Biological transformation of geothermal gases to biomass: a case study

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ABSTRACT

Geothermal electricity generation releases waste gases, including the greenhouse gases methane and carbon dioxide. These gases are currently vented to the atmosphere or re-injected, however there is potential to turn this waste stream into commercial products. This case study profiles the first project to couple the production of a protein with geothermal gases and extremophilic microorganisms sourced from geothermal environments.

Laboratory scale-research experimentally demonstrated proof of concept, showing that a co-culture of endemic geothermal microorganisms (a bacterium and a microalga) can consume the industrial gases, carbon dioxide (CO_2) and methane (CH_4) as a food source for growth. This generates a biomass that is rich in protein (ca. 60%) and was shown to be non-toxic, nutritious, and digestible (in mice). The biomass produced also contains several potentially valuable components, which could be extracted to enhance commercial viability.

To advance towards commercialisation, we are scaling up from laboratory (80 L) to pilot scale (ca. 900 L) to optimise operating conditions and test with actual geothermal gases on a geothermal steam-field site. The scale-up will generate sufficient volumes to trial the biomass on larger, commercially-farmed animals and/or fish, as well as allow for fractionation experiments to explore the viability of premium products. Concurrent with the technical development, we are evaluating target markets and pathways to these markets, including regulatory requirements and analysis of the techno-economics. This paper and presentation shares the project history, goals and learnings to date.

1. INTRODUCTION

1.1 Geothermal Greenhouse Gases

Geothermal power stations draw on subsurface fluids which contain a variety of gases that are brought to the surface to generate electricity. These geothermal greenhouse gases (530 kT per annum CO_2(eq) (MBIE, 2025; McLean & Richardson, 2024) are currently injected deep underground or are vented to the atmosphere post electricity production. Reducing carbon emission costs over $32M pa at current pricing (based on $60/t), to NZ's geothermal power generation industry. Carbon pricing is likely to treble in the not-too-distant future, and this will hinder the economic viability of some geothermal projects which are crucial to reducing our reliance on fossil fuels. However, there is an opportunity to use these waste gases.

1.2 The Technology

This innovation uses native New Zealand extremophilic microorganisms (extremophiles), grown on waste gases from geothermal power plants, to produce a protein-rich animal feedstock that is nutritious and digestible.

Indigenous microbial species are central to the uniqueness of this technology. Extremophiles are microorganisms, including bacteria and algae, that live in conditions humans consider 'extreme', e.g. high temperature, acidity, salinity, pressure. The extremophiles used in this research were sourced from geothermal features at Parariki, within the rohe of Tauhara North No.2 Trust (TN2T). These microorganisms were isolated and characterised through previous research (e.g. Buckridge et al, 2024; Carere et al, 2017).

Industrial gases can be used by a co-culture of two extremophiles (one bacterium and one microalga), working together as a consortium (Fig.1). The bacterium, *Methylacidiphilum* RTK17.1, uses methane for energy and growth, but to do this it requires oxygen, and it also generates carbon dioxide. The microalga (genus *Galdieria*) uses light as its source of energy, assimilates carbon dioxide during growth, and produces oxygen. In this way, each microorganism consumes the metabolic waste products of the other (Fig.1), and a mixed biomass is generated.

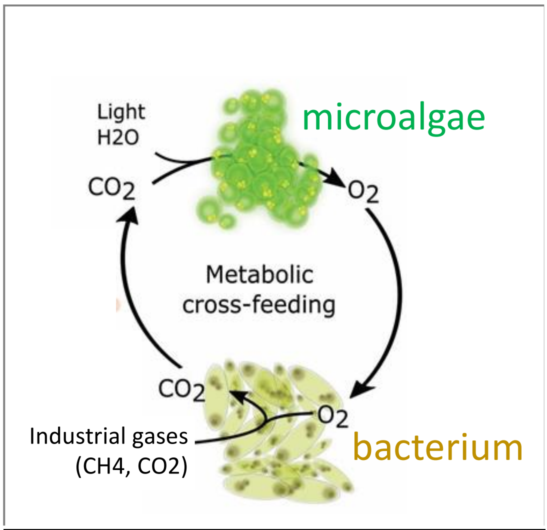

Figure 1. The co-culture of microorganisms work together as a consortium.

This process occurs at ca. ~50 °C and at pH ~2.5. These growing conditions negate issues that normally hamper and increase the operational costs of bioprocessing operations that occur at 20-40 °C and neutral pH (e.g., contamination, reactor cooling costs, defined substrate streams). Further process gains (i.e., increased yields) are achievable by optimising operating conditions in the bioreactor to take advantage of the adaptability of extremophiles (e.g., high pressure and gas concentrations). There are significant optimisation opportunities that can make the process commercially competitive.

For geothermal power stations, the production of feedstocks could transform a cost-incurring waste stream (greenhouse gases) into a valuable asset, and put these emissions to positive use.

2. PREVIOUS RESEARCH

This opportunity arose from a series of NZ-based research projects.

2.1 The 1000 Springs Project (2012-2014)

This MBIE Smart Idea ($1M; GNS Science & University of Waikato) aimed to collate the physical, chemical, and microbial biodiversity information from 1,000 geothermal ecosystems in the Taupō Volcanic Zone (Stott et al, 2012). While geothermal ecosystems are understood to be hotspots for unique and diverse microbial populations, very little was previously known about the microbial populations resident in these environments (Power et al, 2018; 2023; 2024). One key outcome was a publicly accessible online database (www.1000springs.org.nz) of microbial and geochemical diversity, which acts as a springboard for microbial ecology research, conservation and biodiscovery.

2.2 Flipping the paradigm: feeding methane to cows (2017-2020)

This MBIE Smart Idea ($1M; University of Canterbury & Scion) aimed to develop a biotechnology platform to take industrial waste gases and convert them into protein-rich biomass to feed dairy, stock, and other farmed animals (including aquaculture). The process utilised the unique characteristics of naturally occurring and non-genetically modified indigenous extremophilic microorganisms from geothermal ecosystems. The biotechnology platform was demonstrated using the industrial example of geothermal power generation. The process/bioreactor was designed to be nutritionally flexible, allowing biomass to be tuned to meet the needs of specific biofeedstocks. Laboratory-scale bioreactor-based processes (Fig. 2) were successfully developed, with many learnings in process optimisation, and a co-culture biomass was produced (Fig. 3).

2.3 Harnessing photoheterotrophic metabolism to convert methane into biopolymers (2019-2022)

This MBIE Smart Idea ($1M; Scion & University of Canterbury) aimed to develop a biotechnology platform for new methane-derived product markets whilst significantly improving the efficiency of methane bio-oxidation (methanotrophy). The central hypothesis was that light energy can be incorporated into methane gas fermentations, thereby improving metabolic productivity. Through a combination of careful enrichment, bioreaction-engineering and genomic assessment, the project investigated the coupling of aerobic methane oxidation with bacterial anoxygenic (non-oxygen producing) photosynthesis. Utilising light to promote methanotrophy (photomethanotrophy) was shown to be metabolically and practically feasible.

Figure 2: Left, 10 L fermentation bioreactor growing the extremophilic methanotroph (bacterium) at Scion. Right, 80 L photobioreactor growing the extremophilic microalga at University of Canterbury.

2.4 Biofeedstock from indigenous New Zealand extremophilic microorganisms (2022)

This Callaghan Innovation R&D Project Grant ($250 k) was undertaken by Tauhara North No.2 Trust, University of Canterbury and Scion. The scope was to complete preliminary animal trials and test the biomass produced on mice for digestibility.

Figure 3: Biomass used for initial digestibility trials. The left most vial has the microalga, the right most vial the bacterium, and the centre vial has the two organisms grown together (co-cultured) in smaller lab photobioreactors (not shown).

In Phase 1, a limit test was undertaken to identify any acute toxicity effects. No symptoms of toxicity at the prescribed dose rate of 2000 mg/kg were observed and, over the 14-day observational period, mouse bodyweight and food consumption were normal. The organ weights were within normal limits for all samples. The limit test raised no toxicity concerns for each of the biomass types, and thereby allowed Phase 2 (a palatability and digestibility study) to proceed.

Phase 2 was a palatability and digestibility study. Mice were fed co-culture biomass, up to a dose rate of 3000 mg/kg/day for 21 days (Fig. 4). This diet had no effect on their growth, and no adverse effects were observed. At necropsy, all mice looked normal and no toxicologically significant differences were noted for the organ weights, the blood chemistry or haematology. Thus, it was concluded that co-culture biomass was palatable and non-toxic to mice at a dose rate of up to 3000 mg/kg/day. No effects on protein and apparent fat digestibility were observed.

Overall, the results of this study indicated that the extremophile co-culture biomass had no observable negative impacts on a mammalian (mouse) diet – benefits were equivalent to a non-co-culture supplemented diet. These results presented no reason not to proceed with the next steps of the project, including upscaling production for larger animal biofeedstock trials.

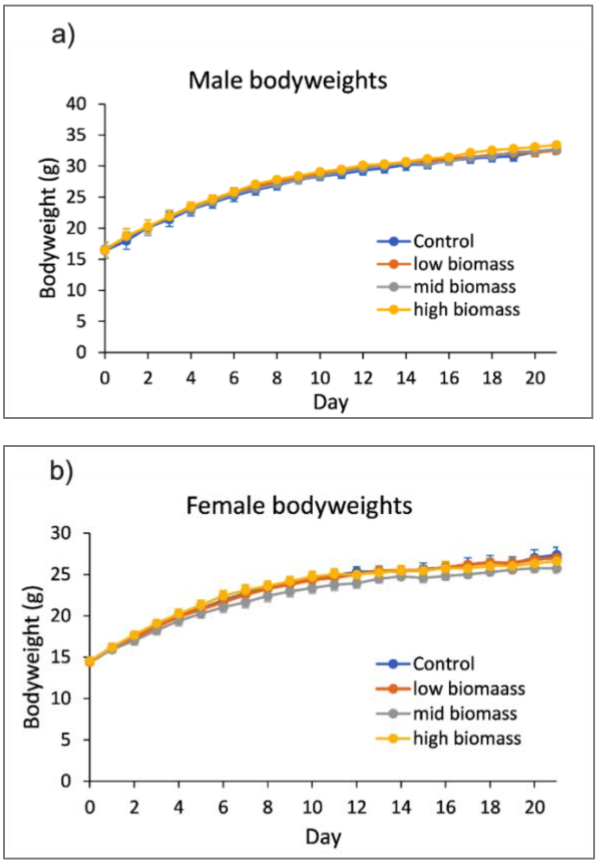

Figure 4: Mice bodyweight results during feed trials (2022).

3. SCALE-UP TO PILOT

3.1 Novel biofeedstocks using indigenous resources (2024-2027)

Having shown the technical viability of generating the biomass at a laboratory scale, and that trials on mice proved the biomass to be non-toxic, digestible, and provided a nutritional benefit, the next step towards commercialisation was to optimise operating conditions and improve yields at pilot scale (ca. 900 L). Animal feed was targeted initially because of the biomass composition. The biomass produced has a total protein content of around 60%, which is high for non-animal sourced feeds (e.g. Batista et al, 2023; Gorissen et al, 2018). Also, the amino acid profile of the biomass contains a high proportion of essential sulphur-containing amino acids which supports tissue growth in animals.

3.2 Drivers

The current project is a partnership between TN2T and the Ministry of Primary Industries (MPI). MPI have provided 50% of the $5M funding through their Sustainable Food and Fibre Futures (SFFF) fund, which aims to drive innovation and problem-solving within the agriculture, food, and fibre sectors. This necessitated that the project focus on food security (rather than geothermal benefits). As such, the SFFF project examines the problem of New Zealand's reliance on imported feedstocks.

- **Increasing Demand**. Demand for high-quality protein is projected to rise dramatically, and as New Zealand feed suppliers and consumers are at the mercy of global trade markets, new sustainable, non-traditional protein sources are needed. Human food, livestock feed and (more recently) biofuel production will all compete for a relatively small pool of surplus product.
- **Volatility of Supply and Price.** NZ livestock systems are reliant on internationally produced feed, thus are exposed to risks associated with disruption in international trade, fluctuations in global prices, quality and composition of imports, as well as increasing instability in feed supply due to the effects of climate change on traditional growing locations and geopolitical issues also affecting access. This represents a risk to profitability and sustainability of the primary sector.
- **Emissions Reduction.** There is increasing demand from customers for greater transparency on where and how food is produced, including the size of carbon footprints and environmental impacts of food systems. This is driving food manufacturers and retailers to support low-carbon production, meaning animal feed processors, distributors and agriculture/aquaculture farmers will need sustainable alternatives to carbon-intensive importation. Scope 3 emissions can account for 90-95% of a food manufacturer's emissions [Best, 2022; Deloitte, 2023], which are hard to calculate and, given a food manufacturer works with numerous suppliers, can be difficult to address and reduce.

3.3 Vision

The project aims to address these challenges by locally producing a biomass that can be incorporated into feedstocks. For feed distributors and animal feed purchasers, our aim is to produce a local, competitive offering that also supports decarbonisation targets. This indigenous source of protein won't rely on scarce arable land and water resources nor compete with human food production. For geothermal power stations and operators (such as TN2T), the production of feedstocks can transform a cost-incurring waste stream (greenhouse gases CH_4 and CO_2) for a positive use. Beyond animal feed, the biomass could be used as an animal feed ingredient (biofeedstock), for human nutrition, and, perhaps, to produce high value nutraceuticals or pigments. Long term, the business model could be to produce biomass at the same location as commercial geothermal operations (as geothermal is a location-specific energy source), and then supply this material to distributors. The technology could be rolled out across New Zealand's geothermal network, whose operations provide ready access to low-carbon electricity, methane, carbon dioxide, water, and heat. There may also be international uptake, creating new NZ food export markets without the carbon emissions burden of transporting product.

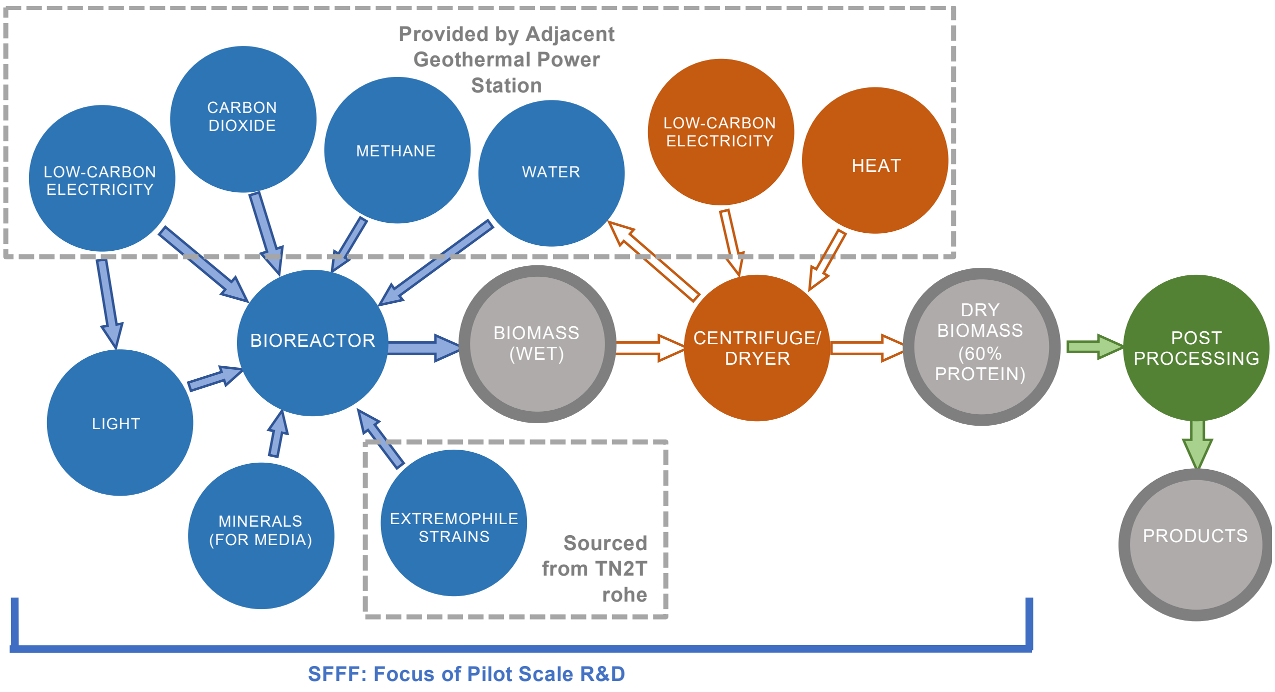

Figure 5: Conceptual process diagram. Geothermal operations provide ready access to low-carbon electricity, methane, carbon dioxide, water, and heat. The biomass will be produced on-site, adjacent (within the same land blocks) to the geothermal power station and associated infrastructure.

3.4 Conceptual Model

The concept is that, commercially, the biomass could be produced on-site, co-located with a commercial geothermal facility (i.e., power plant, infrastructure, and steam-field) and then distributed to feed manufacturers. The geothermal facility would provide ready access to necessary process inputs (on a commercial basis, with financial models to be explored), including low-carbon electricity, methane, carbon dioxide, water, and heat (Fig. 5).

3.5 Project Plan

The biomass is not yet a market-ready product, nor has the technology platform been proven at an industrially-relevant environment or scale. We are developing a new product using a novel process that requires a new technology platform (incorporating bioreactors, gas handling equipment and post-processing). The technology platform will include elements of a fermentation bioreactor (for growing the methanotroph) and photobioreactor (for growing the phototroph).

This pilot programme is structured into five parallel, integrated and complementary workstreams (Fig.6).

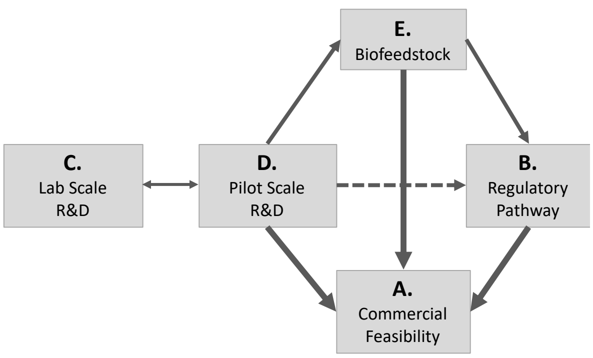

Figure 6. Programme structure.

Workstream 1: Commercial Feasibility

Intended outcome: Business and market analysis proves commercial feasibility and viability which justifies further scale up and continued commercialisation.

This workstream will determine market pathways and opportunities, including exploring agriculture, aquaculture, and the potential for human nutrition and premium products. Ongoing market research and analysis will provide information on products, customers, and competitors, etc. Concept-level techno-economic and financial estimates and analyses will be refined and extended. The scale-up of protein feedstock production to mass production and the economic sensitivity of the production process will be evaluated.

Workstream 2: Regulatory Pathway

Intended outcome: Data and supporting information are collected to progress approvals for regulatory requirements.

We do not expect to have a fully approved animal feed / human nutrition ingredient by the end of the programme. Initially, we will scope the regulatory requirements for production of an animal feedstock (and human nutrition if appropriate) and position the project to align with the requisite regulatory processes. We will initiate partnerships and collate necessary data and supporting information that will be required for future regulatory approval(s).

Workstream 3: Lab Scale R&D

Intended outcome: Scaling factors verified, process model is validated, and troubleshooting undertaken to support pilot R&D.

Ongoing laboratory-scale R&D will support the pilot scale studies (Workstream 4). Initially, the bioreactor configurations will be tested at a lab scale, including geothermal gas pre-conditioning tests and verification of scaling factors. A process model (digital twin) will be developed, and lab-scale R&D will be utilised to validate this model, troubleshoot operating conditions, and undertake supporting studies.

Workstream 4: Pilot Scale R&D

Intended outcome: Operating parameters are explored to maximise biomass yield at pilot scale in an actively operating pilot plant.

A pilot scale bioreactor facility (ca. 900 L) will be designed, built and operated to learn what is necessary to progress to the next scale of development. The bioreactor will be designed to tune methanotroph/phototroph growth ratio, gas, light, and heat consumption. The process will be operated under site conditions, as well as sensitivity testing conducted to promote product output and maximise yield. The pilot facility will produce larger quantities of protein stock for testing on larger, commercially-farmed animals and/or fish (Workstream 5).

Workstream 5: Biofeedstock

Intended Outcome: Nutritional value of biomass demonstrated, and product-market fit identified.

Working with industry partners, we will determine how the biomass measures up to comparable products. We will undertake functional testing of the biomass and explore potential uses and values for other components of the biomass (e.g., amino acids, carbohydrates, insoluble fibre, pigments). We will explore post-processing options and economics, to achieve target feed composition and characteristics. Trials will be undertaken on target animals (e.g., toxicity, digestibility, palatability, nutritional value) to ensure nutritional and health benefits on target animals. This will inform the target market (Workstream 1), and gather high level target market data.).

3.6 Market Insights

Concurrent with technical development, we are evaluating target markets and pathways to these markets, including regulatory requirements and analysis of the techno-economics. Product-market fit underpins the development of the commercial pathway (Fig. 7).

Therefore, a core component of the programme is involvement of industry sector partners, such as Ingham's (poultry). As we move through the programme, and in parallel with the technical workstreams, industry partners will be critical to guide us through their market spaces. This will provide insights into product needs, nutritional requirements, competitive options, decarbonisation demands, market specific regulatory processes, etc. These relationships will ensure we ultimately select the best product-market fit for our technology. This approach means that we will invite partners from different sectors.

4. LEARNINGS

4.1 Overcoming hurdles

This programme has been over a decade on a R&D journey thus far. Key hurdles to be overcome have included:

- **Overcoming the funding challenge**. TN2T have been a supporter of this work for many years. Government funding is critical to bridge the gap between research and commercial-ready offering, and to help de-risk investment in scale-up. But New Zealand's options in this area are limited and securing funding is a slow process. It is important to undertake targeted R&D, and to continue to fund innovation, to sustain capabilities, future-proof and to build NZ's resilience.
- **Assembling equipment and expertise**. New Zealand has a relatively small, but growing, biotech sector, especially in precision fermentation and bioprocess engineering – which are our areas of interest. The project involves Scion, the University of Canterbury and Cawthron, and we have contracted in specialist expertise, in order to access the skills of people and equipment. We are also learning from industry partners in New Zealand, and international examples and operations where possible.
- **Process design**. We are still deeply in the process of finalizing the design for the pilot scale reactor. This involves bringing together insights and constraints that arise from new lab-scale testing, process modelling, consulting with experts, working with manufacturers and more.

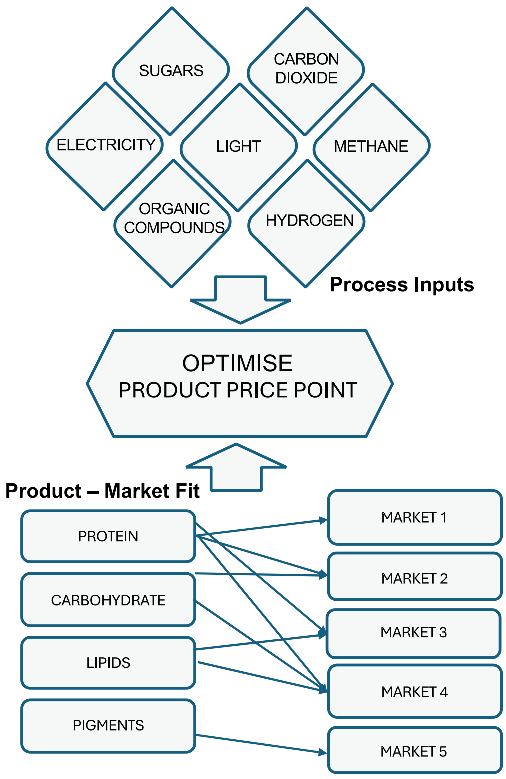

Figure 7: Product-market fit.

4.2 Research Findings

The project in still in its early stages and most of what has been learnt during this phase is commercially sensitive and confidential. However, we can say that we are:

- Learning about the challenges of capturing and processing the waste gases from geothermal power stations so that they can be used for this process and developing cost effective methods to do this at pilot scale;
- Designing a pilot-scale production plant which we hope to build and operate during later phases of the project; and
- Working on how to identify and optimize high-value components / compounds that could be in the

biomass produced by the process and connecting these to potential end-users.

- Investigating advanced techniques for extremophile preservation, revival and maintenance.

6. CONCLUSION

Our long-term vision is to produce a commercially viable, low-carbon product which provides some additional value-add or advantage to end users. By undertaking the current programme, we also aim to understand more about taking this technology from a lab-scale concept into a market reality. That will include proving that the technology works at scale and progressing a plan to bring the product(s) into market. One of the targeted outcomes of the project is to support a future industry beyond just the immediate project. The hope is to create knowledge and IP that can be used for, and by, the wider industry.

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