Innovation briefing

Metamorphosis:

how converging deep tech will propel business in the new bioeconomy

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CC in three your key notes to take away

1. CC believes that the secrets of successful metamorphosis to a scaled bio-economy can be found in the synergistic interactions of emerging technologies.

2. Interactions of emerging technologies will allow us to help add the predictability that is imperative for scaling a profitable, resilient bioeconomy.

3. Business will only be able to realise the full potency and sustainability of the bio-revolution by partnering to harness the collective potential of emerging technologies, sharing data and decentralisation.

Introduction

The bio-revolution is alive with opportunity. Emerging deep tech, including biotechnology and synthetic biology techniques, is presenting novel ways to create materials, chemicals, food and medicine. Ambitious innovators are set to redefine their markets with transformative leaps. Our planet, and the sustainability imperative, stand to benefit. But…

The but is biology. The pace of change is hampered by the complexities of manipulating and scaling it. Outcomes are hard to predict; timescales and cost are always a hindrance. This CC Innovation Briefing sows the seeds of a solution.

In it, we fast-forward to the future and present a bold but plausible vision for the new bioeconomy. We explain how synergistic technology interactions hold the key to scaled, profitable, flexible bioprocesses. And we unpack the reasons why these emerging technologies will combine to deliver the predictability and certainty that will allow the bioeconomy – and perhaps your business – to flourish.

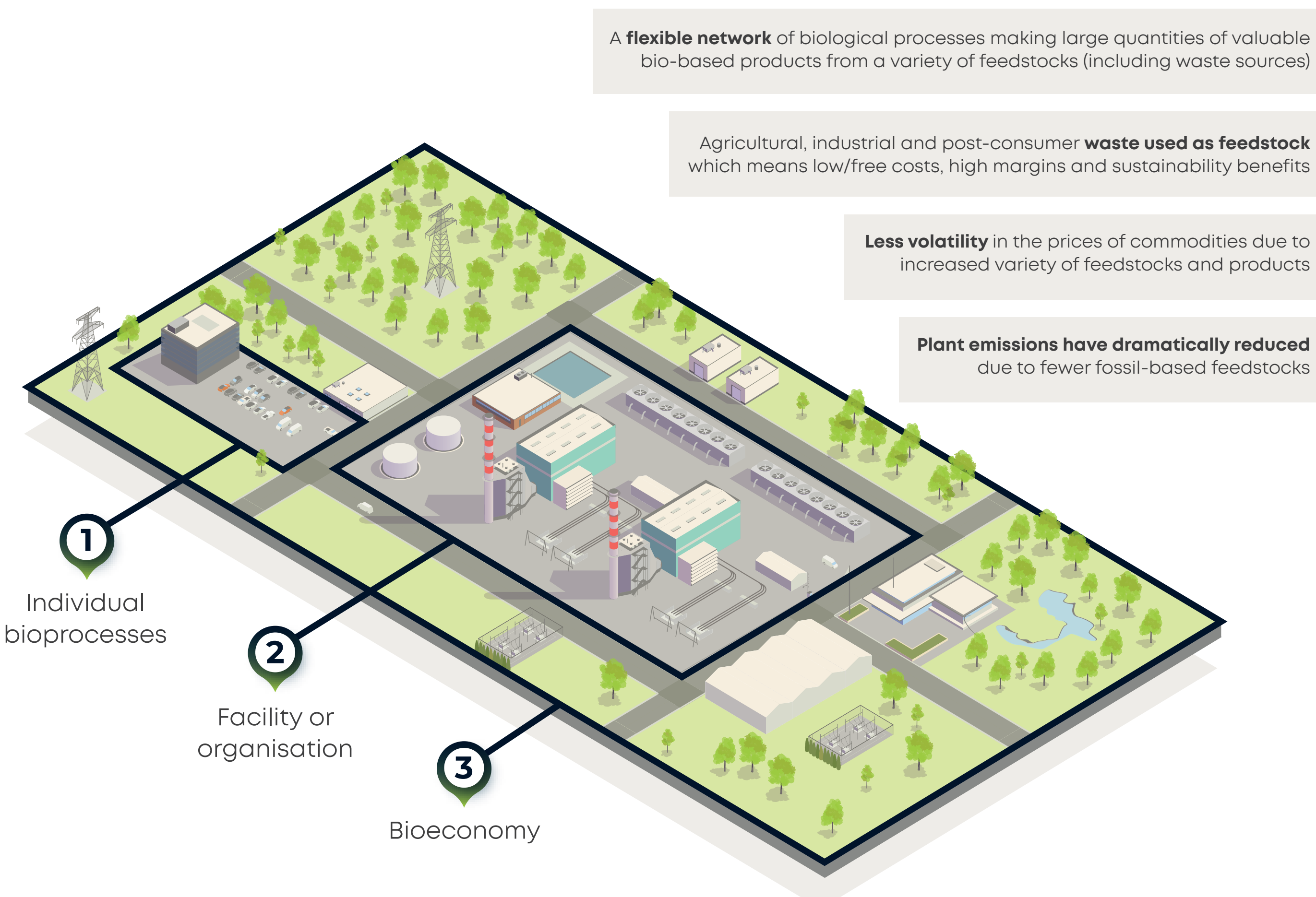
Our authors draw upon CC's unique perspective at the intersection of engineering, biology and advanced computation. Their insights are shaped in an environment where scientists, technologists and industry experts collaborate to question the status quo. Central to everything is the interplay of deep tech – in this case synergistic technologies that can be applied at an individual bioprocess level, a company level or at the level of the entire bioeconomy.

A vision for the bioeconomy of the future

Converging technologies have accelerated a profitable, scaled, networked bioeconomy

Let's spin forward to 2035. You are the bio-based chemical, material or ingredient manufacturer of the times. Your bioprocesses are flexible, but still achieve economies of scale. You exist within the new bioeconomy. It is highly profitable, operates at scale and is networked – with a collection of real-time interconnected bioeconomy functions, constantly communicating with each other to share data and resources. Together, this bioeconomy serves an expanded, ageing population with the materials and chemicals it needs to thrive, without the environmental cost.

A vision for the bioeconomy in 2035

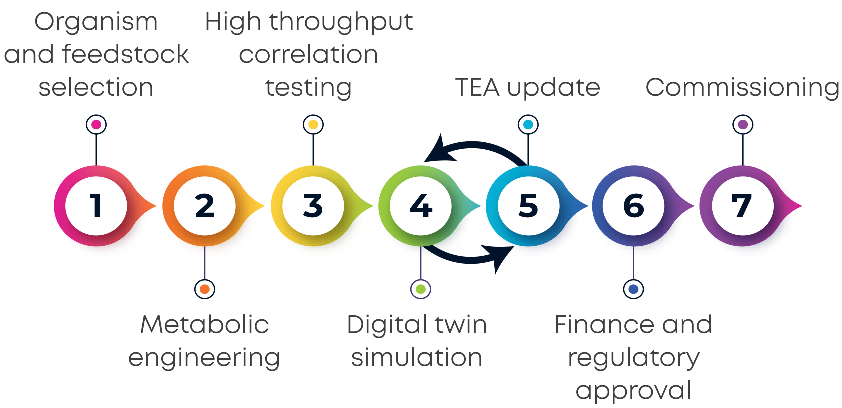


To be clear, this is not a prediction – it's designed to be a provocative conversation starter

Adaptable individual bioprocesses

At an individual level, your bioprocesses have overcome the trade-off between flexibility and economies of scale by harnessing a multitude of technologies. To illustrate this, let's imagine that one of your main feedstocks suddenly becomes unavailable. This might be due to the regulator limiting fossil extraction, a geopolitical event raising the price of a fossil input, an extreme weather event wiping out a particular crop, or a waste stream that you were using becoming obsolete. In the past, this would have been a business-critical problem – but now it's only an inconvenience. You use the following process to adapt:

Stages required to set-up a bioprocess



1. **Organism and feedstock selection:** A database of available feedstocks and prices is fed into an AI which determines a chassis organism and feedstock based on the equipment you have available (with input from a metabolic engineering AI which determines what improvements to yield and titre are likely possible with different chassis and feedstocks).
2. **Metabolic engineering:** AI undertakes metabolic engineering and optimisation to recommend several hundred organism variants that would likely produce your product at the required yield and titre with the best feedstock. The AI runs on a hybrid system of a conventional and quantum computer to accurately simulate the reaction sites of the involved enzymes, improving enzyme activity as it goes. It looks at the downstream processing steps that will be required and makes another several hundred variants that miss out an expensive part of downstream processing. You take these recommendations to your laboratory where you use the latest synthetic biology tools and automated liquid handling equipment to produce these variants.
3. **High-throughput correlation testing:** In the laboratory, high-throughput correlation testing (which is an array of well-plate sized bioreactors with advanced sensing and microfluidic feeding) measures how each variant grows in relation to a number of parameters that will be critical for scale-up and downstream processing including oxygen availability, by-product concentration and pressure changes. It selects variants that give the best results when scaled up. Some of the results are fed back into the AI to produce improved recommendations. This high-throughput correlation testing procedure has demonstrated a good match to results at larger scales when fed into a digital twin model.
4. **Digital twin simulation:** A digital twin of your equipment is used to predict performance of organisms in large scale vessels, using the results from the high throughput correlation testing and similar processes. This twin incorporates computational fluid dynamics to understand oxygen flow through the fermentation vessel alongside metabolic models to understand proliferation and target product production. Downstream processing and upstream processing are also included, using powerful physics engines.

5. **TEA update:** The predictive power of the digital twin (in terms of input, titre, yield and downstream processing efficiency) enables confidence intervals to be given in a techno-economic analysis (TEA). This shows that this new process is highly profitable. It also reveals that the main factors affecting profitability are oxygen availability and the fermentation time.
6. **Finance and regulatory approval:** With your estimated costs, return on investment and confidence intervals, you get a good deal on financing the project. The regulatory approval is straightforward as the regulator is familiar with these technologies, trusts the predictions and the regulatory approval process has been streamlined accordingly.
7. **Commissioning:** When it comes to commissioning this new process on your existing equipment, the digital twin has informed you which parameters are likely to be critical to profitability. You use advanced sensing modalities to sense these in real-time. Artificial intelligence monitors these parameters alongside the critical process attributes to optimise the control system. The process learns from itself and quickly ramps up production to optimal levels. It also flags any unusual events for preventative maintenance.

Automatic iteration: With the updated TEA, your software automatically goes back through all the variants tested in the high throughput correlation testing and performs a digital twin simulation and the same TEA to give you an optimal return. This takes an enormous amount of computing power, but high-performance compute infrastructure is ubiquitous now. Indeed, your classical computer may be integrated with a quantum computer to speed this up.

You've rapidly adapted to what used to be a business-critical problem to achieve economies of scale in the production of the same product from a new feedstock. The price of this product has skyrocketed due to the shortage of feedstock, and you are enjoying the returns enabled by these now well-established technologies. Your ability to provide reliable supply leads to trusted supplier status, enhancing your industry reputation.

Flexible, optimised facilities

Your individual bioprocesses aren't the only ways in which the convergence of emerging technologies has affected your business. Supply chains have become more volatile due to climate change and geopolitics, but your business is resilient to this through the combined effects of leveraging real-time data, modular processes and data fusion.

- Real-time process data is gathered using conventional methods but also with advanced photonic methods (science and technology of generating, controlling and detecting photons) and biosensing (the use of biological entities to measure attributes). Artificial intelligence at the edge (local hardware, as opposed to a centralised data centre or cloud environment) means that a wide variety of parameters can be inferred, and dynamic control systems implemented.

- Modular processes are unit operations that are independent but flexibly connected. These processes are inherently flexible as they can be easily scaled up or down by removing modules, they can be upgraded and adapted or broken without disrupting the whole system and they can be combined with various other modular processes for diverse functionality. Modularity is specifically called out as an R&D focus area in the Schmidt Futures Report – a prominent thought piece on advancing the US bioeconomy.

- Data fusion is the combination of different types of data to infer insights. In the facility of the future, we might combine data from the scheduling software with real-time dynamic electricity prices, weather predictions, process data and market data to optimise our sites. This leads to higher utilisation of assets, lower operating costs and higher revenue. For example, according to a Capgemini Research Institute report, basic site-wide digital twins are already bringing average system performance improvements of over 25% even without incorporating data from the wider enabling environment.

Overall, your multiple bioprocesses achieve economies of scope (the cost advantages and efficiencies achieved when producing a variety of products rather than specialising in a single product), are resilient to supply chain volatility and achieve synergies in production, sales and marketing.

A networked, tokenised bioeconomy

The bioeconomy is responsible for meeting a variety of human needs; from feeding us, to powering our homes, to cleaning our workplaces. Your future bio-based business operates in a networked bioeconomy where efforts are co-ordinated to meet these needs. This helps when tackling the 'grand challenges' that the industry faces, including moving across regulatory territories, improving sustainability, and security (which is particularly complicated due to the convergence of cybersecurity and biosecurity).

In the future bioeconomy, data is shared on a distributed platform (a system or network in which components and functionalities are spread across multiple nodes rather than one central hub) that combines real-time pricing information, real-time supply information, future predictions, sustainability best practice and security resources such as known vulnerabilities.

Tokens facilitating a decentralised bioeconomy

Tokens gained by:

1. Sharing your data
2. Maintaining/improving the platform
3. Buying tokens

Tokens spent by:

1. Accessing data
2. Selling/trading tokens

This system is built on open standards and tokenised with bioprocess equipment and market data being interoperable within the system. This distributed platform has several advantages:

- No single entity is responsible for resourcing the set-up and maintenance of this platform. There is no intermediary, which removes associated costs.
- Companies maintain ownership and control of their data which reduces data sharing risks.
- Various policy and regulatory bodies can simulate the effect of their potential policy decisions and regulations on the industry to choose restrictions and timeframes that have the smallest impact on companies and the supply of goods.
- Transparency in regulation across territories enables easier planning, collaboration and economies of scale across borders
- Facilitation of smart contracts – self-executing contracts where the agreement is written into code and automatically executed when certain conditions are met.

Smart Contract Example

A company licenses a proprietary enzyme for utilising cellulosic biomass. The contract uses IoT sensors within the bioreactor to measure the volume of product made using the proprietary enzyme and feeds in real-time price data to automatically calculate and trigger payment of the required royalties. Smart contracts enable automated, trustless, and tamper-resistant execution of agreements on blockchain, reducing the need for intermediaries and enhancing efficiency

How do we achieve this vision?

This idealised future isn't as far away as it may seem – even if progress might not be as straightforward as the picture we've painted. The key will be to bring more predictability to biology and bioprocesses, whilst at the same time capitalising on varying scales of decentralisation, a trend that offers a number of benefits to industrial biotechnology. A collective, community wide approach will also be crucial. Let's begin with predictability.

We make biology and bioprocess predictable

The bio-revolution has often been compared to the silicon revolution, which led to the proliferation of electronic devices, personal computing and the digital era. A key difference between the bio-revolution and the silicon revolution is that biology is inherently more complex and therefore less predictable than silicon chips and electronics.

Predictability fosters informed business decisions, reduces risk, ensures consistent product quality and leads to faster regulatory approval. It enables the transition from fed-batch to continuous processing through understanding what impacts phenotype stability. It enables scaled, commercially attractive bioprocess by design, minimising trial and error.

So how do we make biology and bioprocess more predictable within industrial biotechnology?

Biology is complex as it has numerous interconnected parts and variables which often interact in a way which brings out emergent properties – where the sum of a behaviour of multiple parts is different than the individual elements. Biological systems are constantly interacting with their environment and have evolved according to this environment over time. This, alongside the inherent stochasticity of some biological processes mean it can be very difficult to predict what biology will do. There are several ways in which we can overcome these challenges – and we explore them below.

Research

Academic research often focuses on understanding the parts that make up a biological system and using a systems approach to better predict the output. As the tools we use to measure biology become more sophisticated, our understanding is rapidly evolving, thus making biology more predictable. Predictability is specifically called out as one of two core research priorities in the Schmidt Report.

Low-sample AI

AI requires many, many samples to be effective (~at least 2,000 per class or 10 times the number of degrees of freedom of a model, which is very high for a string of amino acids). This is extremely difficult in biology research due to the time-consuming and expensive nature of biology experiments. George Church's lab at Harvard University is changing that by using 'protein large language models' which enable protein structure and function to be predicted from protein sequences.

Validated simulations

In the earlier 'individual bioprocess' section, the concepts of highly correlated screening and bioprocess digital twins were explored. Validation of the predictive powers of these model systems is vital in ensuring they can be trusted to assist with business decision making.

Cell-free expression systems

Cell-free expression systems have been developed which just contain the transcription and translation machinery of a cell, without the cell membrane or reproduction apparatus. This reduced complexity could make these systems more predictable alongside improving yield and cost-effectiveness. Nonetheless, several barriers remain including knowledge and resource gaps, the need for better measurements and issues with predicting performance.

We leverage differing scales of decentralisation

Decentralisation is a trend in industrial biotechnology because it a) allows manufacture closer to sources of waste, reducing transport cost and carbon footprint b) enables supply chain resilience and c) aligns with trends towards decentralisation and personalisation in consumer markets.

In a decentralised bioprocess, the company which owns the process loses some control over it. There may also be a variety of fermentation vessel sizes, aeration methods and feedstock qualities in each of the locations that the process is scaled to. For example, if you are putting your bioprocesses that produces a particular ingredient into various food manufacturing premises, you may lose access to the machine entirely.

Better predictive powers make the process of transferring control much easier as you know which factors are most likely to impact quality and efficiency, so you can focus the handover process on these. While other sectors are also experiencing decentralisation, with bioprocesses, the individual characteristics of a process have more of an impact on quality and efficiency than in other sectors such as manufacturing with plastic.

On the other hand, consolidated biorefineries (with a variety of bioprocesses working synergistically in one place) bring enhanced flexibility due to being able to have a wide variety of processes and equipment in one place. It also brings economies of scale and simplified distribution of end product.

Predictability is also important here for encouraging synergy across processes (for example, what process might I be able to use to valorise this side-stream) and understanding how changes impact the whole system.

By leveraging decentralisation and consolidation appropriately, the bioeconomy becomes flexible, resilient, efficient and scalable.

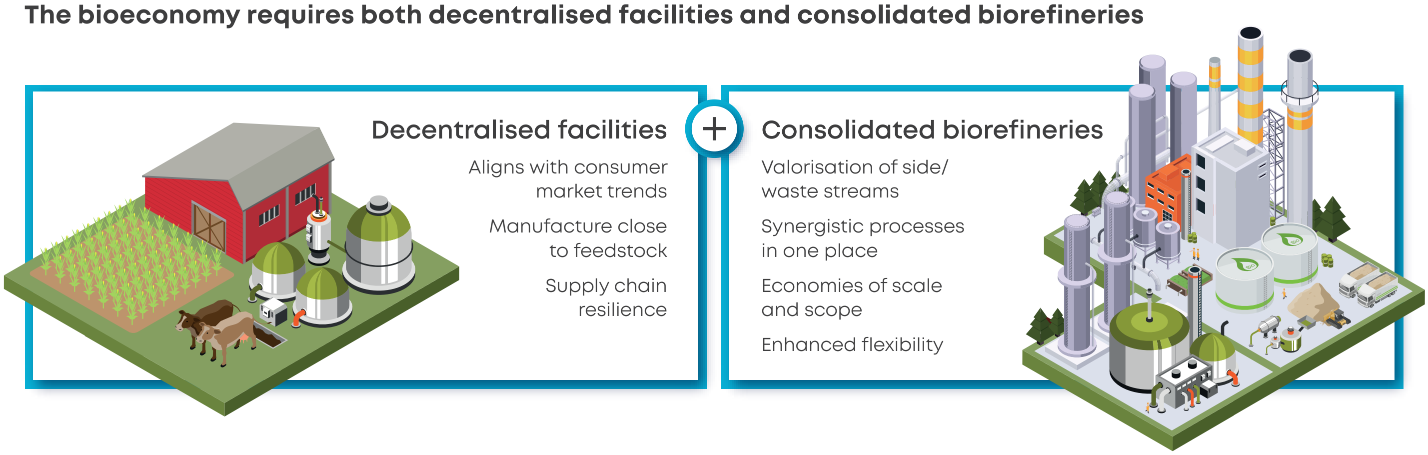
We harness the collective potential of the community

The convergence of technologies is inherently interdisciplinary – it's unlikely you can achieve progress acting alone. Biology is a system. The bioeconomy is a system. So, we need to be approaching both with a systems mindset. Rather than focusing on individual elements in isolation, we need to emphasise the whole picture, understand how entities interrelate and consider the broader context in which the bioeconomy operates.

One of the ways in which we do this is utilising a platform to collate data, share data and interpret data. In the provocative vision described above, a distributed platform was the method for achieving this. In reality, distributed platforms are the right choice when parties cannot agree on a single trusted third party, or third parties bring prohibitive extra time, cost and risk.

Whether a centralised or distributed platform is used, this digital service needs careful design. This must include a good understanding of how access to data is controlled. We must also ensure there is enough value in the platform to encourage a variety of stakeholders to share data and collaborate.

The bioeconomy requires both decentralised facilities and consolidated biorefineries



Conclusion

By now, you should be able to anticipate our central conclusion. Predictability. It is the prerequisite for scale, flexibility and certainty.

Scale

Scale-up of bioprocesses is usually challenging and expensive. Biology is inherently challenging to predict due to its complexity and constant interaction with the environment. This complexity when we understand and can manipulate it is powerful. Being able to predict how biology interacts with our scaled industrial systems is the secret to unlocking this power.

Flexibility

Flexibility and modularity demand the ability to take a variable input and produce a fixed output. This might require different organisms, different vessels, different upstream/downstream processing. Without prediction, you have to keep doing the same, rigid thing as the uncertainty is unworkable.

Certainty

A good prediction gives a range rather than a single value and understands what the prediction is sensitive to. Certainty builds confidence.

These three attributes are the keys that allow us to design, finance and regulate the bioeconomy. How do we achieve this? A systems approach and the right data and knowledge sharing infrastructure must be in place to enable change. Alongside this, partnership is vital. Across disciplines, across the value chain; between industry, deep tech experts, policy makers and society.

The powerful predictability that emerges from the convergence of deep technologies will enable the new bioeconomy to spread its wings; with the ripples propelling businesses to new heights of sustainability and profitability.

Continue the conversation

If you'd like to discover more about the subject – or would like to discuss your ambitions for the new bioeconomy – please get in touch with Frances Metcalfe, SVP Global Biotechnology.

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Why CC?

Cambridge Consultants (CC), part of Capgemini Invent, is a global team of 800 bright, talented people – united by the ambition to turn brilliant and radical ideas into technologies, products and services that are new to the world. We expand the boundaries of deep tech innovation by tackling the tough, high-risk challenges that bring defensible competitive advantage and market leadership for clients. We are trusted by some of the world's biggest brands and most ambitious start-ups to realise their critical technology-based aspirations – and we've been doing it for 60 years.

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As part of the strategy, innovation and process group at Cambridge Consultants, Rebecca helps senior decision makers understand the technology breakthroughs that will have the largest impact on their organisation – and how to capitalise on them, with a particular focus on biotechnology. She is currently a Fellow at the World Economic Forum working on the Bioeconomy Initiative.

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James is responsible for growing ground-breaking industrial biotech capabilities and leading multi-disciplinary teams to invent radical innovations for ambitious clients. His background is in thermofluidics and simulation. He has a passion for challenging current thinking to find impactful, yet unobvious improvements to all stages of bioprocess development.

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