Shell

TechXplorer Digest

2022 Volume 1

WOMEN IN TECHNOLOGY

A sustainable packaging life cycle

Wind and sun power Malaysian wellhead

Lubrication for a hybrid future

INTRODUCTION

Welcome to *Shell TechXplorer Digest*, a publication that showcases the breadth and depth of scientific research and technology applications within Shell by presenting a selection of articles originally published in *Shell TechXplorer*.

Shell TechXplorer was created to report advances in the development and deployment of key technologies to as many interested people as possible within Shell. Most of the articles are written by the Shell scientists, engineers and technicians who have worked on these technologies.

Shell TechXplorer is a strictly internal-only magazine, however. *Shell TechXplorer Digest*, in contrast, provides a medium through which the authors can communicate their achievements to a wider readership.

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DOI: 10.52196/208316.22.1

Published July 2022

Cover image

Thanks to Shell colleague Andrea Patton for the cover art, *Storms a comin'*: "First, there is the power of the Wind, constantly exerted over the globe ... Here is almost incalculable power at our disposal, yet how trifling the use we make of it! It only serves to turn a few mills, blow a few vessels across the ocean, and a few trivial ends besides. What a poor compliment do we pay to our indefatigable and energetic servant!" (Henry Thoreau). You can see more art at Andrea's website.

About the journal
To guide the reader, the articles are labelled according to the four stages of technology maturation: Are there potential capabilities to **DISCOVER**? Or do the technology's capabilities need to **DEVELOP** further? Is it time to **DEMONSTRATE** its capabilities? Or is the technology tried, tested and ready to **DEPLOY**? Like Shell's strategic themes, the articles are also grouped according to whether they contribute most to the **Upstream**, **Transition** or **Growth** businesses.

Upstream

- DEEP WATER
- SHALES
- CONVENTIONAL OIL AND GAS

Transition

- INTEGRATED GAS
- OIL PRODUCTS
- CHEMICALS

Growth

- ELECTRIFICATION

Foreword

"Creating an inclusive culture is our collective responsibility, so I encourage everyone to become an active agent of change."

We should all care about diversity, equity and inclusion. A diverse, fair and fully inclusive workplace allows our employees to flourish, and that, in turn, helps our business to flourish. Across Shell, there is a continuing focus on valuing differences and driving greater equality within our workforce, and what follows in these pages is proof of that.

In this women in technology edition of *Shell TechXplorer Digest*, you will find numerous examples of women leading and participating in vital technology research, development and deployment. These projects range from work on solar- and wind-powered offshore operations (p. 9); subsurface storage of CO_2 and hydrogen (p. 47); reducing the net carbon footprints of Shell's energy products (p. 33) (p. 36) (p. 60); and on to digital technologies for data-driven operations (p. 24).

It is great to see such a clear picture of the depth and breadth of the work by Shell's women scientists, engineers and technologists. I want Shell to continue to foster an environment in which all our colleagues are encouraged to present their points of view. It is only by hearing those courageous voices that we can fully identify the challenges before us – and then tackle them. This applies to the balance of our teams just as much as it does the energy transition. Technical know-how, innovation and ingenuity are critical in every part of Shell, whether this is in our traditional businesses or in the new businesses we are growing. We are going to need everyone to bring everything they can to their work, given the incredible changes we face as the world moves to a low-carbon energy system.

This is why it is vital for our community of women engineers – and I include myself – to challenge gender stereotypes and break any biases wherever we come across them. Creating an inclusive culture is our collective responsibility, so I encourage everyone reading this to become an active agent of change. There is still much work to do, but I see positive signs of many strong, balanced teams, not least in this excellent issue. There is so much more we can achieve together.

Zoë Yujnovich
Upstream Director, Shell

The graphic flags the starting page of a referenced article. If you are reading the foreword on screen, you can just click on the graphic to go there.

CONTENTS

RECOGNISING THE INDIVIDUAL:

PROMOTING DIVERSITY AND INCLUSION

Shell is an innovation-driven global group of energy and petrochemical companies with a profitable Renewables and Energy Solutions business. However, to thrive in the energy transition, we must continue to evolve. Decades of research have shown that having a diverse and inclusive workforce is good for business. By embracing diversity and inclusion, we can become more innovative, agile and competitive, and attract a wider variety of stakeholders. All of which helps us build a low-carbon future and improve the "triple bottom line": people, planet and profit. Our success depends on ensuring that everyone across the organisation knows that they are valued and respected.

Closing the gender gap

Supporting the aims of Shell's Closing the Gender Gap in Engineering and Technology campaign, a year-long drive to accelerate gender balance, in 2022, Shell's internal technology magazine, presented a women-in-technology-themed edition. The enthusiasm among Shell's women scientists, engineers and technologists to be part of this was so great that, for the first time in its history, *TechXplorer* was expanded to two volumes on a single theme. The articles published in this special edition of Digest are drawn from those volumes.

The Shell campaign reflects a key purpose of the human resources function in Shell: to ensure that effective strategies are operating in all areas of people management. This covers everything from hiring practices that ensure we find the best candidates and select on merit through to supporting employees along their chosen career paths.

Throughout onboarding and employee development, human resources' focus is on understanding an individual's needs and potential to contribute. Through this understanding, we help employees maximise their performance and productivity and achieve personal goals. By building detailed diversity and inclusion profiles for the individual and for the organisation, we help ensure that the talent Shell attracts is nurtured, rewarded and retained.

Beyond this, employees need to see that business strategies are being shaped by diverse voices. When they do, there is greater chance of their support and agreement for implementing those strategies.

When individuals with different experiences and different approaches are represented in strategic, advisory and oversight roles, the "silo mentality" and other barriers to fresh thinking can be overcome and knowledge management strengthened. Diversity and inclusion improve problem-solving and help encourage the innovation on which Shell thrives.

In human resources, we want to improve objective decision-making processes for individuals by overcoming workplace biases and promoting inclusive environments that offer equal opportunities for all. Diversity and inclusion is a complex area and, though creating a diverse workforce is important, it is not the destination. Maintaining meaningful diversity and inclusion requires continuous effort, commitment at all levels and careful monitoring.

- Effort means valuing and celebrating the individuality of every employee, rather than allowing differences to marginalise people.
- Commitment means adopting business strategies that identify and support the needs of employees throughout their careers.
- Monitoring means being ready to challenge business practices that undermine our stated values and lead to inequitable treatment of employees.

Searching for new energy: Shell's role in the energy transition

The global population is rising and so is the demand for energy: the world needs more energy and less carbon dioxide. Many people still think of Shell simply as an oil and gas producer, but the reality is that Shell is shifting the focus of its energy businesses.

Our aim is to meet the energy demands of society in ways that are economically, socially and environmentally viable, now and in the future. This will be done by:

- reducing emissions from our operations, and from the fuels and other energy products we sell to our customers;
- building a profitable Renewables and Energy Solutions business;
- researching and developing innovative low-carbon energy solutions and products; and
- working collaboratively with governments and non-governmental organisations.

We are at the forefront of developing new technologies and infrastructure for achieving net-zero emissions, purposefully and profitably, in step with society (see Figure 1). Our purpose is to Power Progress Together by providing more and cleaner energy solutions. This is underpinned by our core values of honesty, integrity and respect for people, as well as our focus on safety.

Shell offers a large portfolio of positions. There are opportunities in engineering, research and development, and techno-commercial roles in our core businesses: Downstream, Integrated Gas and Renewable Energy Systems, Upstream and Projects & Technology. All our businesses are supported by functions such as the human resources, finance, contracting and procurement, information technology and legal departments, each with its own portfolio of positions. We also have career opportunities in marketing and trading in every major energy market around the world.

Shell's strategic ambitions – to be a world-class investment case; to lead and thrive through the energy transition; and to maintain our societal licence to operate – require the best ideas and the highly motivated and engaged people who can deliver them. The articles presented here provide an excellent showcase for recent technology contributions by women in Shell and underline the value and vital importance of diversity in all areas of business, including in scientific and technological endeavour. ■

More information
Shell Career Homepage
www.shell.com/careers.html
Shell Graduate Programme www.shell.com/careers/about-careers-at-shell/shell-graduate-programme.html
FAQs www.shell.com/careers/contact-careers-and-faqs.html

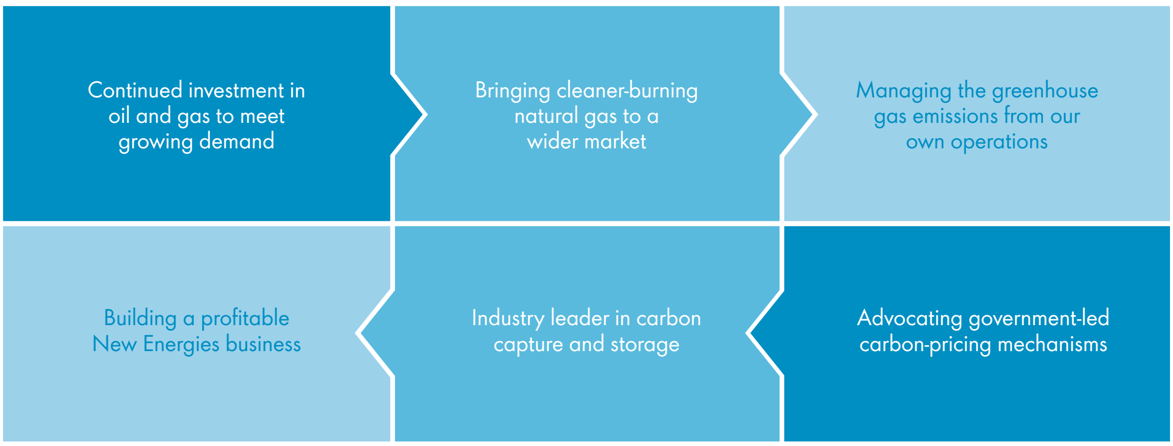


FIGURE 1
Shell is working to meet the energy challenge by shifting the focus of business activities towards a low-carbon future.

HOW IS MACHINE LEARNING CHANGING THE GAME FOR MATERIALS SCIENCE RESEARCH?

Materials science is a broad, interdisciplinary subject that covers the physics and chemistry of matter, engineering applications and industrial manufacturing processes. The influence of materials science is far-reaching, and the developments that come from it make vital contributions in areas as diverse as nanotechnology, quantum computing and energy-storage batteries. A recent trend towards closer collaboration with computational science is having a profound impact on materials science research.

Traditionally, material discovery, synthesis and selection have been driven by experimentation, and researchers have had to deal with a large number of unknowns. However, Shell's computational science team has been working with experimentalists to develop powerful artificial intelligence (AI) systems that help researchers focus their efforts on a smaller number of more likely solutions.

Machine learning from materials databases can accelerate the design and discovery of new materials by developing accurate, computationally inexpensive models that predict material properties without the need for experimentation. These systems work by predicting structure-property-performance parameters from foundational physics and chemistry computations. This could revolutionise the workflow for materials science and enable researchers to rapidly screen materials, narrow the search space and find solutions faster.

External programmes such as the US Materials Genome Initiative and Shell activities such as our company-wide database for hydrocracking catalysts are making it easier to access high-quality information from material database repositories. Such developments provide the foundation for conducting digital-data-based materials exploration using machine learning methods.

Even when size seems restrictive, machine learning can help change the game.

Still, the field of applying AI to accelerate materials discovery contains challenges. The materials data sets describing functional properties are typically small, which creates issues relating to interpretability and transferability, as conventional machine learning approaches work best when they have access to large data sets.

Shell's computational science team has collaborated with scientists from the Jawaharlal Nehru Centre for Advanced Scientific Research and the Indian Institute of Science to address the small database problem. They have developed workflows that integrate statistical methods to uncover latent variables that make the models interpretable and explainable, and optimisation algorithms that make them applicable across data sets and provide interpretability of the modelled outcomes.

With these workflows, our catalyst researchers in our long range research department could identify the relevant characteristics required for electro-catalysts that promote CO_2 reduction to chemicals. Moreover, recently developed deep-learning algorithms can predict the properties of materials such as alumina catalysts; characterise the mechanism for the direct conversion of methane to value-added chemicals; and improve our understanding of the effects of electric fields on catalysis.

Collaboration across disciplines is becoming a norm in technology development, not least when researching the low-carbon technologies that will enable a net-zero future. Even when the size of data sets seems restrictive, machine learning can help change the R&D game.

For further information please contact Suchismita Sanyal (general manager, manager, computational science at Shell Technology Centre Bangalore, India). ■

UNMANNED WELLHEAD PLATFORM powered by a solar–wind hybrid

Shell Malaysia Exploration and Production (SMEP) is determined to make a significant contribution to Shell's commitment to a sustainable future and ambition to reduce its carbon footprint to net zero. This journey began with the Gorek platform (Figure 1), a minimal facility wellhead platform fully powered by solar energy. Following that success, SMEP is now embarking on a journey to power its Timi wellhead platform development using a hybrid power system utilising solar photovoltaic panels and wind turbines.

FIGURE 1
SMEP's first fully renewable-energy powered offshore platform, Gorek, achieved its first gas in May 2020.

Introduction

SMEP's older, unmanned wellhead platform designs were powered by combustion-based equipment such as microturbine generators. That method of power generation is no longer an ideal solution for more sustainable development due to its carbon dioxide emissions. Additionally, conventional power generation systems are complex to design and have high capital and operating expenditure because of the number of equipment items required and the corresponding wear and tear.

A renewable energy arrangement powered by solar and/or wind energy in combination with batteries and standby diesel engines is fast becoming the system of choice for oil and gas operators to power their offshore wellhead platforms. For example, in the North Sea, Shell operates 13 offshore platforms that use hybrid power systems. Of these, eight monopile platforms, including Caravel, Cutter, L09-FA, L13-FI-1 and Shamrock, use a solar–wind hybrid system.

Such systems do not produce any direct greenhouse gas emissions in normal operation, as the diesel engine is in standby mode. They are also less complex to design, operate and maintain than conventional systems. Moreover, because they require the installation of minimal equipment, the resulting platform designs are lighter and the capital expenditure is lower.

However, the biggest challenge for any operator wanting to develop a platform with a renewable energy system is the reduced power available compared with conventional power generation methods. Even given recent developments in solar-panel technology, the conversion efficiency of the panels is 18–22%. Therefore, an 80-m^2, 14-kWp solar photovoltaic array must be installed to generate the 25 kWh/d required to supply the load and charge the batteries during the day in the worst-case solar insolation conditions.

Installations further from the equator also have to deal with reduced winter sunlight hours when calculating solar panel and battery size. A realistic amount of power that a hybrid system could supply for an offshore wellhead platform is only a few kilowatts. The challenge is to design the facility to be able to operate within this power limitation. ▸▸▸

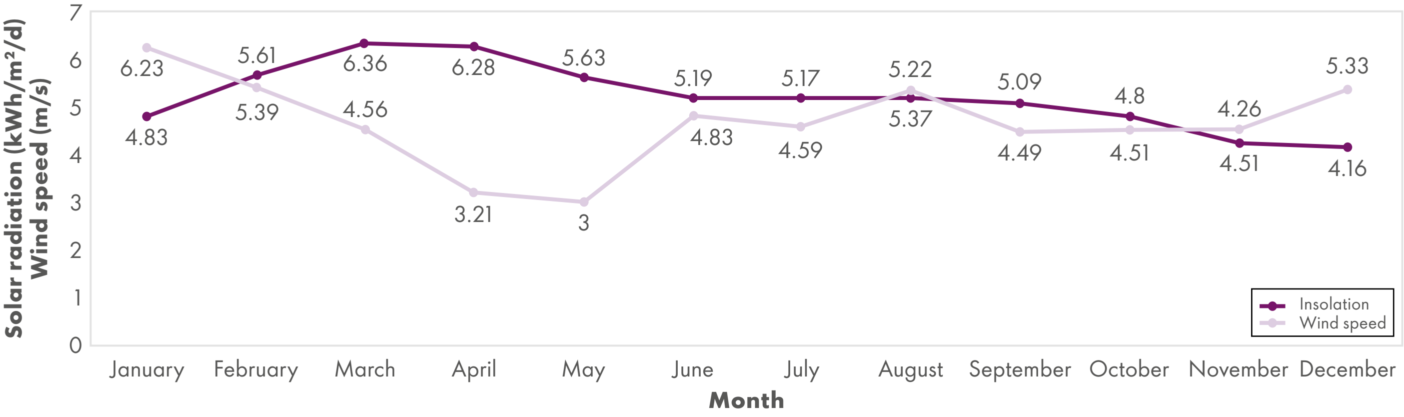


FIGURE 2

Insolation and wind speed offshore Malaysia. These data were obtained from the NASA Langley Research Center Atmospheric Science Data Center [Ref 1].

Wind energy in Malaysian waters

Although the utilisation of wind energy has grown significantly over the past decade in regions such as the USA and Europe, interest in wind energy is still insignificant in Malaysia. According to wind data from NASA, the average wind speed in the waters offshore peninsular Malaysia and Sabah and Sarawak states is 3–6 m/s [Ref 1]. This is considered relatively low for efficiently producing wind energy, which discourages its uptake in this part of the world. However, technological advances in wind turbine technology have led to wind turbines that can work in low wind speeds now being readily available on the market: an example is the Airdolphin from Zephyr. Such turbines have been proven in operation in various offshore oil and gas installations in South East Asia.

The climate in Malaysia

Understanding local seasonal climate change and energy patterns is critical to the efficient design of a renewable energy system. In Malaysia, the eastern part of the country is directly affected by the north-east monsoon, and the country typically experiences heavy rainfall in November, December and January.

During the monsoon season, the wind is normally stronger and solar radiation is at its lowest. However, during the dry season, insolation is at its maximum while wind energy is at a minimum (Figure 2). The mutually exclusive nature of these energy sources can be effectively exploited using a hybrid power system [Ref 2]. In such a system, and depending on the solar panel and wind turbine sizing and configuration, the battery autonomy time and therefore size can be reduced. This is what is envisioned for the hybrid power system for the Timi wellhead platform.

The Timi field and platform

Timi, a sweet gas field, was discovered in 2018 and is part of the SK318 production-sharing contract. Sarawak Shell is the operator and holds 75% of the equity; the other partners are PETRONAS Carigali (15%) and Brunei Energy Exploration (10%). The field will have a new, unmanned wellhead platform tied back to an existing Shell-operated hub platform via

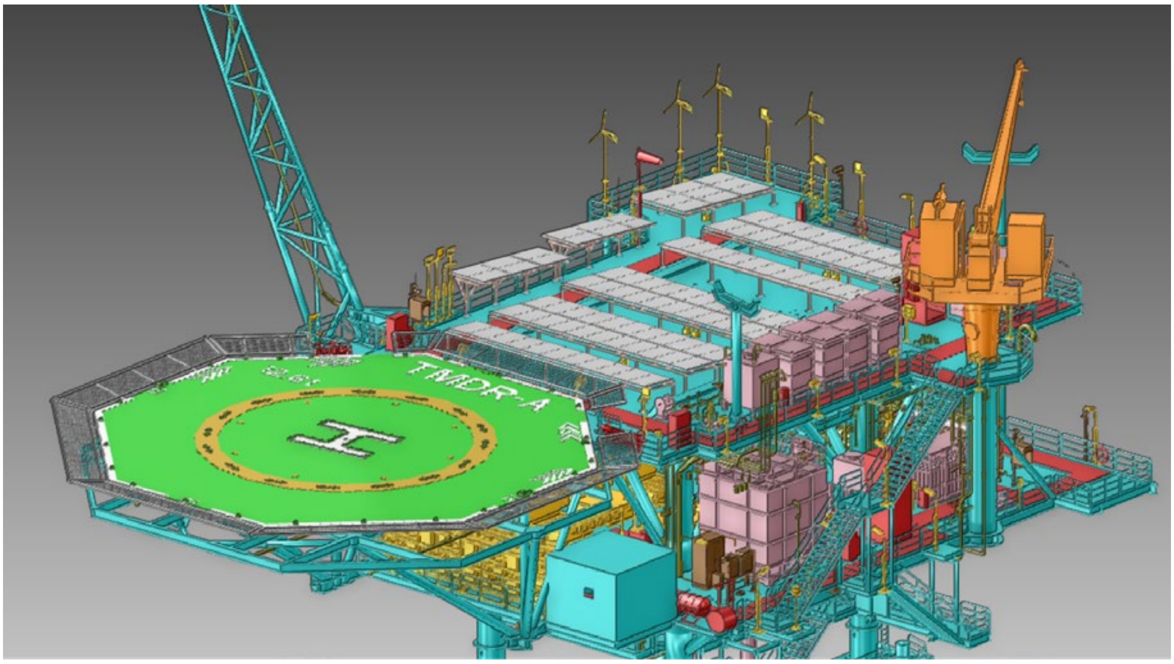


FIGURE 3

3D model of the Timi platform.

a new 80-km pipeline. Figure 3 shows the proposed wellhead platform arrangement: the Timi unmanned platform is about 60% lighter than a conventional tender-assisted drilling wellhead platform.

The Timi hybrid power system

The Timi wellhead platform will be the first in SMEP to be fully powered by a solar–wind hybrid power system. Figure 4 shows an overview of the hybrid system. The arrangement of the solar panels and wind turbines on the main deck is shown in Figure 3.

The solar panels and wind turbines will supply power to all normal loads such as the safety instrumented system/fire and gas system, the process control system, telecommunications, the wellhead control panel, hydraulic pump motors, chemical injection pump motors, helideck lighting and wells equipment. The total daily energy demand will be 73.6 kWh, which corresponds to an average load of 3 kW. Standby power will be supplied by a diesel generator rated at 40 kWe. It is planned to run the standby generator once a month during a maintenance visit to power AC loads such as the diesel and vent knockout pump motors, lighting and crane auxiliaries.

The AC battery chargers will be energised when required during abnormal operating conditions, for example, when the battery voltage falls below the defined minimum level. Nickel–cadmium battery technology was chosen because the battery chemistry is robust to temperature variations. More modern technology such as lithium ion batteries requires better control of temperature and, therefore, of heating and ventilation, which increases the power required.

Design considerations

Several factors were taken into consideration to ensure the optimum design of the hybrid energy system for the Timi platform. For example, all sensitive equipment, including batteries and controllers, will be installed in a shaded area below the main deck (Figure 5) to avoid performance degradation due to direct exposure to sunlight.

The solar photovoltaic panel frame supports are designed for a maximum wind speed of 33 m/s, which is much higher than the typical maximum 10-min wind speed of 20 m/s experienced in Malaysian waters in recent years. They are also demountable to facilitate the removal of solar panels during a well intervention campaign offshore, if required. Higher-efficiency solar photovoltaic panels were selected to reduce their footprint and weight, and a solar panel tilt angle of 5°, instead of the 15° specified in the Shell ▸▸▸

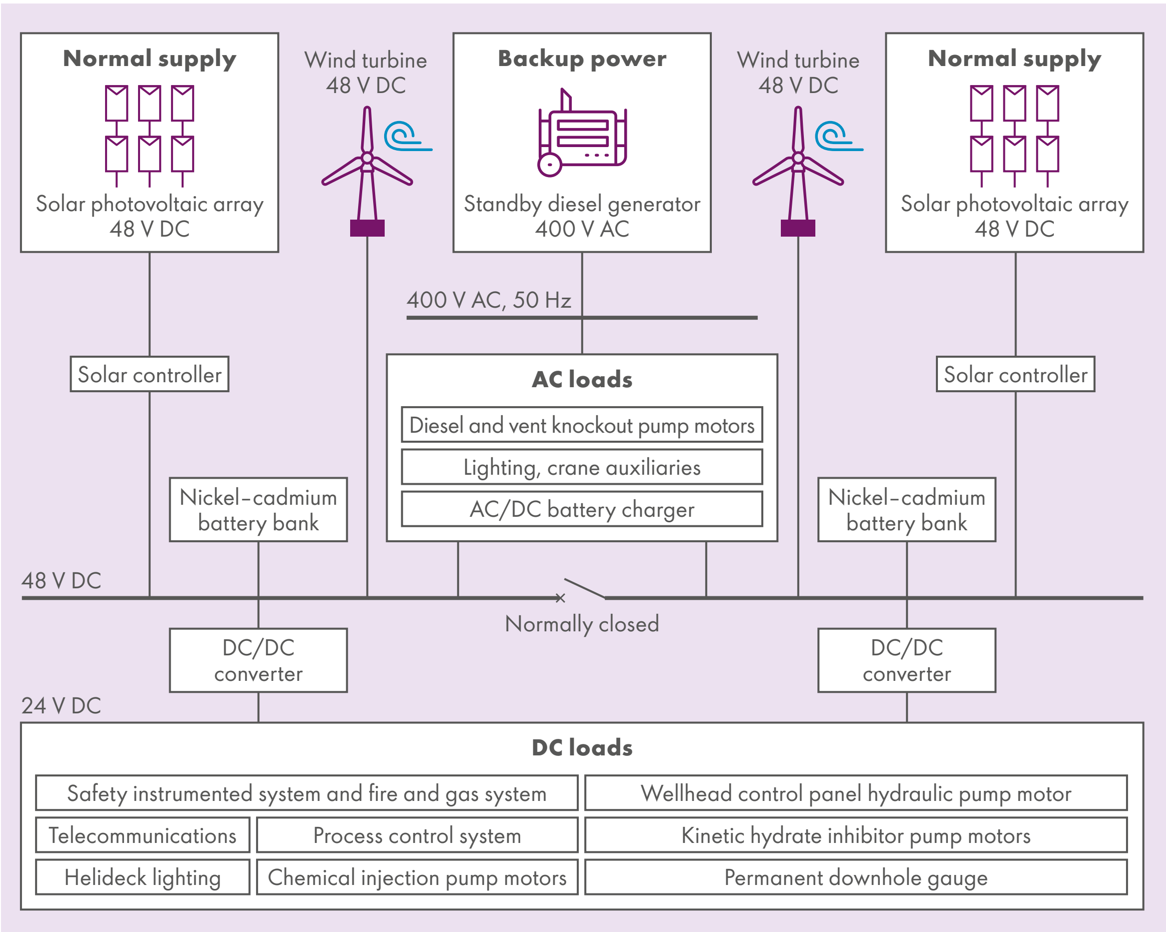


FIGURE 4
Timi hybrid system overview.

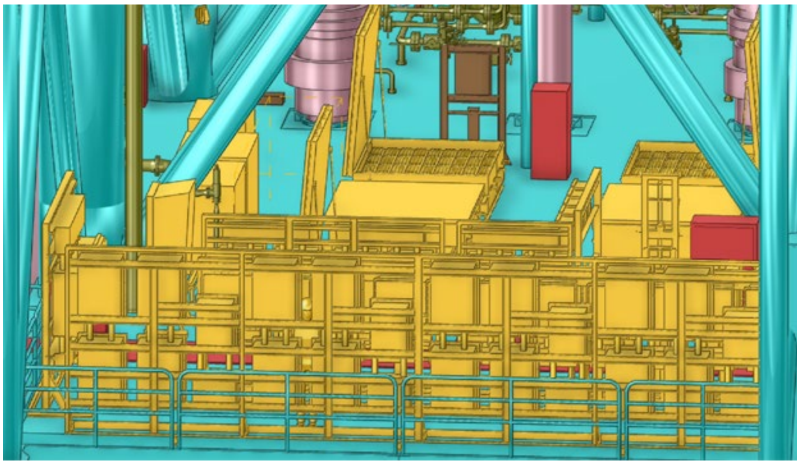


FIGURE 5
3D model of the electrical equipment on the cellar deck.

design and engineering practice for solar energy installations, will be used for better optimisation of insolation.

A higher voltage, 48 instead of 24 V DC, will be used at the power generation level to reduce the size of the cables and batteries and the number of controllers required.

A solar-powered platform in this region is normally designed for an autonomy of 5 d to cater for the cloudy days during the monsoon season. However, the wind speed is then typically higher, which makes up for the solar power deficit. Therefore, a 4-d autonomy was selected for Timi, which results in a smaller battery footprint and lower overall weight.

As another level of assurance, the standby diesel generator will automatically start when the battery charge level is low and will simultaneously power the platform and charge the batteries.

Finally, electrical parameter remote monitoring and automatic or remote control, combined with data trend monitoring from the host platform, will improve system availability, thereby reducing platform visits.

Conclusion

Understanding a specific location's climate conditions is crucial for determining what kind of hybrid system is most suited for that location. A hybrid power system offers a promising solution for an offshore unmanned wellhead platform for several reasons. It produces cleaner energy, is less complex and therefore easier to operate and maintain, and has a smaller footprint than conventional systems. Compared with the alternatives, it means reduced battery size, improved battery charging performance during the night and bad weather, and lower weight and capital and operating expenditure. Moreover, the system can improve overall power generation reliability during seasonal climate changes, such as the monsoon season, in Malaysian waters. ■

REFERENCES

[Ref 1] NASA, "The POWER project," power.larc.nasa.gov

[Ref 2] Hamdan, M. F., Yasir, M. F. and Kamal, A. F. M.: "Wind turbine hybrid – future small power generation for small field," Offshore Technology Conference Asia (2018) 174–179

AUTHOR

Azwin Jeran joined Shell in 2006. She is the electrical lead for projects including Timi and Gorek. Previously, Azwin was an electrical engineer for the Gumusut–Kakap project, the first Shell deepwater project in Malaysia. She has BS and MEng degrees in electrical engineering from Rensselaer Polytechnic Institute, USA.

TRAN-
SITION

JOINT CHEMICAL RESEARCH aims to boost sustainability

Chemistry is a crucial area of human endeavour and underpins many aspects of the modern world. It is also well placed to tackle some of the biggest challenges, including climate change and the need for greater sustainability. Recognising this, and the importance of supporting both fundamental and applied research in these areas, AkzoNobel, BASF and Shell have renewed their joint commitment to an advanced chemical research collaboration, the Advanced Research Center Chemical Building Blocks Consortium (ARC CBBC), for the next five years. The consortium strives to be one of the leading knowledge centres in sustainable chemistry in the world. It is committed to developing advanced technologies to solve complex societal challenges related to chemistry and energy demand by developing the sustainable molecules of the future.

Introduction

Shell is a cofounder and active member of ARC CBBC. This public–private alliance was established in 2016 when AkzoNobel, BASF and Nouryon joined Shell and three Dutch universities, the University of Groningen, Eindhoven University of Technology and Utrecht University, to promote further collaboration with universities in the Netherlands. The consortium receives additional financial support from the Dutch Research Council (NWO), the Ministry of Economic Affairs and Climate (Ministerie van Economische Zaken en Klimaat) of the Netherlands and ChemistryNL.

Each industrial partner has a representative on the consortium's Executive Board, and this group is responsible for decision-making on, for example, promising themes for further development. The selection process involves balancing the short- and long-term perspectives and the innovative character of the proposed research plans.

The Scientific Advisory Board provides the Executive Board of ARC CBBC with substantiated recommendations on the project proposals from a scientific point of view. The Scientific Advisory Board consists of outstanding independent academic experts, each a leader in their own field of research. Additionally, experience in collaboration with industry or past performance in the industry is a selection criterion.

The Supervisory Board exercises supervision on ARC CBBC and the Executive Board for achieving the consortium's mission. This board consists of high-level representatives of the ARC CBBC partners and important stakeholders of the consortium in Europe.

You can find out more about the founding members of ARC CBBC at www.arc-cbbc.nl.

Sustainable chemistry and energy research

As a national research consortium, ARC CBBC is open to excellent researchers associated with Dutch universities and knowledge institutions. The key drivers for the consortium are the ever-growing demand for raw materials, pressure to reduce emissions, efforts to increase sustainability across industry and society, and the need to develop new functionalities and properties in materials so they can meet the changing requirements of the world.

A new generation of scientific talent is building the chemistry of the future.

The research at ARC CBBC spans the breadth of the chemical sector and relies on the involvement of the consortium's cofounding companies. Topics cover the entire knowledge chain, from pioneering research on novel chemical (catalytic) conversions through to new processes and products that will help to deliver higher energy efficiency, new routes to existing or novel products, increased use of sustainable and green raw materials, and alternative fuels and additives.

The founding universities play a central role in uniting relevant research teams and capabilities in all Dutch universities. There are two types of projects in the consortium: the multilateral projects are collaborations between at least two companies and academic partner(s); the bilateral projects are collaborations between one company and one or more academic partners. ▸▸▸

Second-term research themes
The consortium completed its first five-year term at the end of 2021 and has now entered the second five-year term. AkzoNobel, BASF and Shell have renewed their joint commitment; Shell's financial contribution to the consortium comes from the Long Range Research Technology Program.

There were three main research themes during the first term: Energy carriers, Functional materials & specialties, and Coatings. These themes continue in the second five-year term; the multilateral projects are being designed to reflect the advances made in the previous term and global developments in technology and knowledge in recent years.

The design of the Coatings multilateral project was completed and approved by the Scientific Advisory and Executive boards in May 2022. A particular focus of this multilateral project is the development of (i) sustainably sourced supramolecular/dynamic covalent coatings and (ii) (responsive) structural colour coating applications. AkzoNobel, BASF and Shell partner in this multilateral project; AkzoNobel is the leading industrial partner.

The two possible multilateral projects that are in the pipeline are (i) Pyrolytic methane conversion, led by Shell, and (ii) Fundamentals of catalysis, led by BASF (see Figure 1).

Additional research themes for new multilateral projects are also being planned in the second term. A plastic circularity project is currently being considered. If it goes ahead, Shell will be the leading industrial partner. Currently, the boards are in discussion on other themes as well.

Also in the second term is a multilateral project, New Chemistries, led by Shell. This project has been carried over from the first term and focuses on topics such as energy generation via electrons or photons, and upscaling polymer materials.

In addition to potentially leading three multilateral projects, Shell will have 20 new bilateral projects (see Figure 1).

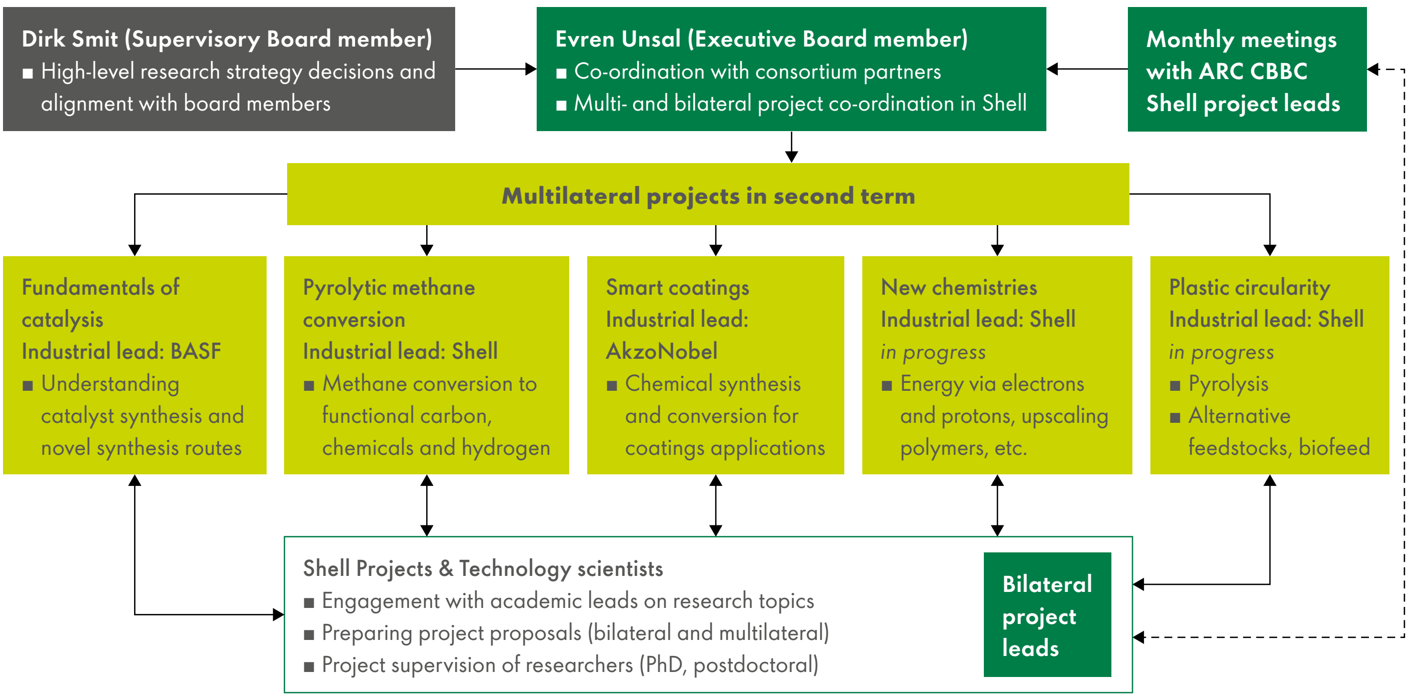
People development and experimental facilities

Currently, there are about 40 high-profile scientists in the Netherlands affiliated with ARC CBBC. These academic experts and the industrial researchers they work with have been developing and fostering new talent in the form of more than 40 PhD and postdoctoral researchers for the last five years. The second five-year term will provide support for more than 80 additional PhD and postdoctoral researchers.

The highly experimental nature of many of the projects the consortium conducts leads to the need to keep up to date experimentally, and the funding has enabled setting up high-quality joint laboratories that reflect the specialities of the three university hubs. These facilities are available for use by other universities and industrial partners.

The research hub at Utrecht University has three fully equipped laboratories including research equipment such as a grazing incidence X-ray diffractometer and an advanced infrared microscope combined with atomic force microscopy. The research hub at Eindhoven University of Technology has also acquired new

FIGURE 1
Shell roles and responsibilities in relation to the ARC CBBC consortium.



instrumentation through consortium funding: its laboratories have magnetic resonance imaging facilities for 3D imaging of fluid flow applications.

The University of Groningen hub opened its laboratory facilities on 13 April 2022; capabilities include photochemistry, chromatographic separation, automated organic synthesis and fluorescence spectrometry.

Strategic importance for Shell

The stakeholders are pushing for Shell to demonstrate its progress in developing and adopting more sustainable solutions in the chemical sector, including increased circularity and greater use of biochemicals. The Downstream business is aiming to create sustainable energy parks on and around established refinery sites.

Shell finds relevance across the spectrum of research conducted at ARC CBBC that aligns with these ambitions. The catalysis research strands are core areas and there are also potential benefits from projects in the materials and coatings strands.

For example, researchers in the materials domain are exploring new catalytic approaches for waste water treatment and energy storage that will reduce the environmental impact of chemical processes.

In coatings, efforts are focusing on making polymer films more durable and curable, and adding functionalities such as fouling prevention that have applications in offshore engineering, pipelines, and shipping and maritime.

For further information on any of these projects or how to access the research capabilities of ▸▸▸

An AkzoNobel perspective on ARC CBBC

André van Linden, Director Coatings Technology at AkzoNobel R&D, explains the role that ARC CBBC fulfils in their research and development portfolio.

Q: What societal and educational roles do you see for ARC CBBC (and other such consortia) in the energy transition?
A: ARC CBBC is a leading Dutch research consortium, and we hope the insights it provides will lead to a quicker and more effective energy transition, as well as material and feedstock transitions, and keep these high on the academic agenda. It is vitally important that young researchers interact with these topics and share new ways forward through their research projects and conference presentations. Involvement with young people and tapping into fresh ideas are some of the major attractions for AkzoNobel.

Q: Why did your company join the ARC CBBC consortium in 2016? What were the initial expectations?
A: We joined for the materials and molecular conversions (and catalysis) parts of the consortium. We are interested in several key areas. The first is new (greener) building blocks and materials that lead us to new (biobased) opportunities by finding value in side-stream materials. The second is enhanced functionalities that could, for instance, reduce material use or deliver enhanced product lifetimes. And the third is projects aimed at replacing materials of concern. Establishing a network that offered direct contact with top Dutch universities and students was another major aim.

Q: Which research and technology topics are most relevant to your company?
A: Our focus is on waterborne coatings with biobased building blocks and on smart coatings with enhanced functionalities. These are the topics that are most relevant to us as a paint and coatings company.

Q: How was the first five-year term? Did expectations or the direction of research change?
A: We were very satisfied with the first term. We kept close and regular contact with all participants, and the outcomes included great scientific insights that will lead to further research or potential use in the products. We have filed three patent applications originating from work in the CBBC projects.

Q: What do you see as the way forward for the second five-year term?
A: We will be following up on the results obtained in the first term and working further on the possibilities with the new chemistries to create smart coatings that offer more than protection and aesthetics. For example, we are very interested in coatings that have self-healing or self-cleaning properties to enhance their practical lifetimes. Our aim will be to take things to higher technology-readiness levels and look for scale-up and pilot project opportunities.

Q: Is there benefit in having academic and industrial partners with different business interests working together?
A: It was, to begin with, a little more difficult than expected. But now we have seen that we can work together to deliver interesting results through joint projects. In the second term the overlap between business interests will become bigger, and that will mean we can do more together. Work at ARC CBBC supports our collaborative innovation programme and helps us communicate the things we are doing around sustainability.

ARC CBBC, please contact the Shell author, Evren Unsal, who is Shell's representative on the Executive Board of the consortium.

See the green text boxes for the perspectives of the industrial partners, AkzoNobel and BASF, on ARC CBBC.

Opportunities for growth in the Netherlands
Through ARC CBBC, Shell connects with leading thinkers and key players in the energy transition. Participating in the funding and subsidy programmes with other consortium members means that Shell can benefit from shared funding, invest in existing facilities and continue to enable upscaling. For example, the Dutch National Growth Fund has earmarked €20 billion ($22 billion) over the next five years for investments for structural and sustained economic growth in the country. A significant share of the growth fund is for supporting research and development relating to the energy transition that will contribute to the country's economic growth in the coming years. With strong ties to the ARC CBBC, Shell is in a strong position to participate in this funding programme.

The benefits of research collaboration can be much greater than the financial ones achieved through the funding programmes. By being a key player in the research partnerships, Shell is well placed to offer resources and facilities to upscale proven research, thereby becoming an active partner in the coming years.

What ARC CBBC means to BASF

Robert Terörde, Senior Research Manager Process Catalysis at BASF in De Meern, describes the significance of the ARC CBBC consortium and some of the benefits derived from this collaborative venture.

Q: What societal and educational roles do you see for ARC CBBC (and other such consortia) in the energy transition?
A: The consortium has projects to help reduce emissions by using carbon dioxide and methane as product feedstocks, projects exploring new energy sources, others to develop more energy-efficient manufacturing processes and some that will improve recycling of materials such as plastics. All of these contribute to improved sustainability and enable us to move towards a lower carbon footprint. The human capital aspect of this is also very important, with excellent research opportunities for the next generation of industrial chemists.

Q: Why did your company join the ARC CBBC consortium in 2016? What were the initial expectations?
A: We wanted to tap into research excellence in areas of expertise that were relevant to our aims but not essential to have within our company. That sort of expertise can be found in academia and that was the case with the CBBC consortium. The approach to establishing the consortium was, I think, unique for the Netherlands. Up front, we sought members based on their skills and track record and the quality of previous research, which was judged by our scientific advisory panel.

Q: Which research and technology topics are most relevant to your company?
A: The consortium was very broadly set up and drew in lots of expertise from different areas. The only thing that was set from the start was a focus on finding "new chemistry". At BASF, our interests initially centred merely on fields such as heterogenous catalysis and coatings-related topics such as printing inks for use in the packaging industry but have widened to the other fields of expertise in ARC CBBC.

Q: How was the first five-year term? Did expectations or the direction of research change?
A: It was great to start such a large programme. We are happy with how constructive the collaboration has been and with the research we have started. For example, the small molecule activation project and projects around improving chemical production are showing great results. But our interests have broadened into areas such as plastics recycling and ways of applying new energy sources. We have found that the consortium is also a place where we can start to examine challenging topics that are more outside the box, for example, finding more direct and energy-efficient ways to go from nitrogen to amines that would involve very different chemistry.

Q: What do you see as the way forward for the second five-year term?
A: We expect to continue with more high-quality research over a wider range of topics. The benefits of having helped to identify and shape the first term of research are that we can build on earlier work, gain even further momentum and train another large group of talented people in industry-relevant research fields.

Q: Is there benefit in having academic and industrial partners with different business interests working together?
A: Yes. There have been both challenges and benefits. There are areas where BASF and Shell overlap, for example, we are both catalyst manufacturers and both interested in transferring methane into hydrogen. This can be a hurdle when setting up a project, but once the scope is chosen and defined, that prevents any potential conflicts of interest. The big benefit for BASF is being able to jointly steer academic projects in the right direction, which really makes them stronger.

Furthermore, the Dutch universities that contribute to the consortium strive for excellence in chemistry education, and students from these institutions are potential recruits for Shell.

Training and support

Shell has been providing support and training to ARC CBBC PhD candidates and postdoctoral researchers. In March 2022, a two-day workshop on industrial reaction engineering and conceptual process design was held at Energy Transition Campus Amsterdam (ETCA). It was organised by Rene Bos (senior principle science expert) and Dominik Unruh (principle process engineer). This course had been delivered more than 20 times at various Shell locations, but this was the first time that Shell had opened attendance to ARC CBBC colleagues, an external audience.

The course focused on the application of theoretical concepts in industrial practice, provided exposure to industrial approaches for defining and solving reactor engineering problems, and examined how chemical reaction engineering concepts can be applied to real-life cases. The course also covered work with key elements and criteria for industrial conceptual process design, including technical reliability; economic attractiveness; compliance with safety, health and environment requirements; and intellectual property aspects.

Shell previously offered another training course to the ARC CBBC community. This focused on intellectual property matters for industrial partnerships.

The way forward

The Netherlands is home to world-class academic research groups in chemistry and physics as well as chemical and materials engineering. World-renowned multinational chemical industries have research and development facilities here, and the country acts as an industrial production site that supplies mainland Europe and beyond.

During its first five years, ARC CBBC has built a strong national reputation for chemical research. Being a founding member of the consortium has created a valuable opportunity for Shell. The alignment of ARC CBBC research programmes with Shell's energy transition strategy and sustainability goals has prompted the company to commit to a further five years of support, during which time it is expected that research activity will continue to grow through ARC CBBC and other external research partnerships.

The recent transformation of Shell Technology Centre Amsterdam into ETCA shows the collaborative approach Shell is taking. This facility has now opened its doors to start-ups, scale-ups, research institutions, academia and companies that want to work together on cleaner energy solutions. Some of the ARC CBBC projects may just be the right candidates for upscaling at ETCA in the near future. ■

AUTHORS

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Robert Terörde is senior research manager process catalysis at BASF in De Meern, the Netherlands, where he leads a process catalysis research group. He started his career at AkzoNobel as section head industrial silicates research. Robert then joined the chemical catalyst research group of the former Engelhard corporation, now part of BASF. He has a PhD in inorganic chemistry and catalysis from Utrecht University, the Netherlands.

André van Linden is director coatings technology at AkzoNobel R&D. He joined Akzo as a researcher and, after roles in laboratory and marketing management for decorative paints in Russia and the Netherlands, was appointed R&D director for decorative paints in North and Eastern Europe. Andre then became global R&D director for many decorative categories and, in 2017, assumed his current role. He is a graduate of Technical University Delft in the technology of macromolecular substances.

In the 1950s, rock 'n' roll played an important role in breaking down racial and cultural barriers. Today, McRock Capital is doing the same in the world of venture capital investing.

MCROCK 'N' ROLL:

STRIKING A CHORD WITH THE INDUSTRIAL INTERNET

The Industrial Internet of Things (IIoT) is transforming industry. But it is connecting more than just machinery; it is also connecting people and purpose. TechXplorer spoke to Whitney Rockley, cofounder and managing partner of McRock Capital, and Rens Valk, investment associate at Shell Ventures, to learn more about how the power of collaboration, diversity and inclusion are driving the fourth industrial revolution.

Imagine the scenario: an offshore wind turbine has broken down. A maintenance crew have been deployed to diagnose and fix it, but they do not know what is wrong or if they have the right parts to fix it. They are also concerned that other turbines may suffer a similar issue.

This is a common situation facing ageing wind farms that often have increasing and unpredictable operating and maintenance costs – a challenge made worse by variations in geography, turbine manufacturer and turbine vintage.

But what if the turbine was fitted with smart sensors that could have diagnosed the issue before it caused the turbine to break down or to need expensive repairs? What if the maintenance crew already knew what repairs were needed when they arrived on-site? And what if the operator knew which other turbines were vulnerable to similar issues and could schedule pre-emptive maintenance?

This is what the IIoT is all about: smart connectivity that enables machines to speak to each other and their operators. Specifically, it enables services such as predictive and prescriptive maintenance, which can help to reduce maintenance uncertainty and costs. By leveraging the power of big data and software analytics, equipment manufacturers are quickly understanding the additional service-based value opportunities offered by the IIoT and the benefits of shifting to more integrated product- and service-based portfolios.

But how do companies that are not digital at heart capitalise on the IIoT and the explosion in software analytics and artificial intelligence (AI)? Although technology is important, digital transformation is also about cultural change that fosters collaboration between equipment manufacturers, digital technology providers and innovation intermediaries, such as McRock. By bridging the gap between equipment manufacturers and digital technology companies, McRock plays a vital – and unique – role in advancing industrial opportunities through the deployment of digital technologies.

Catching waves

McRock is a venture capital business like no other. Cofounded by Whitney Rockley and Scott McDonald in 2012, the Canadian firm is widely known for being the first investment company dedicated exclusively to the IIoT and for its resolute commitment to workplace diversity and inclusion – a cause that sits at the core of everything it does.

The McRock team is small in size but big on impact. With just five core investment professionals based in Toronto and Calgary, the firm is agile and can seize the right opportunities quickly. And it is this agile mindset that drove the firm in its early years. "Before starting McRock, Scott and I had been working together for almost 15 years when we spotted the beginnings of a megatrend in industrial digitalisation," recalls Whitney. "Seeing the impacts of big data, cloud computing and the proliferation of mobile devices on consumers and enterprises made us ask ourselves: 'Will big industrial customers and markets begin to feel the same effects of big data and software? Will they start embedding sensors into their machines and start collecting and analysing the data?'"

Looking around, McRock appeared to be the only investment firm asking these questions. "At the time, we were like surfers paddling out to sea before there were any waves," Whitney remembers. "We were out there so much earlier than any other investment firm, just waiting to take advantage of those waves forming on the horizon. We held a fundamental belief that industrial software companies had real potential to scale quickly and deliver attractive financial returns for our investors." In fact, McRock was so early to the party that terminology to describe the trend did not even exist, so they coined it themselves – the industrial internet, which soon became the IIoT.

Ten years on, McRock is considered a specialist and thought leader in the field of IIoT investing. Across two funds, it has developed an extensive network of corporate and financial partnerships, including Shell, Cisco, Caterpillar, Mitsubishi, and AspenTech, and holds $200 million of capital under management focused primarily on city infrastructure, the energy and mining sectors, manufacturing, supply chains and logistics (see Figure 1).

When it comes to managing their funds, McRock has a hands-on approach. "We love to back founders and invest alongside other institutional investors," explains Whitney. "We are very active with our portfolio investments, so we only invest in a select number of high-potential companies – a maximum of 10 to 12 per fund. We work hard with each of them, as we believe that we can help every entrepreneur in our portfolio to be wildly successful."

Walking the walk: Diversity, inclusion and a pinch of fun

Investing in the right technology has been instrumental to McRock's success. However, investing in the right people has been equally as, if not more, important. For the company, human capital is the most precious resource and one that is at its most potent when there is diversity of opinion, experience and perspective.

McRock lives by its mission to "change the world through responsible investing". And part of this responsibility is to ensure that its own team, and all the teams it works with, act with humility, kindness and integrity. "The awareness and the empathy that we have developed individually, and as ▸▸▸

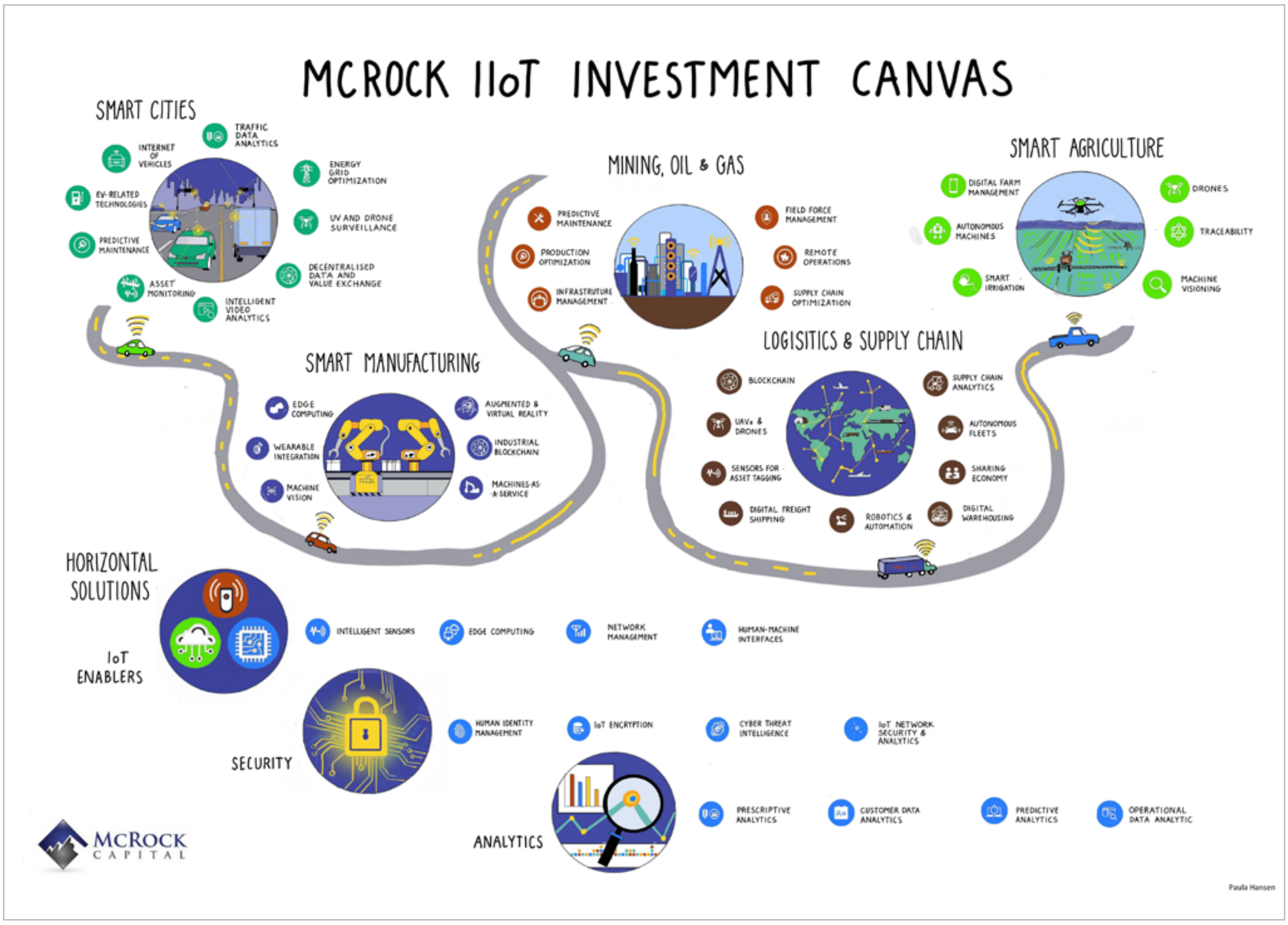

FIGURE 1
McRock's responsible investing IIoT canvas.

an investment firm, have very much formed the foundational values that guide our success and vision," notes Whitney.

Indeed, it was a moment of humility that led them on the path that would shape what McRock is and what it stands for today. "Raising institutional-grade funding can be a humbling experience," says Whitney, openly. "In the early days, we had an opportunity to secure investment for our first fund (Fund I) from Bank of America Merrill Lynch (now BofA Securities). We did not get their money. However, they did ask us to perform an interesting exercise: to look back at all the companies that Scott and I had invested in throughout our careers and examine the ethnicity and gender of the teams. The data were clear: the most diverse teams had the strongest financial performance."

Building on this realisation, McRock started tracking and scoring the diversity of all its portfolio and candidate companies. "To be credible, we needed to walk the talk because too many investment firms talk about diversity and inclusion but do very little about it inside their firms and across their investment portfolios," Whitney continues. "We go far beyond just tracking diversity statistics. We dig deep into inclusivity. You can have a diverse team, but if the members do not feel heard or that they belong, they will leave. You can also have a highly inclusive team but no diversity. So, for our portfolio companies, having both is very important to us. And for those companies that fall short of the mark, there is still hope. If the founder and broader management team genuinely wants to improve its diversity and inclusivity practices, we think this is a good thing. We will work with them on a plan, recommend implementation tools and ensure diversity and inclusion are standing agenda items at board meetings. We want to help companies become more diverse and inclusive because we have experienced how it drives greater performance."

Whitney has also played a leading role in developing and implementing diversity and inclusion best practices across the wider Canadian venture capital ecosystem. Having been elected in 2017 as the first (and still only) female chairperson of the Canadian Venture Capital & Private Equity Association (CVCA) in its 50-year history, she was inspirational in setting up and chairing the association's first diversity and inclusion committee.

"This was something that I felt really passionate about," recalls Whitney. "We had 15 different committees at the association, but we did not have a diversity and inclusion committee. So, I put out a call asking: 'Does anyone want to be a part of this taskforce?' And we had a huge response. We put together a library of best practices, which included recommended software tools to reduce unconscious bias. We provided unconscious bias training to the CVCA board and did cross-country tours to encourage underrepresented university graduates to look at private capital as a career. These grass-root efforts made a big difference."

Another endearing attribute of Whitney and Scott is their ability to not take themselves too seriously. They do serious work, but this does not mean there should be no time for play. "Fun is a key component of who we are and how we operate," says Whitney. "We are passionate about what we do, and we make room for fun along the way."

Head over to the "Friday musings" page on McRock's website and you will see, in big bold letters: "We take our industrial tech with a pinch of fun". Scroll down a little further and you will see exactly what they mean.

Shell's value shift and portfolio integration

A decade ago, while Whitney and Scott were asking if industrial markets would start to feel the impacts of the digital revolution, Shell was already undergoing its own digital transformation, as it looked to leverage digital innovation not only to revolutionise its own operations but to provide better value to its customers.

Today, Rens Valk, Investment Associate at Shell Ventures, is at the forefront of Shell's drive to equip its business-to-business customers with the data and services they need to run safer and more efficient and productive facilities. "Shell's value proposition has traditionally been product driven," he says. "But we want to go beyond just selling products: we want to help our business-to-business customers to run their facilities better. Take the offshore wind industry, for example. Here, we have a great set of lubricant products. But, if we can develop a strategy to leverage our knowledge of these products, we can provide our customers with better understanding of how their machines are performing and offer complementary digital services such as predictive maintenance.

"Our ultimate aim is to provide a fully integrated portfolio of services and products that offers complete solutions for our customers," continues Rens. "But to achieve this goal, we cannot travel this journey alone. Even though we have a lot of knowledge of the IIoT, we are not a digital company at heart. So, it makes sense for us to ▸▸▸

Shell Ventures

Strategic benefits of venture capital partnerships

Successful corporate venture investments offer five key strategic benefits for Shell:

- eyes and ears. Shell can learn from new business models and keep up with the latest developments across the innovation ecosystem.
- equity value. Return on investment through the appreciation of Shell's equity in the start-up.
- deployment value. The start-up's technology can be deployed within Shell, thereby increasing productivity or reducing cost.
- leverage. Investing alongside other investors reduces Shell's capital exposure.
- ecosystem. By having relationships with start-ups and venture capital funds, Shell places itself in the innovation and talent ecosystem.

look for technology partners within the IIoT ecosystem to help us achieve our goal."

A strategic alliance with purpose

Partnering with venture capital funds is a strategic way for Shell to evaluate a broader portfolio of companies that may have the potential to become IIoT technology partners (see boxed text Strategic benefits of venture capital partnerships). "Shell Ventures invests in about eight venture capital funds that fill either geographic or specific technological knowledge gap areas where Shell is not active," explains Rens. "And if we see strategically relevant prospects, then there is the opportunity for Shell to invest in these start-ups."

Choosing the right venture capital fund, however, requires extensive due diligence. "We looked at about 64 venture capital funds that were active in the IIoT space. Five of these were shortlisted and interviewed, and this is how we got to know McRock," Rens recalls. "We really liked both Whitney and Scott; they are very impressive people. They have worked in the IIoT venture space for a long time and have demonstrated some really good exits. They also know the Canadian and US Midwest IIoT ecosystems very well – geographies Shell is less familiar with."

But McRock did not get Shell's buy-in straight away. "We pursued Shell for our first fund (Fund I), but we were unsuccessful; we were a little heartbroken over that," remembers Whitney.

"However, Shell was just doing its due diligence: McRock was a new name to Shell and the IIoT was still a relatively new space. So many groups were watching us from a distance to see if this investment space would take off, which of course it did."

So, when McRock launched its second fund (Fund II) in 2019, Shell was ready to invest: "At this point, we had known Whitney and Scott for about five years. We had seen them grow," says Rens. "The investments they made in their first fund demonstrated that they knew what successful value propositions in this space looked like. The IIoT is such a big theme for Shell, but it is also a new space for it, so we wanted a partner that could work with us to curate a portfolio of IIoT start-ups and that could help us expand our market intelligence. Most of all, though, we invested in them as people."

When it came to the final investment decision, there were three key strategic reasons Shell chose McRock. "First, we felt very comfortable that this was a financially sound investment," explains Rens. "Deals were smartly structured, and investments were well valued with good projected returns on investment. Second, McRock's portfolio is strategically on-point. Many venture capital funds are not sector specific; however, McRock is. They know the IIoT industry very well and have a great network of corporate and financial partners – this was key for us.


Left to right: Whitney Rockley and Rens Valk

"Third, they are uniquely positioned compared to their competitors in the way that they structure their funds. They have outstanding corporate relationships with companies, which gives us the chance to extract knowledge, partnership and co-investment opportunities. For Shell, these relationships hold great value." (For more information, see boxed text, McRock Capital Fund II.)

But the relationship between Shell and McRock goes beyond the core services that a conventional venture capital fund would offer. "McRock is unique because it is a leading promoter of diversity and inclusivity – this is very important to everyone at Shell," enthuses Rens. "In fact, Whitney sat on the panel for Shell Ventures' diversity and inclusion strategy. Additionally, McRock has run sessions for Shell's executive team on how to be an 'industrial shark' during which participants learn how to evaluate companies better."

Working with a company like Shell also provides great value for McRock. "Shell always gives us and our tech companies great credibility," explains Whitney. "Additionally, one of the things that corporate groups such as Shell do for a pure-play financial house such as McRock, is that they 'sense check' you. They provide a practical lens through which to assess opportunities and advise on why certain solutions may not make sense. We have a true partnership with Shell."

An important piece of the climate puzzle
McRock and similar funds play an important role in the energy transition. "McRock is a specialist fund that knows how to distribute capital to the right companies that can help to decarbonise industrial sectors," explains Rens. "It is really important to know that we are not doing this alone. Instead, we are doing it with great partners such as McRock, which is an important piece of a bigger puzzle."

And smart collaborations really are the best way to ensure that companies such as Shell can leverage the power of big data and the IIoT.

McRock Capital Fund II
McRock's second fund represents a growth-stage, Series A and B venture fund focused on the IIoT/artificial intelligence:
- fund size: C$112 million;
- fund start date: August 2019; and
- fund stages: five-year investment period plus five-year harvest period.

Portfolio companies
McRock invests in European, American and Canadian companies that generate at least $1 million of trailing 12-month revenue. Fund II currently consists of eight later-stage technology companies: ThoughtTrace (acquired by Thomson Reuters), Dott, Poka, samdesk, Clearpath AI, Plus One Robotics, Triax and Landing AI.

Fund structure
Corporate limited partners: Total fund share of 25% from a maximum of five corporate enterprises: Shell, AspenTech, Caterpillar, Cisco Systems and Mitsubishi

Financial institutions: 10 institutions with a total fund share of 75%

"I have spent my entire career working with entrepreneurs and helping them to change the world through advancing industrial opportunities with digital technologies," concludes Whitney. "Every one of our portfolio companies is tackling climate change as a core part of their business. As passionate as we are about diversity and inclusion, we are equally as passionate about helping companies such as Shell advance their decarbonisation strategies through digital technologies." ■

TRAN-
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KNOWLEDGE GRAPH TECHNOLOGY: Linking businesses with their data

As a data-driven organisation, Shell has significant information, digital and technology (IDT) expenditure. As there are various global IDT charges with differing charging mechanisms, this complexity presents challenges for business consumers trying to obtain timely, concise insights in a user-friendly format. A proof-of-technology graph database project with US company TigerGraph has enabled Integrated Gas asset Shell QGC to visualise IDT expenditure. This has included unearthing insights not visible in the way the data have been presented previously. Such a visualisation approach brings Shell one step closer to providing greater insights to help IDT managers to optimise their run and delivery function. It will also empower business consumers of IDT services to manage better and own their consumption-based investment expenditure decisions. This single use case has demonstrated the significant potential application of graph technology in Shell.

Shell QGC's liquefied natural gas plant on Curtis Island, Australia.

The challenge

Reports on global IDT charges are created at a frequency ranging from monthly to quarterly. There is a variety of charging mechanisms in play and the individual IDT services have their own unit cost allocation mechanisms within the charging mechanisms. This can make it quite a complex task to show in an easy and intuitive manner the IDT cost stack and to get deep insights into the breakdown of costs or proactively steer them.

The vision is to enable Shell businesses, via intuitive interfaces, to understand better their consumption-based global charge expenditure and identify which costs are controllable and the mechanism by which they can adjust them to meet business needs and restrictions. The requirement from the businesses is to have:

- an intuitive dashboard providing greater transparency and insights on cost drivers, the ability to drill down to deeper levels, for example, the top usage and top costs, and to correlate cost relationships;
- timely access to these insights aligned to budget and billing cycles to enable them to proactively steer consumption expenditure on global IDT charges such as the consumption-based charging mechanism; and
- the ability to benchmark global IDT charge expenditures with other assets to identify further optimisation opportunities.

Shell QGC, one of Australia's leading natural gas producers, has taken the first step.

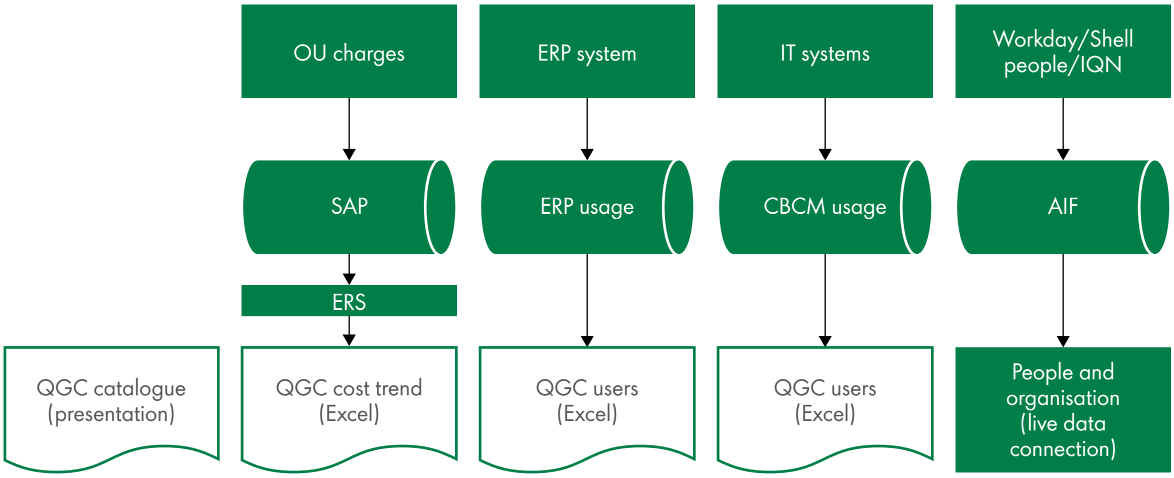

FIGURE 1
The various sources and silos of data.

The solution

Inspired by a conference they attended, the Shell QGC product manager data platform and the Integrated Gas chief data officer decided to experiment with using a knowledge graph to visualise global IDT charges. They also felt that IDT managers would obtain richer insights to optimise their run and delivery functions and the business could proactively own consumption of its global IDT services.

A graph database uses structures for semantic queries. These enable queries and analytics that are associative and contextual in nature, and the retrieval of both explicitly and implicitly derived information based on relationships linking the data. Graph databases hold the relationships between data as a priority and can be intuitively visualised, which makes them useful for heavily interconnected data. In summary, this technique enables a business to "google" its questions and get answers on the spot, including insights and advice based on machine learning from data distributed in a complex digital landscape.

This differs from the traditional Shell approach of creating a common data model, mapping every system and merging this into a data platform. This is resource intensive and not well suited for such disparate datasets.

For the pilot, Shell QGC worked with TigerGraph to visualise IDT costs and get insights for the asset.

TigerGraph

The complexity of IDT costs

Shell QGC employs more than 2,000 people, so has considerable annual expenses. To bring insights into the global IDT charges, the first step was to look at Shell's periodic reports created from various data sources (see Figure 1). These reports offer visibility into large overall categories and provide comparison indexes to previous years and other assets. The reports bring valuable high-level information. However, as the cost breakdown is at asset level and not at department level within the asset, lower-level details are very difficult to obtain. This more granular level would assist asset leaders in understanding their consumption better.

With the current tooling, obtaining that level of detail is labour intensive and requires much time to obtain the data, transform them into one format and combine the data into "information", as details are fragmented and provided by different teams in diverse formats and with different cost structures. With a tool like TigerGraph software, Shell QGC could efficiently overcome those issues and transform the data into information at the level of detail needed for the business to take charge of its costs.

To really dig deep into the detail and opportunities of these cost data, additional datasets had to be sourced or even created. Critical concepts like "software bundles", "marker applications" and the various charging models for applications are currently found in Excel and PowerPoint documents. For example, an audit of all 198 products and services in use at Shell QGC uncovered 9 different charging mechanisms (see Table 1), so charging mechanisms was added as a new data set.

Charge unit	Description
Asset	Single charge for asset
Well	Charge per well
User	Charge per user
Storage	Charge based on volume of data
Site	Charge per physical site
Equipment	Charge per physical equipment
Time	Charge per unit of time used
Transaction	Charge per transaction
Feature	Charge per feature used in the product

TABLE 1
The nine different cost charging mechanisms used.

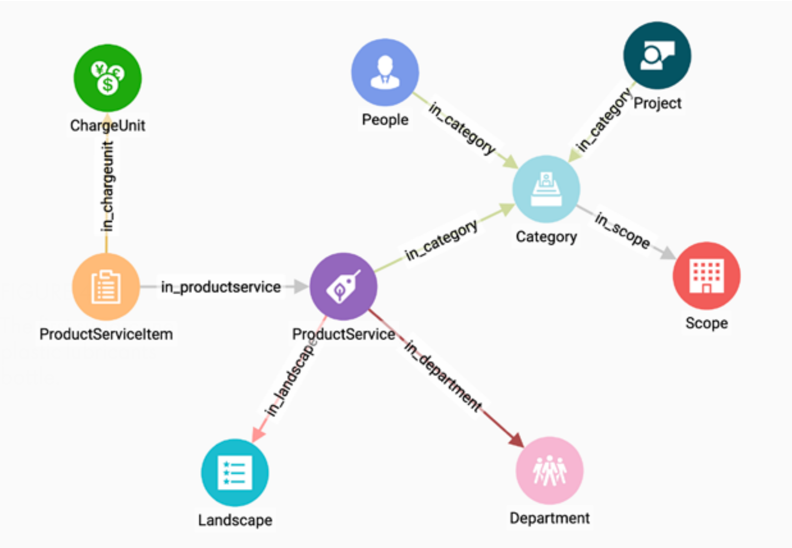

FIGURE 2

The conceptual data model. Image courtesy of TigerGraph.

IT systems log the usage of an application by a user. Portfolio managers describe which different applications together form a software bundle and when a bundle is charged. For example, the consumption-based charging mechanism is a price × quantity based model. This means that only actual usage (updated on a half-yearly basis) will trigger costs. Better insights can help to ensure only the right people have access to these applications and that usage does not trigger unnecessary costs.

This information is all stored, but in silos in different landscapes. The detail level of the raw data is too fine to draw conclusions and is not currently linked to data platforms.

A case for change

In interviews with the IDT managers and key business stakeholders, it was clear that extracting knowledge from multiple systems was time-consuming, repetitive, somewhat manual and, hence, error prone. There was a desire for smarter analytics to present key trends and actions. Decision-makers wanted better tooling than Excel spreadsheets. Their ideal outcomes were:

- a high-quality product to show to business stakeholders unfamiliar with IDT specifics;
- the ability to empower the business to understand how their local decisions directly affect costs and what interventions they can make to change this; and
- a targeted focus in the form of alerts and key actions they need to be addressing based on setting thresholds.

Working with the Shell artificial intelligence team, the Shell QGC team assessed different graph technology vendors and selected TigerGraph to initiate a pilot.

Organising the data for the pilot

To support the pilot, the team sourced key, though not exhaustive, data from various siloed locations. This included digitalising key knowledge in presentations. Usage data was linked and then aggregated to the Shell QGC department levels, see Figure 1 for the silos of data brought together for the pilot. The team used all the cost data captured in SAP, Shell's enterprise resource platform.

Cost data are broadly broken into three categories:

a. delivery at the asset;
b. the information and digital services and operations or support team; and
c. global charges.

Across these three categories, the data were simplified into people costs (i.e., staff time writing), project costs and the remainder as a product or service. TigerGraph's objective was to explore these product and service items and thus to unlock the knowledge the business and IDT managers were seeking (see Figure 2).

For the intended audience of this pilot, the dollar values were removed and replaced with percentages of the overall IDT budget. This provided a valuable view on proportional costs and enabled benchmarking to other businesses at different scales. Personal data were removed to protect privacy and aggregated to a department level.

A graph database

In the past 15 years, with more data being generated than ever before, traditional relational database management systems (RDBMS) have shown limitations in their ability to scale up to handle large or highly connected data sets and still maintain their performance. Thus, NoSQL databases such as key-value/column databases, including Redis and Cassandra, and document databases such as MongoDB have grown in popularity. This is because they can scale to multiple machines and handle large datasets with diverse schema more easily.

However, even these solutions have their drawbacks, as scalability in NoSQL databases comes at the cost of losing their expressive powers. Query languages and application programming interfaces (API) supported by these NoSQL databases are often not as powerful as SQL supported by traditional RDBMS vendors. NoSQL database developers often have to code in Java or Python to do things that are easily expressed in a high-level language such as SQL.

Graph technology overcomes these challenges. The graph database concept has been around since the early days of modern computing. It is only recently, though, that it has reached a level of maturity where

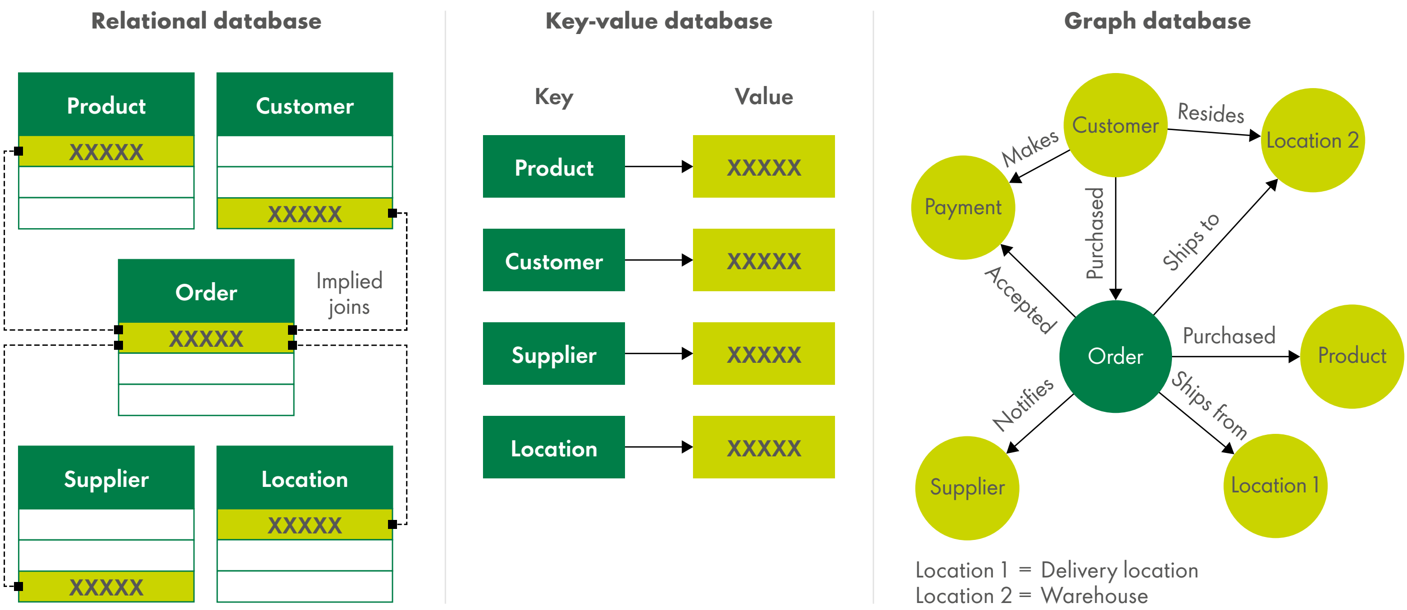

FIGURE 3
The steps to a graph visualisation.

it can challenge the established order. Every table schema designed in an RDBMS has a simple equivalent in a graph database, but the reverse is not necessarily true. Every SQL query can be expressed in a graph query language such as TigerGraph's GSQL, often more concisely. And many high-value business problems can be easily expressed and efficiently solved in graph query languages. Some of the world's most popular applications are underpinned by their own purpose-built graph technology, for example, LinkedIn and Facebook.

The advantage of the graph database results from the underlying data structure. Whereas traditional RDBMSs store and query data as tables (composed of columns and rows), graph databases store and query data as entities and relationships (vertices and edges). The difference in structure that gives the graph database its performance advantage is that the edges effectively prejoin related entities so that queries can have faster run times.

The next capability that graph technology offers is often the most captivating: visualisation (see Figure 3). SQL is undoubtedly successful, powerful and flexible, but it has the unintended side effect of constraining the way people think about, interact with and view data. However, when data in graphs are stored and represented as entities directly connected to each other through a relationship link, they are instantly brought to life. The human eye is also naturally drawn to this type of graphical network representation. Human brains think about the real world, and thus make decisions, in a way that is more like a connected graph than groups of tables.

TigerGraph's visualisation capability is at the heart of the first phase of this pilot. However, before data can be visualised two main activities are necessary:

1. A schema needs to be created (see Figure 2). This is typically a straightforward process when using TigerGraph software. Often, existing and well-understood entity and relationship diagrams can be taken as-is and recreated.
2. Data need to be loaded into TigerGraph software in accordance with the structure of the schema. Loading data is a simple process and TigerGraph software supports several popular means of data ingestion, for example, batch ingestion of CSV files, JSON, Apache Parquet files, REST API based inserts and real-time streaming from Apache Kafka or Apache Spark.

For this pilot, all that was necessary to get going was a short meeting to understand the data, the various sources and, importantly, how they were connected. This enabled the TigerGraph team to create a simple schema that accurately reflected the data set provided for the pilot.

Although schema creation and data ingestion are less exciting than the output visualisation stage, they are when the real magic happens. It is during the data ingestion stage that TigerGraph software connects the many different data sets and stores them in a highly efficient way as a single unified graph, ready for rapid visual exploration and analytics.

Often, when working with TigerGraph software, organisations see data from diverse data sets all connected on a screen in a highly interactive way for the first time. The reason for this is simple. Connecting different data sets across many different tables (often including altogether different DBMS systems) requires joins. Until now, these have been prohibitively slow or, in some instances, impossible to create for highly connected or hierarchical data sets without graph technology. ▸▸▸

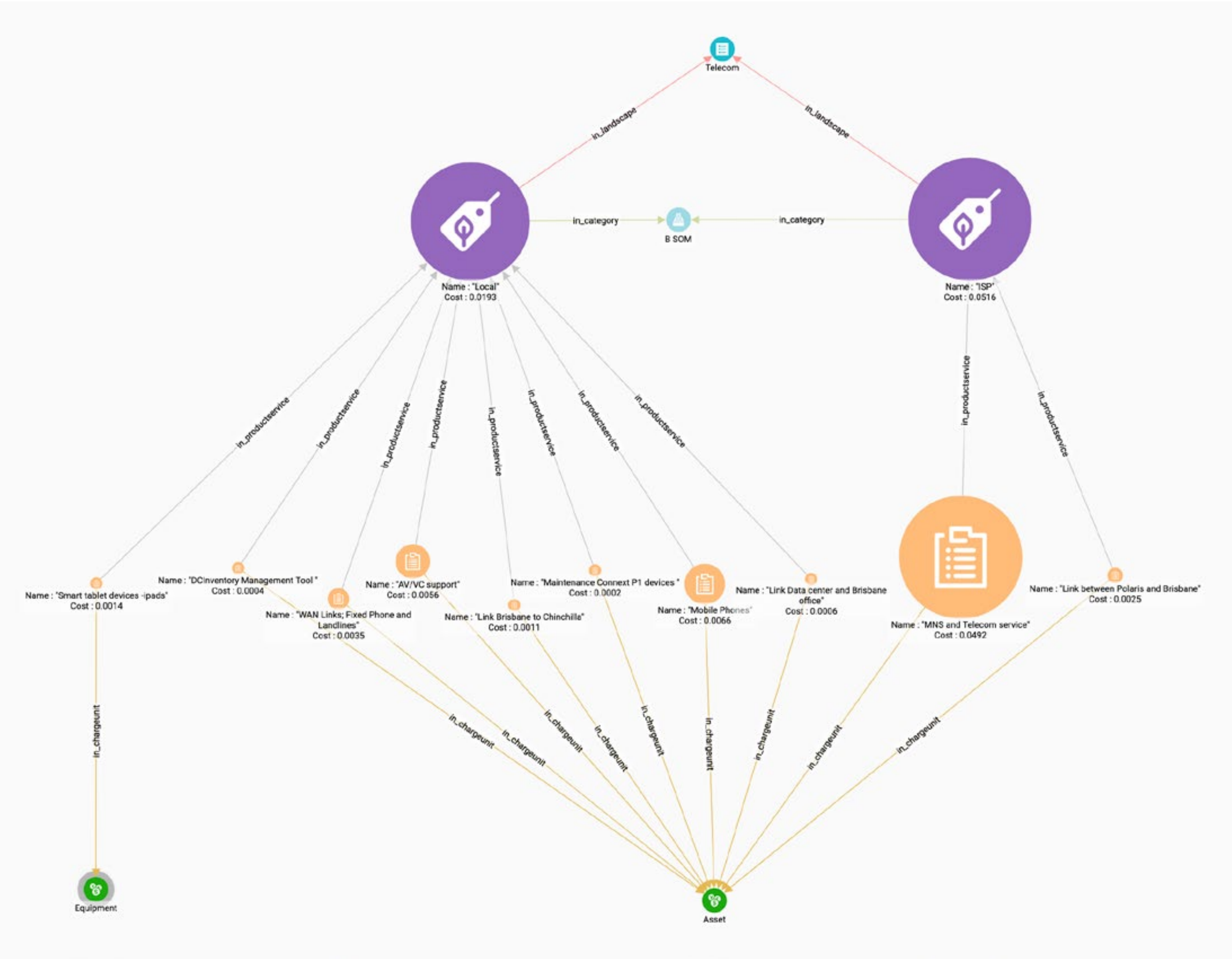

FIGURE 4

An example visualisation. Image courtesy of TigerGraph.

Once the data are in TigerGraph software, exploring it using the TigerGraph Graph Studio user interface is straightforward and enables the creation of a visualisation, see Figure 4 for an example. This information visualises the data in an easy to understand and intuitive way, thereby enabling the business stakeholder to self-serve these insights, set thresholds and notifications, and manage expenditure. In Figure 4, the size of the purple ProductService and orange ProductServiceItem entities are directly proportional to their cost, which makes it very easy to identify the high-cost areas in an intuitive way.

As TigerGraph software is an analytics database platform and not just a front-end visualisation framework, it is well placed to support the additional requirements that naturally spring from this first pilot phase. Rather than just providing a single snapshot of a moment in time, an analysis of how cost or usage changes over time is possible. Accordingly, a powerful visualisation of these data would be created using TigerGraph software to bring the results of the analytics to life in an insightful way that is intuitively understood by all.

Conclusion

This proof-of-technology project was successful: within a month, the team was able to create a visualisation of Shell QGC costs that intuitively guides users to key points that need attention. This intuitive guidance happens via either colour coding of the nodes, for example, global costs that are hard to influence have a different colour to local costs that are within a business's control, or the size of the nodes, for example, the bigger the node, the larger the respective costs. In addition, visualising the relationships immediately explains a situation more clearly than a traditional report does. The visualisation makes it possible to see the relationship of costs to each other and which ones have a stronger correlation for influencing big cost items.

The next step will be a follow-up pilot involving more business users to further address the requirements. Some reflections from the team for next steps to make this even more useful include that the business user should be able to set a threshold on selected costs so that action is triggered when a threshold is reached and to enable the tool to provide exception-based reporting. Also, adding the dimension of time to the data set would create key insights through trending and forecasting. In short, there are many reasons to continue investigating how a graph database and its visualisation can help IDT managers and business users gain greater transparency for understanding, managing and changing the trajectory or magnitude of their IDT investment expenditure decisions.

But this graph technology goes way beyond providing IDT cost transparency to a business. Shell monitors more than 10 million data points every minute and this figure will only increase. The Shell QGC pilot demonstrates the possible value graph technology can bring in combining vast amounts of data from multiple sources and invites further exploration of this technology Shell wide. A key driver for the transition to a data-driven organisation will be how fast people can access, understand and query data related to their domains. The accessibility, combined with the intuitive and visual representations that a graph database brings, shows that this is one of the data technologies Shell must investigate further. ■

AUTHORS

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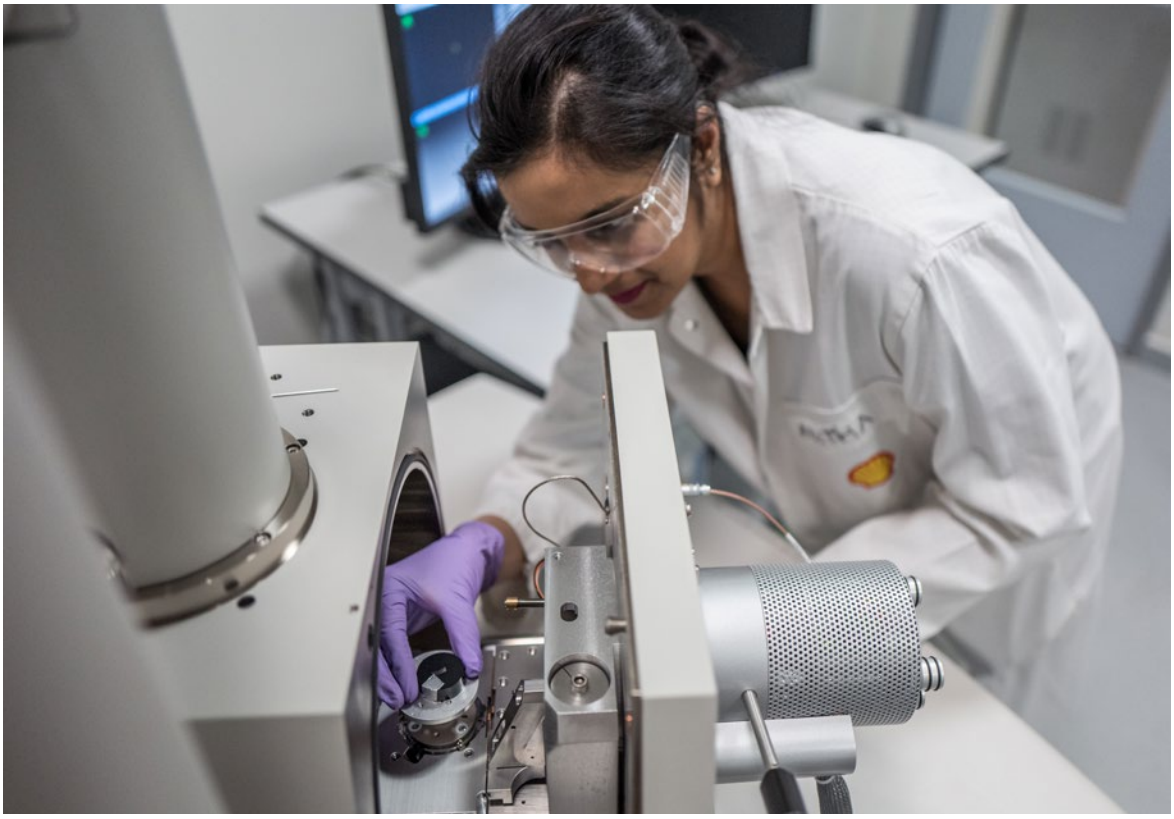
TRAN-
SITION

RAMPING UP SAFETY IN GAS PIPELINES BY smart corrosion monitoring

Underdeposit corrosion in pipelines in sour service is one of the biggest risks to their integrity and also the most difficult type of corrosion to detect. A Qatar Foundation for Education, Science and Community Development[1] (Qatar Foundation) funded project involving the Qatar Shell Research and Technology Centre working in collaboration with project partners at Qatar University and Imperial College London, UK, has resulted in the development of a smart corrosion coupon with three of the most important deposits built in to monitor underdeposit corrosion in sour-service pipelines. The Smart Corrosion Coupons will have a significant role in ensuring the structural integrity of oil and gas pipelines, not just in Qatar but also worldwide locations with sour-service pipelines.



The corrosion research and development laboratory at Qatar Shell Research and Technology Centre.

The challenge

Corrosion, the degradation of a material caused by an electrochemical reaction with its environment, is the most common failure mechanism in oil and gas pipelines. Corrosion-related failures can cause risks to health, safety, equipment and the environment that may disrupt asset operations and result in significant economic impacts and reputational damage. The most prominent type of pipeline damage is internal corrosion and is a result of the specific characteristics of the fluid being transported.

[1] The Qatar Foundation, a nonprofit organisation of more than 50 entities working in education, research and community development, drives regional innovation and entrepreneurship, fosters social development and a culture of lifelong learning, and prepares the brightest minds to tackle tomorrow's biggest challenges.

One of the many forms of internal corrosion in oil and gas pipelines is known as underdeposit corrosion. In this type of corrosion, the pipeline material corrodes in hidden areas beneath surface deposits. This undermines the structural integrity of the pipeline, even though the structure appears intact. Consequently, underdeposit corrosion is difficult to predict, detect and monitor. This makes proactive maintenance difficult and thus compromises the pipeline's integrity and increases the risk of failure. See Reference 1 for a comprehensive review of the mechanisms of underdeposit corrosion, monitoring techniques in the laboratory and the field, and mitigation techniques.

When hydrogen sulphide in sour gas reacts with the walls of a steel pipeline, it produces a thin scale of iron sulphides, predominantly ferrous sulphide along with other variants such as ferrous disulphide. This iron sulphide scale, which effectively seals the pipeline's inner surface against further corrosion, may chip off from its primary location and be deposited, along with silicon dioxide (sand), at other locations within the pipeline. The accumulation of these deposits subsequently leads to aggressive local chemistry underneath them. This underdeposit corrosion causes significant wall loss and pitting and is not captured by standard corrosion monitoring techniques.

Corrosion coupons

The gas reserves in Qatar contain acid gases (carbon dioxide and hydrogen sulphide) that increase the risk of internal corrosion in pipelines. Consequently, monitoring the corrosion rate of pipelines is critical for their safe operation and management. One of the most common ways to do this is by placing a corrosion coupon in the pipeline, thereby helping to monitor the rate of corrosion and enabling the operators to maintain the pipeline systems and respond to unexpected corrosion events.

A corrosion coupon is a small piece of metal of the same material type and grade as the pipeline. These coupons are retrieved from the pipeline at specific intervals, cleaned and then weighed. The difference in weight is used to calculate an average corrosion rate that can be used to determine the integrity of the pipeline. Unfortunately, a conventional coupon cannot help in the complex scenarios where underdeposit corrosion occurs.

Getting smart

To tackle this issue, which is one of the most prominent corrosion challenges in the oil and gas industry, a group of academic and industrial experts teamed up to develop an innovative corrosion monitoring device, designed and manufactured in Qatar.

The team has revamped the traditional corrosion coupon (Figure 1(a)) and created a smarter version called the Smart Corrosion Coupon (Figure 1(b)) that provides information about more than just the corrosion rate. The Smart Corrosion Coupon incorporates three of the most commonly found deposits in sour gas pipelines and an embedded sensor to monitor the conditions beneath those deposits. The aim of having these deposits on the coupon is to directly simulate underdeposit corrosion conditions and hence pick up early-warning signs that underdeposit corrosion may be likely in that pipeline environment.

The coupons are extracted every two months for detailed analysis, thereby enabling very close monitoring of the changes associated with underdeposit corrosion and its most dangerous manifestation, pitting, which is a rapid and localised form of corrosion in which cavities form in the material.

About the technology

To construct the Smart Corrosion Coupon, the first requirement was to gain insights on the role and impact of such deposits on the rate of corrosion, and the key features of these deposits that make them particularly damaging. Detailed knowledge of the critical factors, such as deposit composition, packing and thickness, that determine the deposit types that are most likely to cause underdeposit corrosion enabled tuning of the deposits on the coupon so that they would provide meaningful results.

The conventional coupon design was modified to create a smart corrosion coupon that could house the three most important deposit types in sour-service pipelines. These coupons were then tested under simulated field conditions at Qatar University and Imperial College London to ensure that the deposits and design could withstand the pipeline conditions. After about two years of laboratory-based tests and constant modifications of the design based on the test results, the robust Smart Corrosion Coupon design was finalised and manufactured locally in Qatar for field tests.

This work has resulted in two patents thus far. The first patent (PCT/QA2020/050013, published 21 April 2022) provides methods of fabricating a stable chloride ion selective electrode that is highly sensitive in the absence and the presence of different deposits in miscellaneous environments. The second patent on the design of the Smart Corrosion Coupon is undergoing filing with the Qatar Foundation.

The future

Internal corrosion in pipelines, if not detected early, can affect the economics of production and ▸▸▸

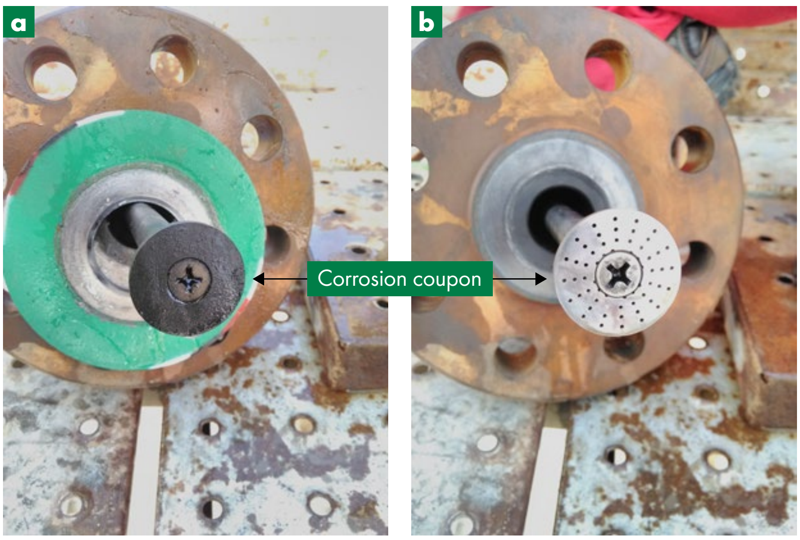


FIGURE 1

(a) A conventional corrosion coupon used to monitor underdeposit corrosion.
(b) A Smart Corrosion Coupon being tested at the Pearl gas to liquids plant in Qatar.

processing, is a safety risk to both people and the environment and may cause long-lasting financial, reputational and environmental damage in the case of failure. The novel underdeposit corrosion online coupon, developed in collaboration among the Qatar Shell Research and Technology Centre, Qatar University and Imperial College London, could play a significant role in ensuring the structural integrity of sour-service pipelines worldwide through the early detection of corrosion and pitting.

The Smart Corrosion Coupons are currently being tested in the field: five of them have been deployed at the Pearl gas-to-liquids plant since January 2021. The expectation is that these modified corrosion coupons could soon replace conventional coupons.

The new corrosion coupons are manufactured in Qatar. The cost of manufacturing the first unit was equivalent to that of traditional coupons from the USA. However, the cost is expected to go down considerably if they are produced in greater bulk in Qatar.

In the next version of the coupon, the team intends to provide additional sensors that can identify potential problems even earlier by detecting the local changes in chemistry that are precursors to corrosion. For example, a drop in the local pH or electrochemical potential or chloride ion concentration changes are indications that the environment is becoming more conducive to pitting. In addition, the embedded sensor will be able to relay information in real time as it detects changes in the local chemistry.

Having an online sensor that can communicate crucial information in real time provides a huge advantage for maintaining safe operations because, once a corrosion pit is initiated, its rate of propagation can be very fast.

Acknowledgements

The authors would like to thank Professor Mary Ryan, Imperial College London, and Professor Aboubakr M. Abdullah, Qatar University, for their contributions to this project; the asset integrity and operations and maintenance teams at the Pearl plant for their help during field deployment of the smart corrosion coupons; and the Qatar Foundation and P&T for their support with funding. ■

REFERENCE

[Ref 1] Sliem, M. H., Fayyad, E. M., Abdullah, A. M. et al.: "Monitoring of under deposit corrosion for the oil and gas industry: A review," *Journal of Petroleum Science and Engineering* (2021), 204, 108752

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UNDERSTANDING SUSTAINABILITY in the packaging life cycle

Shell aims to reduce the carbon intensity of its lubricants value chain by 15% by 2025, by 35% by 2035 and by 50% by 2050. Part of this is a commitment to increase the amount of recycled plastic content in the plastic packaging used for Shell lubricants to 30% and ensuring that all its packaging is reusable or recyclable by design, both by 2030. Making the right choices for packaging formats and materials can reduce carbon footprints dramatically. In addition, it can lower the amount of packaging waste that goes to landfill and support the circular use of materials compatible with recycling. The lubricants business is working on the gradual transformation of its considerable packaging portfolio (see Figure 1) to enable it to reduce, reuse and recycle packaging materials. Therefore, the business constantly screens and investigates packaging innovations and looks for different and more sustainable packaging options.

The packaging life cycle and sustainable packaging routes

Understanding the carbon footprint of a packaging portfolio and knowing the biggest carbon contributors are key steps in defining effective tactics for moving towards sustainable packaging options, i.e., where most of the effort must be expended and which pack formats require transition to different, and sometimes radical, circular solutions. Identifying the full life cycle carbon dioxide (CO_2) emissions of a piece of packaging, i.e., its carbon footprint, is a key data element that helps to answer the question: "How can we achieve this transformation and what will a sustainable 'pack' look like?"

Making a full life cycle analysis of a piece of packaging means assessing its cradle-to-grave impact from fossil material extraction, through raw materials processing, pack fabrication and use, and finally to end of life (see Figure 2). For packaging, 75–85% of its carbon footprint comes from the energy sources necessary to extract and process the raw materials and then to make the packaging.[1] This means the more material the pack contains, the more CO_2 emissions from its production. Thus, this drives the conclusion that reengineering packs to specifications or formats needing less material by design, for example, flexible packs versus rigid plastic bottles, is one of the transformational routes for decarbonisation and reducing waste. Moving from small individual packs to bigger formats that use less packaging material per litre of product will be an impactful sustainable choice. However, no pack (bulk) is the best sustainable option.

Using materials such as recycled plastic avoids all the emissions from fossil material extraction and processing for virgin plastic, thereby ensuring a much lower overall carbon footprint for packaging. Reconditioning or reusing packs, for example, intermediate bulk containers and drums, avoids both raw materials extraction and fabrication emissions, and uses energy only to clean and repair the packs: reconditioned steel drums have a 30–50% lower carbon footprint than new drums.

CO_2 emissions vary by type of packaging material (see Figure 3), which is another factor to consider when thinking about potential future sustainability scenarios and pack choices. Where packs are necessary for customers, conventional packs could be replaced by more radical disruptive solutions fabricated from different materials. For example, single-use, rigid plastic bottles could be replaced by dispensing from bag-in-a-box packs that ▸▸▸

[1] According to an internal Shell packaging study supported by an external consultant and the baseline for the portfolio in 2018

FIGURE 1
The annual impact of the Shell lubricants packaging portfolio (baseline 2018).

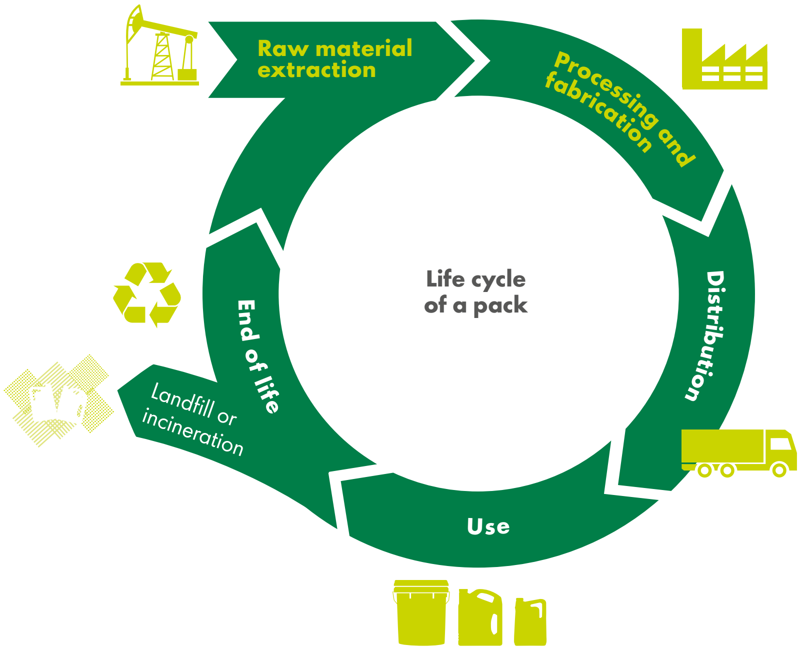


FIGURE 2
The life cycle of a pack.

have a liner bag needing significantly less plastic than a bottle to contain the lubricants and a sustainable cardboard box outer for protection and rigidity and that is accountable for 95% of the total packaging weight.

Consumer behaviour

Sustainability is now becoming a real driver of brand choice. Modern consumers care more about sustainability, and it can affect their brand choice. A recent IPSOS survey [Ref 1] revealed that 80% of global consumers are concerned about the use of disposable, nonrecycled products, 87% understand that the world's climate is changing, and 36% of global consumers would like to stop buying goods that come in nonrecyclable packaging.

It is important that Shell makes packaging changes now, as these concerns are only becoming stronger. For example, Google searches for plastic waste and zero waste increased markedly in the three years from 2016 to 2019 [Ref 2] and 82% of adults in the USA now believe that manufacturers should actively support recycling initiatives for the products they sell.

FIGURE 3
CO_2 emissions equivalent (per kilogram of material) comparison for different packaging types.

*Cradle-to-grave analysis

Shell customers are also looking for help with sustainability. Key customers have their own commitments to reducing waste and carbon dioxide emissions. For example, the supermarket chain Walmart works with suppliers to reduce product and packaging waste and preserve natural resources, and car manufacturer BMW has all its production locations obtain their electricity exclusively from renewable sources.

What is the lubricants business doing?

A transformation to sustainable packaging does not happen overnight. It takes many small steps, sometimes challenging ones and some into the unknown.

One of the first fundamental steps in the lubricant business' journey was Shell's development and publication of the Sustainable packaging playbook in 2019. This massive internal toolkit, which was updated in 2021, educates and equips users with easy-to-digest knowledge about pack life cycle and what elements of pack "features" contribute to and create carbon footprints. It helps businesses to choose tactics and identify targets. The playbook tool provides guidance on the main sustainability routes and illustrates which packaging solutions can be activated to transform packaging portfolios.

Armed with this ammunition, the lubricants business has been able to start its big journey. In recent years, Shell has implemented several global initiatives, including moving from new to reconditioned intermediate bulk containers and downgauging packaging specifications for steel drums, plastic bottles and corrugated cardboard cases where technically possible. All regions have been actively working on qualifying and implementing recycled plastic in packaging for lubricants, i.e., intermediate bulk containers, pails and bottles. For example, plastic lubricant bottles in North America contain 25% recycled resin; the bottles used in Western Europe will have up to 40% of recycled plastic in 2022; and other countries are catching up through technical trials or small-scale pilot launches.

The use of renewable sources for packaging materials is another big theme the lubricants business is incubating. In 2019, the business piloted 1-L Shell lubricant bottles made in Brazil using 51% sugar cane resin with 83% less net CO_2 emissions on a life cycle basis compared with the previous (100% fossil-based resin) bottle specification (Figure 4). And, in France, a reusable 1-L stainless steel bottle was piloted in 2020 (Figure 5).

What does the mid- to long-term future look like?

More radical changes, such as new packaging materials and pack types, and dispensing refill solutions, sound easy in theory, but are not the same in practice. Innovative changes in packaging formats alter the end customer experience and thus challenge legacy customer habits and convenience, and the traditional ways Shell sells or distributes its products to customers. Therefore, progressing towards a large-scale transformation requires an end-to-end approach in which the pack is only one component of the entire customer value proposition, and the new pack concept needs to be "packed" into a unified solution with product–place–price–promotion marketing elements.

Reduce–reuse–recycle remains the key lubricants strategy for sustainable packaging. Various ideas are being jointly explored with the regional and global sustainability champions in the lubricants organisation. Research and development on concepts such as packs that are lightweight, need less virgin material, or can be reused and refilled multiple times will continue.

Partnering with Shell Chemicals on circular polymers is an area where the lubricants business wants to build collaboration, along with looking into new opportunities to work with external parties on circular solutions to solve the problem of packaging waste by recycling it back to Shell packs. ■

FIGURE 4
The first sugar cane plastic lubricants bottle.

FIGURE 5
A reusable 1-L stainless steel bottle.

REFERENCES

[Ref 1] Ipsos: "Global views on the environment – 2018," survey (2018)

[Ref 2] Google Trends: "Year in Search 2019," Google report (2019)

AUTHOR

Lidia Zaytseva is the global product manager for packaging in the lubricants supply chain. She has been with Shell Lubricants for 17 years, is a pioneer in driving the sustainability agenda in lubricants and truly believes in innovations that make the future better. Lidia has a master of science degree in applied mathematics from Moscow State University of Radio Engineering, Electronics and Automation, Russia, and a marketing diploma from The Chartered Institute of Marketing.

TRAN-
SITION

RELLI+: REPURPOSING RHEINLAND FOR fuelling sustainable aviation

The energy transition programme will transform the Shell Rheinland refinery, one of Germany's largest, into Shell Energy and Chemicals Park Rheinland, in-line with Shell's net-zero ambition. As part of this plan, a wide portfolio of energy transition projects is being developed. These include the Relli+ project to build the first commercial bio power-to-liquids (bio-PTL) plant to produce sustainable aviation fuel (SAF). This will also involve expanding the site's hydrogen electrolyser capacity.

FIGURE 1
The Shell Rheinland refinery by the River Rhine.

Shell Rheinland refinery

Shell's Rheinland refinery resulted from a 2001 merger between the Shell refinery in Godorf, Germany, and the refinery operated by German oil company RWE DEA in neighbouring Wesseling (Figure 1). It is an integrated oil and chemicals site producing aromatics such as benzene, toluene and xylenes, and other products such as diesel fuel, heating and heavy fuel oil, propane, butane and bitumen. It is one of Germany's largest refineries, occupies a total area of 440 ha and has a crude oil processing capacity of about 17 Mt/y (340 Mbbl/d).

Transition for the future

In 2017, Shell developed and published two energy scenarios for Germany. These looked at the potential opportunities and challenges in the various sectors of the German economy in terms of the politically agreed carbon dioxide (CO_2) reduction targets and the country's increasing energy needs. The two scenarios developed, "Winning the marathon" and "Slowing momentum", were each influenced by energy and production demands over time, and each affects emission scopes differently. Among the opportunities they highlighted were:

- reducing primary energy needs by increasing the use of renewables (scopes 1 and 2);
- implementing the electrification of new and existing installations (Scope 2);
- utilising carbon capture and storage (Scope 1); and
- developing products made from "greener" components (scopes 1 and 3).

A key focus for Shell is to reduce the well-to-wheel emissions of its products, that is, all those relating to fuel production, processing, distribution and use, by more than 20 Mt/y by 2030 through investment in low-carbon and circular value chains. To meet these objectives and help achieve Shell's net-zero ambition, the Rheinland site is currently being transformed into Shell Energy and Chemicals Park Rheinland, and a wide portfolio of energy transition projects is being developed for it (see boxed text, Shell Energy and Chemicals Park Rheinland).

The Godorf site is expected to continue distilling crude oil into mineral oil products as a way to fund the emission-reduction projects that are going through front-end engineering and design before final investment decisions.

Industrial-scale SAFs: Relli+

Through the Relli+ project, Shell is planning to build the world's first industrial-scale bio-PTL production facility at Shell Energy and Chemicals Park Rheinland. The bio-PTL unit will initially produce 80,000 t/y of synthetic kerosene and raw gasoline (naphtha) using green hydrogen from electrolysis and pyrolysis oil derived from biomass (wood waste). Construction could start in 2024 with a view to commercial operations by the end of 2026.

Shell Energy and Chemicals Park Rheinland

In November 2021, Shell announced its intention to move the Shell Rheinland refinery at Wesseling away from crude oil and towards low- or zero-carbon products from 2025. This is in-line with Shell's goal of achieving net-zero emissions by 2050 and society and Shell customers' demand for a low-emission energy supply to meet the Paris Agreement and limit the average global temperature rise to 1.5°C.

Under these transformation plans, the Wesseling complex will become one of six integrated oil and chemicals sites that Shell has identified as critical to its energy transition (Figure 2). The Rheinland site will focus on low- or zero-carbon transportation fuels, including renewable-energy-derived hydrogen, renewable liquefied biogas and SAF.

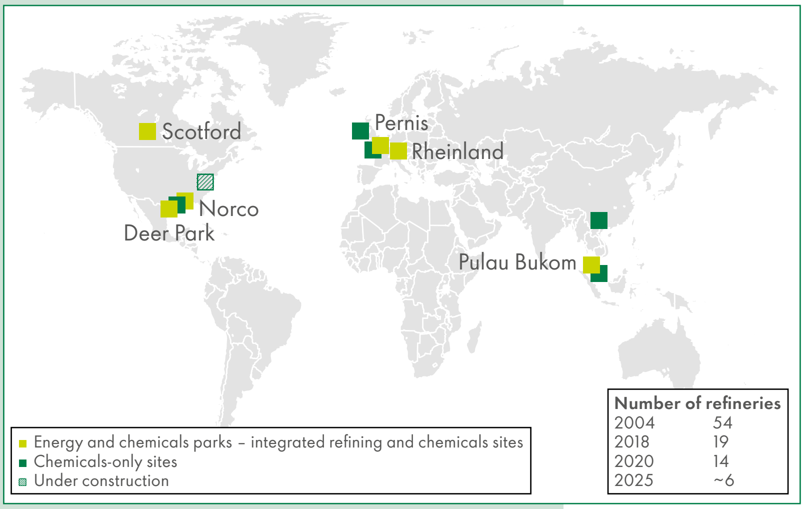
The Rheinland site is already at the forefront of the energy transition. It will be the first site in Germany to use new bio-PTL technologies to produce biofuels from an alternative feedstock: pyrolysis oil from wood residues. The means of production will also be transformed by using renewable energy from sources including green hydrogen and electrical power produced by wind turbines and solar photovoltaic panels.

The site has already begun several smaller-scale pilot projects and has planned a portfolio of major projects that will require investment above $500 million. These include:

- a major revamp of the hydrodesulphurisation units to process biogenic oils and fats for hydrotreated vegetable oil and SAF production;
- a major revamp of the partial oxidation and synthesis unit to process biogenic pyrolysis oil for SAF production. This will be combined with a novel reverse water–gas shift process to combine CO_2 with hydrogen to produce renewable liquid products;
- processing pyrolysis oil from plastic waste in the steam cracker to provide circular chemicals;
- a revamp of the hydrocracking unit for base oil production that will include circularity through reprocessing spent lubricating oils;
- the installation of a new bio liquefied natural gas plant; and
- the construction of a 100-MW hydrogen electrolysis plant, REFHYNE-II (Figure 3).

This transition is intended to achieve the goal to transform, by 2030, the Rheinland site's output from fossil transportation fuels to an energy-transition-resilient product offering. Shell ▸▸▸

FIGURE 2
The transformation of Shell's refining portfolio.



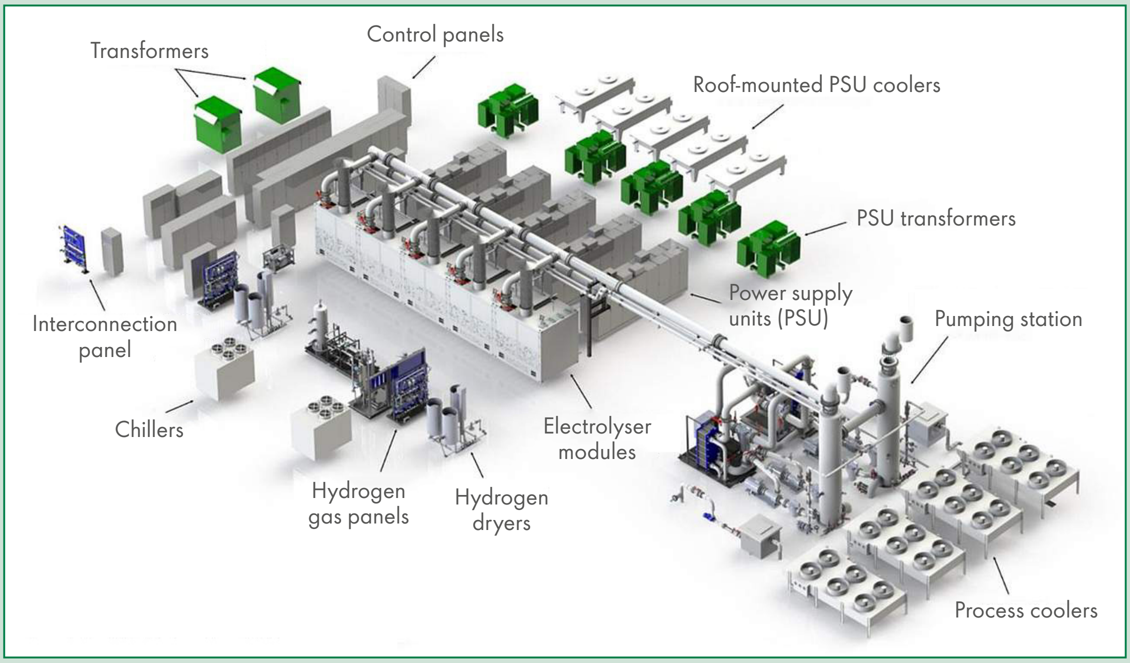


FIGURE 3
The REFHYNE hydrogen electrolysis plant.

Germany will thereby be the leader in developing Shell's first industry park as an example for the other planned energy and chemicals parks.

Important to the economic success of the Rheinland transition is the EU's Renewable Energies Directive II (RED II), which became law in Germany in 2021. It sets transport fuel decarbonisation objectives (mandates reducing the carbon intensity of fuels) and requires the energy industry to respond to customer demand for low-carbon-emission products. RED II provides regulatory certainty and a legal framework supporting the processing of biofeedstocks and the development of their supply chains.

The refinery transition has support from the EU, which has granted subsidies for the REFHYNE hydrogen electrolysis project and from which further subsidies for projects are being requested.

The ongoing energy transition remains a global challenge and uncertainty is high. It therefore remains critical to continue monitoring societal signals and changes in regulations, customer attitudes, feedstock risks and technology readiness.

To supply hydrogen for the project, a new 130-MW electrolyser with associated electrical infrastructure is part of the base-case scope. This will be a major expansion from the 10-MW, lighthouse REFHYNE project that began operation in 2021 and the 100-MW REFYHNE-2 project currently in the final design stage.

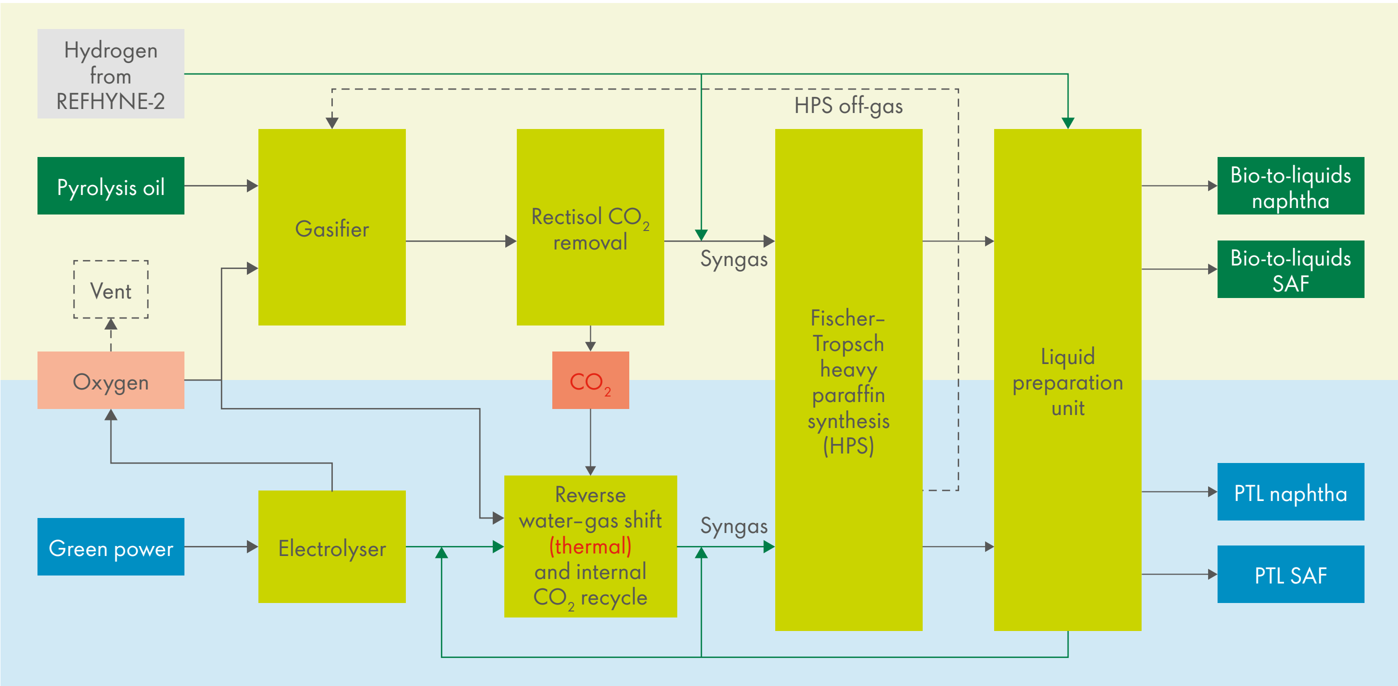
The SAF project provides an opportunity to become the industry front runner in Germany for the production at scale of energy-transition-resilient SAF from sustainable sources. A carbon intensity reduction of about 90% is anticipated. The overall project concept is shown in Figure 4.

The plant will produce sustainable aviation kerosene, or SAF, and by-product naphtha. Some of the output, termed bio-to-liquids products, will be derived from pyrolysis oil feedstock from wood residue that is reacted with oxygen in a partial oxidation, or gasifier, unit. This will be supplemented with hydrogen from REFHYNE-2 to yield a syngas of the right quality for Fischer–Tropsch synthesis.

CO_2 is separated in a Rectisol unit and converted to additional syngas in the reverse water–gas shift unit. The hydrogen required for this reaction is produced by water electrolysis using green energy. The combined syngas streams are routed to a Fischer–Tropsch reactor to produce heavy wax. Power-to-liquids (PTL) products are those made using the fuel portion that is derived from CO_2.

The partial oxidation unit and the Rectisol acid gas removal unit will be repurposed to process the pyrolysis oil feedstock and the methanol synthesis reactor will be converted to a Fischer–Tropsch reactor to produce wax. Investigations have confirmed that these revamps are feasible.

FIGURE 4
The SAF overall concept.



For wax stabilisation, intermediate slops storage, hydrotreating and product fractionation, new units will be built, as a detailed investigation concluded that this was more attractive than repurposing existing equipment. The design of the new units is based on minimum technical scoping results.

Fuels from the Relli+ project will have well-to-wheel carbon intensities about 90% lower than the fossil-fuel comparator of 94.1 g CO_2e/MJ defined by RED II. The project will therefore result in a greenhouse gas emissions avoidance of more than 3 Mt CO_2e in its first 10 years of operation.

Conclusion: Critical success factors

Feedstock

Pyrolysis oil is currently not a commodity product. Global production is only 250,000 t/y and supply is tied to specific customer projects. However, growing demand is driven by refiners that wish to coprocess pyrolysis oil in fluidised catalytic cracking units. Shell is investigating such coprocessing at other locations to maximise value and optimise the supply chain.

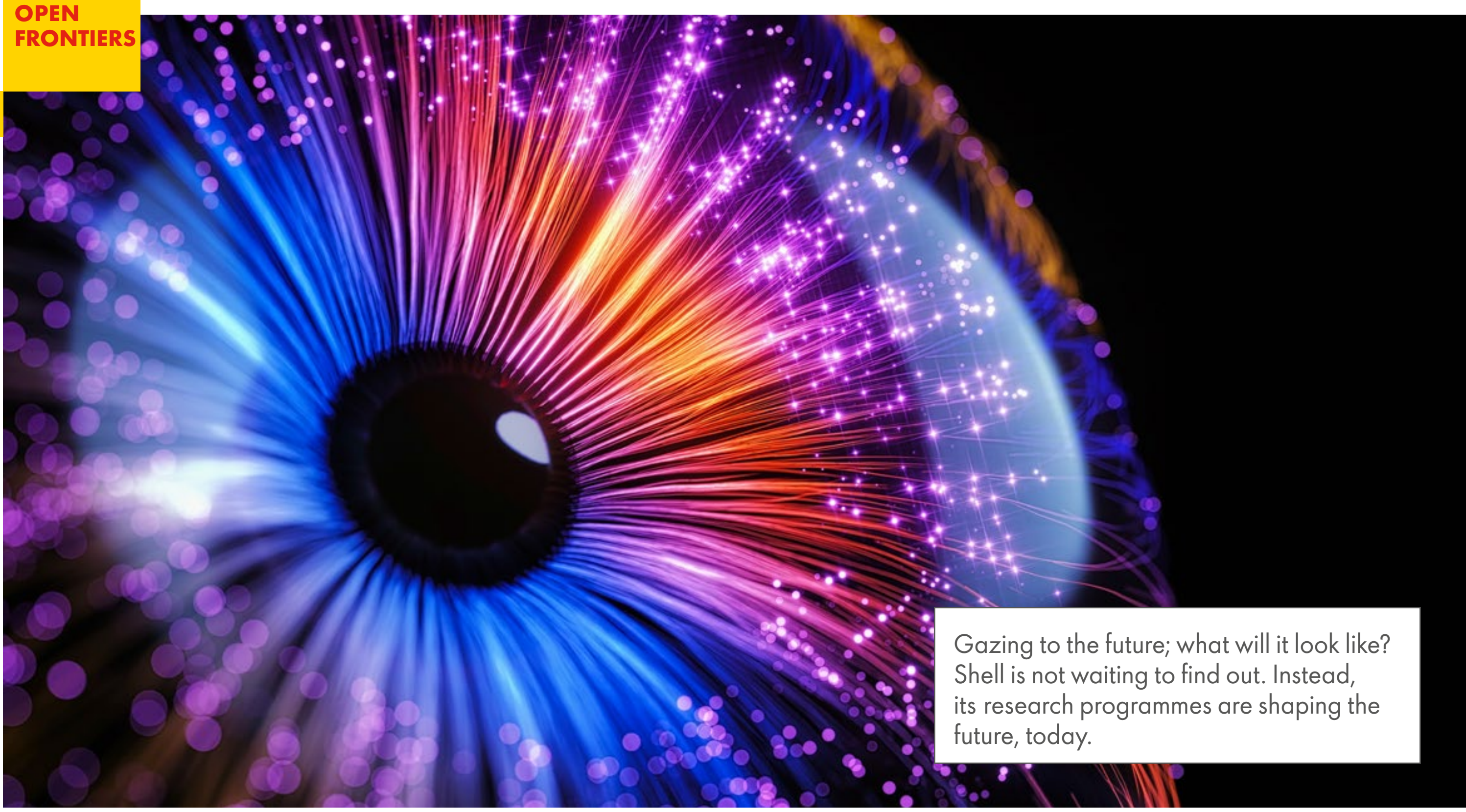
Potential feedstocks include forestry waste, agricultural residues and fast-growing energy crops such as eucalyptus, all of which are RED II compliant. Three main companies have, for 5–25 y, been producing pyrolysis oils at commercial scales of 50,000 t/y in Canada and 24,000 t/y in the Netherlands and Finland. Some technology risks remain for scaling up these technologies, but all three providers have demonstrated an ability to process a wide range of waste-based biogenic feedstocks. Additional work to establish pyrolysis oil yield and quality may be required to support individual projects.

Subsidies

To be successful in the energy transition, the Rheinland site needs to maximise its utilisation of subsidies for relevant projects. Shell Energy and Chemicals Park Rheinland needs processes that are adaptable, as subsidy compliance will depend on adhering to external timing and rules. Resourcing concepts must be explored, and the short-term focus should be on external professionals who can help in building an integrated subsidy strategy that moves from individual project assessment to a more holistic portfolio route for forward progression. ■

AUTHOR

Aigerim Azhenova is an energy transformation projects process engineer at Rheinland. She has also worked in the offshore upstream oil and gas business with Nederlandse Aardolie Maatschappij, the Netherlands, and on the Kashagan project for the North Caspian Operating Company, Kazakhstan. She has a bachelor of science degree in oil and gas processing technology from the Atyrau University of Oil and Gas, Kazakhstan.



Gazing to the future; what will it look like? Shell is not waiting to find out. Instead, its research programmes are shaping the future, today.

PLAYING THE INNOVATION LONG GAME:

LOOKING TO THE FUTURE

Shell's Long Range Research (LRR) Technology Program is a global technical programme dedicated to searching out and nurturing transformative climate technologies that will help the organisation and global society achieve a net-zero and more sustainable future. With a worldwide network of internal and external partners, the LRR programme feeds into Shell's numerous research programmes: elected technology streams that guide high-potential climate technologies to commercialisation.

Shell colleagues Marwa Al-Ansary, general manager long range research and experimentation, and Allison Falender, general manager biotechnology, talked about the power of leveraging natural teams and external partnerships to drive technology innovation and strategy towards a more sustainable and climate-aligned future.

Long range research

What is the LRR programme and how is it helping to influence Shell's long-term technology and net-zero strategy?

Marwa: The LRR programme was established in 2016 to help shape Shell's technology future. It is a capability-based organisation that sits at the beginning of Shell's innovation funnel (see Figure 1). It looks 10-plus years into the future for game-changing climate technologies that can help transform Shell into a net-zero energy company. A question we often ask ourselves is: "If we were to start an energy company today, what would we want it to look like?"

Identifying new technologies, validating ideas and complementing commercialisation are important parts of what we do. We undertake a lot of competitive intelligence and if we find something that we like, then we look to make it strategic; this has been our core strategy since the programme's start. The technologies we consider are far away from commercialisation, so it is a great space in which to experiment and be creative.

The energy and technology ecosystem, including Shell, has moved on a lot in the last five years. Decarbonisation and the energy transition are huge challenges that require innovative solutions in the near, mid and long terms. Consequently, the programme is undergoing a significant refresh. We want to redefine Shell's research and development (R&D) funnel to align with its Powering Progress strategy, which means looking for the next big-ticket items in climate technology R&D such as low- and zero-carbon technologies, waste management solutions and enablers for the circular economy.

But not all our projects are about commercialising technology. Some are to help educate and build internal capabilities, which helps us be smarter investors. Funding projects associated with LRR themes also enables us to hire people committed to

the technologies of the future and train them to continue the work from within. They provide the best possible technology transfer process. To deliver true shareholder value, Shell needs to have committed people and a healthy and resilient project portfolio – and this is what the LRR programme is all about.
Allison: As we progress through the energy transition, technology and innovation are really important. We will not flip a switch in 2030 and have all the technologies we need, so, we need to move quickly to identify and validate promising concepts now. Therefore, the LRR programme is extremely valuable because it enables Shell to test high-risk ideas, but without committing too much capital.

What sort of climate technologies is the LRR programme targeting and how do you determine which technologies will be important more than a decade into the future?
Marwa: It is a key challenge to predict which technologies will be important in the coming decades, so, to do this, we need to start with our future customers. We must understand how their behaviour and demands are evolving, and how we can best equip ourselves to continue providing the best value. But situations can change a lot in a short time, so we constantly consult with internal leadership, experts from Shell's scenarios team and external partners to understand better the technologies to target.

For us, LRR is all about fundamental and early-phase R&D and looking for technology areas that Shell wants to build capabilities in, that have significant innovation headroom, and that could have impact across multiple applications. So far, these include new energy solutions and the development of radically better dense energy carriers and energy storage aimed at electricity on demand, that is to say, dispatchable energy; and new chemical pathways to convert methane into low-carbon products. One area that we are very proud of is sustainable aviation fuel (SAF).

Collaboration
Collaboration is very important for the LRR programme, so how does this work across Shell?
Marwa: The LRR programme really is a global team in terms of both internal and external collaborations. And these partnerships are vital to the success of the programme and Shell's long-term innovation strategy.

At Shell, we work as one big natural team. We have a core team of about 60 people and a wider team of about 115 experts collaborating across the company and from all over the world, including North America, Europe, Brazil, India, Australia and Asia. We also provide funding to the advanced development programmes, which are the next step in Shell's innovation funnel (Figure 1).

Allison: I work very closely with Marwa; we speak almost weekly. We have several biotechnology projects related to nature-based solutions (NBS), including blue carbon, which examines the use of mangroves and other marine ecosystems for carbon storage. These projects are still classed as high risk, so we are working with the LRR programme to try and progress them and diversify the NBS portfolio.

Marwa: We also work closely with the Shell Innovation Council (SIC), an internal review board with members from Shell's executive board. They support us on deciding which projects to invest in and where to locate funding, as well as on defining our external technology collaborations (ETC) strategy.

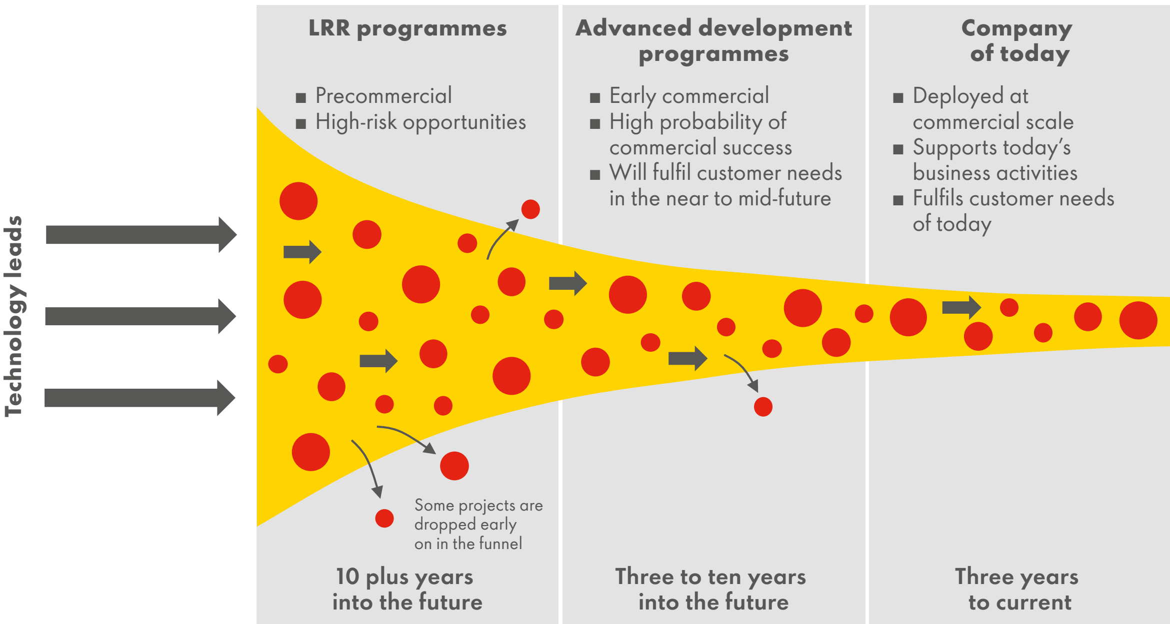


FIGURE 1
Shell's global innovation funnel.

You have mentioned ETCs. Why are external partnerships important for the LRR programme, and can you give some examples?
Marwa: Shell is always looking to strengthen its capabilities, particularly in areas where it is not a specialist. So, when the LRR programme was established, the team set out to find partners that were the best in the world at R&D and facilitating innovation in the specific technology areas that Shell is interested in.

We currently have 130 ETCs in more than 12 countries, ranging from leading universities and national governments to private enterprises. It is a very healthy innovation ecosystem. We spend about 50% of our budget on our ETCs, most of which are based in the USA, the UK and the Netherlands.

External collaborations are vital to the success of the LRR programme. For example, it is important that Shell is aligned with the strategic direction of countries that it operates in. By partnering with government research agencies such as the Dutch Research Council (NWO) or the Qatar National Research Fund, we can develop strong stakeholder relationships, leverage government funding and enhance our credibility. Governments are also keen to involve industry partners in research consortia to steer the research towards application.

A great example of government and company collaboration has been Shell's partnership with Dutch airline operator KLM. The two companies successfully met a challenge set by the Dutch Ministry of Infrastructure and Water Management to produce sustainable, synthetic kerosene. In response, Shell produced 500 L of the zero-carbon fuel, which was mixed with conventional kerosene and used to fuel a passenger flight from Amsterdam, the Netherlands, to Madrid, Spain.

Another success story has been the various partnerships we have set up along the lines of the LRR activities – such as for methane pyrolysis (production of hydrogen and carbon products), CO_2 capturing and conversion, and processing of plastic waste for high-end chemicals and improved circularity – in close collaboration with the Shell GameChanger and Shell Ventures programmes.

Advanced development programmes
You mentioned R&D projects. What are they and what role do they play in Shell's innovation strategy?
Allison: Our advanced development programmes are the next step in Shell's innovation funnel, after the LRR programme. They cover technologies that have a high probability of success and that we hope will be market-ready within three to ten years. As we transition to net-zero emissions at Shell, we approach all our research programmes with a clear sense of mission and collaboration so we can achieve the seemingly impossible.

Marwa: We currently have three advanced development programmes under way that have been funnelled through the LRR programme. The first focuses on low-carbon hydrogen produced by electrolysis or from natural gas using methane pyrolysis. The second centres on industrial electrification and advanced energy storage, while the third focuses on NBS, which is Allison and the biotechnology team's domain. We also have other research programmes in the pipeline.

What is the NBS advanced development programme and what role does the biotechnology team have in it?
Allison: Leading Shell's biotechnology programme is my dream job because the work we are doing directly touches Shell's net-zero carbon ambition, whether that is supporting the low-carbon fuels or chemicals businesses or solutions to capture atmospheric carbon dioxide using NBS.

It is a really exciting time for biotechnology, as the NBS advanced development programme has just been ratified. NBS are effective ways to reduce atmospheric carbon dioxide in the short- to medium-term because they do not require significant capital investment compared with, for example, carbon capture and storage (CCS) in geological formations. They offer exciting and sustainable ways to achieve our goals faster.

The NBS programme is a great example of how we collaborate with the LRR programme. For almost a decade, Christian Davies, our principal scientist, has been conducting research on NBS funded by the LRR programme. Through this work, we realised just how important NBS are, so, working closely with Yuri Sebregts, Executive Vice President Technology and Chief Technology Officer, and Dirk Smit, Vice President Research Strategy, Christian and the team submitted a formal proposal outlining what a NBS programme would look like. It was endorsed for 10 years of funding through to 2030.

External partnerships are also vital to the success of the NBS programme. What sort of partnerships do these include and what technologies are they working on?
Allison: One exciting partner is Prairie View A&M University, a historically Black university just down the road from our biotechnology laboratory here in Houston. When we look at the impacts of climate change, it is often poorer communities or those in developing countries that suffer the most. Here in the USA, the impact of hurricanes Katrina and Harvey disproportionally affected local Black communities. So, when we work with universities like Prairie View A&M, we are working with scholars who have been directly affected by these disasters. This gives us

unique perspectives into the challenges more vulnerable communities face and the best solutions.

We are also working with the University of Exeter, UK, on the application of eddy covariance[1] to the measurement and verification of carbon offset schemes. The technology is a low-cost method for measuring and predicting the near-surface atmospheric concentrations of carbon dioxide over different land areas. It has proved so successful that the research has spun out into a start-up called Quanterra Systems in which Shell Ventures is an initial investor. This is a great example of how an idea identified by LRR can progress to a start-up.

Outside academia, we are also developing a company partnership plan for the agriculture and forestry sectors so that we can work on business applications for NBS. Additionally, we are currently in early discussions with several governments about forming consortia for NBS. This helps us align our strategy with the direction of national policymakers.

Finally, it is really important that we continue to expand our partner network. So far, our partner portfolio is Euro-American-centric; however, it is also important for us to go to China, India, Singapore and countries in Africa to gain new and unique perspectives.

Any final thoughts?

Marwa: The LRR team develops technology components and explores novel, potentially integrated platforms and supply-chain archetypes in which such technology blocks could be deployed. Its success is measured by the number of technologies that are transferred to other businesses in Shell for further development.

The energy transition is a huge challenge, so we need to have a healthy combination of in-house capabilities and external collaborations to find the best solutions for our customers and society. We have amazing researchers and experimentalists at Shell helping the LRR programme to identify and develop the technologies that the organisation needs to support its strategic ambition to become a net-zero-emissions energy provider by 2050.

That support should come from two logically connected perspectives:

1. outside–in: option generation through scouting, exploring and assessing potentially disruptive technologies and connecting them to our own capabilities to define options for innovation; and
2. inside–out: future-ready our technology community and our own technology capabilities on the basis of expected thematic business demand (thematic shaping).

Allison: We really recognise the important role that technology plays in the energy transition. In the past, I felt that we focused more on the evolution of existing thinking, but now, it feels like we are moving from evolution to revolution.

Shell's strategic ambition to lead and thrive through the energy transition requires the best ideas and the highly motivated and engaged people who can deliver them. We are constantly looking for new, talented individuals, from all backgrounds and in all areas of business, who are as passionate about working on energy solutions as we are: www.shell.com/careers. html. ■

[1] Eddy covariance technique is a key atmospheric measurement technique to measure and calculate vertical turbulent fluxes within atmospheric boundary layers.

BIOGRAPHIES

Marwa Al-Ansary is the general manager for long range research and experimentation in Shell's technology organisation and leads a global team developing transformative and competitive technologies to provide more and cleaner energy solutions. Her areas of expertise include sustainability and circularity, decarbonisation (carbon accounting, management, policy and advocacy) and technology commercialisation. She has a PhD in engineering from Cambridge University, an MSc in environmental science from Strathclyde University, both in the UK, and BSc and MSc degrees in construction engineering from the American University in Cairo, Egypt.

Allison (Allie) Falender is the general manager for biotechnology at Shell. Her multiple leadership roles in Shell have included commercial manager for chemical enhanced oil recovery and business advisor to the executive vice president, both in Shell Chemicals, and general manager for gasoline development. Allie is a United States Patent and Trademark Office patent agent. She has a BA in biology and sociology from Oberlin College and a PhD in molecular and cellular biology from Baylor College of Medicine, both in the USA.

SUPPORTING APAC MARKETS WITH a new STCB lubricants laboratory

The Lubricants Asia Pacific (APAC) management team proposed setting up a lubricants technology laboratory at Shell Technology Centre Bangalore (STCB), India, to support local markets through lubricant development and testing. The objective was to build technical intimacy with key customers and demonstrate technology leadership by creating "fit for the Asia Pacific market" solutions. This initiative was supported by senior management, so a project was initiated and implemented by a technical team from STCB. The laboratory is now providing faster turnarounds to meet customer technical requirements and developing local solutions to support and exploit the full potential of the region's markets. In the future, the laboratory will also help develop carbon-neutral products and integrated energy transition solutions for Shell.

Establishing a new lubricants technology laboratory

The execution plan for setting up the laboratory was developed in 2018 with input from the technology, marketing and business teams in India and Indonesia. Two major areas were identified as the foci for the laboratory's activities: a business-to-customer capability to support the automotive sector and a business-to-business facility supporting industrial lubricants businesses.

After the final investment decision (FID), execution was fast forwarded by rapidly completing the enabling activities of onboarding a new team, finalising the capital expenditure requirements and engaging with the STCB site team, including the operations; health, safety, security and environment; and real estate functions (see Figure 1). This was completed by mid-2018. Instrument commissioning was performed in early 2019 and the STCB lubricants technology laboratory was inaugurated in April 2019 by then Executive Vice President Global Commercial Huibert Vigeveno. By the end of 2019, the new laboratory had started supporting the business through activities such as benchmarking and global and local new product development (NPD).

By the end of 2021, the new laboratory had delivered several impressive business-support activities. In the business-to-customer sector, these included the rollout of an upgraded additive technology for Shell Advance AX3 and AX5 motorcycle oils; the introduction of a new, branded motor oil to the Philippines; and the localisation and approval of a passenger car diesel engine oil.

Notable NPD activities to meet business-to-business customer requirements have included those for a hydraulic oil for a construction-sector manufacturer; various fit-for-purpose applications for low-tier hydraulic oil; a new Shell high-flashpoint hydraulic fluid for the Korean market; and the implementation of re-refined base oil manufacture in China.

The laboratory has provided field-trial support for current and potential customers, for example, for Shell Omala S5 Wind for a leading renewable energy company in India and Shell Corena S4 R for a major manufacturer of compressors. It has also provided oil-blending support for field trials of universal tractor transmission oils for key manufacturers in the agricultural sector.

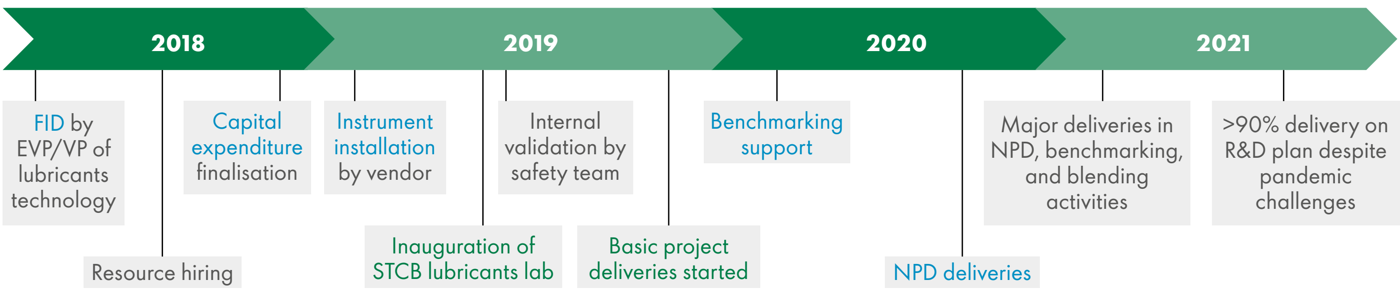
Success stories

Developing a new motor oil

The engine oil development team at STCB co-operated with a leading Indian motor vehicle manufacturer in the development of a next-generation fuel economy passenger car motor oil for its new engine platforms. This oil was needed to meet India's Bharat Stage VI emission standard. The Shell team's development strategy involved screening new viscosity modifiers and substituting the base oil in the existing product with a fully synthetic base oil manufactured using gas-to-liquids technology.

Viscosity modifiers were selected on the basis of their chemistry and shear-stability index. Screening

FIGURE 1
STCB lubricants technology laboratory timeline.



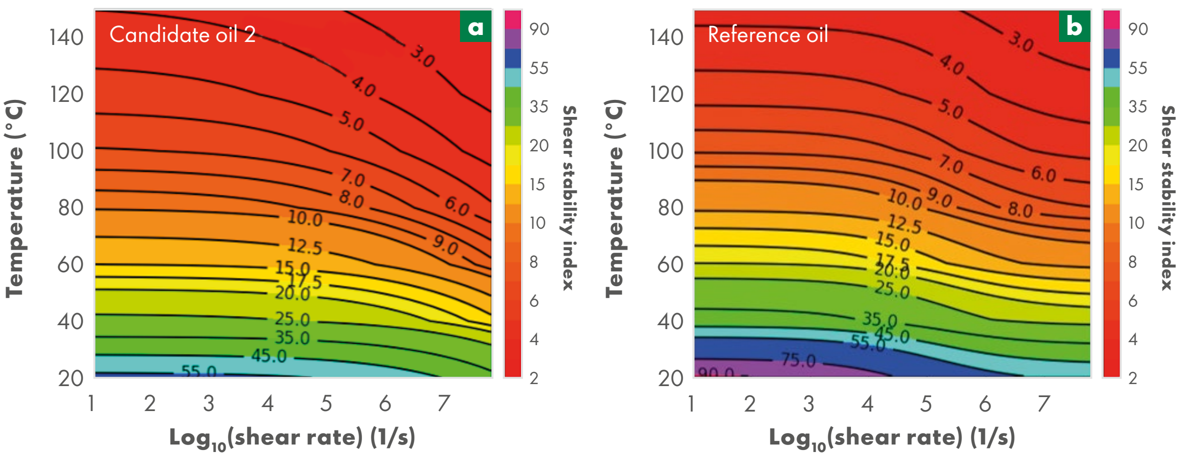


FIGURE 2
Shear curves for **(a)** the candidate and **(b)** the reference oil.

studies at STCB involved developing a multigrade engine oil that met a tighter viscometric specification. The candidate oils were then sent to a Shell Technology Center Houston laboratory in the USA for advanced screening studies. This laboratory generated full shear curves, that is, viscosity profiles generated at varying shear rates and temperatures. These simulate the viscometric variations encountered in real engine running conditions (see Figure 2). On the basis of this collaborative study, Shell selected two candidate oils that were passed to the customer for internal evaluation; this is currently in progress.

Hydraulic oil formulation

In another project, the STCB industrial team showed strong customer intimacy by formulating a hydraulic oil, Shell Hydraulic V TX, for the South Korean market in the shortest possible time. According to the South Korea Fire Service Act, companies having storage tanks for petroleum oils, including hydraulic oils, of 6,000 L or greater capacity must obtain a fire permit unless the flashpoint of the oil is above 250°C. This is commonly the case in many industries, including the metals and general manufacturing sectors.

If the flashpoint requirement is not met, the facility must install explosion-proof equipment and obtain a fire permit; this represents a significant capital investment for customers. Because of this challenge, the South Korea business team requested a product that would satisfy the flashpoint criterion and meet Korean Standard KS M 2129:2015 and steelmaker POSCO's specification.

The development of a dedicated, high-flashpoint product, Shell Hydraulic V TX, enabled the local business not only to defend its existing hydraulic oil business and pursue cross-selling opportunities, especially in the steel sector, but also to seek to exploit new business opportunities for more than 1.5 million litres of hydraulic fluid in the South Korean market. As well as having a high flashpoint, the product satisfies the requirements of the Korean Act on the Registration and Evaluation of Chemicals and the performance requirements of the KS M 2129:2015 standard. The lubricants team also received particular appreciation from Shell's Korean customers, as the launch of the new product saved them the high capital investment costs necessary for building explosion-proof storage facilities. ▸▸▸

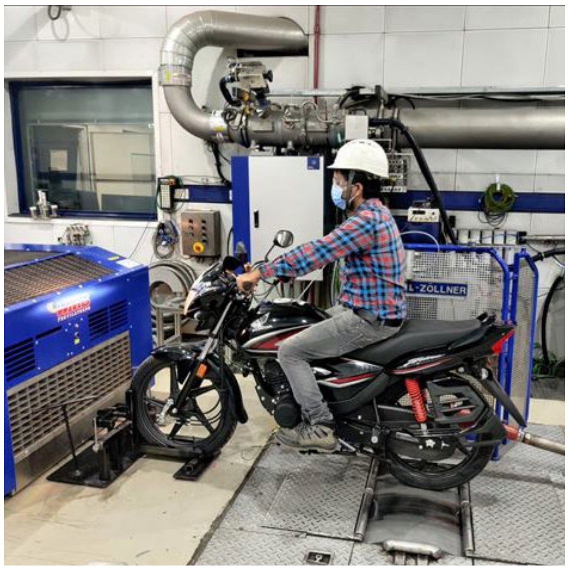


FIGURE 3
A motorcycle on the chassis dynamometer.

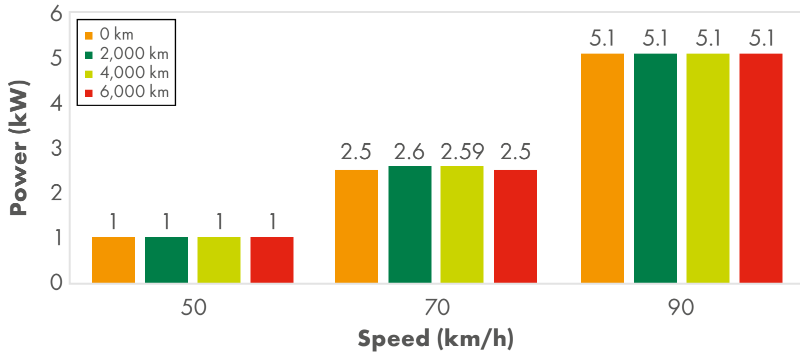


FIGURE 4
Dynamometer results for power versus distance travelled.

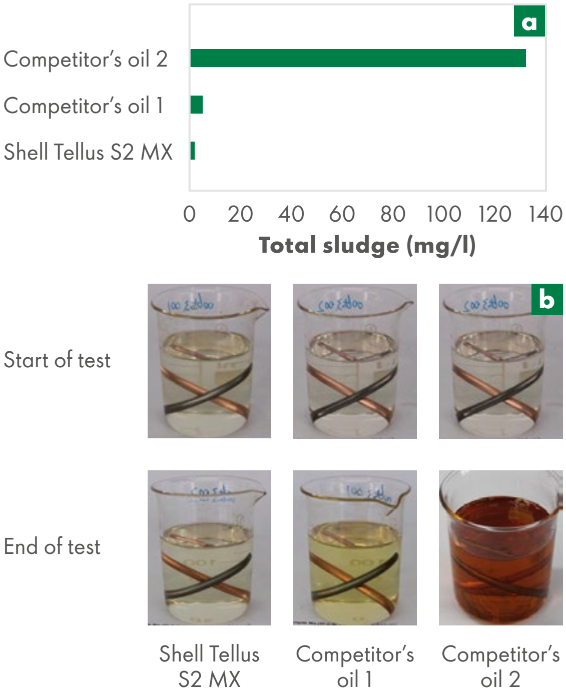


FIGURE 5
Typical thermal stability test results: **(a)** sludge formation and **(b)** samples before and after testing.

Motor oil approval

The motorcycle oil team contributed to a business win by obtaining manufacturer approval for the supply of a branded motor oil in the Philippine market. Teams from STCB and the global motorcycle oil team devised innovative technical studies to address the client's technical approval requirements.

The lubricants technology laboratory supported this initiative by blending and supplying a Shell candidate oil to the AVL India and Shell Lubricants Japan laboratories for vehicle-level and friction performance tests. These were conducted to showcase the performance of the Shell candidate oil and get technical approvals for winning business.

The STCB laboratory took complete ownership of project activity with AVL India for running endurance and no-harm tests on a motorcycle to demonstrate lubricant performance. This included no power loss after running for 6,000 km on a chassis dynamometer (see Figures 3 and 4). This work led to the award of a 50% share of this business in the Philippines.

Product benchmarking

Injection moulding is a key sector in India that provides a potential annual market of about 7 million litres of hydraulic oil. Shell currently supplies one fifth of this. Manufacturer approval is a critical factor for this sector, and Shell is doing well owing to preferential approvals from some leading manufacturers. However, to secure a leading position, Shell needs to counter the increased competition with technical claims.

The lubricants technology laboratory performed benchmarking of Shell Tellus S2 MX oil against leading competitors' oils. The Shell oil showed exceptional oxidation-resistance performance, as shown by minimal sludge formation in the ASTM D2070 thermal stability test (Figure 5). Shell Tellus S2 MX also showed balanced performance in surface property (air release, water separation and foaming tendency) and antiwear (four-ball wear and pump) tests. A marketing communication was developed on the basis of the benchmarking results.

Conclusion

The examples cited show that the lubricants technology laboratory is already achieving its aims of demonstrating technology leadership and building technical intimacy. The laboratory has also proven its ability to support retaining existing customers, gaining new ones and entering new markets.

Acknowledgements

The authors would like to thank Mansi Tripathi and Selda Gunsel for proposing and developing the laboratory concept; Rosemary Ran for project execution; Srikant Viswanath, Jiao Yan, Felix Guerzoni, Sathya Narayanan and Deepti Bapat for their support and guidance; Priyanka Desai at Shell Technology Center Houston for her support on the new motor oil development project; and Cameron Watson for his support, guidance and valuable comments on this article. ■

AUTHORS

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Swati Malgi is a technician in the Shell lubricants and fuels technology team in Bangalore. She provides oil-testing support to the business-to-business and business-to-customer sectors. Swati has 10 years of experience in the lubricants industry. She has a master's degree in inorganic chemistry from the University of Mumbai, India.

ENERGY TRANSITION VALUE CHAINS REQUIRE reliable subsurface storage

Shell supports the UN Paris Agreement on climate change and targets becoming a net-zero emissions energy business by 2050 through an approach including carbon capture and storage (CCS) and hydrogen strategies.[1] Subsurface storage of carbon dioxide and hydrogen is critical for protecting the value of the associated energy transition value chains, so Shell is working to develop a range of tools and techniques to help ensure the safe storage of carbon dioxide (CO_2) for permanent sequestration and of hydrogen as an energy carrier.

The energy transition challenges

In October 2021, Shell set a target to reduce the absolute scope 1 and 2 emissions under its operational control by 50% by 2030 compared with 2016 levels on a net basis. This supports its overarching target to become a net-zero emissions energy business by 2050, in step with society. The changes required include improving operational efficiency, increasing the production and sale of low-carbon power and renewable fuels, including hydrogen, and utilising CCS natural sinks.

For CCS, Shell's ambition is to have access to 25 Mt/y or more of CO_2 storage capacity by 2035. Its strategy includes developing commercial CCS hubs that enable decarbonisation of multiple industries and customers by providing them with low-carbon energy (see Figure 1).

[1] Shell's operating plan, outlook and budgets are forecasted for a 10-year period and are updated annually. They reflect the current economic environment and what can reasonably be expected over the next 10 years. Accordingly, Shell's operating plans, outlooks, budgets and pricing assumptions do not reflect its net-zero emissions target. In the future, as society moves towards net-zero emissions, Shell's operating plans, outlooks, budgets and pricing assumptions are likely to reflect this movement.

Hydrogen is an energy carrier that can balance the intermittency of renewable energy sources in space and time. Shell intends to be a first mover in the nascent hydrogen business and to offer integrated hydrogen solutions to its customers, initially in the industrial and transportation markets. The ability to have subsurface hydrogen storage will support the scale-up of the hydrogen economy to a fully net-zero energy system.

CCS is critical for goal achievement

Many climate scientists recognise that CCS is essential for society to achieve the climate goal of the Paris Agreement. CCS is vital for the decarbonisation of industrial sectors such as steel, cement and chemicals manufacturing, and for reducing the emissions related to fossil fuels. CCS requires safe, long-term and large-scale CO_2 storage, which is also a key enabler for energy transition value chains such as bioenergy CCS, direct air capture and low-carbon hydrogen. There are no fundamental technical limitations to CO_2 storage in depleted oil and gas fields and saline aquifers. However, the selection of storage sites and operational designs must always consider and manage the risks of induced ▸▸▸

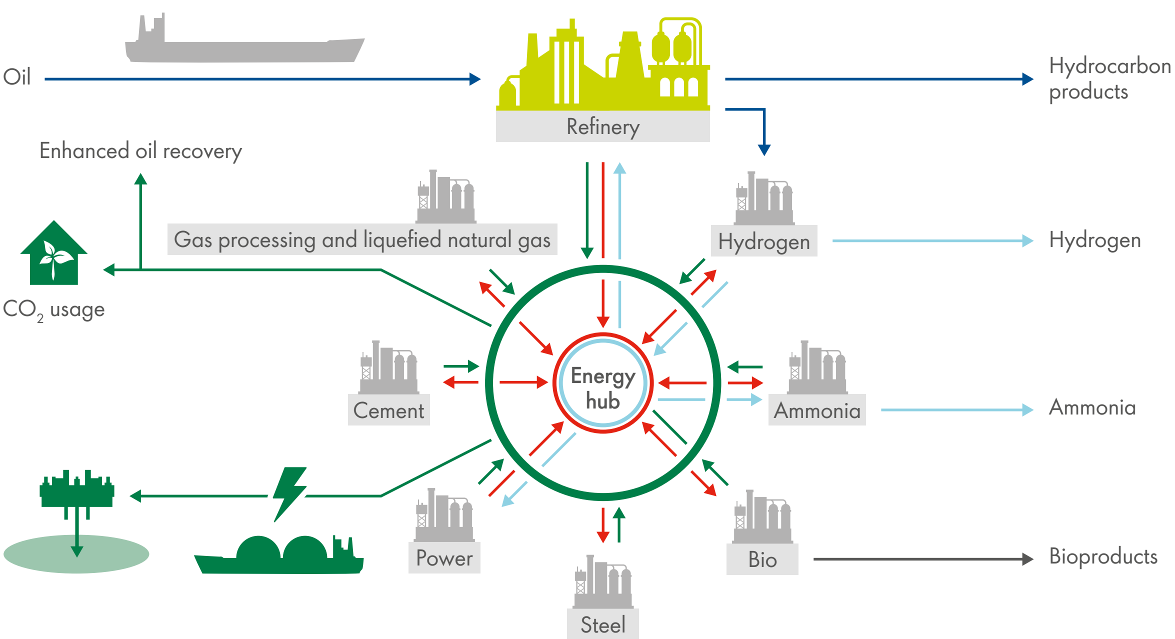


FIGURE 1
Developing CCS to accelerate decarbonisation through carbon-neutral energy hubs.

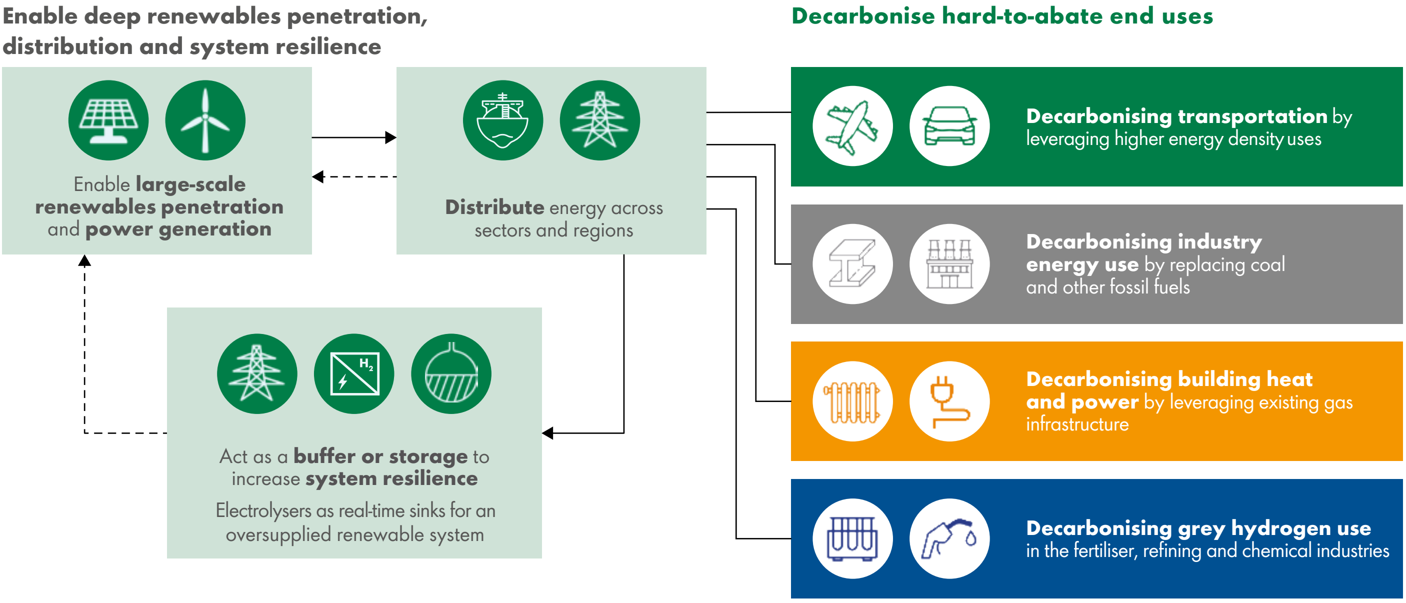


FIGURE 2
Shell's 2021 predictions for hydrogen in the future energy system.

seismicity (seismic events that are a result of human activity) and the long-term containment of the injected CO_2.

Storage in depleted reservoirs is attractive, as these fields come with production history, appraisal and exploration data, and have demonstrated containment over geologic timescales. However, CO_2 injection into depleted reservoirs has a unique challenge because the phase behaviour of CO_2 differs from that of natural gas. Specifically, CO_2 is transported as a high-pressure liquid, but the temperature and pressures in a highly depleted field are such that the injected CO_2 will transition to the gas phase. The expansion of CO_2 from the liquid to the gas phase causes significant Joule–Thomson cooling. This could lead to the formation of hydrates and water ice, and create thermal and pressure effects that could affect containment and injectivity. Current solutions are costly or limit the range of injection rates. It is, therefore, critical to develop the required modelling capabilities and evaluate engineering solutions for de-risking a portfolio of potential storage sites.

Vision and road map for hydrogen

Clean hydrogen is expected to play a key role in the energy system of the future and will be crucial for reaching net-zero carbon emissions (Figure 2). The ability to transport hydrogen over large distances and store it for long periods makes it useful for balancing the intermittency of renewable energy sources in space and time and, hence, permits a higher share of renewable energy to enter the energy system. Hydrogen produced from renewable energy also enables the effective transfer of renewable energy to regions with limited wind and solar resources. It is the most promising solution for decarbonising hard-to-abate sectors in which electrification is not possible or not the preferred decarbonisation route, for example, refining, fertiliser production, steelmaking and heavy-duty transport.

There is uncertainty around the pace at which the hydrogen market will develop. The EU's hydrogen strategy sets targets for hydrogen production via electrolysis of 6 GW in 2024 and 40 GW in 2030. Shell's new energy transformation scenarios Waves, Sky 1.5 and Islands project demand for hydrogen being between 0 and 50 TWh/y in 2040, depending on policy support, alignment and timing, and rising to 3,600 TWh/y in 2050.

Hydrogen storage will be critical to ensure the continuity and security of hydrogen supply to Shell customers. It can be most cost-competitively achieved in the subsurface by utilising (man-made) salt caverns or porous reservoirs (depleted fields and aquifers). In Scandinavia, the storage of hydrogen in lined rock caverns is being explored. These caverns are constructed by conventional mining and lined with stainless steel to seal off the cavern from the surrounding rock. Their specific costs are significantly higher than for salt caverns and porous reservoirs. However, they could be attractive where the geological conditions do not provide other storage opportunities.

Salt caverns are already used for storing hydrogen at four locations globally, one in Teesside, UK, and three near the US Gulf Coast. Operating experience data for these caverns are scarce, so further investigations are necessary to ensure the safe and economic operation of salt caverns for hydrogen storage and to establish the basis for regulatory and public approval.

Porous reservoirs offer storage capacities several orders of magnitude larger than salt caverns, so will be essential to satisfy the storage demand of a hydrogen economy at scale and over longer periods. Depleted gas fields will be the first targets. The same benefits apply for hydrogen storage in depleted gas fields as for CO_2 storage: a well-characterised state, the availability of free pore space after depletion and the possibility of reusing wells and facilities. Unlike CO_2, hydrogen will be transported at pressures similar to or lower than the initial pore pressure in the depleted reservoirs and will be gaseous across the full working pressure range. Consequently, no severe Joule–Thomson effects will occur during hydrogen storage (the Joule–Thomson coefficient for hydrogen is much smaller than that for CO_2 and negative).

The experience with hydrogen storage in porous formations is very limited and relates mainly to the storage of town gas (mixtures of 25–60% hydrogen with mainly methane) in aquifers from the 1950s to 1970s.

Technology development for efficient and safe CO_2 storage

To secure value for Shell's developing energy transition business, CO_2 storage operations must be safe and efficient with no tolerance for leakage. For large-scale CCS deployment, new technologies are required to actively control, rather than simply avoid, low-probability, high-impact geological storage risks. CO_2 storage technology developments must, therefore, deliver trusted and cost-effective methods to identify, assess, mitigate and monitor all the credible subsurface threats to the integrity of long-term CO_2 storage. These CO_2 storage technologies will be important for reducing life-cycle storage costs and long-term liabilities while enabling efficient use of storage capacity across a range of geological settings. These technologies may also strengthen Shell's ability to secure regulatory permits and enhance public acceptance.

The current CO_2 storage technology development programme started this journey in 2018 and is well on the way to stepping up CO_2 storage capabilities from mega- to giga-tonnes per year utilising an extensive network of external collaborations to share costs, accelerate progress and build trust. It covers four technology themes:

- containment integrity of faults, seals and the near wellbore region, including geochemical effects on faults and seals;
- induced seismicity due to injected or produced fluids;
- storage efficiency and reactive transport modelling (RTM), including geomechanical effects; and
- verification monitoring for long-term and large-scale CO_2 storage.

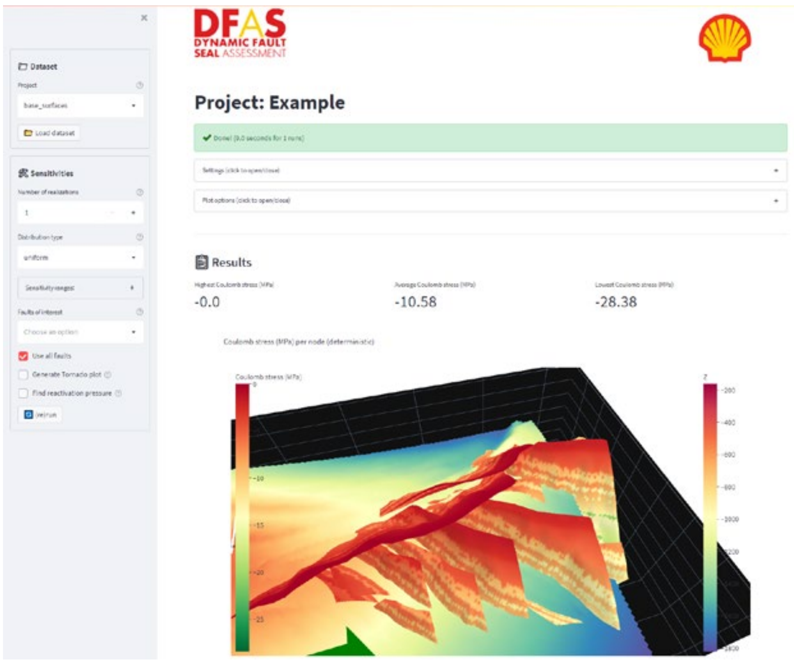
The following sections explain the themes and provide examples to illustrate proposed solutions for problems worth solving identified through close collaboration with the CCS deployment organisation and ongoing CO_2 storage projects. Many of the technologies are also being progressed through deployment in hydrocarbon assets for managing integrity and containment risks.

Containment integrity

The containment integrity team is developing modelling and risk assessment tools that are informed and calibrated by in-well and areal monitoring data for CO_2 storage projects and assets with potential integrity challenges. It currently covers three projects: assessment and detection of fault and seal integrity loss, including the risk of leakage across caprock; geomechanical history matching; and the near wellbore toolbox (NWT). Loss of containment can be induced by changes in pressure, temperature, rock stress, saturation and fluid reactivity. To assess the impact of these changes, the team performs integrated geomechanical and geophysical analysis that delivers data-driven probabilistic forecasts of potential integrity issues.

For example, the recently developed dynamic fault seal assessment (DFAS) tool enables rapid preliminary screening of fault reactivation and leakage risks in support of site selection for CCS and risk identification for well abandonment (see Figure 3). In addition to early demonstrations of the tool for CCS projects (Gorgon, Australia; Aramis, the Netherlands; and El Camino, USA), DFAS has been demonstrated in Brunei to assess fault stability and leakage risks as part of a well abandonment effort.

FIGURE 3
The DFAS tool.



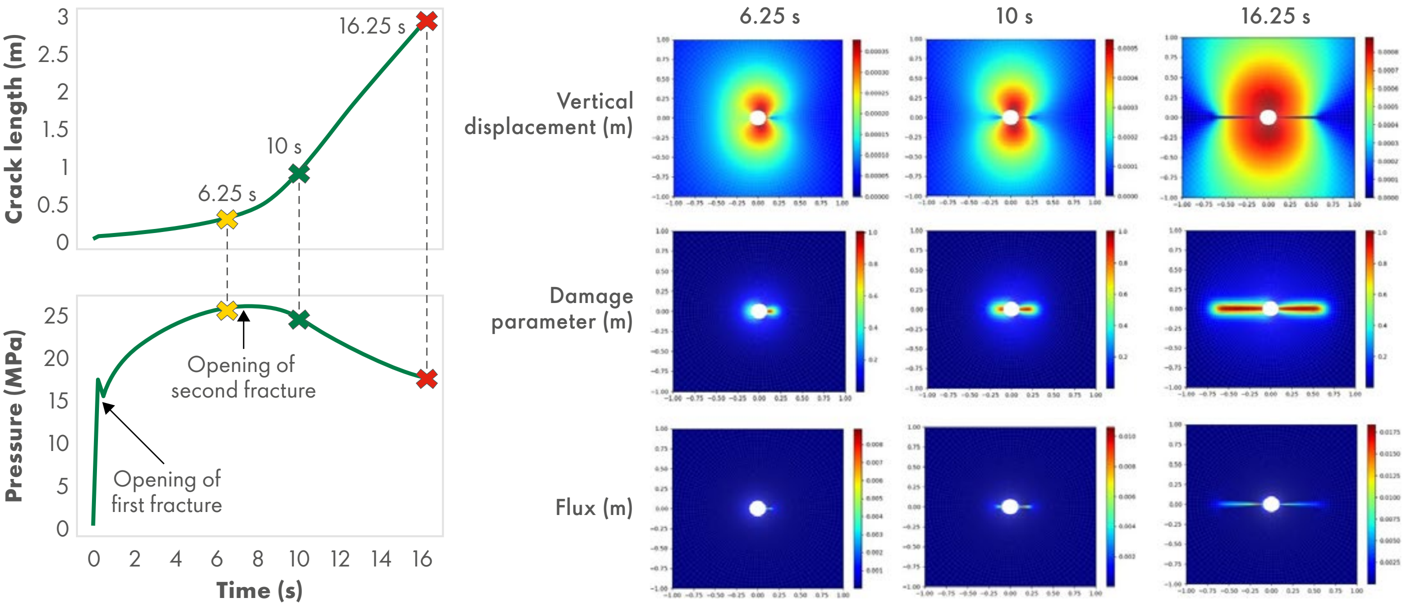


FIGURE 4
Modelling of induced fracturing in the near wellbore region.

Geomechanical history matching uses surface monitoring data (showing heave or subsidence both on- and offshore) to calibrate forward predictions of geomechanical models. Early demonstrators include the Qarn Alam, Oman, and Ormen Lange, Norway, gas projects, and the Gorgon CCS project. The ambition is to extend this data-driven containment risk assessment workflow to include production, well and seismic data. In the next step, a fully probabilistic and stochastic version of this geomechanical history matching capability is being developed.

The NWT is a 3D multiphysics numerical toolbox that can assess the deformation and failure likelihood of near wellbore formations and completions. It is thermo-hydro-mechanically coupled and can be used to derive injection constraints for waterflooding and CO_2 injection. The tool can also be used to benchmark vendor packages such as the REVEAL reservoir simulator and for well test assessment and appraisal. Other potential applications are envisioned for current CO_2 storage projects and assets where downhole stress tests and their interpretation are required to demonstrate caprock integrity. Deviations from textbook examples and more complex behaviours, for example, the late opening of second fractures causing misinterpretation of test results with conventional methods, can be investigated with this capability (see Figure 4).

Induced seismicity
In the Netherlands, where induced seismicity is a major concern, the Groningen seismological model developed by Shell colleague Stephen Bourne [Ref 1] was accepted by the Dutch government and regulator as the technical basis for informing gas production policy and infrastructure strengthening decisions.
A probabilistic, induced seismicity risk and hazard analysis and optimisation workflow based on this work was developed and applied to CO_2 storage projects currently in operation (Quest in Canada and Gorgon). The remaining challenges to address include integrating monitoring bias, that is, assessing the impact of having limited microseismic monitoring coverage, and pressure plume interference from neighbouring operations.

Storage efficiency and RTM
The storage efficiency team is developing new modelling workflows using RTM to forecast fluid flow, the transport of heat and solutes, and geochemical reactions. This includes growing capabilities to assess the performance of CO_2 injection into depleted reservoirs; potential injectivity issues; the impact of contaminants; and the risk of leakage across caprock due to geomechanical reactions. Work on developing and benchmarking integrated modelling capabilities to assess the risks of CO_2 injection into depleted reservoirs has recently started in collaboration with experts in Shell Upstream.

Further, large-scale deployment of CCS at the gigatonnes-per-year scale may result in cumulative pressure effects from multiple individual storage sites in the same area, which could lead to unacceptable risks. Therefore, the team is also developing methods to efficiently assess CO_2 plume pressure propagation and management, for example, water extraction, with a direct link to induced seismicity risk assessment.

The reactivity of contaminants in a CO_2 injection stream with the minerals and dissolved species in formation water necessitates assessment of the relevant geochemical reactions because the reaction products may lead to pore throat plugging and a decline in permeability. RTM can be used to make a quantitative prediction of the reaction products generated in the reservoir and in the near wellbore region. For example, for the Polaris CO_2 storage project in Canada, an evaluation of the injection of a CO_2 stream containing oxygen and nitric oxide showed that the levels of oxygen and nitric oxide were sufficiently low that any decrease in permeability was likely to be very limited.

An additional risk is the potential dissolution of pyrite minerals (iron sulphide) due to either CO_2–brine–mineral interactions or the presence of hydrogen in the injection stream. This could lead to the formation of hydrogen sulphide, which is toxic and corrosive, and can threaten well integrity and health, safety and the environment during workovers, recompletions and infill drilling. However, the concentration of hydrogen sulphide may be suppressed by the dissolution of other iron-bearing minerals such as siderite (iron carbonate). Here, RTM simulations will help to predict the expected levels of hydrogen sulphide in the reservoir and the wellbore region, and provide critical input to materials selection and facility design; see Figure 5 for an example.

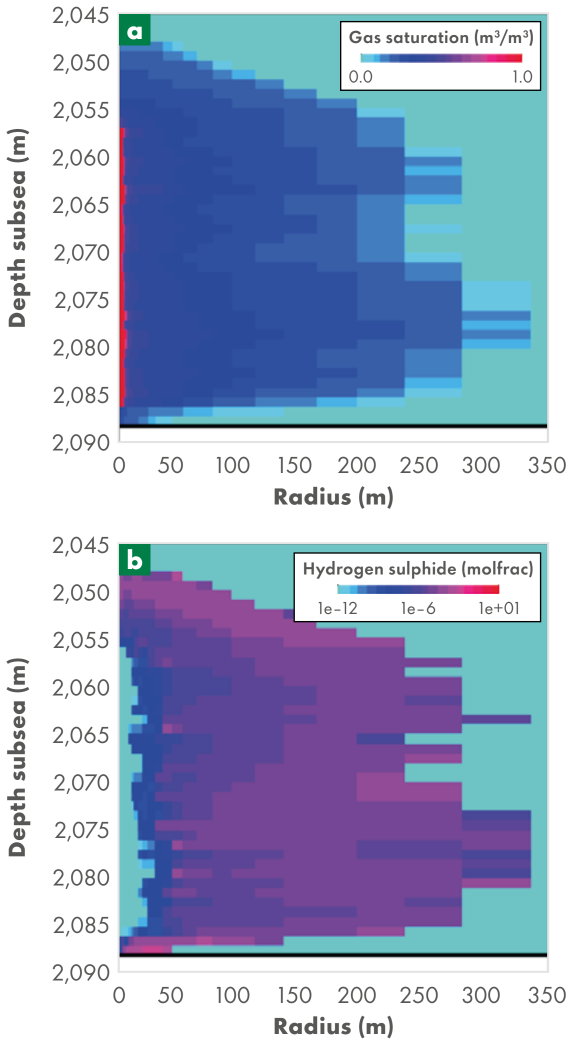


FIGURE 5

(a) CO_2 saturation and **(b)** hydrogen sulphide concentrations at the end of a 25-year injection period from a 2D radial model.

Monitoring and verification

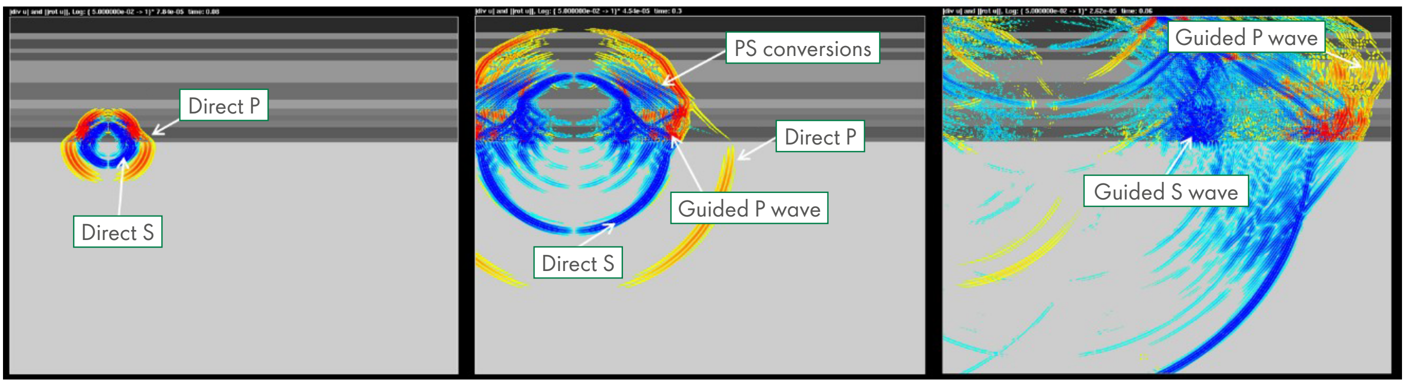
The focus of the monitoring and verification team is on enabling risk-based measurement, monitoring and verification (MMV) for the large-scale (Gt/y) deployment of CCS to verify containment and establish the conformance of the injected CO_2. This requires driving down costs and speeding up the time it takes from monitoring data acquisition to the triggering of alerts. In addition, the team is identifying and closing the remaining MMV technology gaps (low-cost, effective induced seismicity monitoring and abandoned well monitoring) and enabling measurement, monitoring and verification knowledge sharing with CCS projects in the funnel.

Important progress has been made in recent years on advancing microseismic data analysis. For example, elastic waveform modelling was performed for the Quest CCS project to improve the understanding of wave propagation in the subsurface, see Figure 6. The modelling showed that interpretation is complex because of the constructive interference of different types of arrivals that are trapped in the low-velocity layers, thereby creating guided waves. These waves make event localisation unstable, for example, determining where an earthquake is originating from, if a location method relying on picking direct arrivals is adopted.

Further, in collaboration with the Quest CCS project and fibre optic experts in Shell, the ▸▸▸

FIGURE 6

Snapshots of the elastic wavefield modelled for the Quest project.



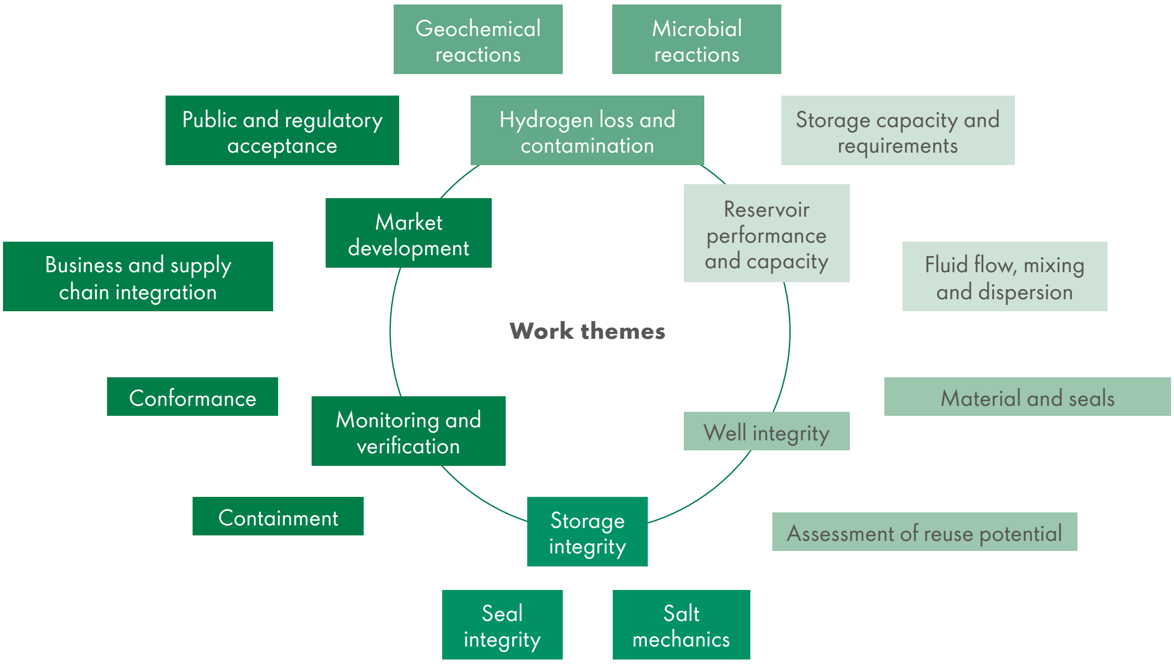


FIGURE 7
Main work themes of Shell's subsurface hydrogen storage research programme.

team is currently acquiring microseismic data from distributed acoustic sensing and surface arrays. Until recently, only a single downhole geophone array had been deployed in one monitoring well since the start of CO_2 injection in 2015. Having three different microseismic monitoring technologies deployed at a single CO_2 storage site will enable Shell to benchmark the different approaches and optimise designs for future sites, and help to reduce event uncertainties for the Quest project.

Introduction to the hydrogen storage programme

Recognising the need for large-scale hydrogen storage and the competitive edge of its extensive subsurface expertise, Shell launched a dedicated research programme in early 2021. The programme aims to de-risk subsurface hydrogen storage and to demonstrate its technical and economic feasibility. The programme is taking a phased approach: 1) salt cavern storage, 2) storage in depleted reservoirs and 3) storage in saline aquifers. The programme has six main themes that address the major challenges and risks (see Figure 7).

Each technical workstream comprises experimental investigations and numerical simulations. The experiments will enhance Shell's understanding and the quantitative description of the interactions of hydrogen with reservoir rocks and caprocks, in-situ fluids and microbes in aqueous environments, and well materials. The numerical simulations will help to scale up the findings to the reservoir scale and enable an integrated assessment of storage performance and storage risks.

Hydrogen loss and contamination

A key hydrogen storage risk that must be addressed relates to loss and contamination. When hydrogen is stored in the subsurface, geochemical and microbial reactions can result in the consumption and contamination of the stored gas. Most importantly, these reactions can create hydrogen sulphide and thus increase the health, safety and environmental risks and the costs for corrosion-resistant materials and for hydrogen sulphide removal from the back-produced hydrogen.

The occurrence of microbial activity in subsurface systems is widely acknowledged and well known from naturally occurring processes such as oil biodegradation and reservoir souring. Hydrogen is an excellent energy source for sulphate-reducing microorganisms (producing hydrogen sulphide and CO_2), methanogenic microbes (producing methane) and acetogenic microbes (producing organic acids). The windows of viability for these microbial reactions under subsurface conditions are, however, not yet fully understood. In addition, the kinetic rates of the microbial reactions and the effects of competition between microbial metabolisms will have to be established, so they are currently being investigated both internally and through collaboration with academic partners.

To set up suitable experiments for this work stream and to obtain the relevant information, it is necessary to collect fresh environmental samples, including subsurface formation water samples and solids. In the Netherlands, samples have been obtained from salt caverns through collaboration with Gasunie and from a producing gas field through collaboration with Nederlandse

Aardolie Maatschappij using the L3MU well testing unit, see Figure 8.

The formation water samples are used for both microbial community analyses and to serve as a source for microbes that will be grown under a hydrogen atmosphere in different conditions.

The acquired kinetic data for microbial reactions and similar information for geochemical reactions can be utilised in reactive transport simulations, along with the formation water composition, the mineralogical analyses and the gas composition. This will deliver insights into hydrogen loss and contaminant formation in the salt cavern or reservoir, and enable estimation of contaminant concentrations in the back-produced hydrogen stream.

FIGURE 8

Sampling formation water with the L3MU testing unit during a well, reservoir and facility management campaign: **(a)** wellsite with the L3MU unit on the left; and **(b)** a separator for collecting liquids with the sampling unit in the centre.

Reservoir performance and capacity

In porous reservoirs, lateral spreading, dispersion and mixing of the hydrogen with the in-situ fluids can result in further loss of hydrogen in the reservoir during storage when it becomes inaccessible for back-production. Hydrogen mixing with the in-situ fluids also results in co-production of these fluids during back-production. These fluids must be separated from the hydrogen, which could result in a sizable waste stream that needs to be reinjected if no other utilisation or disposal routes are available. Salt precipitation and biofouling can result in injectivity reduction, which needs to be understood and mitigated.

Storage integrity and well integrity

Ensuring containment of the hydrogen and any contaminants in the reservoir raises questions concerning the sealing capacity of caprocks and faults and the integrity of wells, particularly in view of the higher diffusivity of the small hydrogen molecule and its reactivity. For salt caverns, the mechanical response of the salt to cyclic variations in cavern pressure and the associated changes of its permeability require further investigation to define safe operational limits for injection and withdrawal rates, and storage pressure. The compatibility of existing wells, both salt caverns and depleted reservoirs, with hydrogen is a key question in view of their intended reutilisation for storage. From a surface perspective, the cost-effective compression and purification of hydrogen requires technology advancements. ▸▸▸

Monitoring and verification

In addition to potential safety issues (possible toxic contaminants and the risk of explosion), leakage is a concern, as hydrogen is a so-called indirect greenhouse gas that slows down the breakdown of atmospheric methane [Ref 2]. Hence, monitoring and verification of storage containment and conformance will be crucial. Detecting hydrogen from conventional oil and gas and CCS using existing technologies will be challenging, so it will be necessary to advance hydrogen detection and data processing and integration capabilities.

Acknowledgements

The authors gratefully acknowledge work done on various aspects of CCS and hydrogen storage by Shell colleagues Kees Hindriks, Kevin Bisdom, Stephen Bourne, Steve Oates, Jeroen Snippe, Tim Tambach, Diederik van Batenburg, Suzanne Boekhout, Rouhi Farajzadeh, Sara Minisini, Claudio Filomena, Karen Valencia, Niko Kampman and Bart Lomans, and the rest of the subsurface hydrogen storage team; and Nederlandse Aardolie Maatschappij colleagues Esther Vermolen, Ximena Rodriguez, Robert de Jonge and the L3MU crew. Special thanks go to Klaas-Jan Ynsen for the well test pictures. ■

REFERENCES

[Ref 1] Heimisson, E. R., Smith, J. D., Avouac, J.-P. and, Bourne, S. J.: "Coulomb threshold rate-and-state model for fault reactivation: Application to induced seismicity at Groningen," *Geophysical Journal International* (2022) 228(3), 2,061–2,072

[Ref 2] Derwent, R. G.: "Hydrogen for heating: Atmospheric impacts," BEIS research paper No. 21 (2018)

AUTHORS

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UNLOCKING MARKETS WITH LARGE-SCALE, renewable hydrogen supply chains

Shell has an ambitious target to become a net-zero-emissions energy business by 2050 or sooner. In this context, it is exploring renewable energy solutions for long-distance energy transport. Hydrogen could be an alternative energy carrier if produced sustainably, so it could be used to transport and deliver low-carbon energy on the path to zero emissions, and Shell Hydrogen is working to develop opportunities across the hydrogen supply chain. However, there are challenges for the commercialisation of long-distance hydrogen supply chains, but Shell is working to address these on multiple fronts.

Hydrogen supply chains for long-distance energy transport

Throughout its history, Shell has successfully shipped energy around the world in the form of molecules and was one of the pioneers of shipping liquefied natural gas (LNG) to diversify the energy mix. Today, large volumes of energy are transported as LNG: a business that creates significant value for Shell and its customers but that does need the management of carbon emissions. This long-distance shipping business model can be maintained throughout the energy transition. It just requires a different kind of energy carrier, and that could be liquefied hydrogen (LH_2).

Today, LNG is typically imported by countries that are energy short: they have an energy demand that exceeds the local energy production, generally because of the limited availability of low-cost conventional energy resources such as oil and gas. Likewise, in a future scenario in which countries demand low-carbon energy, some countries will benefit more from abundant and affordable renewable resources such as wind and solar than others. In fact, there will be many countries that cannot themselves generate sufficient renewable energy to sustain an adequate standard of living. In addition, reducing carbon emissions to avoid the dramatic impact of climate change means that these countries will need to rely on imports of carbon-free energy.

With the development of renewable energy sources, power will become a more and more abundant energy carrier. It is, however, difficult and expensive to store and to move across long distances. As the conversion step from power to hydrogen is relatively straightforward, hydrogen could serve as a key enabler to bridge the emerging disconnect between the when and where of energy production and the when and where of energy consumption.

Moreover, renewable hydrogen could be a useful solution for hard-to-abate industries that do not have the option to electrify and use renewable power for their processes, for example, the production of high-quality steel. Potential offset markets for imported hydrogen include aviation, heavy industry, maritime, heavy-duty mobility and power production where hydrogen is used to fire gas turbines. Here, hydrogen as an energy carrier could be a key enabler to help the world transition to a net-zero-emissions system.

Hydrogen can be transported in gaseous form (compressed) in pipelines or trucks. However, for longer-distance transport, the infrastructure costs become too prohibitive and a higher energy density is preferable to be able to transport more energy in a similar volume. There are several hydrogen carrier solutions for long-distance transport:

a. as an element in molecules such as ammonia, methanol, formic acid and synthetic natural gas;
b. as an element in liquid organic or inorganic hydrogen carriers (transportation that involves the hydrogenation of a chemical compound at the site of production and then dehydrogenation at the point of delivery); and
c. in molecular form as a liquid, LH_2, at –253°C.

An LH_2 supply chain needs to include a hydrogen liquefaction unit, an export terminal including LH_2 storage, an LH_2 shipping vessel, an LH_2 import terminal and the means for distribution to customers. Figure 1 shows an example of an export facility with hydrogen supply through solar photovoltaic-based electrolysis. Depending on the hydrogen production method, for example, steam methane reforming with carbon capture and storage, or electrolysis, the delivered hydrogen product can achieve different levels of decarbonisation.

Australia and Japan leading the way

Japan, historically a key energy importer, is one of the frontrunners when it comes to the deployment of hydrogen technology and projects. Spurred on by the Fukushima nuclear disaster in 2011, Japan issued its Basic Hydrogen Strategy in 2017 and became the first country to adopt a national hydrogen framework. The Japanese Ministry of Economy, Trade and Industry (METI) has developed and published a comprehensive aspirational strategy and road map projecting potential hydrogen demand ▸▸▸

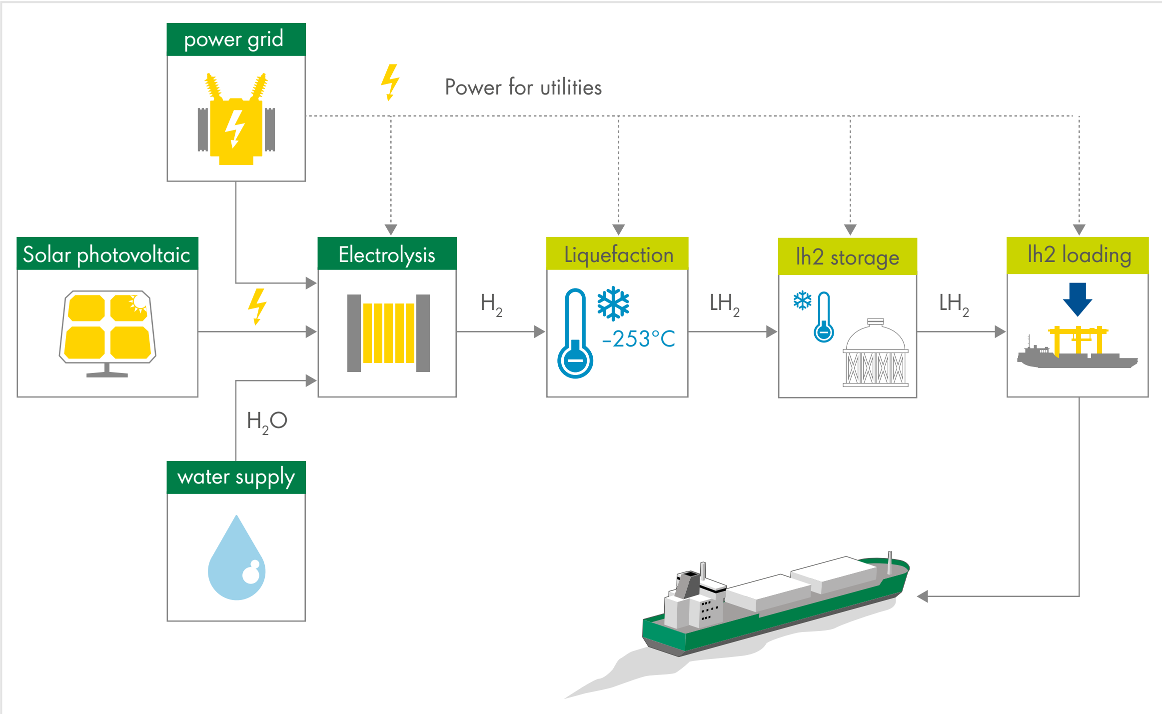


FIGURE 1
Example of a hydrogen supply chain export facility.

in the years to 2030 and beyond. Interestingly, if Japan were to revert to nuclear power generation, this would not suffice to help the country reach its decarbonisation targets in the long run. In other words, Japan needs to import clean energy.

After several years of subsidising hydrogen technology and deployment projects, METI also has several billion dollars of subsidy opportunities to offer for future projects. This is demonstrated by the announcement in 2021 that the Japanese government will allocate up to $3.4 billion from its Green Innovative Fund for two projects to accelerate the research, development and promotion of hydrogen usage in the next 10 years.

The combination of its need for energy while meeting Paris Agreement obligations and the governmental subsidy support means that Japan is seen by many companies as the leading launch market for a commercial-scale supply chain. Other notable countries whose energy demand may exceed or develop faster than the local supply of affordable renewable energy are Korea, the Netherlands and Germany.

Of the energy-exporting countries, Australia has expressed ambitions to become a key player in the LH_2 space owing to its vast potential for sweet-spot renewable energy and proximity to Eastern markets. It currently supplies a large amount of LNG to the energy-short energy markets and is keen to export lower-carbon molecules to its customers.

The Australian government is interested in maintaining its status as an energy exporter through the energy transition, thus it desires to build and grow this new business by offering subsidies. Other key resource holders for hydrogen export include Norway, Chile, North Africa, Namibia and the Middle East.

The journey towards commerciality

The development of hydrogen markets is going to be an uphill battle economically. Green energy supply chains will need to be developed because the global cost of continuing carbon emissions will become unbearable. However, it will be difficult to map this global climate cost properly to the current energy price. Consequently, the market price of hydrogen will, in the foreseeable future, likely be higher than that of conventional energy carriers, so markets will need to rely on regulatory frameworks to develop.

At the same time, from a practical perspective, the cost of hydrogen (as a measure for the cost of energy) cannot become too high. The aspirational, and very low, price of $3/kg of hydrogen that METI published reflects an energy price that is comparable to $20/MMBtu for LNG. These are price levels that are deemed acceptable in a net-zero context, but getting there will require significant improvement steps relative to the technology as it exists today.

As in the early days of LNG development, pioneering in this novel industry is not without high risks and costs. To reach the cost target for hydrogen delivered by a commercial-scale project, substantial technology development and economies of scale are required. The first movers will bear high development costs, so investment strategies call for prudent and heavily leveraged projects. Long-term collaboration among hydrogen suppliers, customers and governments will be essential to the successful commercialisation of a large-scale hydrogen supply chain. Therefore, it is notable that, in June 2022, European Union member states established the first Important Project of Common European Interest in the field of hydrogen.

Project HySTRA

One of Shell's success stories and its first step on the LH_2 journey is Project HySTRA (CO_2-free Hydrogen Energy Supply-chain Technology Research Association, www.hystra.or.jp/en). This is a technology pilot project to demonstrate an LH_2 supply chain for hydrogen produced in Australia and transported on the world's first LH_2 carrier, the *Suiso Frontier* (see Figure 2), to an import terminal in Kobe, Japan. Shell Hydrogen is providing technical capability for the project..

The *Suiso Frontier* was built by Kawasaki Heavy Industries, Ltd. It will be managed and operated by Shell while transporting hydrogen produced in Australia by Electric Power Development Co., Ltd (J POWER) to an LH_2 loading terminal, Hy Touch Kobe, managed and operated by Iwatani Corp. The Japanese government has supported this project with a substantial subsidy.

The LH_2 vessel has a vacuum-insulated cargo containment system of about 1,250 m^3 and can carry 75 t of LH_2 (see Figure 2). The *Suiso Frontier* was incorporated into the Japanese ship classification society, ClassNK, register in Q4 2021 and has now made its maiden voyage (see boxed text, The first voyage of the *Suiso Frontier*).

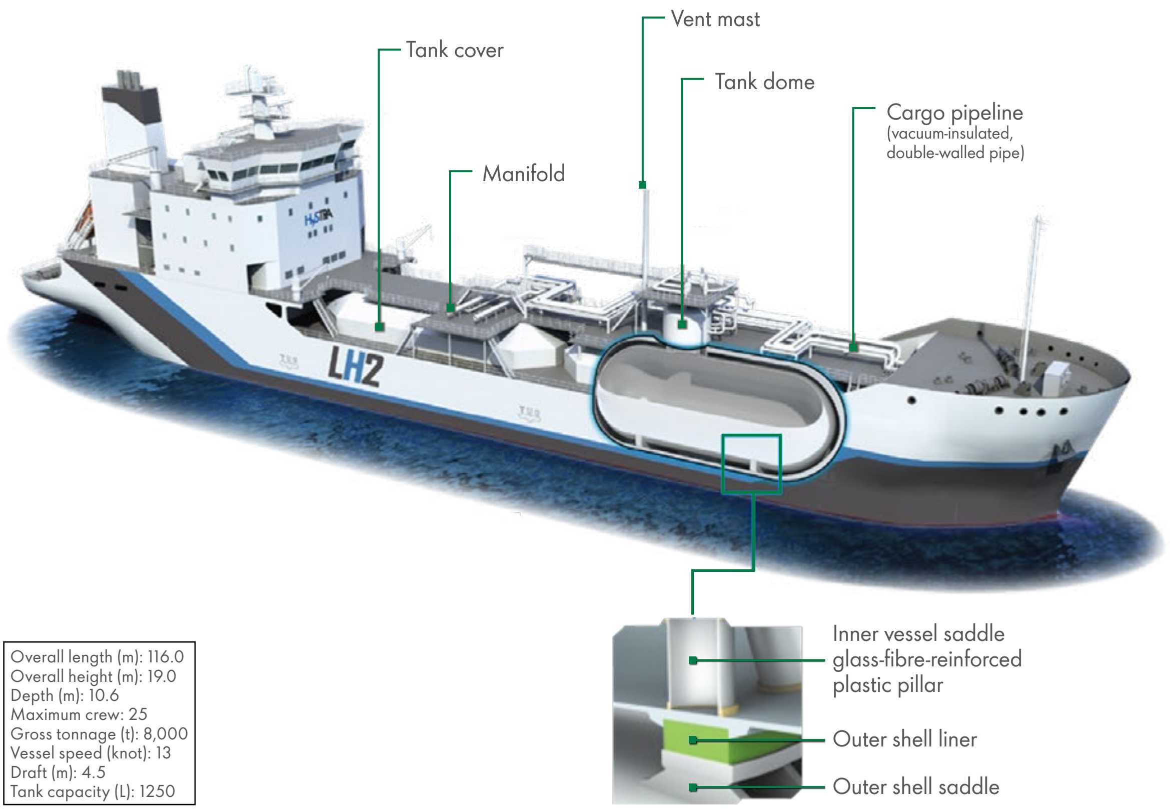
Technology development: The key to success

Technology for the liquefaction of hydrogen, storage and transport of LH_2 has been around since the 1950s, though only on a very small scale compared with that required for a commercial LH_2 supply chain. For decades, the largest end-user of LH_2 has been National Aeronautics and Space Administration (NASA) for fuelling the Apollo, Centaur and Space Shuttle programmes.

Current technology, therefore, cannot serve as a building block for the development of an energy system. Substantial technology scale-up (orders of magnitude) will be required to meet meaningful energy delivery targets. In addition, economy of scale is required to achieve affordable cost targets.

Hydrogen liquefaction

Today, the globally installed liquefaction capacity is about 300 t/d (the biggest single line capacities in operation are about 50 t/d). In terms of heating value, this 300 t/d represents an energy flow of less than a gigawatt, which is barely 10% of the output of a 6-Mt/y LNG train. ▸▸▸



Overall length (m): 116.0
Overall height (m): 19.0
Depth (m): 10.6
Maximum crew: 25
Gross tonnage (t): 8,000
Vessel speed (knot): 13
Draft (m): 4.5
Tank capacity (L): 1250

FIGURE 2
The *Suiso Frontier*'s design parameters.

The first voyage of the *Suiso Frontier*

The *Suiso Frontier* was launched in Q4 2019 and entered sea trials in early 2021. The vessel completed its maiden voyage at the end of 2021, sailing from Japan to Australia, where it was loaded with liquified hydrogen before returning to Japan in early 2022. This successful demonstration of the potential for international marine bulk transport of LH_2 was celebrated as a major milestone for Project HySTRA, as shown in this video.

FIGURE 3
The *Suiso Frontier*, the world's first LH2 carrier.

Clearly, much larger plant capacities will be required if LH_2 is to be developed into a traded energy commodity for the energy system of the future. The hydrogen supply chain and mobility technology development team is working towards addressing these scale-up challenges.

LH_2 storage
For storing and shipping LH_2 to develop it as an energy commodity, the volumes must become comparable to those for LNG storage and shipping today, of the order of 100,000–200,000 m^3. Current LH_2 storage capacity is about 5,000 m^3. Figure 4 shows the project HySTRA LH_2 spherical storage tank in Kobe terminal in Japan, which has a capacity of 2,500 m^3.

The key challenge to a cost-effective scale-up is to find an optimal insulation concept. The vacuum insulation, as applied today in Kobe, appears to be costly to scale up. In addition, the extremely low temperature of LH_2 (–253°C) means that it requires a fundamentally different insulation concept to LNG, which is only at –162°C.

One of the joint technology development projects the Shell team is working on is a LH_2 storage project for the US Department of Energy. This aims to design and demonstrate a commercial-scale LH_2 storage tank for maritime and international trade applications. Consequently, it will identify the appropriate insulation and demonstrate a scalable tank design for commercial applications.

Next steps: Demonstrating a mid-size LH_2 supply chain project

In today's world, the role of hydrogen in the energy system is modest. However, it is envisioned that the first end-to-end LH_2 supply chains will become operational towards the end of the decade. Although this may seem far in the future, substantial technology de-risking for several elements of the supply chain are necessary.

The Shell team believes that at least one scale-up step (mid-scale, towards a 100-t/d LH_2 supply chain) will be necessary before a commercial-scale supply chain investment decision can be made from both the technical feasibility and economic viability perspectives. The earliest timeline for achieving a commercial-scale project is by the early 2030s, which aligns with the Japanese basic energy road map for deploying carbon-free hydrogen into a full-scale power plant.

FIGURE 4
The vacuum-insulated LH_2 storage tank in Kobe.

Currently, the team is working on several LH_2 supply chain opportunities. The objective is to find the right opportunity to develop and demonstrate the first full-renewable, end-to-end LH_2 supply chain. This is the next crucial step, after the HySTRA Project, on the road map to the commercialisation of LH_2, as it will enable the demonstration of several novel technologies and create momentum in the Australian and Japanese hydrogen industries.

Acknowledgements

The author would like to thank colleagues Arnoud Higler, Cas van Doorne, Linda Boukhelifa and Jo-Tsu Liao for their help with this article and all their hard work in driving hydrogen supply chain commercialisation, and, of course, everyone else contributing to the LH_2 supply chain journey. ■

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GETTING AHEAD: BESPOKE lubricants for hybrid electric vehicles

Hybrid electric vehicles (HEV) are those that run on an internal combustion engine and an electric motor powered by batteries. On average, an HEV car emits 46% less greenhouse gas than a conventional vehicle. In combining an electric battery with a traditional gasoline engine, HEVs can be attractive options for consumers, though they have new requirements for engine oil. In the next 5–10 years, there will be a boom in HEVs, both full and plug-in (PHEV), in China and, indeed, in other markets. Preparing for the trend with bespoke lubricant products will ensure Shell has continuing market leadership and maintains good relationships with customers, so understanding the engine operating conditions in these vehicles is key.

HEVs are set to boom, so Shell needs to understand their engine operating conditions.

Global electrification in passenger cars

Shell's target is to become a net-zero emissions energy business by 2050, in step with society. As well as achieving net zero on all the emissions from product manufacturing, it also aims to partner with customers to decarbonise energy use by helping them to reduce their emissions to net zero. In the lubricants area, Shell has announced that it will offer customers various carbon-neutral lubricants for passenger cars, heavy-duty diesel engines and industrial applications. It is also committed to providing customised lubricant products to help its customers' carbon neutralisation actions. Shell aims to offset the annual emissions of more than 200 million litres of advanced synthetic lubricants and thus to compensate for about 700,000 t of carbon dioxide equivalent emissions per year, which is equivalent to taking about 340,000 cars off the road for a year.

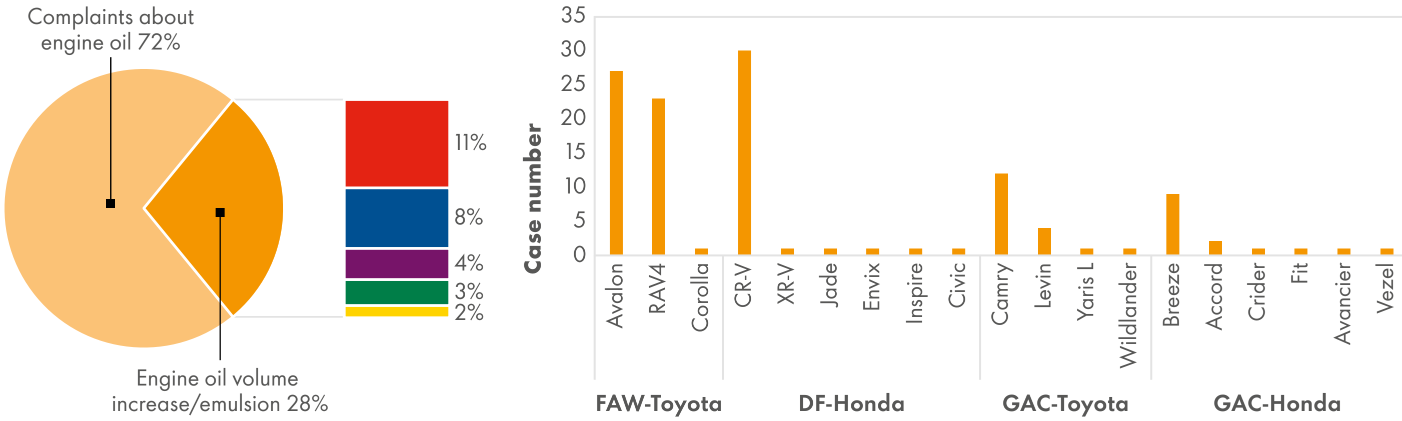
For passenger cars, "hybrid" is a very hot topic. IHS Markit projections in 2018 suggested that the global vehicle production share of HEVs is likely to be more than 40% by 2030. They will be the largest category of production vehicles.

HEV requirements for engine oil

The 2020 "Energy-saving and New Energy Vehicle Technology Roadmap 2.0" compiles feedback from the industry on the direction of passenger car and commercial vehicle sales in China. It predicts that half the total sales in 2035 will be fuel-economy vehicles and that these all will be HEVs, which will account for an annual volume of at least 15 million passenger cars. With the driving force of the Chinese regulations (see boxed text, Electrification trends in China), there is no doubt that, in the next 5–10 years, 48-V mild hybrids (MHEV), full HEVs and plug-in hybrids (PHEV) will be critical parts of the Chinese market.

There are different types of HEV (micro, mild and full), depending on the size of the battery (12 V for micro, 48–200 V for mild and 200–600 V for full HEV) and the power sharing ratio between the

FIGURE 1
Investigation of engine-oil-related complaints in China.



Electrification trends in China

Tackling climate change is a key concern in China. The country aims to reach a peak in carbon dioxide emissions before 2030 and to achieve carbon neutrality before 2060, which is challenging. However, the Chinese government has launched a series of policies and regulations to drive low-carbon growth.

For passenger cars, which contribute about 8% of carbon emissions in China, the Phase V standards (corporate average fuel consumption, CAFC; and the new energy vehicle[1] [NEV] credit) and the "Energy-saving and New Energy Vehicle Technology Roadmap 2.0" jointly promote the electrification of the automobile industry.

As of December 2019, Phase V standards set a fleet average fuel consumption target of 4.0 l/100 km (New European Driving Cycle) by 2025 for passenger vehicles produced in or imported to China. This is a 20% reduction from the target of 5.0 l/100 km set for 2020. Specifically, fuel consumption limits are based on vehicle mass. The Phase V standards will be the baseline for further policies and regulations.

It will be impossible to achieve the fleet-wide fuel consumption goal by promoting just conventional vehicles with energy conservation technologies or just NEVs. Such a goal can only be met by developing the two types of vehicle in a co-ordinated way and considering the widespread concerns about battery safety and recycling, charging infrastructure and sustainable electricity sources. Since September 2017, the CAFC and NEV credit requirements have been applicable to manufacturers or importers of more than 30,000 vehicles a year in China. Automotive manufacturers are required to meet both requirements and can amass credits by producing gasoline vehicles with lower carbon emissions than the country's standards or by producing NEVs. Noncompliant manufacturers face penalties.

The NEV credit requirement increases incrementally to 2025 and is designed to encourage the production of HEVs, which are classified as "low fuel consumption passenger vehicles", over conventional nonhybrid vehicles.

Credit trading between the two standards allows surplus NEV credits to offset CAFC credit deficits. Surplus NEV credits can be sold to other companies but surplus CAFC credits can only be banked for future use within the company or transferred to affiliated companies. That means that if automotive companies cannot meet the dual-credit requirements, their sales of high-fuel-consumption vehicles will be banned.

Consequently, Chinese automotive manufacturers, both joint ventures and local companies, have announced carbon-neutral timelines (see Table 1).

Manufacturer	Carbon-neutral target
BMW	2030
Porsche	2030
Mercedes-Benz	2039
GM	2035 (new type of light-duty) 2040 (global products)
Volvo	2040
Great Wall	2045
Audi	2050
Nissan	2050
Ford	2050
VW	2050
Honda	2050
Renault	2050
Toyota	2060 (in the Chinese market)

TABLE 1
Key manufacturers' carbon-neutral timelines.

internal combustion engine and the electric motor. A PHEV is essentially an HEV with a larger battery pack, which can be charged by plugging it into an electric station, that enables a significant distance of pure-electric driving.

Although automotive manufacturers use similar engines in HEVs and PHEVs to those in conventional vehicles, the engine operating conditions are very different, as the following example shows. An investigation of complaints from northern China about HEV/PHEV engine oil made between December 2020 and January 2021 found that 124 out of 446 complaints related to "increased engine oil volume" or "engine oil emulsion" (see Figure 1). Investigation showed that the increased oil volume and engine oil emulsion were caused by fuel and water (combustion product) ingress into the oil sump. HEVs and ▸▸▸

[1] NEV is the Chinese government term for plug-in electric vehicles eligible for public subsidies and includes only battery, plug-in hybrid and fuel-cell electric vehicles.

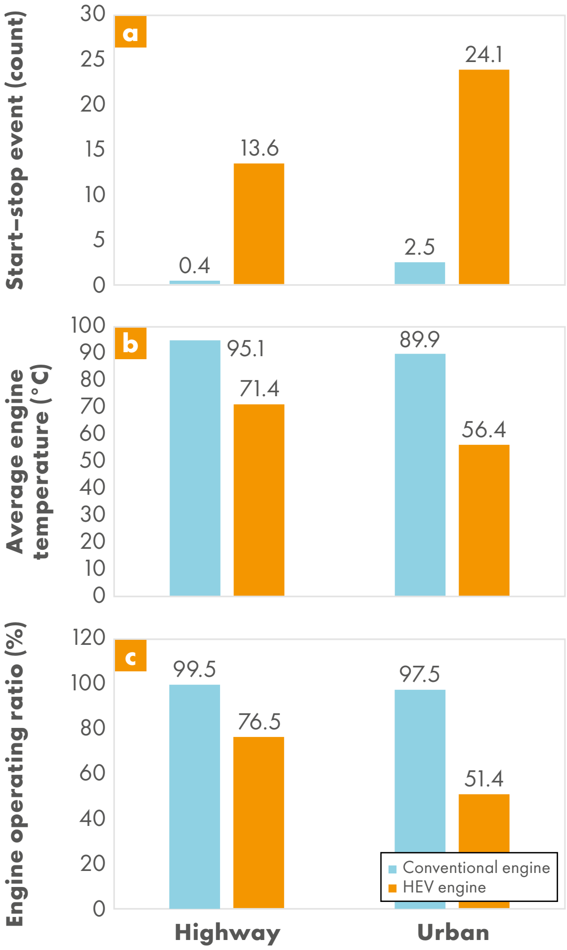


FIGURE 2
The unique HEV engine operating conditions: **(a)** stop–start events; **(b)** average engine temperature; and **(c)** engine operating ratio.

PHEVs have a lower engine operating ratio and a lower engine oil temperature than conventional combustion engines, so the fuel and water cannot evaporate from the oil sump and thus accumulate. This issue becomes more severe in the short-distance winter-commuting scenario in northern China.

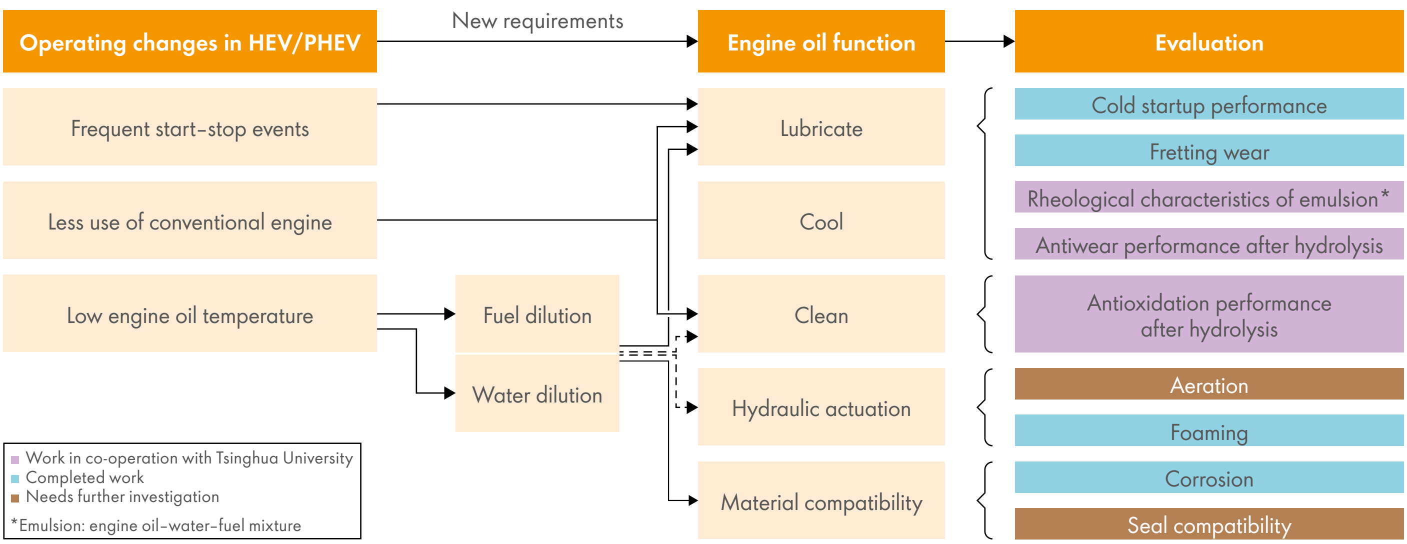
There is not yet any specific industry standard or special requirements for engine oils used in HEVs. Consequently, it is important to identify and clarify the potential risks that the unique "hybrid" operating conditions bring, so Shell must be proactive and provide customised solutions before too many HEV failures occur. Therefore, the passenger car motor oil team at Shell (Shanghai) Technology initiated an investigation into HEV engine oil requirements based on the International Automotive Task Force tool (quality function deployment to achieve an overall risk-based functional analysis).

In addition to data on fuel and water dilution issues, the team collected on-board diagnostic data for both HEVs and conventional combustion engines from field trials. They found that HEV engines usually experience more frequent start–stop events and are used less, as shown in Figure 2. From the methodology viewpoint in engine oil development, the operating condition differences can be correlated to the five major aspects of engine oil: lubricating, cooling and cleaning the engine, hydraulic actuation and compatibility with contact materials. The relationships are shown in Figure 3.

The impact of the operating conditions on engine oil should, however, be evaluated and clarified using a series of performance tests. And, for the unique conditions in HEVs, new tests should be developed if there are no appropriate standard tests. Some of the evaluation tests have already been conducted; others are in progress or planned.

A fretting wear test rig had been set up for a previous project in co-operation with Tsinghua University, China. The research found that in long-term, pure vibration mode, which was equivalent to 100,000 km of pure-electric driving conditions, abnormal fretting wear occurred in the journal bearing, whereas in start–stop mode, which simulated the driving conditions when the engine and the motor are used alternately, no abnormal wear was seen.

FIGURE 3
Correlation between HEV/PHEV engine operation, engine oil function and the evaluation required.



The rheology characteristics of emulsions and the antiwear and antioxidation performance evaluation of engine oil and key components after hydrolysis are being investigated in collaboration with Tsinghua University.

Aeration performance and seal compatibility mainly correlate to fuel content and fuel type mixing with the engine oil, so co-operation with the fuels team is being discussed.

The Shell (Shanghai) Technology team has carried out tests on the emulsion stability, corrosion and foaming performance of a specially developed Shell HEV engine oil, evaluated the relevant risks and made comparisons with competitors' HEV engine formulations.

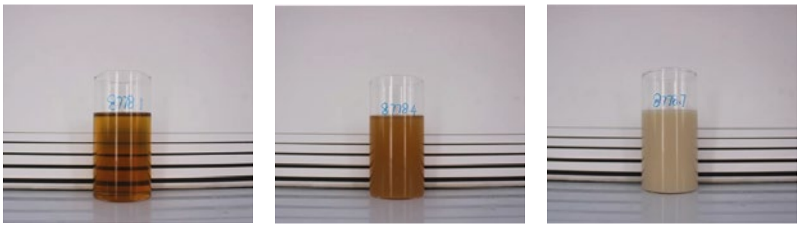


FIGURE 4
Engine oil emulsions with differing water contents.

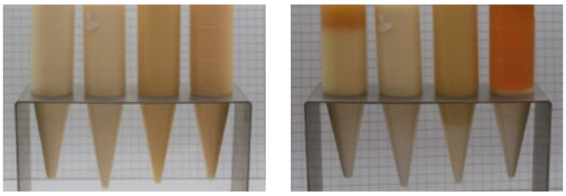


FIGURE 5
Engine oil emulsion phase separation.

Emulsion stability performance

An emulsion is defined as a dispersion of one liquid (internal or dispersed phase) within another (external or continuous phase) in the presence of a surface-active agent (emulsifier). When engine oil mixes with water, an emulsion forms, as shown in Figure 4. Density differences between the oil phase and the water phase mean that phase separation (emulsion breakage) happens after several hours or even days, as shown in Figure 5.
Emulsions, because they comprise two immiscible liquids, are inherently unstable. However, emulsion stability can be retained for a fixed time by manipulating and suppressing the mechanisms causing emulsion breakdown. The team compared different engine oil formulations and found that they had inherently different emulsion stability performance. Although emulsion stability performance is not an engine oil functional requirement, one question needed answering: which is better for engine performance, an emulsion or phase separation? Consequently, the team ran several tests to compare the performance characteristics of the emulsion and both separated phases.

Element distribution in separated emulsion phases

Engine oil is composed of base oil and several key components, including a calcium- or magnesium-based detergent, a sulphur-, phosphorus- or zinc-containing antiwear agent, and an organic molybdenum friction modifier. By analysing the elemental contents in both separated phases, as shown in Figure 6, it was possible to determine the component distribution and to speculate on the impact of this on oil function. The results showed that the key functional components were distributed reasonably well between both phases, whereas boron, which usually acts as a dispersant, was concentrated in the lower emulsion phase, the water. This indicated that engine oil function will be significantly affected by emulsion phase separation. Further function investigation of both emulsion phases is ongoing.

Low-temperature startup performance of separated emulsion phases

Oil thickens in subzero winter conditions and causes increased startup difficulty. Most engine wear occurs during cold starts when the engine is temporarily starved of oil. Therefore, standard viscosity test methods, using a cold cranking simulator (cold cranking viscosity) or a mini-rotary viscometer, have been developed to evaluate the cold startup performance and pumpability of engine oil in both high- and low-shear environments. Industry specifications set viscosity limits for ▸▸▸

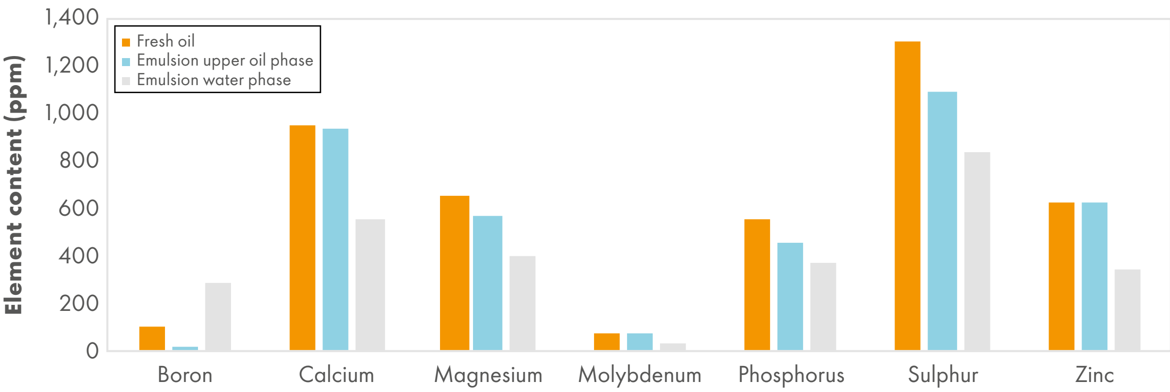


FIGURE 6
Key function element content of emulsion separated phases.

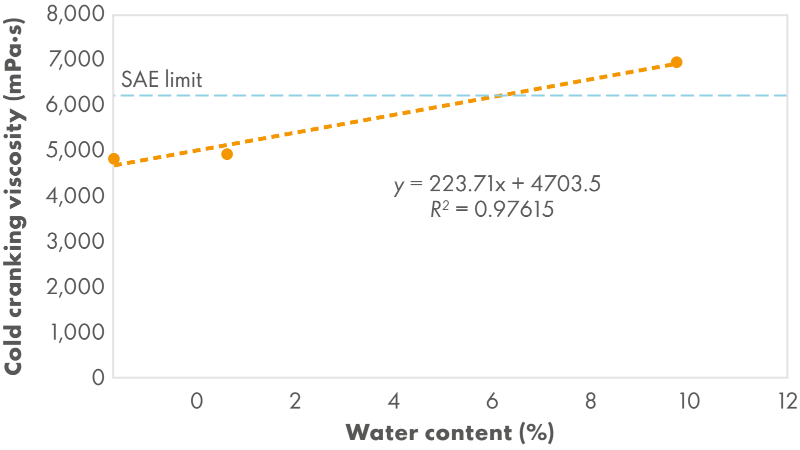


FIGURE 7
Water content impact on cold cranking viscosity.

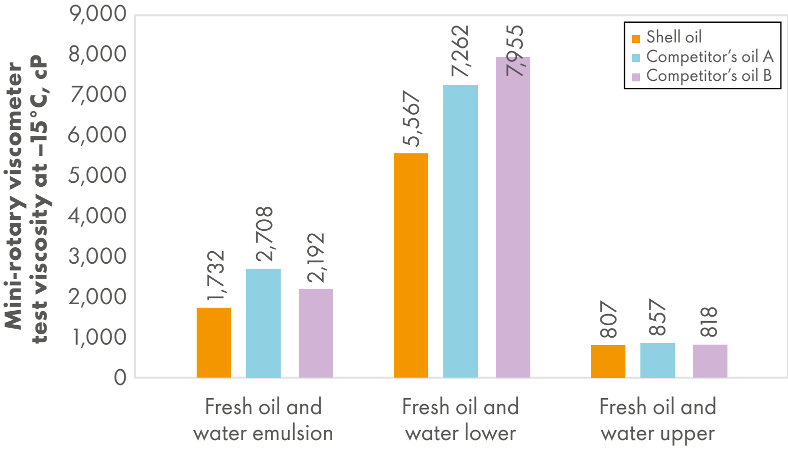


FIGURE 8
Water content impact on mini-rotary viscometer test viscosities at −15°C.

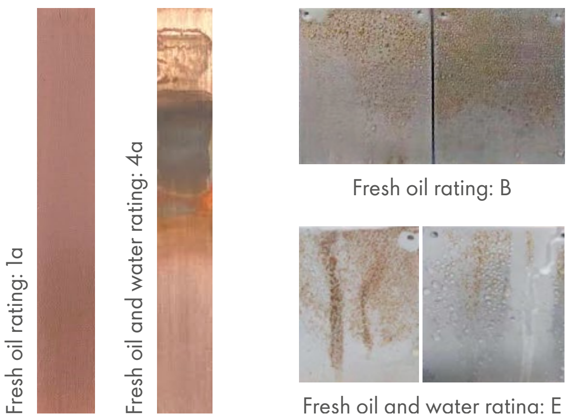


FIGURE 9
Water content impact on corrosion test results.

these tests and out-of-limits values indicate a high possibility of startup failure in real engines.

Figure 7 gives the cold cranking simulator test results at −35°C for oil samples containing different water contents. The results show that the sample failed to meet the SAE specification when mixed with 10% water, so, by linear regression, it is likely that a water content above 7% will not meet the specification and may cause low-temperature startup issues.

Mini-rotary viscometer tests at −15°C showed even more profound effects of water on viscosity (see Figure 8). In particular, the viscosity value for the separated lower water phase, as shown in the middle columns, was excessive (the SAE mini-rotary viscometer limit for 0W-20 oil at −35°C is 60,000 cP. The water-phase test results at −35°C exceeded the equipment test limit [270,000 cP], so the mini-rotary viscometer tests were made at −15°C for better comparison). This indicates higher risks in real driving conditions, as the reduced pumpability means longer oil starvation that could cause severe wear issues.

These test results provide clear support for the question: "Which is better, emulsion or phase separation?" It is clear that retaining a full emulsion without phase separation reduces the cold startup risks.

Anti-corrosion and anti-rust performance
Although there are several standard tests for investigating the corrosion and rusting (the corrosion of iron and its alloys) performance of industrial and engine oils, there is no public test method for evaluating the anti-corrosion and anti-rust performance of a water–engine oil system. Therefore, the Shell (Shanghai) Technology team has developed a series of test methods to cover different scenarios, from fully emulsified engine oil and water to the separated phases, and from the metal parts fully immersed in oil to the metal parts protected by a thin oil film for copper and for steel parts. Figure 9 shows the test results. The severe corrosion on the copper and steel specimens provides evidence that the anti-corrosion and anti-rust performance of engine oil is compromised when the oil is mixed with water.

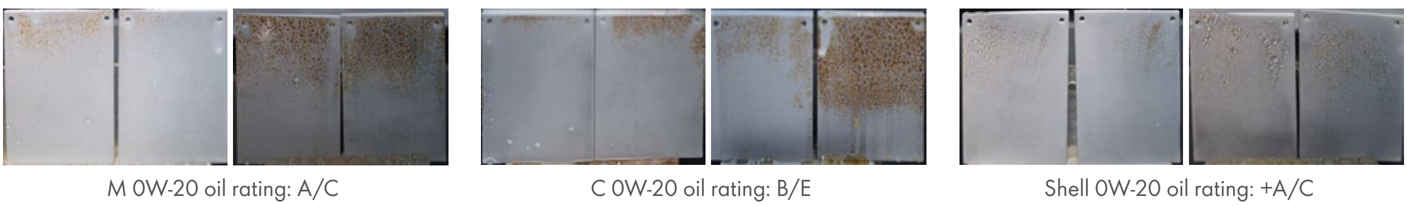


FIGURE 10
Benchmarking the anti-corrosion and anti-rust performance of specialist HEV oils.

	Interfacial tension, ASTM D971 (mN/m)	Foaming characteristics, ASTM D892, Seq I
Fresh oil 1	17.3	0/0
Fresh oil 1 and 5% gasoline	16.7	0/0
Fresh oil 1 and 10% gasoline	15.8	0/0
Fresh oil 1 and 1% water	16.9	0/0
Fresh oil 1, 1% water and 5% gasoline	16.8	0/0
Fresh oil 1, 1% water and 10% gasoline	16.1	0/0
Fresh oil 1 and 10% water	17.3	0/0
Fresh oil 2	16.9	0/0
Fresh oil 2 and 5% gasoline	15.7	0/0
Fresh oil 2 and 10% gasoline	15.4	0/0
Fresh oil 2 and 1% water	16.6	0/0
Fresh oil 2, 1% water and 5% gasoline	16.5	0/0
Fresh oil 2, 1% water and 10% gasoline	15.2	0/0
Fresh oil 2 and 10% water	17	0/0

TABLE 2
Foaming and interfacial tension test results.

Oil formulation development has improved anti-corrosion and anti-rust performance and produced dedicated HEV formulations. Benchmarking of competitors' specialist products against a Shell improved formulation showed the excellent anti-corrosion and anti-rust performance of the Shell candidate (see Figure 10).

Foaming performance
In general, engine oil foam comprises many air bubbles separated by thin films of oil and typically sitting on top of a larger volume of oil. Foam is different from entrained air. Air entrainment refers to the suspension of air bubbles within a large volume of oil. Foam is undesirable in a lubrication system because it can undermine operating efficiency, inhibit heat removal, increase wear and the degradation of additives, and, ultimately, lead to higher maintenance and component-replacement costs.

To evaluate engine oil foaming performance, the team selected the ASTM D893 Sequence I (foaming characteristics) and ASTM D971 (interfacial tension) standard tests and applied them to engine oil with differing gasoline and water contents. The test results in Table 2 show that neither the water nor the gasoline content has any impact on foaming performance at a low temperature.

Overall engine oil performance in field trial
In addition to evaluating the engine oil performance in laboratory tests, the team also conducted a field trial to demonstrate the overall performance of the HEV dedicated engine oil. Used oil was analysed after completing the 10,000-km field trial and the engine was torn down and inspected. The used oil analysis included kinematic viscosity, total acid number and metal (iron) content for evaluating the antioxidation and antiwear performance. The test results shown in Figures 11 and 12 indicate that the dedicated HEV formulation provided good engine protection.

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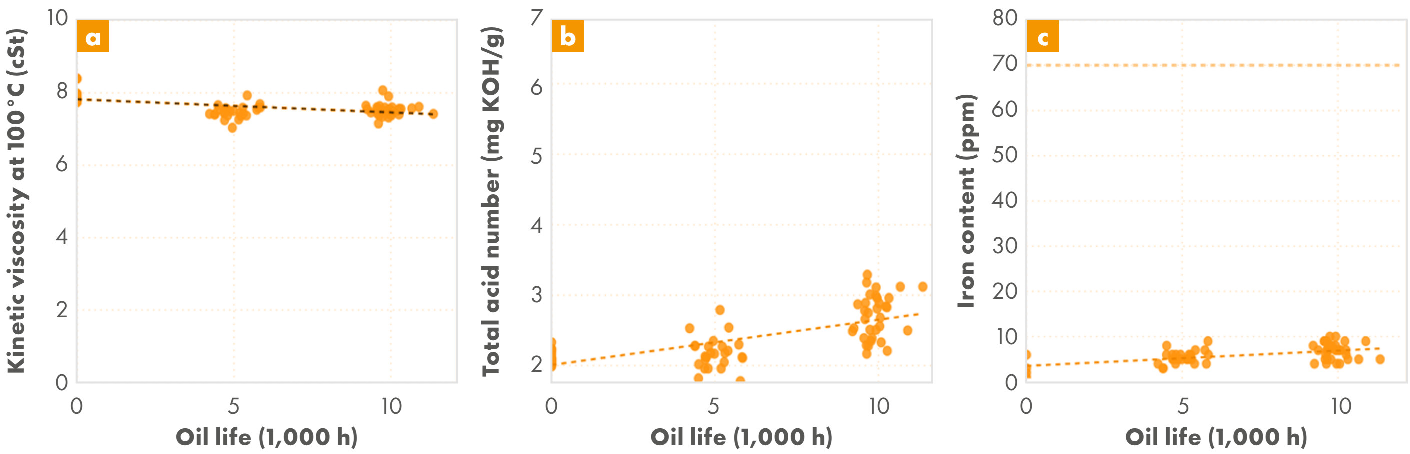

FIGURE 11
Used oil analysis: **(a)** kinetic viscosity at 100°C; **(b)** total acid number; and **(c)** iron content.

FIGURE 12
Engine tear-down inspection images.

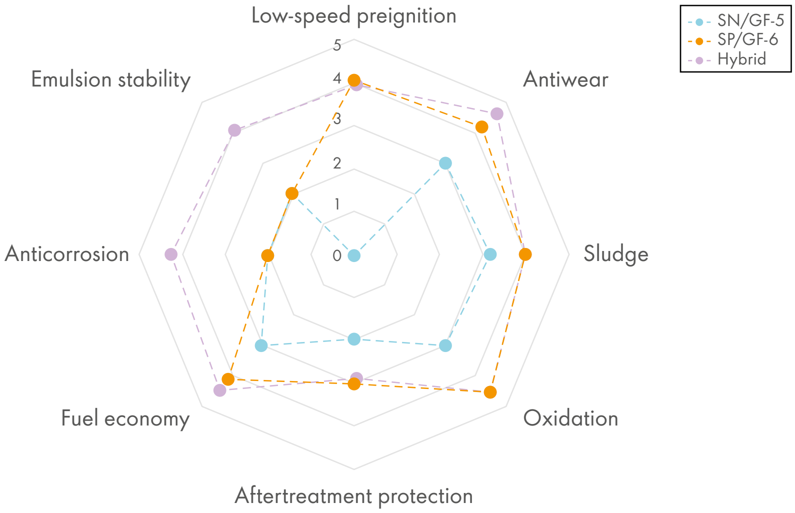

FIGURE 13
The requirements for a dedicated HEV engine oil.

HEVs have special requirements for engine oil, different to those of conventional engines, so work is ongoing to create suitable formulations. Key performance indicators for next-generation PHEV/HEV engine oil have been identified from previous work (see Figure 13). Special attention should be paid to the oil's low-temperature viscosity because of the high risk of low-temperature startup issues. Anti-rust and anti-corrosion performance also need to improve owing to the adverse impact of water ingress.

The Shell (Shanghai) Technology team has developed appropriate bench tests to evaluate the corrosion-inhibition performance of HEV engine oil; these will form the foundation of future joint research and development projects with automotive manufacturers. They have also developed a new formulation development strategy that will also benefit product development in other areas. However, there are many aspects about engine oil for HEVs that are still unknown; relevant collaborations with research institutes and a cross-function team have been initiated.

This work has identified and clarified the requirements for the high-tech powertrains of HEVs. Significantly, these developments have resulted from research in Shell laboratories and from working in close technical partnerships with equipment and component manufacturers.

AUTHORS

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XTERNAL CONNECT

What interests you most about the work that you've recently been doing for Shell?

Like Shell, the University of Houston has been a leader in the energy transition. Our shared approach to addressing global energy changes and its societal implications, through a lens of equity and inclusion, strengthens our partnership. Through the university's energy initiative, we have aligned on important issues such as decarbonisation through carbon management, the growth of hydrogen as an industrial fuel and embracing the circular materials economy. Locally, we partnered with Shell and others in founding EVolve Houston to expand electrified transportation in Houston.

What aspect of that work in particular do you think Shell should learn more about – and why?

Organisations need to act holistically when addressing the challenges of the energy transition. The University of Houston is fortunate to have one of the USA's most diverse student bodies. Perhaps more important are the steps we take to foster a culture of inclusion and equity. At the same time, as a research powerhouse, the university topped $200 million in research last year. That diversity of perspective, coupled with its approach to addressing complex challenges, makes it a unique partner. Shell's work to grow and promote innovation from the grass roots through the GameChanger network reflects the university's entrepreneurial and innovative spirit. Shell may be interested to learn that the Cyvia and Melvyn Wolff Center for Entrepreneurship ranked number one in the USA in 2022. Wolff Center students have launched more than 1,400 businesses since 2011 with $399 million in funding.

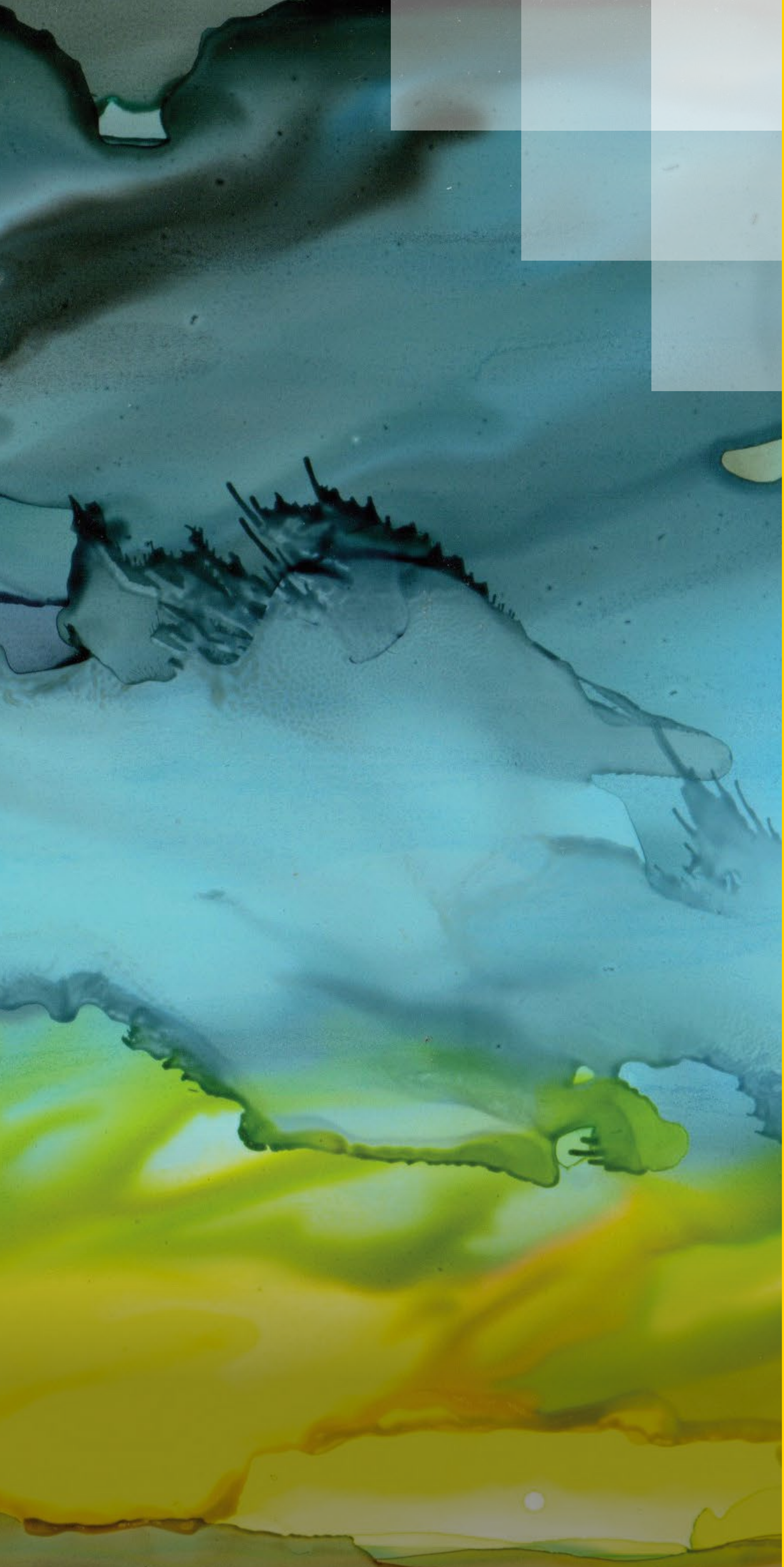
In your dealings with Shell, what aspect of the company surprised you most?

The efforts by Shell to re-image the energy paradigm and bring a practical approach to solving the complex challenges of global climate change and economic growth are remarkable. I know at first hand how slow large organisations can be to adapt to change. Shell has been a trailblazer in the innovation needed to address the energy transition while maintaining a focus on people and building a culture of inclusiveness.

Renu Khator is in her second decade as both the chancellor of the University of Houston System and the president of the University of Houston, USA. As chancellor, she oversees four public universities that collectively serve nearly 76,000 students and have more than a $6 billion economic impact on the Greater Houston area each year.

Under her presidential leadership, the University of Houston has experienced record-breaking enrolment, achieved Tier One status for highest research activity, been awarded a Phi Beta Kappa chapter, established a college of medicine and improved graduation rates by 10 points in 10 years.

A noted scholar in global environmental policy, Renu is the first Indian immigrant to head a comprehensive research university in the USA and the first female chancellor of a Texas higher education system.



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