.

Three potential oil-free bearing options were identified, which allowed for a single shaft, two-stage architecture to be adopted for the product concept.

[redacted] bearings were down-selected as the preferred oil-free bearing solution because of their low-production cost, relatively low technical risk, and for the fact they can be evaluated in the short term. Should they not perform sufficiently then AMBs would provide a low risk, if more expensive alternative.



[redacted]

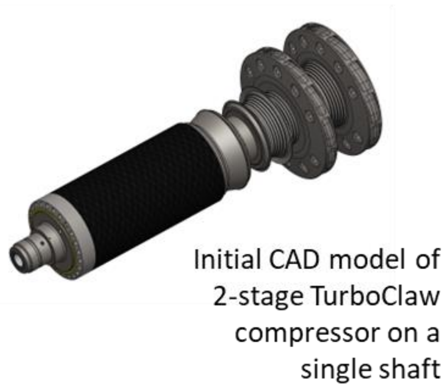


Figure 18. Concept design architecture

7.3. Compressor specification

The following specification is for a single 300kWt TurboClaw HTHP compressor, as many as four or which may be used within the concept Greensteam product.

No.	Requirement	Value	Units	Comments
2.1	Gas	R1233zd	n/a	
2.2	Evaporator saturation temp (nominal)	78	°C	
2.3	Condenser saturation temp (nominal)	143.6	°C	
2.4	Number of stages	2	n/a	On same shaft
2.5	Suction pressure	6.26	bara	
2.6	Interstage pressure	12.52	bara	
2.7	Discharge pressure	24.46	bara	
2.8	Mass flow rate	2.86	kg/s	
2.9	Design capacity	314	kWt	Max at 63.6°C ΔT
2.10	Shaft power	129	kW	72.5 Nm
2.11	Speed	17,000	rpm	Nominal
2.12	Stage #1 impeller diameter	169	mm	Mass = 1.01 kg
2.13	Stage #2 impeller diameter	129	mm	Mass = 0.5 kg
2.14	Estimated motor shaft mass	c. 14.5	kg	TBC by design
2.15	Magnetic rotor sleeve inner diameter	82	mm	
2.16	Gas temp in motor bearing housing	78	°C	At suction
2.17	Gas pressure in motor bearing housing	6.26	bara	At suction
2.18	Impeller end load	582	N	
2.19	Balancing grade	G2.5	n/a	
2.20	Radial load due to imbalance	71.2	N	45.6 N for G1.6

Table 15. Greensteam HTHP compressor specification

8. Techno-economic analysis

8.1. Assumptions

For a techno-economic model to be built, several assumptions must be made to provide representative annual cash flows for each technology.

8.1.1. Currency

Assumptions have been used to scale data in different currencies and from older reports, to remove any disparities due to exchange rates or inflation.

- 2% annual inflation has been assumed
- Euro and dollar exchange rate have been set at 0.0839842 and 0.742666 respectively, from December 2021

8.1.2. Discounting

An appropriate discount rate was selected.

- A 7% discount rate is used
- Whilst this is low compared to a standard value for an investment, it reflects a cost of carbon considered alongside profits and is more common amongst environmental projects

8.1.3. Heat Demand

Heat demand and annual operational hours were based off typical factory values.

- A $1MW_{th}$ heat demand and 5000 annual operating hours have been selected as plant requirements

8.1.4. Technical Assumptions

The following assumptions cover the data found from government appraisals and academic papers concerning competitor technologies.

Capital and Operational Costs

- The data found considers MW_{th} rather than MW_e, meaning values are based on heat delivered rather than the size of machine needed
- Data tended to show costs per kilowatt. Any data referring to machines with much higher or lower capacities were not considered as the cost per kilowatt would likely be skewed

Energy Prices and Emissions Factors

- Fuel prices are based on values seen in the European market.

- Costs for electricity and gas were found on Eurostat, the European Union's statistical office, with the most recent data collection referring to prices in the second half of 2021
- BEIS Green Book Long Run Variables have been used to forecast electricity and natural gas prices. These have been scaled to show the same 2022 price as found from the Eurostat data
- The BEIS Green Book also provides emission factors for gas and electricity. Gas has a constant emission factor associated with it, whereas electricity's factor reduces as a large percentage of renewables is projected to make up the energy mix
- Effort was made to consider the recent spike in energy inflation due to the current economic climate, with an additional current case. Inflations of 130%, 170% and 115% were applied to electricity and PEM, SMR and Biomass respectively. This was reduced linearly to the regular forecast in line with the world banks energy inflation forecast
- The biomass under consideration is wood chips and wood pellets
- Emissions factors for biomass are also found from BEIS Green Book
- Steam Methane Reforming with carbon Capture and Storage (SMR+CCS) and Polymer Electrolyte Membrane Electrolysis (PEM) considered as two sources of hydrogen. Multiple sources were used to produce forecasts for their price developments. High and low projections were set at above and below the original forecasted values
- SMR+CCS emission factors were found from three sources. The low emission factor came from the Industrial Fuel Switching Study, Mid as 10% of the SMR process, therefore assuming 90% CCS efficiency and high from the Global CCS Institute
- Emission factor for PEM has been set at 130% of electricity's as of the efficiency at producing hydrogen of the process
- Projected cost data tended to come at intervals each decade, this has been interpolated to find values for each year from 2022-2042 where relevant

Carbon Price

- Internal carbon pricing has been set at 25 £/t$CO2_e$, in line with the current (Q2 2022) EU average
- EU carbon taxes vary and many target specific forms of emission rather than putting a price on carbon equivalency, therefore taxes have been omitted from the analysis

8.2. Cost Cases

Three costs cases have been considered to establish a representative range of possible cash flows throughout the commissioning and operation of each technology. A pessimistic case, denoted by P in graphs, pairs high low carbon energy prices with low gas prices, giving the least favourable energy price ratio. The model case, M, uses expected projects for all energy prices, showing the most probable cashflows. An optimistic case, O, pairs the lowest low carbon energy prices with the highest gas prices, modelling a best-case scenario regarding fuel savings. The ratios between electricity and gas have been displayed below, in table 16. As the price of each develops between 2022 to 2042, the range has been provided. An additional case has been added to reflect the current spike in energy prices, and the effect this will have on the economics of each technology, with the current prices indicated with C on the following graphs.

p/kWh	Optimistic 2022-2042	Model 2022-2042	Pessimistic 2022-2042
Elec	8.80-9.20	12.32-12.88	17.41-18.20
Gas	7.83-10.00	4.82-6.16	3.44-4.39
Ratio	0.92-1.12	2.09-2.55	4.15-5.07

Table 16. Fuel Price Ratios

A literature review was undertaken to determine data points, with outliers discarded and from this low, mid, and high-cost assumptions have been determined. Low per kilowatt cost values for operation, fuel requirements, carbon taxation and initial costs have been used to find the optimistic NPV values. The same approach was used when finding the model and pessimistic cases, using median and high values respectively. The current values reflecting the recent fuel price increase have been calculated using median values for all other variables, giving the most representative outlook on the fuel's volatility. Whilst a range of three cost cases for natural gas boiler were determined through research, only the mid case has been considered for all metrics other than fuel price. As LCOH and LCOC metrics use the difference between each technology and natural gas, using differing costs cases for the natural gas boilers begins to consider their economic efficiencies. This is unhelpful in determining the economic benefits of the green technologies as it introduces unnecessary variables regarding natural gas into consideration. Similarly, to choosing only the natural gas mid case in calculating NPV, the same value for annual heat supplied has been selected when calculating the LCOH. As covered in the assumptions, a 1MW machine operating for 5000 hours a year has been considered. Having variations in heat supplied causes large variations between the three cases. Again, this brings additional factors into play, diluting the information available from purely cost parameters. Varying the annual heat whilst considering one cost case would better illuminate the effect of differing annual heat supply.

For electricity, biomass and natural gas, the government provides a list of emission factors. These are values showing the equivalent of a kilowatt hour of each fuel's emission in kilograms of carbon dioxide. These have been used to find the emissions reductions associated with each technology. This value has been used with the three costs cases to find the range of LCOC values. An issue arose in finding emission factors for hydrogen. No single value is given in government reports, although a range of values have been determined through research discussed in the assumptions. Due to this, the low-cost case was paired with the low emissions case to give a best case LCOC, with the same being done for mid and high scenarios.

8.3. Net Present Value

8.3.1. Methodology

$$NPV = \sum_{t=0}^{T} \left(\frac{OM_t + Fuel_t + CO_{2_t}}{(1+r)^t} \right) - C_0$$

All metrics first rely on determining the net present value of each option across its lifetime. This is a method used to consider the time value of money over the asset's operation. Money had at present is more valuable than the same sum of money at a future date, as money can be invested, providing further value rather than being eroded by inflation.

The use of a discount rate, r, allows for the total lifetime cashflows to be translated into a sum of current worth, showing a projects financial feasibility. This is selected in relation to the expected return on investment and reflects what investors expected returns on an investment made today at the same expense as the project's costs.

The annual cash flows considered in the model comprise of the operation and maintenance costs, O&M, fuel costs, F, and Carbon taxation, CO_2. Literature has been studied to provide values per kilowatt for all technologies. This model has been built under the assumption that a switch from natural gas will be necessary for plants using low temperature steam. Due to this, all values show the difference in costs between each technology and that of a natural gas boiler. The savings in relation to this counterfactual case show the difference in cashflow the company installing the green technology will expect. Initial costs, CAPEX, are also considered. This is subtracted from the net present value, as the capital cost associated with project commencing immediately will not need to be discounted.

Effort has been made to provide representative values for all technologies. The main sources of information used in building the cash flow model come predominantly from government reports across Europe. Studies from the UK, Netherlands and Denmark form the bulk of data, with supplementary findings from scholarly articles included to provide further information.

8.3.2. Graphical Data

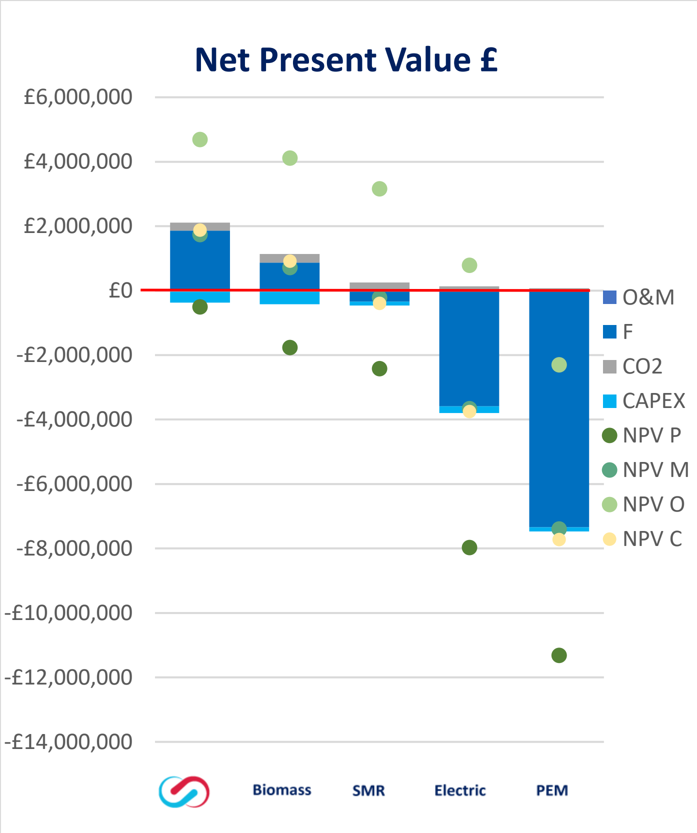


Figure 19. Lifetime Net Present Value with Cost Breakdown

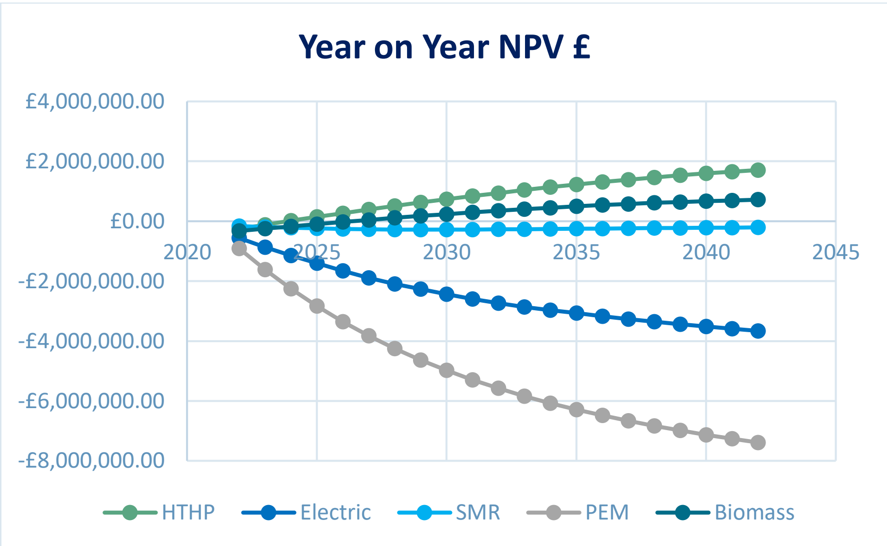


Figure 20. Year on Year NVP, Model Case

8.3.3. Conclusions

As seen from the graph, fuel costs make up the vast majority of expenditures over the project's lifetime. Initial and carbon costs also make significant contributions to the projects cashflows. As only the difference between gas boilers and their low carbon counter parts are considered, operation and maintenance costs make up a small proportion of expected lifetime savings, with relatively comparable values seen between all technologies.

A small difference is seen between the model values, based off late 2021 prices, and current values. As the current price inflation is projected to last until 2025, diminishing year on year, little difference in lifetime fuel costs is seen. The difference between the model and current case net present fuel values by the end of the project and percentage of that to current case net present fuel values summarised in table 17 below. As percentage changes of 2-35% are seen, relating only to fuel and no other cost variables, the effect of current fuel prices is not projected to make any changes to the trends supported by long term fuel price forecasts.

	HTHP	Electric	SMR	PEM	Biomass
Price Difference	£175,255.37	-£88,297.56	-£179,337.22	-£331,776.05	£198,369.08
Percentage of Lifetime Fuel Expenditure	9%	2%	35%	4%	19%

Table 17. Difference in Fuel Price Cash Flow Between Model and Current Cost Cases

When considering the model and current case, only heat pumps and biomass boilers are profitable. Due to heat pumps high efficiency and biomasses low cost, both can save money compared to continued use of a gas boiler. Considering the model case, pay back is achieved by year 3 for heat pumps and in year 6 by biomass boilers. SMR produced hydrogen boilers offer close costs to that of gas boilers, although will require a higher lifetime expenditure. As of this, payback is never achieved. Both electric and PEM options incur large costs on the investor. As electricity is forecasted to be more expensive than gas for the project's lifetime, savings due to carbon costs never outweigh fuel expenditure. As electric boilers show 95% efficiency, they provide steam at a lower cost than PEM equivalents. As electricity is used in the hydrogen production process, far more electricity, and hence fuel expenditure, is needed to produce hydrogen through PEM electrolysis. Again, both electric and PEM boilers do not produce paybacks.

The optimistic case provides a much brighter outlook, with all but PEM boilers becoming profitable. Due to the much-improved low carbon fuel to gas price ratio, heat pumps, biomass and SMR boilers are able to provide payback in year one. Electric boilers begin payback in year 5. Again, due to its inefficiency at converting electricity into useable power, PEM electrolysis does not become profitable.

The pessimistic case paints a much worse picture. No technologies are able to compete with the low cost of natural gas, meaning payback is not achieved by any of the five options.

8.4. Levelised Cost of Heat

8.4.1. Methodology

$$LCOH = \frac{\sum_{t=0}^{T}\left(\frac{OM_t + Fuel_t + CO_{2_t}}{(1+r)^t}\right) - C_0}{\sum_{t=0}^{T}\left(\frac{MWh_{tht}}{(1+r)^t}\right)}$$

Levelised cost of heat is a metric assessing the average cost of purchasing and operating an asset per unit of heat production over the asset's lifetime. It comprises of the net present value divided by the discounted sum of heat production, giving a value in £/MWh for each technology. Greater values show more money is spent per megawatt of heat produced. Negative values reflect savings compared to a natural gas boiler per megawatt of heat production.
The heat requirement has been assumed to be 5000 MWh annually. This is based off assumptions of a 1MW_{th} steam requirement and 5000 hours of operation annually.

8.4.2. Graphical Data

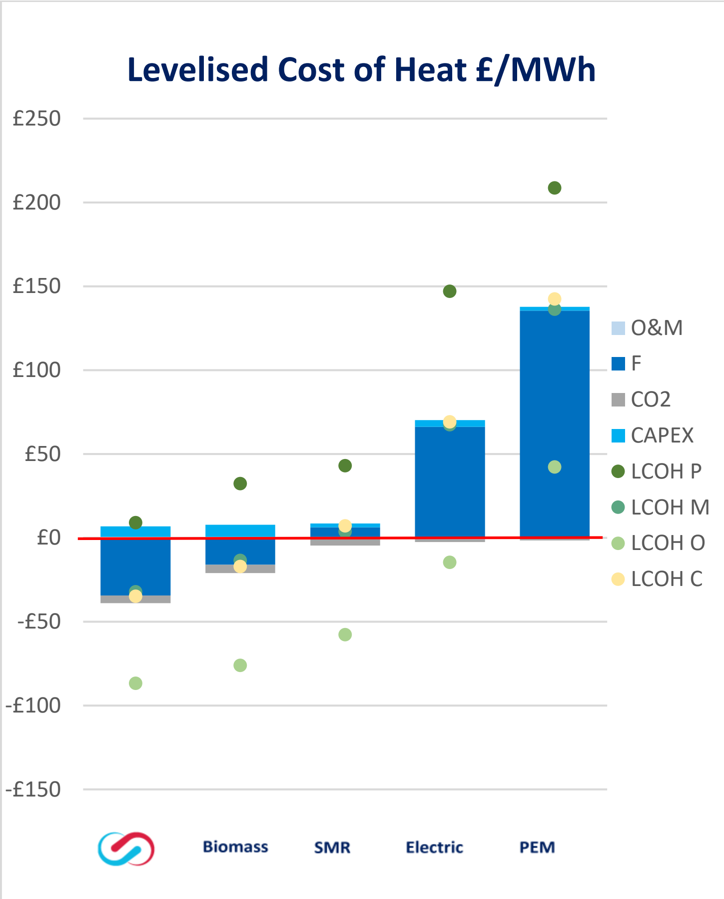


Figure 21. Final Levelised Cost of Heat with Price Breakdown

8.4.3. Conclusions

All low carbon options will produce the same amount of process heat over the course of their lifetime. As of this, the net present heat value will be the same for all projects. As this is the denominator of the LCOH equation, the final values exactly corelate to the net present value. As expected from their greater NPV, heat pumps and biomass options provide the greatest savings per megawatt hour when compared to natural gas. Heat pumps can, in the model case, save £32 per MWh of heat provided with Biomass boilers saving £13. SMR comes close to providing heat at a profit, costing only £4 per MWh, with electric and PEM options costing progressively more at £68 and £136.

The improved operating costs in the optimistic case allow for all but the PEM hydrogen option to provide heat at a profit when switching from a natural gas boiler. Savings per MWh range from £87 for the heat pump to £15 for the electric boiler. PEM boilers cost £42 per MWh in the best-case scenario.

No option provides cheaper heat than gas boilers in the pessimistic case. Unfavourable fuel prices, initial, operating and carbon costs cause all options to cost more than the gas boilers they are set to replace. Heat pumps come the closest to competing, costing £9 per MWh of heat provided. Higher costs are incurred for each option, with PEM costing the greatest at £208 per MWh.

8.5. Levelised Cost of Carbon

8.5.1. Methodology

$$LCOC = \frac{\sum_{t=0}^{T}(\frac{OM_t + Fuel_t + CO_{2_t}}{(1+r)^t}) - C_0}{\sum_{t=0}^{T}(\Delta GHG_t)}$$

The levelized cost of carbon shows the costs to purchase and operate an emerging green technology per ton of carbon abated over the project's lifetime. Similarly, to the levelized cost of heat, net present value is divided by the sum of discounted carbon abatement, showing a value in £/tCO_2e of how much money is needed to abate each ton of pollution equivalent to carbon dioxide. A lower value shows less money is necessary to abate each ton of carbon, with negative values showing money is made along with carbon abatement. This is due to a technologies savings in fuel price pairing with lower emissions than its counterfactual case, providing both financial and environmental benefits.

Carbon abatement can be determined using emission factors for each fuel source. These are values showing the equivalent weight of carbon emitted from each kilowatt hour of energy used. This can be used to determine the yearly emissions from a natural gas boiler and its replacements, the difference between the two showing the carbon abated. Variations in electricity's emission factor are seen due to the transition to a 0-carbon grid, with the value lowering over the time period. Static values for biomass, hydrogen and natural gas are assumed.

8.5.2. Graphical Data

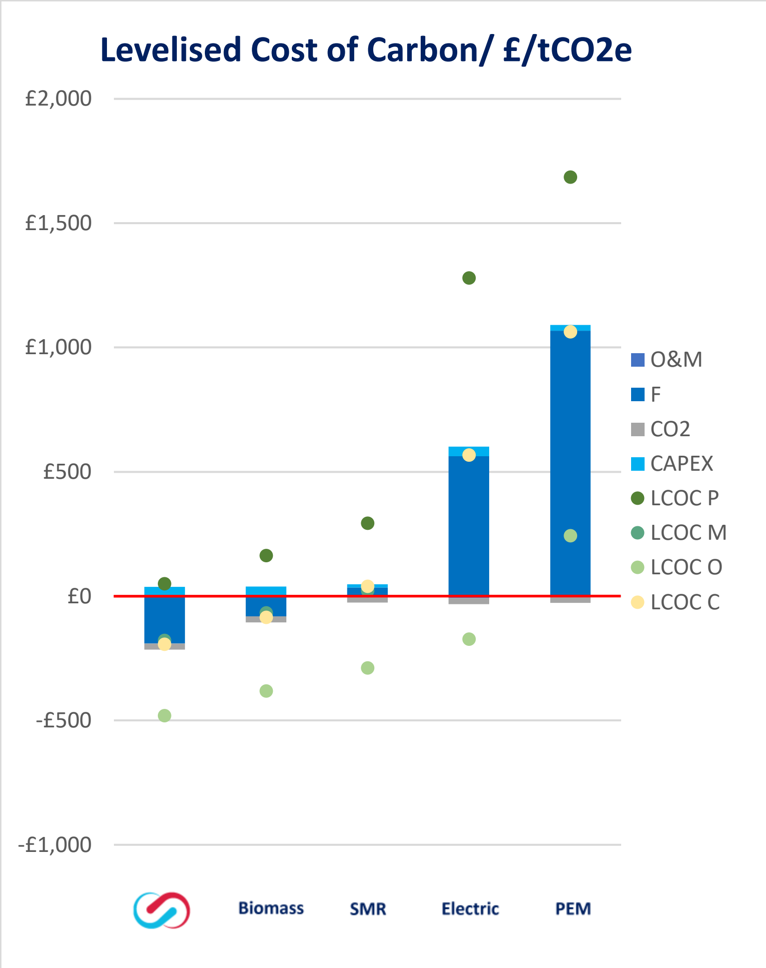


Figure 22. Final Levelised Cost of Carbon with Price Breakdown

8.5.3. Conclusions

Due to varying carbon abatement between each technology and abatement varying between cases, results will not be scaled directly from NPV. Although, as net present carbon values are all fairly close, the same trends are seen as in NVP and LCOH results.

As neither PEM nor electric boilers provide carbon abatement from 2022 due to the pollution associated with grid electricity, they were not applicable for use in the levelized cost of heat model until 2025. As LCOC allows for cash flows to be discounted to their value in today's money, their cash flows have been started from later dates and run until 2042.

Heat pump and biomass options can provide carbon abatement, whilst operating at a lower cost than natural gas boilers. Savings of £178 per ton of carbon dioxide are seen for heat pumps, with £67 for biomass boilers. Due to electric and hydrogen options costing more than natural gas boilers, their carbon abatement comes at a cost to investors. Abatement from SMR boilers cost £22 per ton of carbon dioxide. Electric and PEM options abatement cost are £568 and £1064 respectively.

Similarly, four of the five technologies provide carbon abetment at lower operating costs than a gas boiler in the optimistic case, ranging between heat pumps at £480 per ton to electric boilers at £173. PEM boilers are not able to outperform gas boilers, leading to carbon abatement at £243 per ton.

The pessimistic case leads to all options costing more than gas boilers to purchase and operate. Due to this, carbon abatement comes at a cost to the investor. Heat pumps provide the best economic performance, leading to a levelised cost of £51 per ton of carbon. The remaining options cost progressively more, reaching a maximum with PEM boilers showing carbon abatement at £1685 per ton.

8.6. Marginal Cost of Carbon Abated

8.6.1. Methodology

The marginal cost of carbon abated shows the cost of each ton of carbon abated against the total lifetime carbon abatement for each technology. The vertical axis displays the levelized cost of carbon at the end of the project's lifetime, with negative values correlating to carbon abatement at a profit when compared to the cost of running natural gas boiler. Positive bars show the money must be spent to abate each ton. The width of each bar shows the lifetime carbon abated, with wider bars denoting a greater lifetime carbon abatement. This value has been determined using emissions factors to find the lifetime emissions from each technology.

8.6.2. Graphical Data

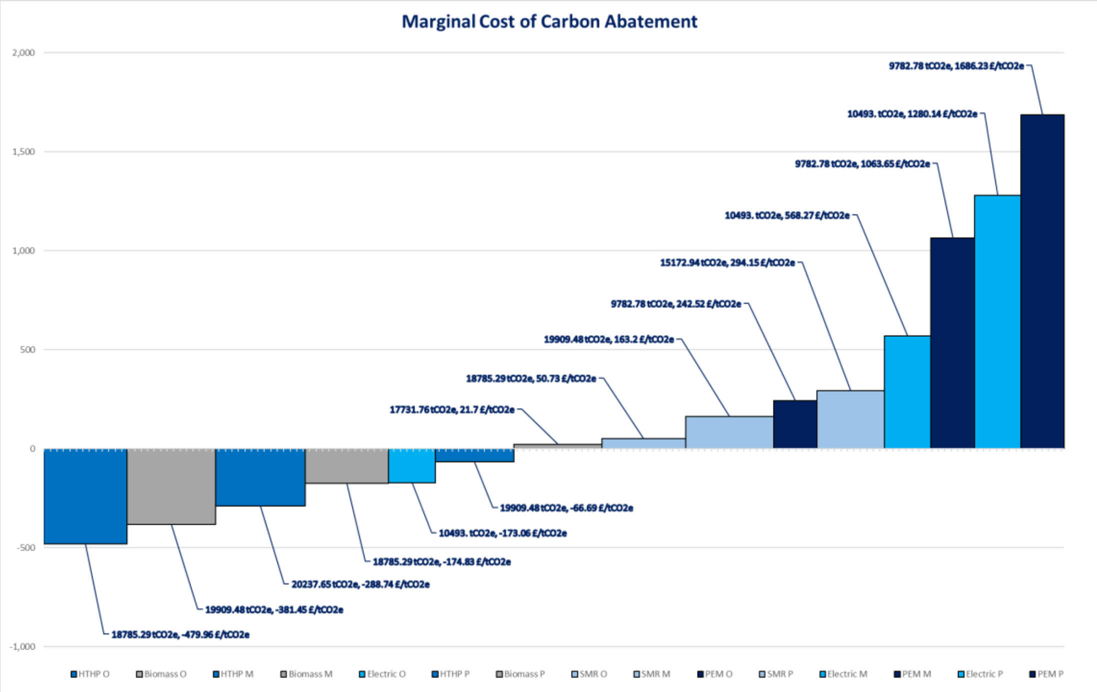


Figure 23. Marginal Cost of Carbon Abated Curve

8.6.3. Conclusions

As shown in the graph, heat pumps are the leading option able to provide carbon abatement at a benefit to the investor, with the saving associated with each ton of carbon abated 452 £/kgCO2e in the low-cost case. Even when considering the highest cost case, it costs £21 to abate one ton of carbon. SMR provided the largest carbon savings across all scenarios, with 20,240 tCO2e being abated in the optimistic case. Heat pump and biomass options show lifetime abatements in the same ballpark, with a range of 18,785 to 17,730 tCO2e and a flat value, due to both biomass and natural gas having set carbon equivalents, of 19,900 respectively. Biomass boilers are clearly less promising than heat pump, although outperform all other options. Similarly, to heat pumps, biomass boilers save money per ton of carbon abatement in the optimistic and model cases, only unable to in the pessimistic case. Hydrogen and electric options are again shown to be worse investments, with both having significant investments needed to abate carbon and abate less over their lifetimes. Lower total abatement is also seen with pessimistic cases for PEM, SMR and Electric options, abating around 10,000 tons over their lifetimes.

8.7. Verification

To provide verification to the results found in this model, a review of existing techno-economic analyses has been undertaken. Due to differences in modelling assumptions, values are unlikely to be the same, although similar trends can provide a level of confidence to the results presented.

In the "HTHPs for Large Scale Industrial Waste Heat Upgrade and Power-to-Heat-to-Power Applications" paper presented in the 2022 High-Temperature Heat Pump Symposium, several scenarios are considered, providing techno-economic analyses for different industrial scenarios. One particular scenario applicable to the Futraheat case considers upgrading waste heat in the paper industry, taking 90°c wastewater to provide 141°c steam. There are differences exist between the variables considered, with COP being 3.7 rather than 4 and investment costs being 400 €/kW rather than 430 £/kW. Fuel prices are also based of European 2020 prices and are outdated. Despite this, as the values show a general corelation to those used in Futraheat's analysis, the trends shown can be used to validate the model. The discounted payback period provides a good metric to validate the economic model as it takes into consideration all cashflows and discount rate, thereby showing an all-encompassing value summarising the results of the analysis. A range of discounted payback periods from 2.26 to 3.09 years have been calculated, lining up with the payback seen in this analysis.

"Techno-Economic Analysis of Steam-Generating Heat Pumps in Distillation Processes", again taken from the High Temperature Heat Pump Symposium, provides analysis into several pharmaceutical applications in both Switzerland and Japan. The analysis finds the discounted payback period and shows a sensitivity analysis noting the influence of the factors considered in the analysis on the discounted payback period. The sensitivity analysis considers a 45°c to 115°c heat source and sink for a 1MW machine, resulting in a discounted payback period of 3.2 years. With both the temperature, heating capacity and payback similar to those considered in Futraheat's case, this research will provide relevant insights into effects of each variable on cost. As reflected in Futraheat's research, fuel prices play the biggest financial role. Increasing electricity price by a factor of 1.5 leads to a discounted payback period of 6 years, with a reduction by half providing a discounted payback of 1.7 years. Gas prices provide even larger swings, with an increase in gas prices causing a reduction in discounted payback to 1.5 years and a decrease in gas prices by half leading to discounted paybacks of significantly more than 6 years. Initial costs were not considered in the sensitivity analysis, although CO_2 costing and maintenance both were. CO_2 costs provided a more significant effect than maintenance, with the latter have a very limited effect. All results discussed reflect the results found in Futraheat's analysis, providing a validation to the analysis.

9. Business plan

9.1. Introduction

Futraheat has plans for its commercialisation, growth, and scaling. To support these plans, we will be completing an equity funding round in early 2023. As part of this strategy a full-length business plan, targeted at investors, has been produced. **The full business plan document can be found annexed to this report.**

The business plan has been developed by aggregating findings from the techno-economic modelling work that has been completed, demonstrator design and build, market research, working with commercial partners, and of course the feasibility study.

This report includes a brief overview of the commercialisation strategy of the business.

9.2. Product & Commercial Plan

9.2.1. GREENSTEAM High Temperature Heat Pumps

Futraheat is developing its Greensteam, steam-generating high temperature heat pump as a beachhead product designed for industrial process heat needs between 100°C and 150°C. It generates useful, low-pressure steam from waste factory-process heat, or from lower temperature heat pumps. Product benefits include CO_2 reductions of up to 100%, energy reductions of up to 90%, fuel-cost savings of up to 40%, and payback in as little as 2 years. The heat pumps use one or more electrically powered TurboClaw compressors in a modular, scalable architecture, to deliver usable heat to around 1.3MW.

9.2.2. Business Model

Our go-to-market plan is to manufacture, market and sell our Greensteam product to industrial end users and industrial equipment integrators. As a stand-alone retrofit product offering, we expect our Greensteam products to establish a commercial beachhead, which will validate the technology and brand, and break down reluctance in industry to adopt new technologies. This will open up a second commercial pathway - selling TurboClaw compressors to process equipment OEMs and integrators. Further long-term scaling of the business will be through technology licencing.

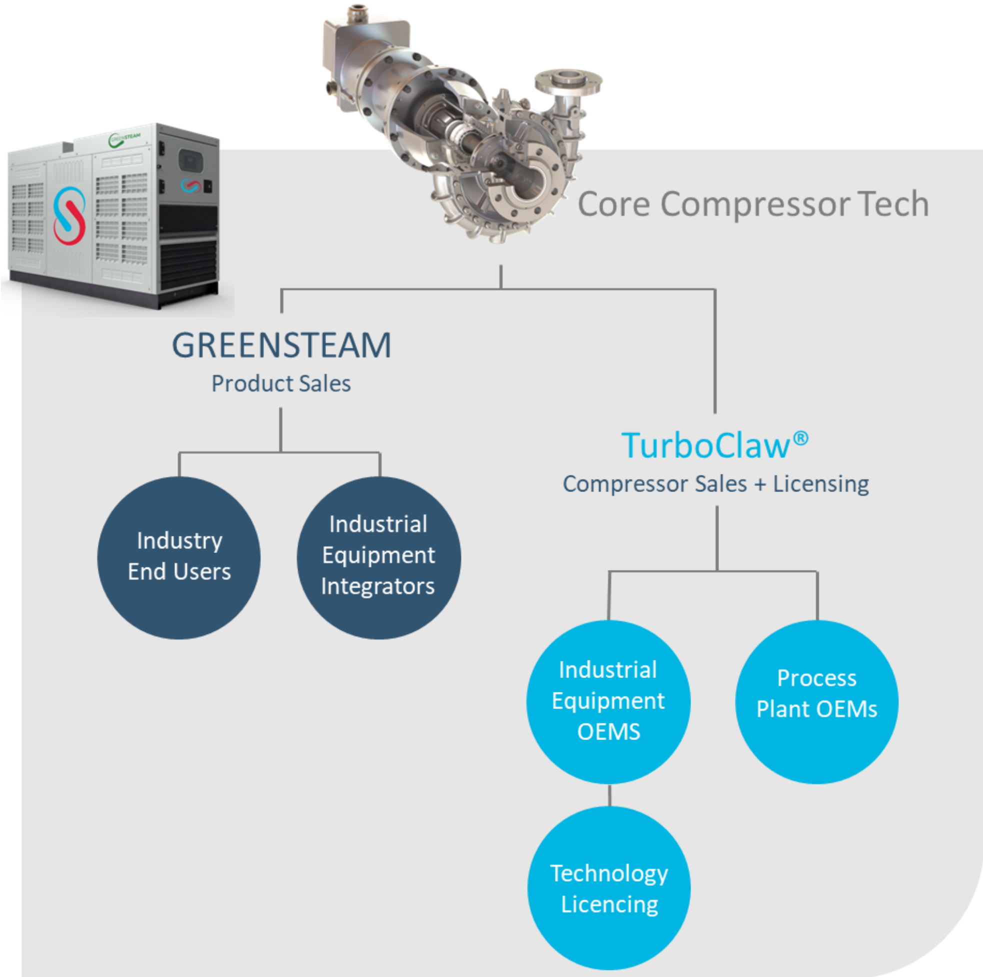


Figure 24- Commercial Pathways

9.2.3. Route to Market

Our current demonstrator is being tested in-house this year before being installed later at an operational brewery for demonstration under real factory conditions to achieve TRL 7 in 2023.

In parallel we'll be developing our minimum viable product (MVP), which will focus heavily on production readiness, using findings from the feasibility study. We aim to deliver an MVP for industrial trials in late 2023.

Additionally, we are working with a number of blue-chip manufacturers to define the MVP specification and identify suitable pilot applications to pave the way for piloting from late 2023 and subsequent sales in 2024.

Our MVP development and piloting plan is the basis for our IFS Phase 2 proposal.

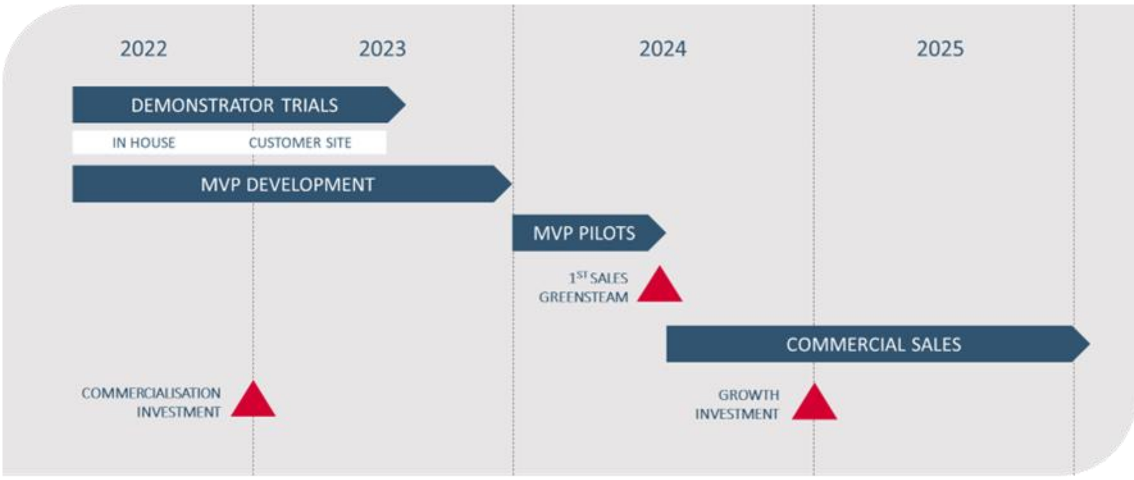


Figure 25- Commercialisation plan

9.2.4. Investment

Futraheat is looking to secure £2m investment to complete pre-commercial product development and validation, and secure first sales by mid-2024.

Investment will be used to drive several key aspects. Firstly, team growth, with plans to double the team in 2023 to include an experienced Product Engineering & Operations Director, and engineering roles in refrigeration systems design, systems & testing, procurement, and mechanical design.

Funds will also be used towards product development by engaging specialist support, and MVP engineering and hardware costs. Lastly, dedicated development of our core technology through TurboClaw R&D.

9.2.5. Revenue Projections

	2023	2024	2025	2026	2027
GREENSTEAM Units Sold	0	2	5	15	44
Heat Pump Revenue £	0	500,000	1,250,000	3,750,000	11,000,000
Compressor Units Sold	0	0	2	10	70
Compressor Revenue £	0	0	250,000	1,250,000	8,750,000
Total Revenue £	0	500,000	1,500,000	5,000,000	19,750,000

Table 18. Revenue Projections

10. IFS Phase 1 feasibility study conclusions

- The client consultations and site visits detailed in section 3 concluded that a HTHP delivering steam up to 3barg (143°C) and capable of operating with heat sources down to 60°C would serve the majority of industry's low-pressure steam driven processes, and all those encountered as part of this study.
- Net-zero is no longer optional for industry, to the extent that process heat users are now comparing the cost of alternative low-carbon heating technologies against the cost of direct-electrode heating, rather than the gas-boiler status quo.
- On this basis it becomes economically feasible to recover lower temperature heat with a conventional heat pump, either from waste streams or the environment, and then utilise a HTHP to generate low-pressure process steam.
- The parametric analysis of TurboClaw established that with two-stages of compression on a single shaft it could deliver 300kWt of low-pressure steam at 3barg (143°C) from source heat as low as 60°C.
- Although turndown is limited to about 25% - 30% for a single compressor, where multiple compressors are used to deliver the more commonly found higher capacities of around 1MWt, turndown of around 75% is achievable.
- The ambition of simplifying the architecture of Futraheat's current compressor design by adopting an oil-free bearing technology and combining the motor and compressor (reducing parts count) was found to be feasible through the use of [redacted]
- Achieving up to 150°C heat output rather than the 130°C possible with the current compressor design was found to be feasible through a review of the wider HTHP bill-of-materials, which identified those areas where the existing specification fell short and proposed alternative solutions.
- A cost study quantified the cost benefits of adopting oil-free bearing technology and reducing the parts count, and also established how production costs would reduce with volumes. This concluded that an installed cost to the customer of £400/kWt was achievable under nominal conditions.
- The feasibility evaluation culminated with a proposed concept design for a steam generating HTHP, 'Greensteam' product.
- A comprehensive techno-economic analysis illustrated how a HTHP technology with Greensteam's target performance would provide the lowest lifetime cost, and lowest lifetime cost of carbon abated vs fossil fuels and other low-carbon alternatives.
- The culminating output from the study was a business plan for the commercialisation of Futraheat's HTHP technology.

11. IFS Phase 2

During the course of the Phase 1 feasibility study, Futraheat has established a strategic, pre-commercial partnership with one of this report's subject global pharmaceutical clients. Under this partnership a programme of product development and demonstration has been outlined and agreed. Should Futraheat apply for and be successful in securing Phase 2 funding then the project proposal will directly align with the partners' strategic programme. This strategic opportunity supersedes the two-client/two-site demonstration project proposed in the phase 1 application.

Details are at this stage confidential as it has not yet been agreed whether phase 2 funding will be sought, but the high-level activities and timeframes will be as follows:

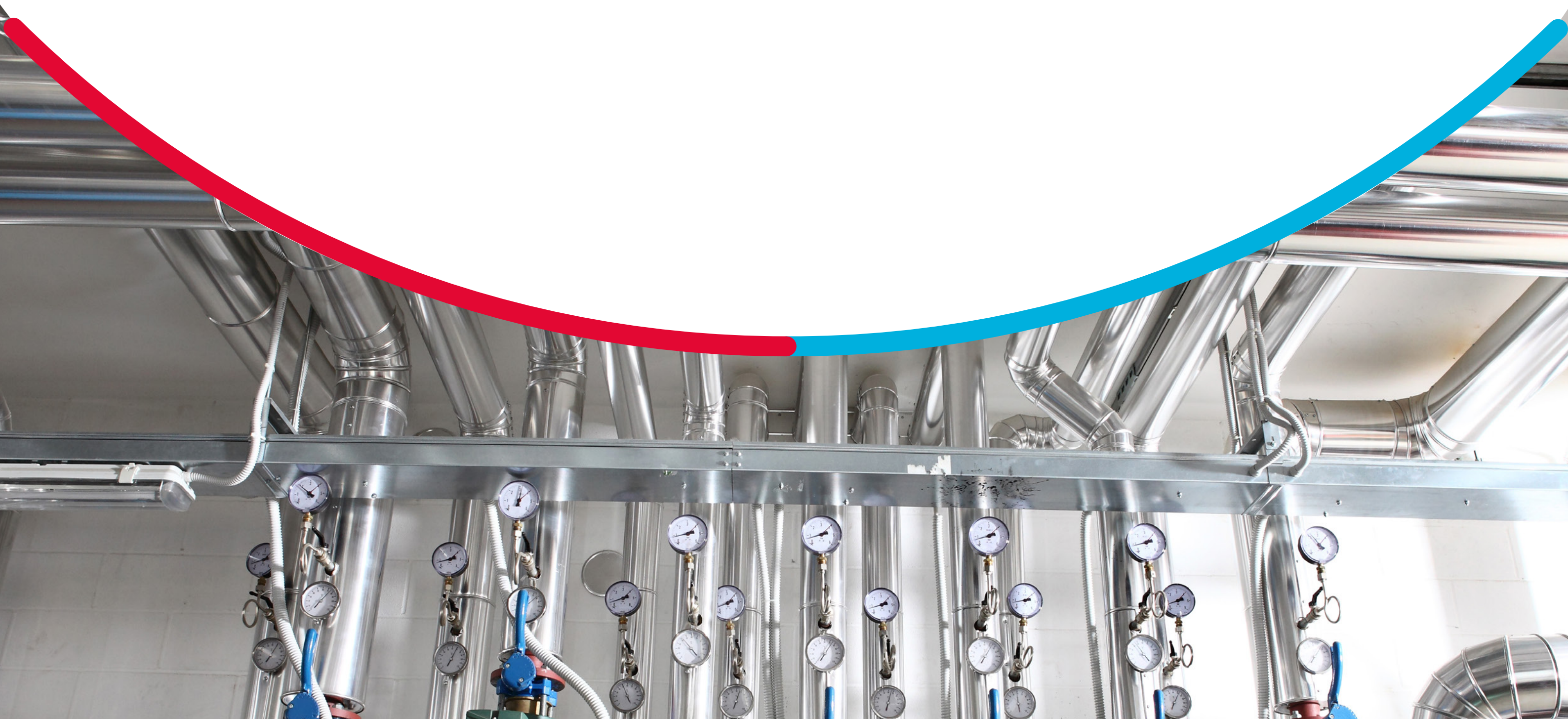
- MVP design and build – 9 months
- Commissioning and in-house testing for pass-off – 3 months
- Installation and testing at client's pilot distillation plant – 6 months
- Installation and commercial demonstration at known operational site – 6 months

FUTRAHEAT

HIGH TEMPERATURE HEAT PUMP TECHNOLOGY FOR INDUSTRIAL DECARBONISATION

BUSINESS PLAN BRIEF

CONTENTS



"Electrifying industry's heat for a zero-carbon future"

INTRODUCTION

Industry emits more CO_2 in generating 100-200°C process heat than the entire aviation industry. Decarbonising this heat could reduce global emissions by more than 3%, but low-carbon heating technologies are either unavailable, or their cost unviable. Futraheat is pioneering the development of high temperature heat pump products - an electrification technology that will enable industry to cost-effectively decarbonise its process heat.

PROBLEM

Two-thirds of all the energy consumed by industry is for process heat, yet the higher temperatures required by industry mean this is typically generated on site using fossil fuels.

Now industrial heat users are looking to the market for low carbon alternatives to meet corporate net-zero targets as soon as 2030, yet cost-effective solutions are not available due to both historic and enduring techno-economic challenges.

SOLUTION

Heat pumps are a low-to-no carbon technology, which efficiently use electricity to concentrate low-temperature heat into useful, higher-temperature heat. We've combined recent advances in green refrigerant gasses with our unique TurboClaw technology to develop pioneering industrial-temperature heat pump products.

TurboClaw - our answer to the compressor at the heart of all heat pumps - yields production, operation and maintenance cost benefits, allowing Futraheat to target the most common market applications where others can't compete.

PRODUCT

Futraheat's GREENSTEAM heat pump is a beachhead product designed to address the problem of cost effectively decarbonising industrial process heat needs between 100°C and 150°C. It harnesses unique TurboClaw® compressor technology to cost effectively electrify factory-steam generation, offsetting or replacing existing fossil fuel boilers.

Our GREENSTEAM high temperature heat pump generates useful low-pressure steam from waste factory-process heat, or from renewable heat recovered from the environment by lower-temperature heat pumps.

GREENSTEAM heat pumps use one or more electrically-powered TurboClaw compressors in a modular, scalable architecture, to deliver usable heat to around 1.5MW.

Each compact heat pump is self-contained, weather-proof and mobile to facilitate retrofit installation. Multiple GREENSTEAM heat pumps can be collocated for larger applications.

Futraheat Product Illustration

Steam is the heat-transfer medium preferred by industry and is used to drive most processes between 100°C and 200°C, from drying to frying. GREENSTEAM products will therefore be able to integrate directly into existing steam infrastructure, minimising installation costs and disruption to factory operations.

Product benefits include:

- CO_2 reductions of up to 100%
- Energy reductions of up to 90%
- Fuel-cost savings of up to 40%
- Payback in as little as 2 years

GREENSTEAM is our beachhead, stand-alone, retrofit product solution to enable manufacturers to future-proof existing process plants. Futraheat also plans to market its TurboClaw high temperature heat pump compressor for integration into new-build factory process plant as part of integrated heat recovery systems (see Commercial Plan).

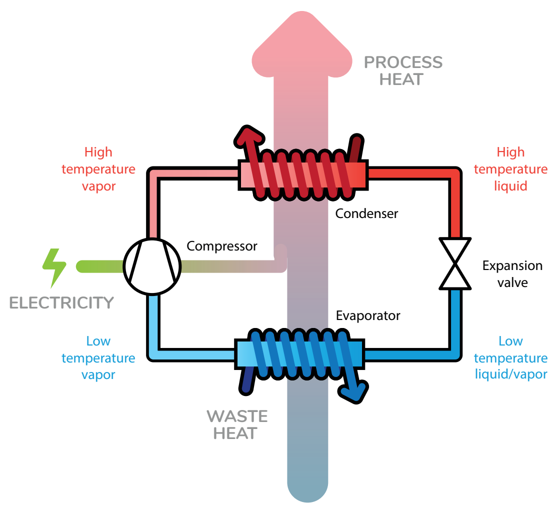
Key Target Product Specification

Rated heat output	300kW to 1.5MW
Max output temp	150°C (later 200°C)
Min input temp	70°C
COP	up to 6.5
Refrigerant	R1233zd
Size	2m x 2m x 2m
Weight	<1000kg

WHAT IS A HEAT PUMP?

A heat pump efficiently 'concentrates' lower temperature heat to higher temperatures using a refrigerant gas and an electrically powered gas compressor. They can deliver significantly more heat-energy than they use in electrical-energy. This efficiency, known as COP, is the ratio of heat kW delivered to electricity kW used.

How a Heat Pump Works



TECHNOLOGY USP

A turbo-compressor simplified; TurboClaw operates at greatly reduced speeds without oil, yielding lower manufacturing, operating and maintenance costs. These advantages enable Futraheat to overcome the techno-economic challenges faced by traditional compressor technologies in delivering the high temperatures required by industry.

TurboClaw's impeller, (see figure 2), has a unique, patented geometry with low specific-speed characteristics, which bring the benefits of turbo-compressors to 'lower flow-rate' applications (see figure 1). For high temperature heat pumps this means 300kW to 1MW applications - by far the most numerous in industry.

Its highly forward-swept blades deliver a given pressure ratio at ~0.3 – 0.5 times the rpm of a conventional centrifugal compressor: less than 20,000rpm vs up to 60,000rpm in the target application.

Futraheat holds an exclusive license to commercialise and develop TurboClaw in the field of industrial heat pumps.

The core, patented TurboClaw components are directly driven by an electric motor, with bearings, magnetic coupling, and electronics comprising the remainder of the overall compressor assembly (see figure 3).

We design our own motors to ensure optimal product performance. This, along with maximising the use of off-the-shelf components yields the most cost-effective solution.

The Futraheat team has over 30 years combined experience developing high-speed rotating machinery and is the world authority on TurboClaw.

Fig 1. TurboClaw's Unique Advantage

COMPRESSOR TYPE

	Positive Displacement	Conventional Dynamic	TurboClaw®
KEY FEATURE			
Oil-free compression	✗	✓	✓
Low speed	✓	✗	✓
Low parts count	✗	✓	✓

Fig 2. TurboClaw Impeller

BENEFITS OF OIL FREE

- Avoids complex and costly oil management system
- No performance deterioration due to heat exchanger fouling

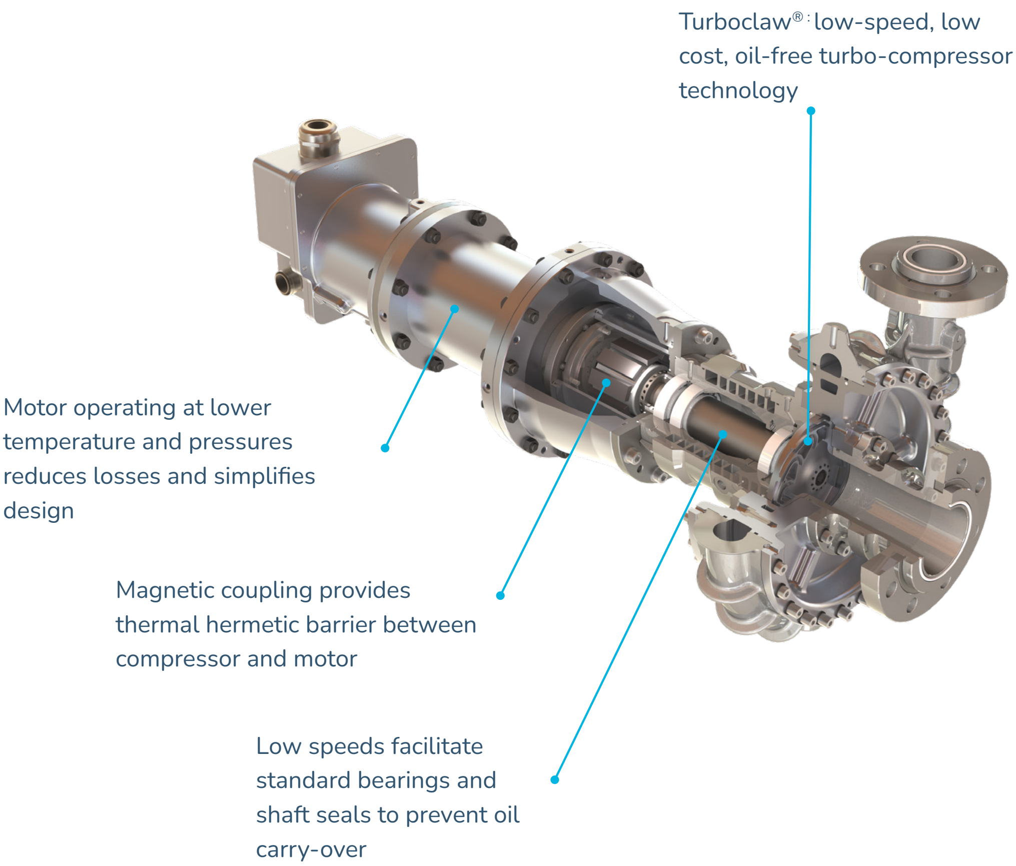
BENEFITS OF LOW SPEED

- Facilitates use of standard/lower-cost motors, drives and bearings

BENEFITS OF FEW PARTS

- Dynamic compressors (inc. TurboClaw) have just one moving part supported by bearings, resulting in more compact, less £/kW designs

Fig 3. Futraheat Compressor



CUSTOMER VALUE & ECONOMICS

Most global manufacturers are targeting net-zero between 2030 and 2040, recognising the growing value of decarbonisation, driven by consumer demand, energy pricing and carbon policy/taxation. Sustainability is no longer optional; but industry still demands the most cost-effective solutions to decarbonise its heat. High temperature heat pumps are set to be the breakthrough technology to deliver such solutions up to 200°C, with Futraheat targeting the lowest-cost (£/kW) products in the target market, thanks to its unique technology advantages.

COST DRIVERS

Heat pumps can readily deliver useful temperature lifts with efficiencies of between 300% and 600%, meaning they provide 3 to 6 times more heat energy than they consume in electricity. This gives them an immediate OPEX advantage over natural, hydrogen, or bio gas boilers (~85% efficiency) and direct electrical heating (~100% efficiency), despite today's gas-electricity price disparities. An expected narrowing of these disparities, tightening of net-zero policy (particularly around CO_2 taxation/trading, and companies' own internal carbon pricing) will only increase the operational savings delivered by heat pumps.

CAPEX is the other major consideration for heat users looking for sustainable alternatives to burning gas or oil. Consultation with industry, technology developers and the European research institutions at the forefront of industrial heat pump development has established that ~£400/kW is the broadly accepted fully-installed price at which heat pumps become the clear choice. This makes it a target for industry, but evidence suggests early market entrants are near double this at target capacities.

ILLUSTRATION

The above points are illustrated below in a comparison of a heat pump with other sustainable heating technologies.

Item	High Temp Heat Pump	Direct Electric	SMR (Blue H2)	PEM (Green H2)	Biomass	Natural Gas (As Is)
Capacity (kWth)	1,000	1,000	1,000	1,000	1,000	1,000
Energy Capacity (kW)	250	1,053	1,176	1,176	1,111	1,176
Efficiency (%)	4	0.95	0.85	0.85	0.9	0.85
Annual Energy Requirement (kWh) at 5000 Hours Operating	1,250,000	5,263,158	5,882,353	5,882,353	5,555,556	5,882,353
CAPEX	-£367,667	-£214,501	-£123,278	-£123,278	-£410,011	-
OPEX Savings	£1,595	£4,396	£1,134	£1,134	-£1,096	-
Fuel Expenditure Savings	£129,759-£201,423	-£364,850--£315,668	-£306,897--$4,046	-£658,689--£541,548	£66,403-£69,975	-
Carbon Expenditure Savings	£18,887-£26,698	-£7,122.25-£25,765	£18,966-£25,297	£11,135-£25,621	£24,887	-
20 Year NPV at 7% Discount Rate	£1,739,286	-£3,661,230	-£208,439	-£7,387,813	£719,346	-
Payback in Years	3	N/A	N/A	N/A	6	-
LCOH (£/MWh)	-£32.10	£67.58	£3.85	£136.36	-£13.28	-
LCOC (£/tCO2e)	-£177.80	£568.27	£21.70	£1,063.65	£66.69	-

VALUE PROPOSITION

TurboClaw enabled heat pumps operate at efficiencies comparable with the state-of-the-art in the target market and will therefore deliver OPEX advantages in full.

Our advantage is delivered in two ways:

1. TurboClaw's simplicity, oil-free operation and low-rotational speed, together with its standardised, modular design, mean it can be produced in production volumes at lower cost/kW than other compressors.
2. Futraheat is OEM for both the compressor and its GREENSTEAM heat pump products. Conversely, most heat pump manufacturers purchase third-party compressors, meaning the compressor can make up as much as half the total heat pump manufacture cost.

Together, these advantages will enable Futraheat to target the £400/kW price point with its GREENSTEAM products, gaining us market traction and technology validation through commercial demonstration. But, in addition, as the compressor OEM we will be able to sell our TurboClaw heat pump compressors as stand-alone products for integration into new-build process plants as part of integrated heat recovery systems, in which case much of the installation cost associated with retrofit equipment won't apply, allowing for margin to be maximised.

CUSTOMER VALUE & ECONOMICS

We have conducted a comprehensive techno-economic analysis of high temperature heat pumps (with Futraheat's cost-performance combination) and those other industrial low-carbon heating solutions shown in the previous illustration. This analysed which technology offered the lowest total lifetime cost for a typical 1MW application in our target market.

MODEL CASE

The levelised-cost model allows for a comparison of different technologies with varying annual cashflows and uses 'best, worst and average' cases for sensitivity. For any given operating specification, a heat pump's performance is most sensitive to fuel and electricity price disparities, relative to one another and between countries/markets. Recent global events have caused significant increases in current energy prices, and reflect a 'best case' for HTHPs. But long-term forecasts (3+ years) remain largely unchanged, and so our business case is based upon 'average' energy prices at the beginning of 2022 across our target European market.

p/kWh	Low	Average	High
Elec	8.80-9.20	12.32-12.88	17.41-18.20
Gas	3.44-4.39	4.82-6.16	7.83-10.00
Ratio	1.12-0.92	2.55-2.09	5.07-4.15

The analysis first calculated the net present value (NPV) of each technology to give an indication of its financial feasibility in the form of current worth. This shows that only heat pumps and biomass provide lifetime savings over a natural gas boiler, with heat pumps providing the greatest cost benefits.

Correspondingly, heat pumps can be shown to have the lowest Levelised Cost of Heat (£/MWh) - a metric assessing the average cost of purchasing and operating an asset per unit of heat production over the asset's lifetime (figure 4): And lowest Levelised Cost of Carbon (£/kgCO_2e) - the cost to purchase and operate a green technology per ton of carbon abated over the project's lifetime. In both cases heat pumps are again shown to provide the largest savings relative to the baseline case of a natural gas boiler.

PRODUCTION COST VALIDATION

In a typical 1MW application our GREENSTEAM heat pumps will save more than £130,000 per year in fuel costs alone, hence we're targeting a £400/kW fully-installed cost, delivering customer payback within three years.

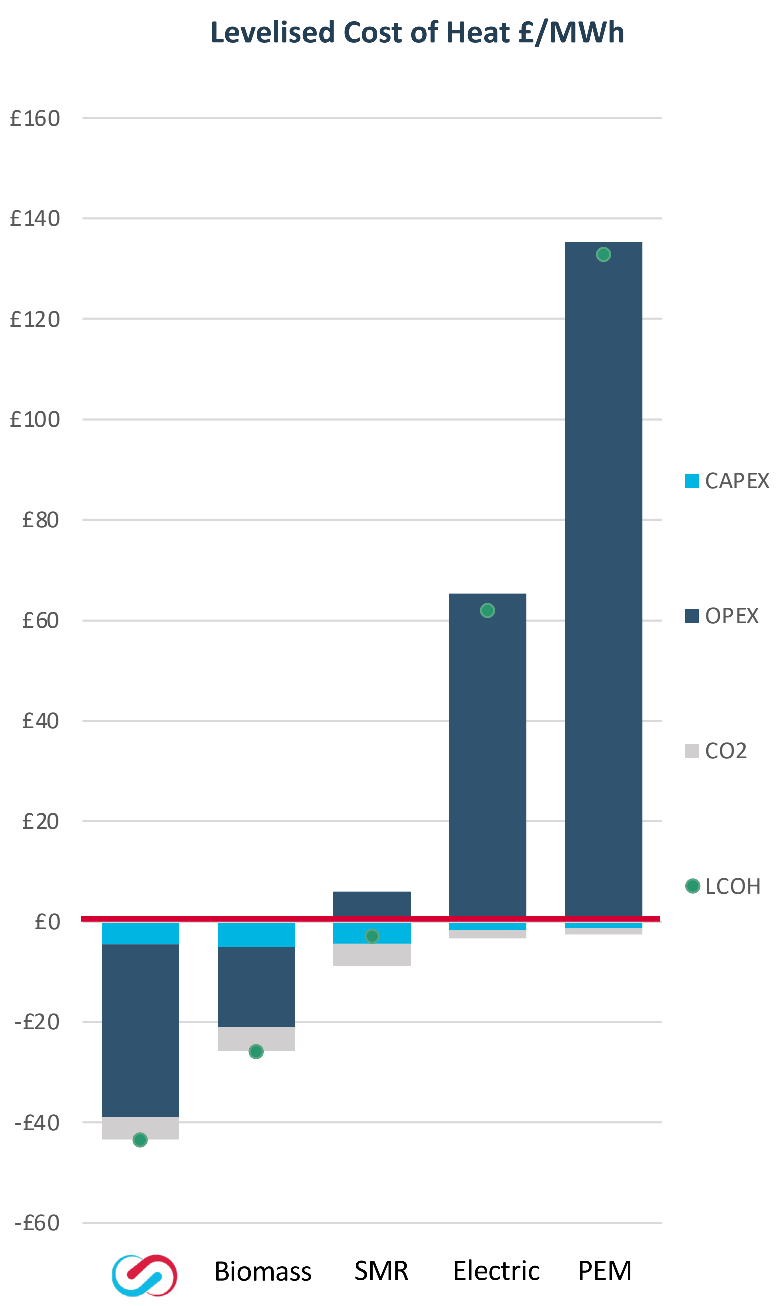
Fully-installed (retrofit) costs are typically 1.5 times the cost of the equipment alone and so to achieve a 50% margin as GREENSTEAM product OEM, our target cost-of-goods-sold (GoGS) is about £135/kW.

Discussions with our supply base confirmed that without modification, our existing first-off demonstrator prototype design could be produced for around £300/kW if produced in modest batch volumes.

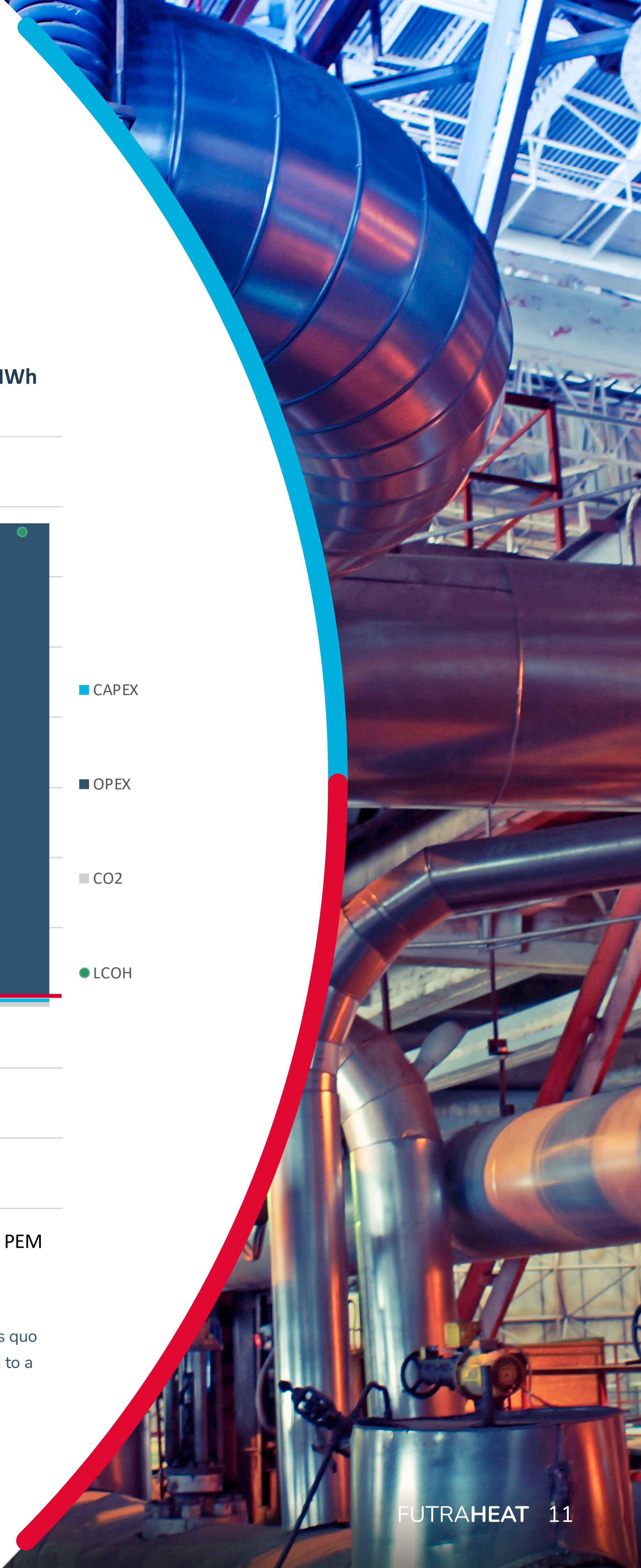
Further preliminary evaluation - both in-house and by Productiv Ltd., (a company which helps 'productionise' technologies for market) - has identified a number of areas of opportunity for cost-reduction that will enable us to meet our production cost target. These include design rationalisation and parts count reduction, materials selection and production process design.

Realising these opportunities will be the focus of next-phase product development and validation activity.

Fig. 4 - Levelised Cost of Heat (LCOH) showing that a HTHP with Futraheat's specification delivers lowest lifetime cost vs other low carbon alternatives and natural gas



- £0 red line represents the cost of the gas boiler status quo
- A negative value represents cost savings, as opposed to a positive value which represents added costs of heat



MARKET

More than two-thirds of industry's energy demand is for process heating. This heat is generated almost exclusively by burning fossil fuels on-site and contributes about 15% of global CO_2 emissions. Crucially, binding net zero targets, global energy-price moves, and consumer demand for sustainable goods have created a powerful shift in market forces to incentivise industry to rapidly decarbonise its heat.

ADDRESSABLE MARKET

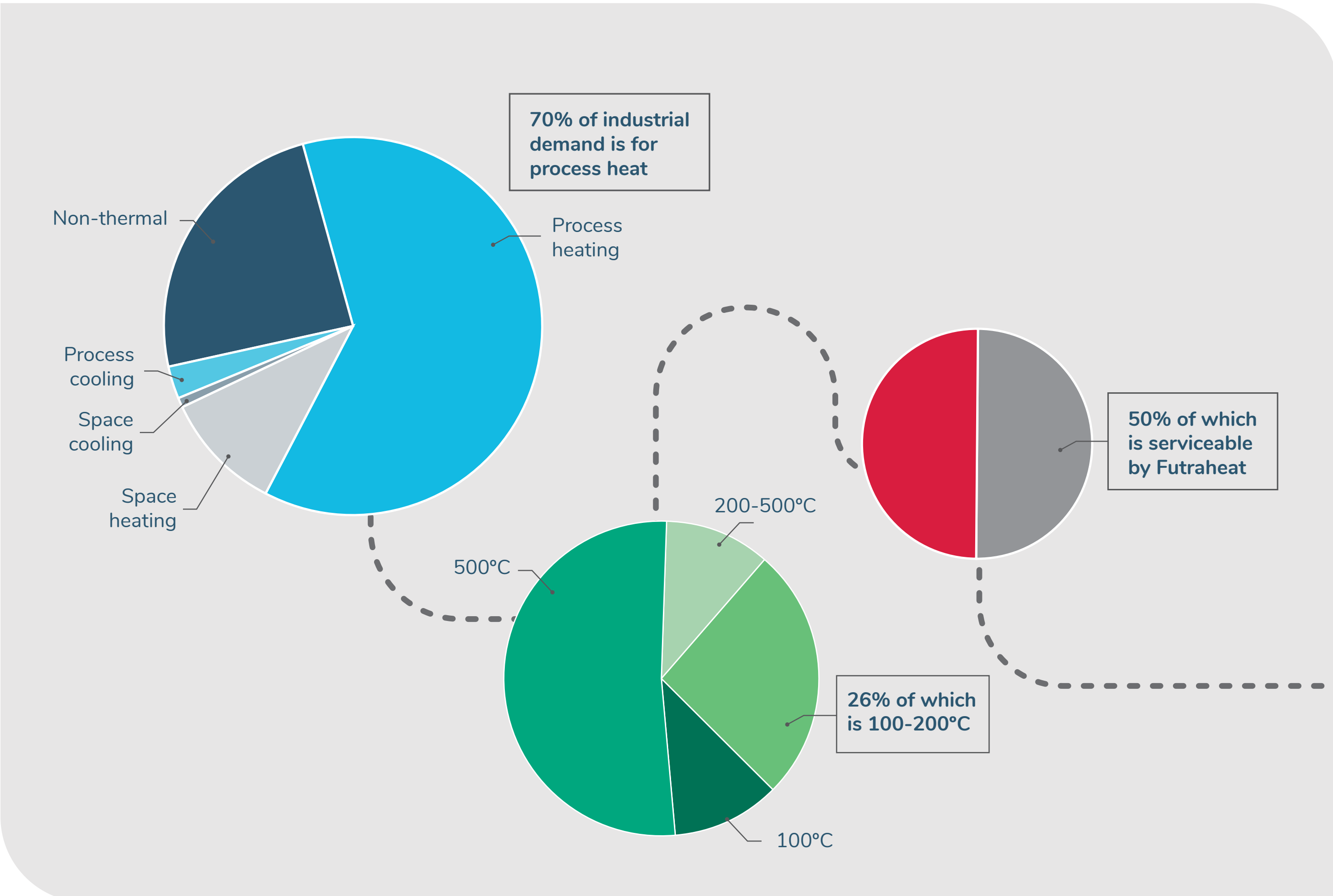
High, or very high temperature heat pumps are seen as the breakthrough technology for sustainable process heat needs between 100°C and 200°C (DNV Technology Outlook 2030). This translates to more than a quarter of industrial heat energy use (European research institutions' white paper, de Boer et al, 2020).

Higher, combustion temperatures (200°C+) are the focus of hydrogen, biomass and direct-electrification technology development, whilst the market for existing heat pumps now extends to applications up to 100°C.

Our total global addressable market is estimated to be all applications requiring up to 1.5MW of heat between 100°C and 200°C, which equates to about 50% of the total heat energy delivered at these temperatures (Mariana et al. 2021).

Our beachhead market for GREENSTEAM products targets low-pressure steam applications up to 150°C, or ~25% of all 100°C to 200°C applications.

Fig 5. Futraheat Global Market Size



INDUSTRY SECTORS AND APPLICATIONS

The target temperatures and capacities are found across industry, but are particularly commonplace in the food & drink, pharmaceuticals, chemical and paper sectors. Processes include pasteurisation, sterilisation, distillation, drying and concentration, which in most cases use low-pressure steam as the heating medium.

Most process plant is designed for 20+ years' operation, which means there is both a ready market for retrofit GREENSTEAM heat pumps to future-proof plant and extend its life, and for TurboClaw high temperature heat pump compressors for integration into new, sustainable factory plant designs with built-in heat recovery systems.

POLICY LANDSCAPE

UNITED KINGDOM

International climate change agreements, energy pricing and energy security, are shaping domestic net-zero policy in favour of electrification and other low-carbon technologies. Here the UK Government has committed to net zero by 2050, with a goal of 70% emissions reduction from industry by 2035.

Key upcoming policy levers include:

- Policy for the electrification of industry from the UK Government expected in 2022
- Government consultation in 2022 on Renewable Obligation levies, expected to reduce the gap between relative gas and electricity prices
- Alignment of the UK's Emissions Trading Scheme (ETS) with Net Zero policy, which is expected to widen its scope and increase the cost of carbon

EUROPE

The EU is a key market for Futraheat, and boats an attractive policy landscape that aligns strongly with the development of high temperature heat pumps, fuelled by current economics and urgency to reduce reliance on Russian gas.

Released in May 2022, the REPowerEU plan calls for increased development and installation of heat pumps and focus on energy efficiency.

COMPETITION

HTHPs have yet to penetrate broadly into the industrial process heating market, yet with market forces increasingly favourable, products are being marketed providing technical, if not economical, solutions. Futraheat is targeting the most common applications where up to around 1.5MW of heat is required. Here techno-economic challenges for conventional technologies are greatest and direct competition limited.

DIRECT COMPETITION

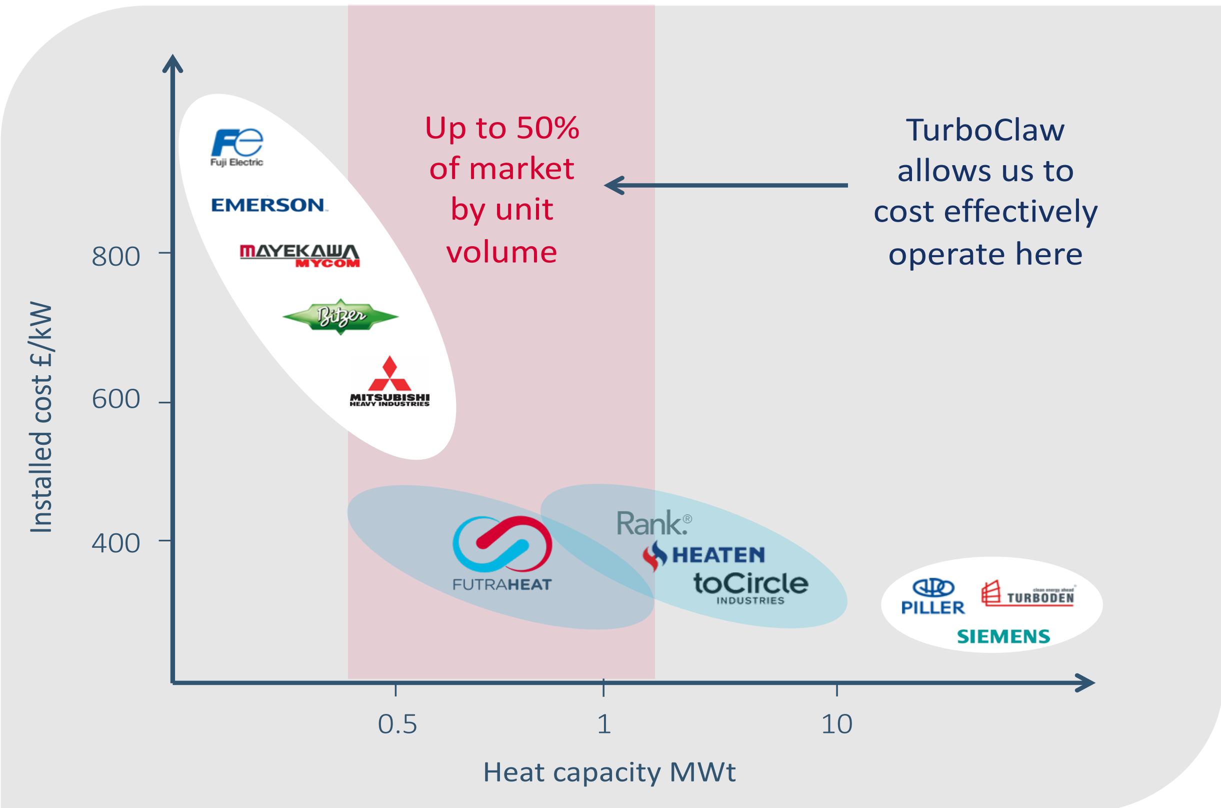
There are a number of companies developing or marketing high temperature heat pumps. The most technically and commercially mature are very large (>10MW) systems, where economies of scale have made such installations cost effective for some time and which suit existing turbo-compressor technologies.

At the other end of the spectrum a number of major brands have developed very small (<0.5MW) units for niche applications based upon their existing positive displacement compressor technologies. These carry a high specific cost (£/kW), but illustrate the fledgling interest in the market from established technology providers.

A handful of new companies are developing products in the 1-5MW range, where the specific costs of their technologies become acceptable.

At Futraheat we're harnessing our unique technology benefits to target the largest market segment by volume, at a cost-effective price point (see figure 6).

Fig 6. Direct competitor positioning by heat capacity and specific installed cost, based upon a techno-economic analysis of HTHP technologies the by the Swiss Institute for Energy Systems.



INDIRECT COMPETITION

Once developed, heat pumps with Futraheat's cost-performance combination should always deliver the lowest-cost solution in terms of heat and carbon produced for the target market. Other potential indirect competition comes from technologies more suited to industry's higher temperature needs (>200° C). Pros and cons of these alternatives are considered in the table below:

Alternative	Pros	Cons
Direct electrical	• Temps >200degC • Zero carbon when renewable • Modest CAPEX	• Very high OPEX • Supply capacity and infrastructure cost
Biogas	• Temps >200 °C • Cost effective where gas produced locally from bi-product	• Expensive where fuel not from own bi-product • Carbon footprint of transport
Blue H2	• Temps > 200 °C • Could utilise existing gas infrastructure	• 10 years+ to widespread roll-out • Expensive – requires 1.5 times more energy to make than provides • Uses fossil-fuels - Requires CCS to be zero-carbon
Green H2	• Temps > 200 °C • Could utilise existing gas infrastructure • No CCS required	• Most expensive • 15+ years to widespread rollout

COMMERCIAL PLAN

We plan first GREENSTEAM product sales in 2024 and will work with Productiv Ltd. to develop the production systems for commercial launch. With this established commercial beachhead we will seek partners to achieve broader scale with our core TurboClaw technology. We are now working with blue-chip customers to identify strategic sites for minimum-viable-product trials in 2023, whilst completing our full-size demonstrator for technology validation at an operational brewery, later this year.

BUSINESS MODEL

Our go-to-market plan is to manufacture, market and sell our GREENSTEAM product to industrial end users and industrial equipment integrators. We are targeting a 50% gross margin from modular systems selling at between £200k and £300k, depending upon heat capacity. We will provide after-sales support, but allow third-parties to provide installation and maintenance services.

As a stand-alone retrofit product offering we expect our GREENSTEAM products to establish a commercial beachhead, validating the technology and the brand, and breaking down reluctance in industry to adopt new technologies. This will open up a second commercial pathway - selling TurboClaw HTHP compressors to process equipment OEMs and integrators - which supports higher margins and could scale rapidly if we leverage manufacturing partnerships.

Our ultimate aim will be to deliver optimal shareholder value through technology licensing and/or sale.

PRODUCT DEVELOPMENT

We aim to deliver a minimum viable product (MVP) for industrial trials in 2023. We are working with a number of blue-chip manufacturers, to define the MVP specification and identify suitable pilot applications.

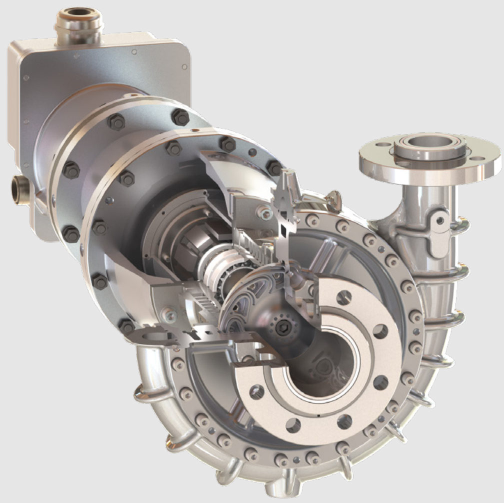
In parallel, we have developed a full-scale, TurboClaw enabled HTHP demonstrator in partnership with Projective Ltd and with support from Honeywell. This is being tested in-house before being installed later this year at an operational brewery, for demonstration under real factory conditions.

Product development benefits from more than £1m Innovate UK and BEIS grant funding to date and secured.

PRODUCTION

Productiv Ltd work with new green-tech companies to take products to market. Their 'Proving Factory' supports all stages of the product-development lifecycle, from early prototyping, to manufacturing modest volumes, and their product introduction process is based on the automotive industry.

We will partner with Productiv through our MVP development to prepare the production processes and supply chains for cost optimisation and production scaling.



Core Compressor Tech

GREENSTEAM
Product Sales

- Industry End Users
- Industrial Equipment Integrators

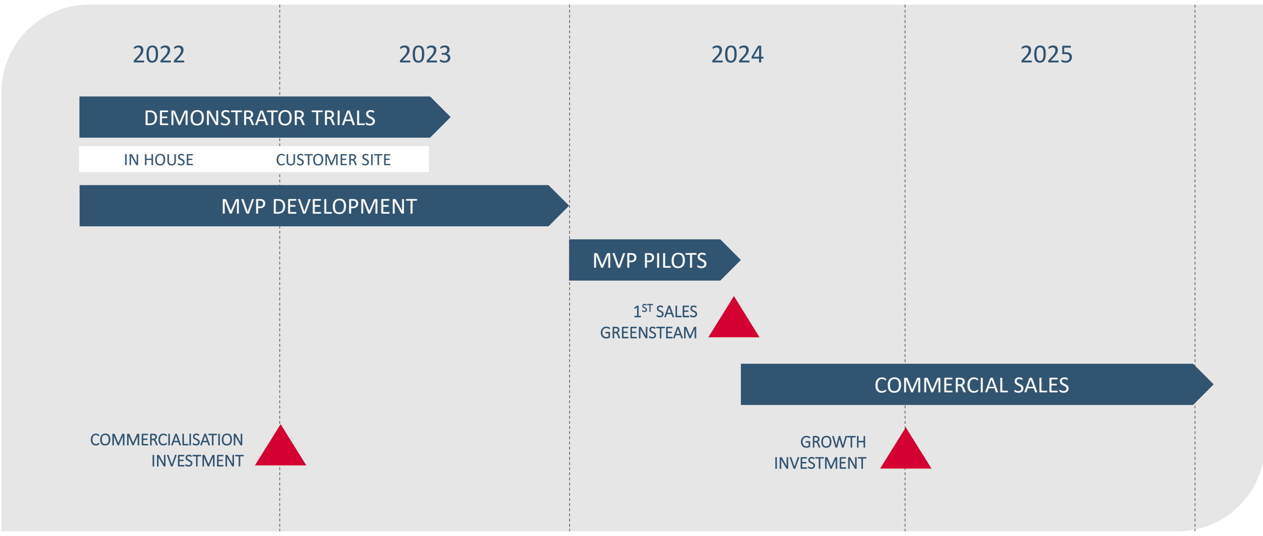
TurboClaw®
Compressor Sales + Licensing

- Industrial Equipment OEMS
- Process Plant OEMs
- Technology Licencing

Fig 7.
Futraheat commercial pathways

INVESTMENT & FINANCIALS

Futraheat is looking to secure £2m investment to complete pre-commercial product development & validation, and secure first sales by mid-2024.



INVESTMENT

£2m investment will be supplemented by a further £0.5m in grant funding in 2023 to in total fund all pre-commercial activity to mid-2024, largely driven by the following:

1. Team growth: A doubling of the team to include: An experienced Product Engineering & Operations Director, and engineering roles in refrigeration systems design, systems & testing, procurement, and mechanical design.
2. Product development: Engaging specialist support in specific areas of product development, including in production readiness (Productiv ltd), bearing technology (SKF) and power electronics (KEB).
3. MVP delivery: Production of MVP GREENSTEAM demonstrators and their installation on site.
4. TurboClaw R&D: Dedicated development of our core technology to further improve efficiency and secure new IP.

FINANCIAL PROJECTIONS

	2023	2024	2025	2026	2027
Greensteam Units Sold	0	2	5	15	44
Compressor Units Sold	0	0	2	10	70
Opening Cash Position	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Sales	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Direct Costs	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Gross Margin	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Indirect Costs	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
EBITDA	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Investment Equity & Non-dilutive Funding	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Closing Cash Position	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

ASSUMPTIONS

- 2 x MVP GREENSTEAM product sales in late 2024 then 5, 15, 50 in next 3 years
- Investment raise in June 2024
- £0.5m grant awarded in 2023

PEOPLE

TOM TAYLOR

Founder & CEO

Tom is a Chartered mechanical engineer with an MEng from Manchester University and MBA from Warwick Business School. He gained techno-commercial experience to executive level with BAE Systems and Rolls Royce, primarily in manufacturing, production and supplier management, before leaving the corporate world to pursue his passion for innovation. As CEO of early-stage technology companies Tom has since successfully completed a £2m fundraise and secured a number of contracts with global blue-chips. In May 2021 he and Futraheat's Chairman, Ray Wellham, spun the company out from DBS Ltd., bringing with them exclusive rights to TurboClaw and the core team essential to its commercialisation.

DR RUTH CATTELL

Chief Technology Offcier

Ruth is the world's authority on TurboClaw: After graduating with an MEng (Hons) in aeronautical engineering from Imperial College London, she spent a decade becoming expert on the technology before making it the subject of her PhD, completed in 2020 at City, University of London. In addition, Ruth's expertise cover all areas of mechanical and aeronautical design and analysis, including CFD, thermal, structural and rotordynamic.

SCOTT MACKENZIE

Senior Mechanical Engineer and Project Delivery Manager

Scott brings our technology to life. He leads mechanical design, modelling & drawing, procurement & production, quality assurance, assembly, project control and facilities readiness. Scott is an MEng (Hons) mechanical engineering graduate from City, University of London and has more than 10 years'worth of experience in developing high-speed motors, generators and turbo-compressors.

MEGAN DOBBIN

Communications and Business Developement Mananger

Megan leads on PR and communications, as well as supports Tom in preparing Futraheat for its next phase of growth through fundraising and business development activity. After graduating with a Bachelor of Commerce Co-op, Megan gained experience in strategic marketing and business development roles before completing an MBA at the University of Edinburgh in 2021.

JOSH HOPPER

Mechanical Engineer

Josh is a recent Mechanical Engineering Graduate from Manchester University. Josh joined the team in 2021 to assist with all mechanical design and analysis aspects of our high temperature heat pump technology. He also leads on techno-economic analysis, drawing on knowledge gained delivering his university degree thesis.

RAY WELLHAM

Founder & Chairman

Ray is Futraheat's largest shareholder and the owner of Projective Ltd., a leading sustainable energy consultancy and engineering services provider to industry.

Ray started his career as a engineering apprentice, before gaining a BSc in Engineering & Business from the University of East Anglia and progressing to design engineering, engineering & operational management, and asset management roles.

Ray joined Projective in 2004 and took the role of managing director soon after. He has since transformed the business, which is now the go-to provider of net-zero solutions consultancy and services for many of Futraheat's target global blue-chip clients, including Pfizer, GSK, DSM, P&G, PepsiCo, Nestle, Heineken, Coca-Cola, Diageo and many more.

Ray's intimate knowledge of industry's needs, his hands-on, 'lead by example' approach, and the relationships he has with his clients provides Futraheat with a unique advantage.

projective

Futraheat has a strong technical, commercial and strategic-leadership foundation in place within its existing team and board. As we move from technology to product developer, and increase the scale and pace of activity, we will prioritise attracting experienced individuals into key roles, including:

PRODUCT ENGINEERING AND OPERATIONS DIRECTOR

This board level position recognises commercial product development as being the main business operation over the coming period and will require an individual with proven experience leading the development of new products and their introduction into the industrial market.

SYSTEMS AND TEST ENGINEER

An electro-mechanical test engineer role dedicated to putting our tecnology and products through their paces both in-house and in the field.

REFRIGERATION SYSTEMS DESIGN ENGINEER

A capability provided by Projective to date, but which will soon be a full-time requirement at Futraheat.

TurboClaw® R&D ENGINEER

A role dedicated to further improving the efficiency and understanding of our core TurboClaw technology, and to expanding and strengthening our IP portfolio.

FUTRAHEAT

HIGH TEMPERATURE HEAT PUMPS

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