Renewable Food

A Transformed and Renewable Food System is Now Possible

Paul Gilding

Future Visions: Provocations to Spark Dialogue

Independent views from CISL's Network

Future Visions

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Part 1: Executive summary

The core premise of this paper is that the global food and agricultural system is about to undergo a major market disruption which will lead to a system transformation of major historical significance. This is not a paper about theoretical potential, or things we could or should do. It is a paper warning a market disruption is going to happen and has arguably already begun.

While the signs of this are clear to see in today's science and markets, most in the industry take comfort in a belief that transformational change is 'difficult and complex' and will be 'very slow'. They put forward barriers like the challenge of shifting farmer behaviour, the resistance of consumers to change, the political power of the farm lobby, the cultural context around food and the widespread affection for traditional farming. Furthermore, they see sustainability as an optional 'something we should do', rather than a set of physical limits that will undermine the economics and stability of the current system, making change inevitable.

While comforting, these are the usual self-serving illusions of an incumbent industry. They ignore the inevitability that unfolds when change is driven by science and economics, rather than noble intentions or public opinion. They also ignore the momentum created when markets, entrepreneurship and innovation are fully unleashed.

The ideas in this paper are framed by the University of Cambridge Institute for Sustainability Leadership (CISL) report *Competing in the Age of Disruption*, which argued for business to see sustainability through the lens of protecting and creating value, rather than primarily through a social responsibility lens. Using that framework, this paper argues that the changes coming to the food and agricultural industries are profound competitive threats and opportunities for current businesses. Therefore, they should be analysed and approached through such a value-centric framework.

This paper aims to be a provocation to the industry, policymakers and experts to imagine a different future, highlighting the lack of focus on both the risk of a global food crisis and the opportunity for genuine food system transformation. It argues transformational change in the food industry is not just likely, but largely inevitable for two intersecting and now unstoppable reasons.

1. Industrial farming, and the food system built around it, is unsustainable. Not in a philosophical sense but in physical, scientific reality. Between climate impacts, water scarcity, soil degradation, land use and other issues, the industry as it currently functions cannot possibly expand food production by the 35–56 per cent[1] required over the coming decades. This is the case anyway, but more so when you add in the need to also slash its greenhouse gas emissions. This theoretical 'need for change' is widely accepted, but the incremental responses proposed by even the most progressive forces in the incumbent industry are just sticking plasters on a broken system. Even if they were fully implemented, such responses would not change the trajectory.

   Therefore, as climate and other impacts on the food system accelerate, there is a high likelihood of supply shocks and a global food crisis, or at the very least a rolling series of regional ones that build into crisis as the new normal. This will create geopolitical upheaval, conflict and disorder – with major global economic impacts. This will in turn put the food system's 'unsustainability' into sharp focus and drive an acceptance of the need for radical, transformational change. The directional choice will then become action to accelerate transformation or a passive response to accelerating global decline.

2. Meanwhile, in parallel, a range of new approaches to food production are in widespread use today and will soon proliferate across global markets. These include leveraging age-old fermentation techniques combined with modern technologies like artificial intelligence (AI) and biotech to produce protein and other food ingredients through biological processes, rather than traditional agriculture. They will be producing the same food but doing so more efficiently and cleanly. The market acceleration of these approaches will not be driven by a moral or social imperative, nor by consumer choice. It will be driven by national food security imperatives and by the economics of manufacturing and technology creating food ingredients that are simply more competitive – cheaper, healthier and safer.

   Though not the primary driver, a by-product will be a dramatic reduction in land use, greenhouse gas emissions and water use. As a result, these new approaches to producing food will provide us with an opportunity for a truly **'renewable food' system**.

We hear the arguments against both drivers, and these will continue to be made. The incumbent industry will fiercely resist change and do all it can to slow it down, as we have seen with energy. But radical change is inevitable for these two reasons: Firstly, climate change is accelerating, and this means supply shocks, inflation and geopolitical instability. Secondly, we have emerging solutions that will enable us to produce all the food we need. Food that will be cheaper, better and more reliable and that can still be produced in a changing climate.

The question is, will we drive the adoption of these new approaches fast enough to outpace a changing climate and build a 'renewable food' system? The opportunities outlined in this paper show we now have the capacity and technologies to achieve this. Will we pursue them with a determination appropriate to the risks we otherwise face? Or will we be too slow and take the alternate path of building food crises, disorder and economic decline?

Criteria for a 'renewable food' system

Expand production to feed 9 billion + people, healthily and affordably.

Do so within the now inevitable rapidly changing climate and ecosystem.

Allow for the steadily growing needs, of a larger and wealthier population, for land – for biodiversity, urban development, energy generation and carbon absorption.

Deliver this in the context of possibly extreme geopolitical instability and climate migration that will undoubtedly now unfold given the lack of attention to these risks.

Continue doing so indefinitely, using resources within the ecosystem rather than extracting them and making them unavailable for further use.

The core arguments of this paper

1. Food is the foundation of civilisation

Food is the single most important foundation of human stability and progress. Instability of supply has more profound and rapid impacts on politics, social cohesion and economies than anything else. Throughout history, secure supplies have opened up possibilities for great wealth and human advancement, while major supply shocks have created instability and even crashed civilisations.

In modern times, middle- to high-income countries have become largely immune from food supply shocks and thus discounted the risks, seeing food shortages as an issue for poor countries and poor people. This is a dangerous and incorrect view given the interconnectedness of the modern global economy. A food supply shock could easily destabilise countries and regions, create huge numbers of refugees and trigger conflict and war. Thus, the world economy is at risk in a food crisis, not just those who might then lack food.

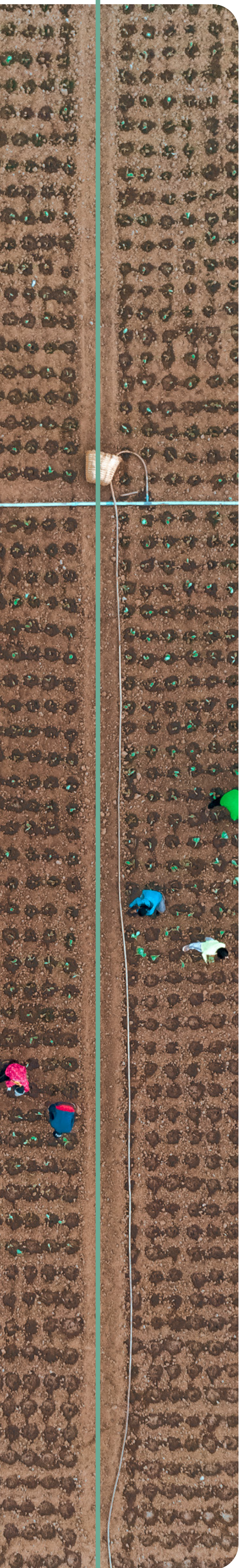
2. Food supply is a global market system

With the exception of some smallholder farms providing local food, global food and agriculture is now wrapped in a global market system, with all the attendant benefits (eg lower costs, global trading, efficiency through scale) and risks (instability, financialisation, speculative behaviour, global shocks) of that system. Like energy, this is not a simple market of supply and demand but rather a complex market system which is deeply influenced by – and influential on – geopolitics and local culture. But nevertheless, food supply is primarily driven by the global market system, and decisions are made by major market players.

3. The food system depends on nature and is deeply affected by it

The current food system is built on, and around, the behaviour of natural systems and depends on them for its stability. More than any other major part of the economy, it is heavily influenced by fluctuations and changes in those natural systems. It is particularly at risk of hitting against the limits of, and changes to, those natural systems, most notably climate, soil and water.

It is often said that a strong economy is dependent on a stable environment. The food system is where that idea practically manifests. With food the foundation of civilisation, an unstable climate and ecosystem will translate, through the global food system, into economic shocks and geopolitical instability.



Given this context, it is surprising how little attention we give to the fragility of our current food system. It is an extractive and increasingly industrialised system that is dependent on resources that it is, in turn, rapidly depleting or damaging. Without radical, transformational change it will not meet growing global demand in the coming decades, estimated to be 35–56 per cent greater than today.

Few question that individual challenges like climate change, soil quality and water security are serious. However, there is surprisingly little strategic focus on the global geopolitical and economic risks posed by them acting together to create a global food supply and geopolitical shock. If there was such a major disruption to food supply, coming on top of existing geopolitical tensions, it would reverberate throughout the global economy, cause widespread conflict and drive unprecedented refugee flows.

Given the severity of these risks, and the centrality of food to global stability, it is also surprising how little attention is being paid to the radical and disruptive market and technology opportunities emerging in food production. These have the potential to transform the food system and start to address these risks, while delivering a stable supply of food that is cheaper, healthier and safer. These new approaches have the capacity to follow technology growth curves and rapidly accelerate, particularly given AI and other emerging technologies, including abundant, low-cost renewable energy.

With the above as its framework, this paper argues that the global food system is at the early stages of a disruption of major historical significance, which will accelerate over the next decade or two. This has the potential to lead to a transformed and 'renewable food' system.

The key drivers of this transformation will be:

- Global supply instability as the system is impacted by natural limits like climate change and water scarcity, creating widespread conflict, disorder and economic damage. This will create sharp focus on the fragility of the global food system.
- A range of disruptive technologies and processes in food production becoming price and quality competitive, initially driven by the business-to-business (B2B) market, and forcing widespread change in the food and agricultural industries.
- This means disruptive market change is inevitable. It will either occur through the food system breaking down due to global supply instability and the resulting conflict and disorder, or through an economics-driven transformation that leverages new technologies and processes to create a stable and 'renewable food' supply. Either way, the current industry is facing large-scale, disruptive market change.
- Within the next decade it will be widely accepted that this market disruption has begun, with significant global economic and social impacts – some positive and some negative. The shape and potential of this new system will start to be understood, causing major shifts in policy, market investment decisions and the focus of research and innovation. At its core, the challenge will be understood to be for society to move from an extractive food system to a 'renewable food' system.[2]
- The new 'renewable food' system now on offer has the potential to address hunger globally, and make human society and economies more stable, more prosperous and healthier. It could largely eliminate food and agriculture's contribution to climate change and pollution, reduce the risks of conflict and the number of refugees, and free up large areas of land for biodiversity, carbon removal and energy transition infrastructure.

- That outcome is not inevitable. While there will be the opportunity for a positive and historic transformation, such a transition will be complex, non-linear and resisted by the incumbent industries. It will create significant economic and social disruptions and have major consequences, especially for farming communities and workers in related industries. This will need to be well managed to minimise negative impacts and social risks.
- It is important to note here that the new approaches to food production will not fully replace traditional farming but will primarily impact 'industrial agriculture' such as intensive beef and dairy 'factory farms' and broadacre cropping. Nevertheless, many people will be negatively affected, and therefore resistance to change by incumbent industries and populist politicians could slow food system change and see it overrun as critical risks like climate change and water scarcity accelerate.

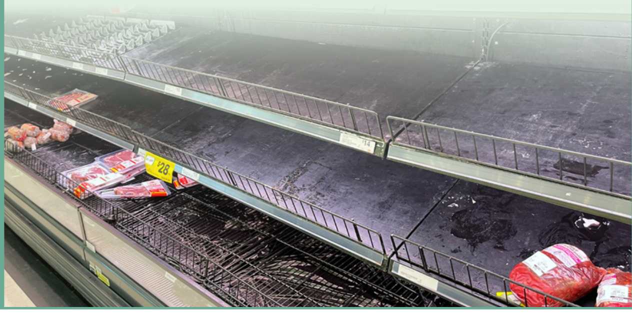
In summary, the four major drivers that will create this disruption are already in place and will each accelerate from here. They are:

1 New food production approaches, such as precision fermentation of key food ingredients like dairy and other proteins, and key oils like fish and palm.

2 Parallel technologies, including AI, biotech and renewable energy, that are now improving exponentially and will in turn accelerate the pace, quality and price reductions of these new food production processes.

The four drivers of market disruption in food and agriculture

3 The current food system being impacted by climate change, soil loss and water scarcity leading to supply instability and shocks.



4 The current food system's impacts on climate change, particularly methane emissions from beef and dairy, coming into sharp focus as climate change impacts accelerate and threaten the economy.

The first two drivers are enablers of a transition; the second two will accelerate the change towards it. All four will occur in parallel, and act synergistically.

This paper explores each of these four drivers, provides detailed examples of what is happening in the market today, and uses the lessons of the energy transition to lay out some scenarios on how this might play out in the market over the coming few decades.

Part 2:
The inevitability of disruptive change

Change is not an option. The type of change is.

This paper's central premise, that we need a transition to a 'renewable food' system, will be confronting to many. Is agriculture not the very embodiment of a renewable system – a harnessed natural cycle of plants, sun, soil and water?

The short answer is no, and it is not even close.

Many like to see it that way, as evidenced by the effectiveness of food industry marketing which romanticises farming and agriculture as a wholesome natural process that produces our food, as it largely was throughout history. The reality is that our current food system – taken as a system rather than being distracted by individual exceptions – is just as damaging, arguably even more so, than the fossil fuel industry.

This applies not only to its impact on the climate and ecosystem, but increasingly also the broader negative direct and indirect impacts of the industry's products on our health, our economy and the livelihoods of the family farmers and the rural communities the system used to support. This is covered in some detail in an earlier paper from CISL: Methane, Markets and Food.

Of course, our current food system incorporates a hugely diverse range of approaches. These range from high-rise urban pig factories in China, monoculture genetically modified organism (GMO) soy farms in Brazil, ultra-processed food producers and massive feedlot dairy and beef 'factories' in the US, all the way through to smallholder farms and artisanal fishers in developing countries, and regenerative dairy and beef farms in the UK.

However, diversity and perceptions aside, the system is clearly dominated by industrialised, centralised and corporatised agriculture, evidenced by the largest 1 per cent of the world's farms occupying 65 per cent of agricultural land. The system has become highly efficient and has done a remarkable job of generating growth in supply over the last century. It is also highly centralised, with just 12 crop and five animal species supplying 75 per cent of the world's food.[3] The power of market forces and its relentless, inherent drive for efficiency means this industrialised approach to agriculture and food will inevitably accelerate its dominance until it is disrupted, either by biophysical limits – a changing climate, water scarcity and soil degradation – or by solutions that address the physical limits and are more competitive in market terms.

Many people, including nearly all experts and most industry leaders, accept that the current food system is unsustainable, particularly given climate change and the growing demand for food.[4] Proposed solutions fall into two camps:

1. One camp argues for incremental improvements like regenerative agriculture, precision farming and lowering agriculture's impact through greater 'efficiency' and scale: ie, shifting more aggressively to slightly 'cleaner' industrialised agriculture.[5]

2. The other camp argues for going back to smaller, more local food production. They see the problem as 'big ag' and 'big food', and believe if we walked back from that system, we would revert to a more sustainable food system that once again created good livelihoods and nutritious, healthy food.

Based on the science and evidence, both camps have an unrealistic view of what is possible at the system (vs the individual farm) level. Neither approach will happen on a global scale sufficient to feed over 9 billion people – not for reasons of philosophical choice, but due to physical reality that in turn translates into economic reality.

This means:

- we cannot expand the current extractive system without crashing into physical, ecological limits that will prevent it delivering an adequate food supply
- we cannot go back to the old system at our current, let alone forecast, scale without also crashing into physical, ecological limits that will prevent it delivering an adequate food supply.[6]

We have no path to success on the table today. So, we need a new path.

There is legitimate criticism to make about 'big ag' and 'big food'. They have caused damage to our social fabric, to farmers and our health while driving inequality, creating water scarcity,[7] depleting soil quality and accelerating climate change.[8] They have also, to their enormous credit and despite various earlier concerns all the way back to the time of economist and demographer Thomas Malthus, delivered massive increases in both food supply and calories across the globe (even if that was often to people who did not need any more calories).

None of these issues however are the immediate problem. The problem is that, on its current trajectory, this system that most of us rely on for food, and that the global economy relies on for stability, will inevitably crash. This is science – not philosophy or ideology. Nor is it likely to be decades away. Subject to the unpredictability of weather, markets and geopolitics, the basic drivers like climate change, water scarcity and soil degradation are likely to trigger a global food crisis in the next decade or two. See appendix.

While many in both expert and industry areas recognise the problem, the incremental changes they mostly propose will not address the central risk of a food crisis. Their proposed improvements are useful, emotionally appealing and hard to argue against – regenerative agriculture, lowering carbon and methane emissions, improving soil quality, building water resilience, improving the efficiency of smallholder farms, precision agriculture to lower input use and so on. And they are all worth doing for short-term gain. But this is tinkering at the edges of a system that inherently cannot deliver the outcome of a stable, affordable food supply. Even more so when you consider accelerating climate change and water scarcity.

The problem with the extensive focus on such incremental, apparently worthwhile improvements is it distracts us from the fundamental change required. It gives false comfort that progress is happening and avoids the uncomfortable conversation that we need systemic transformational change, not sticking plasters.

Distraction means delay, and given the social and economic chaos a global food crisis could bring, delay is enormously risky.[9]

Part 3

The lessons from other market disruptions for food and agriculture

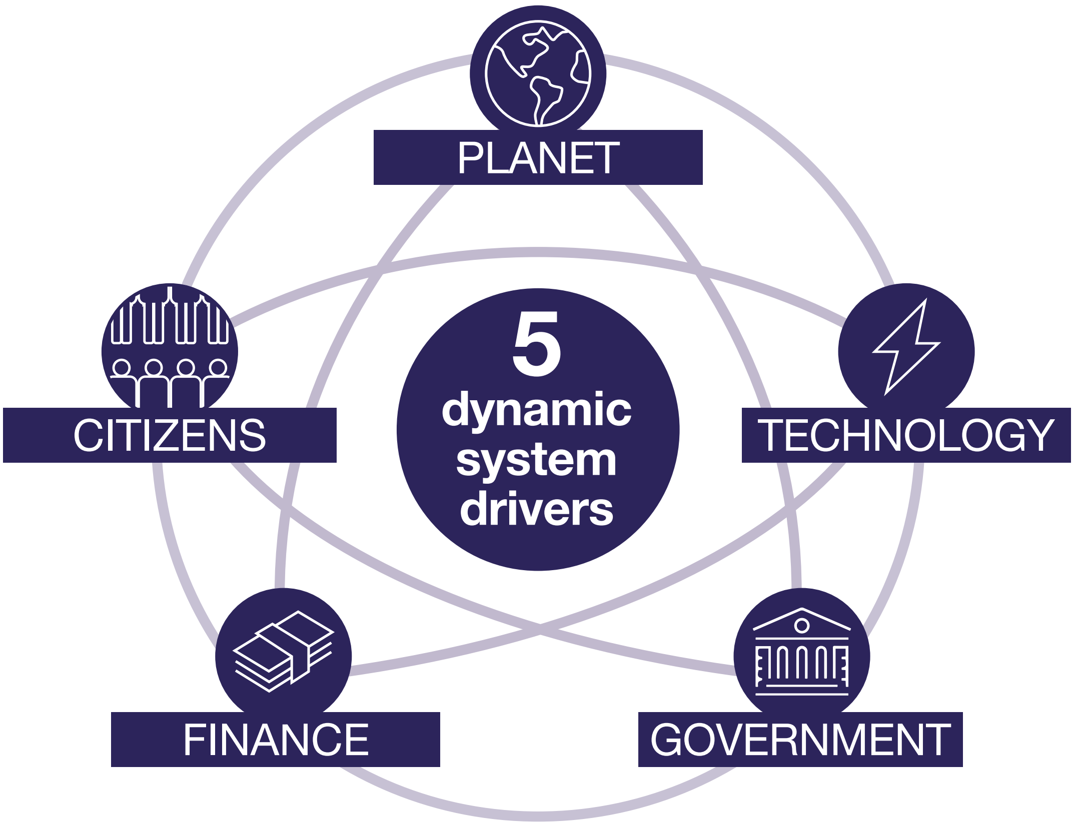
How market disruption happens

The core premise of this paper is that the global food and agricultural system is about to undergo a major market disruption which will lead to a system transformation of major historical significance. This is not a paper about theoretical potential, or things we could do if we chose to. It is a paper arguing a market disruption is going to happen.

Given this, it is important to lay out some views on how market disruptions occur. While the full detail is beyond the scope of this paper, an analysis by CISL on this topic[10] provides a more comprehensive analysis of the assumptions used here.

Figure 1 below identifies the five dynamic system drivers which influence systems and can make or break market disruption.[10]

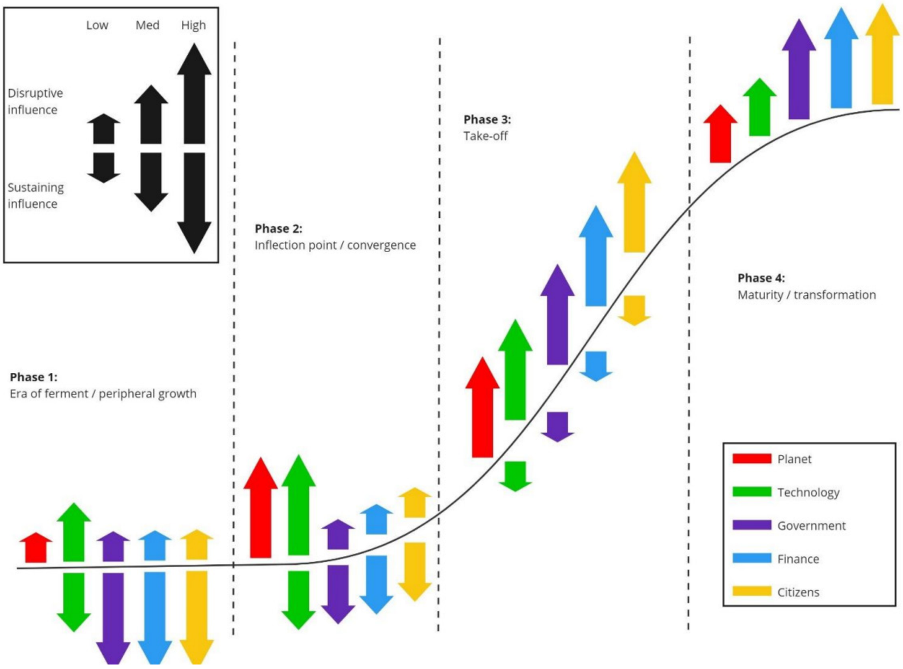
Figure 1: The dynamic system drivers



Source https://www.cisl.cam.ac.uk/news-and-resources/publications/navigating-low-carbon-disruption-systems-thinking-and-dynamic-system

Figure 2 (below) illustrates how these drivers can be sustaining or disruptive factors over time.

Figure 2: Example sustaining and disrupting influences over time



Source https://www.cisl.cam.ac.uk/news-and-resources/publications/navigating-low-carbon-disruption-systems-thinking-and-dynamic-system

We have now seen many global market disruptions and learnt a great deal from them. For simplicity's sake here, we will consider two types of relevance:

- First is when a technology alone drives the disruption without any significant social context or policy involvement, nor any strong incumbent resistance. These occur because the technology is so superior. An example would be digital photography. There was no social problem being solved, there was no coalition of 'mom-and-pop' photo processing stores fighting against it, there was no policy to encourage or discourage it. It was just better technology, delivering a better consumer experience.
- The second type is when a social imperative is involved, which initially leads to both public and consumer attitude shifts, intensive research and innovation, and government policy intervention. While it still ultimately translates into market shifts, usually driven by technology, there is a long lag, with widespread market disruption not occurring until superior solutions (performance and cost) are available. An example would be climate change and the energy transformation. This type is the one most comparable to food and agriculture (the particulars of the energy transformation are salient and will be covered below).

What we have learnt from this second type of disruption is the following:

- The social imperative can be very powerful and drive significant responses, including government policy, publicly funded research and innovation, widespread efforts by entrepreneurs and philanthropic investments.
- It leads to resistance, often fierce, from incumbents who intervene to reduce the amount and intensity of non-market action being taken, particularly in public debates and on policy.

- Despite the high profile such issues create, truly disruptive market change does not occur until the combined impact of the above – most significantly policy measures and entrepreneurial innovation – results in solutions which are superior in cost and consumer attractiveness. They often also deliver other market benefits such as lower risk, time to market, lower running costs etc, which bring further market advantage.
- Of course, transitions are complex, non-linear and messy. They often require government interventions to facilitate, accelerate and manage the change, such as we see with energy and grid resilience. Another example from energy is the 'hard to abate' sectors. But the trend becomes clear once the core solutions are more competitive.
- This point of competitiveness is therefore the key tipping point, because incumbents' resistance is no longer viable when the alternative is significantly superior in market terms (there is a transition period where they still resist, but it ultimately fails).

So, in summary, in the case of disruption where there is a social imperative, the pattern is this.

Limitations within an incumbent system trigger, in various ways, policy, innovation and investment to find a better solution. But it is only when these solutions are superior, both in performance and costs, that the disruption takes off. In the case of energy, the limitations were around climate and pollution – with a smaller influence of energy security. In the case of food and agriculture, this paper argues the limitations will be security and quality of supply, with a smaller influence of the climate impacts of the industry.

An additional lesson from energy (including electric vehicles) is the critical impact that occurs when an industry shifts from being defined by slow-moving change (usually due to capital and physical resource intensity or product development cycles) to fast-moving change (usually due to the transition to technology growth and innovation cycles).

For example, while much of the focus on the energy transition has been on the climate impacts of fossil fuels, it is arguable that the most critical driver of the energy transition accelerating – to the point of being truly disruptive – was the energy system's shift from:

- being a centralised, slow-moving resource industry with a business-to-business (B2B) focus (with business decisions based on assumptions over decades)

to:

- a decentralised manufacturing and technology industry with a significant business-to-consumer (B2C) focus (with business decisions based on assumptions over years or less).

This shift meant the new energy system of renewables and battery storage, and electric vehicles, is now a 'technology' business, more akin to information and communications technology. This is a market and business ecosystem where prices keep falling, quality keeps rising, change is rapid, and market disruption is normal and constant. It is hard to overstate just how influential this factor is on the cultural and market inability of incumbents to react in time.[11]

It also means the fundamental drivers of disruption in the energy and transport markets are no longer environmental, whereas they were earlier when the environmental imperative motivated many to act, including climate policy to create the momentum and breakthroughs. The core drivers are now market ones – a superior product that is cheaper, more efficient, more attractive to consumers, has lower risk and is easier to deliver. Perhaps most critically, in a technology-driven market, each of those attributes becomes more so every year and on a compound basis.

The premise of this paper is that the same process (with some obvious but not profound differences) is now underway with food and agriculture, with that system entering a disruption based on similar fundamentals. While it is earlier in this case, the shift to 'renewable food' will display patterns of change that are very similar to those already observed in 'renewable energy'. This will include incumbents' fierce, but ultimately futile, resistance but also their structural and cultural inability to compete with the new technology.[12]

To use a simplistic comparison, when the car arrived as a means of transport, with technology and manufacturing cost curves then applying, the competitor could not make a faster horse![13]

When the economics turn, the tipping point is reached. This is why the economics are the key, and why understanding all the drivers of change in the food and agricultural industry in that economic context is critical to any analysis of how this will unfold.

> *We shall escape the absurdity of growing a whole chicken in order to eat the breast or wing, by growing these parts separately under a suitable medium.”*
>
> Sir Winston Churchill, 1931

Part 4

The drivers of market disruption in food and agriculture

The first two drivers described here will *enable* the change while the second two drivers will change the societal context and thereby *accelerate* it. They are all considered through a lens of what changes the *economics* of food production.

The four drivers of market disruption in food and agriculture

1 New food production processes

New production processes for food, many of which are being used at significant scale in the market today, will deliver the capacity to drive radical and disruptive change in the global food system. These processes include:

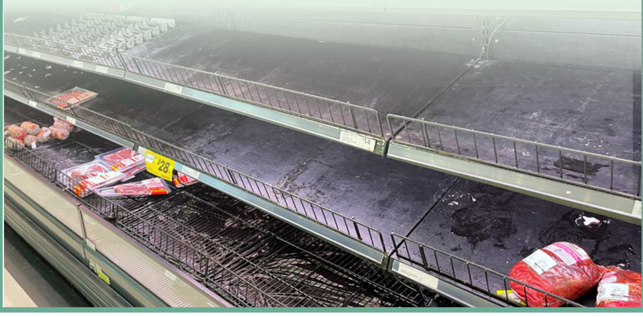
- precision fermentation to more efficiently produce foods, ingredients and nutrients that are currently extracted from animals and plants
- cellular agriculture to more efficiently produce foods, ingredients and nutrients that are currently extracted from animals and fish, particularly livestock
- plant-based foods being enhanced by various technologies, like biotech and AI, to be cheaper, healthier and more appealing to consumers by enabling superior taste and nutrition.

2 Parallel technology developments

Developments in a variety of parallel, enabling technologies will drive this transformation much faster than most expect. These will include developments in AI, biotech and computing power. Furthermore, with energy a key input into many of the new approaches, this will be further driven (and locally enabled) by the falling costs and distributed nature of renewables. These parallel technologies mean the new production approaches will follow technology cycles of lowering costs and improving quality on a compound basis.

3 The changing climate's impacts on a fragile food system

The food system is hitting various physical limits, with signs of strain already showing, brought into starker relief by the growth needed in food supply. On top of that already existing context, the climate is changing, which is shifting weather patterns and changing water supply (volume and timing). Critical to the assumptions on the market disruption occurring soon (<20 years) is that credible climate scientists argue warming, and its resulting impacts, are now accelerating faster than expected. This brings the attendant risk of tipping points being passed, further driving the acceleration.



4 The impact of the food system on climate change

The global food system is both a major cause and a major victim of a changing climate. It seems likely, given current trends in the evidence, that climate change will become recognised as a global, economic and geopolitical emergency – not least because of its impact on food supply. This will likely result in much greater focus on actions that can deliver short-term benefit (ie, slow the rate of warming to give society time to adapt).[14] Short-term benefit can only come through reductions in methane, with agriculture being the largest source of human methane emissions. While there is clear evidence from the climate and energy debate that this greater attention does not drive major consumer shifts directly, it does influence policy, corporate behaviour and the rate of innovation.

Driver 1: New food production processes

There are a range of new production processes for food, many of which are happening at significant levels in the market today. Collectively, they have the capacity to drive radical and disruptive change in the global food system.

These processes include:

- precision fermentation to more efficiently produce foods, ingredients and nutrients that are currently extracted from animals and plants
- cellular agriculture to more efficiently produce foods, ingredients and nutrients currently extracted from livestock
- plant-based foods being enhanced by various accelerating technologies, like biotech and AI, to be cheaper, healthier and more appealing to consumers by enabling superior taste and nutrition.

A range of these 'new approaches' to food production are in many cases old processes enhanced by new knowledge and capacities. So, whereas some see these approaches as 'novel' or 'artificial', this is generally incorrect. For example, the process of fermentation has been around for thousands of years, to preserve food and to make and transform ingredients into products like yoghurt, cheese, beer and wine. What is now often referred to as the 'new approach' of 'precision fermentation' simply applies new understanding of biology combined with better analytical power and production knowledge to enable fermentation to occur with greater precision and at larger scale, and thereby be applied to a broader range of products.

The research organisation RethinkX frames the overall shift as "the second domestication of plants and animals. The first domestication allowed us to master macro-organisms. The second will allow us to master micro-organisms".

The current food system – which we built on the back of the "first domestication" – uses vast amounts of resources to grow animals and plants to then extract specific parts before disposing of leftovers (or finding a low-value use for them). This has been hugely valuable to society, enabling us to produce ever greater quantities of food, but it is an inherently inefficient approach with huge amounts of wasted inputs and outputs. It is this inefficiency and waste that now limits the food system's growth due to overuse of limited resources and the inability of the environment to absorb the waste, including methane.

The new food system – being built on the "second domestication" – leverages micro-organisms and cells to grow the key nutritional elements we need from the micro level up. This "domestication" of micro-organisms allows us to bypass the macro-organisms and produce these individual nutrients (proteins, oils etc) directly. In most cases we are producing exactly the same product – not just functionally but biologically. Thus, it is not 'artificial food', it is the same food being produced more efficiently.

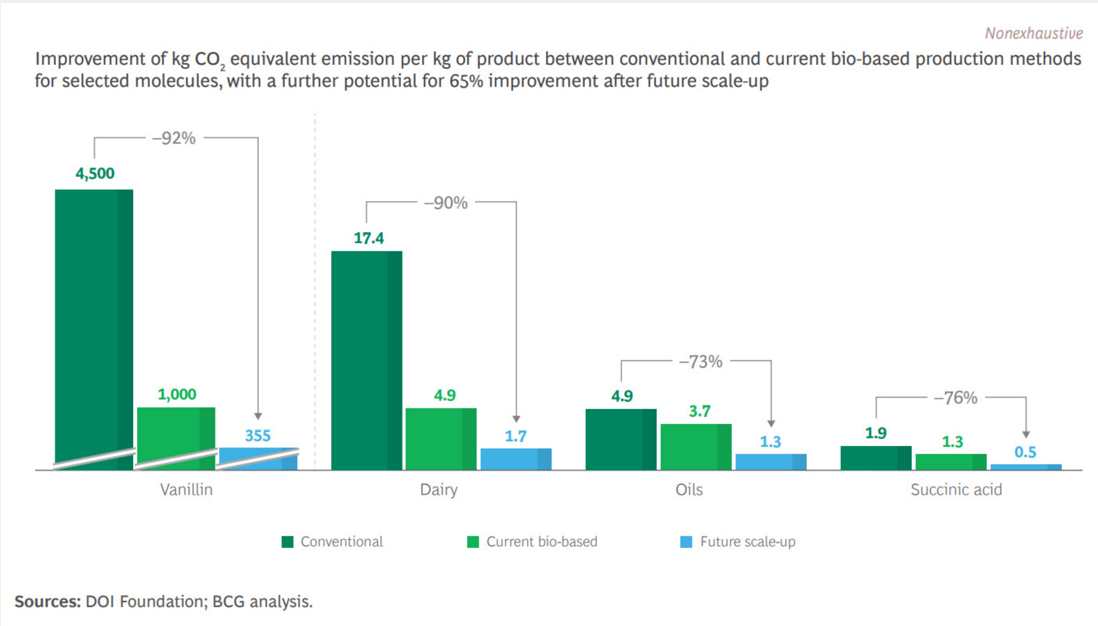
It is generally no less 'natural' than most of our current food system. Long ago we took wild animals and plants and then, over thousands of years of breeding and adaptation, we 'domesticated' them. The result today is a very 'unnatural' plant or animal in the sense that it did not ever exist in nature.

These new approaches will bring many collateral benefits – including massive reductions in climate impacts, water consumption and land use. In many cases they will deliver the same product with 80–95 per cent reduction in such areas.[15]

Precision fermentation, for example, relies on a micro-organism with an inserted string of DNA, effectively acting as an instruction manual to produce the desired product. This micro-organism is placed in a bioreactor and given ideal conditions to grow, including carbon, nitrogen and phosphorous. So there are still inputs, as there are in traditional agriculture, but the inherent efficiency means these inputs are much, much less regardless of their source. The source of these inputs however still determines the overall sustainability of the technology. For example, using cellulosic sugars, green ammonia and phosphate recycling would be an ideal sustainable solution. However, even without this ideal combination there are dramatic changes in the emissions and land and water use of the end products due to the higher efficiencies. There are a number of links to further information on this topic in the endnotes.[16]

As all these new food production processes are heavily influenced and enabled by technology, their development and growth in the market will likely follow technology business and product cycles. This means they will continually fall in price and improve in quality as they are deployed at scale. Critically, this improvement will likely continue on a compound basis, following the same principles as Moore's Law applied to computing power, getting cheaper and better on an ongoing basis. This pattern can be observed with other technologies, with solar, batteries and electric vehicles a live example today.

Figure 3: Production of most molecules



Step change reductions in GHG emissions are expected from new production approaches

Consumer acceptance of these 'new processes' is often raised as a likely barrier to growth – that consumers prefer 'natural' products to processed ones. The reality is much of the food eaten today is not at all 'natural' in the way it is perceived. These new production processes simply allow us to grow the required food to the specifications we need, rather than breaking down macro-organisms to access them through extraction. We thus replace an extravagantly inefficient system that requires enormous quantities of inputs and produces huge amounts of waste, with one that is precise, targeted and tractable. A good example of both these issues is 'renewable food', which is marketed as 'natural sweetener'. On the one hand this is legitimate, as it comes from a plant, but like many 'plant-based natural foods', it is highly processed with over 95 per cent of the plant wasted. Producing it through fermentation, which is happening today, is enormously efficient, reducing that waste by 80–90 per cent and thus water, land use and greenhouse gases by a similar proportion.

Analysis of a system's or production process's efficiency is a good way to isolate and understand long-term drivers of disruption. As discussed earlier, the inherent inefficiency of smallholder and family farms has led to the rise of industrial and large-scale agriculture. This is an inevitable consequence of a market system where efficiency is rewarded with lower prices and market share.

This can be seen in other markets as a driver of change. For example, in energy there is huge waste of thermal energy in applications such as oil-driven cars or coal-fired power stations. Over time this gives an advantage to inherently more efficient technologies such as, in those cases, electric vehicles and then solar and battery electricity generation.

In the food case, as we show with many examples in Part 4, we can see how the inherent inefficiency of traditional agriculture invites more efficient solutions. Imagine, for example, over the life of a cow, the 'wasted' food feeding a dairy cow for two years before it produces any milk, then the amount of feed keeping that dairy cow alive and milk-producing; or the amount of physical mass wasted in a beef cow to extract the high-value protein in beef steak.

In the beef case this leads to 100 calories of feed being required to produce 1 calorie of beef, so a conversion efficiency of 1 per cent. Other animal agriculture products are better but not dramatically so, with even eggs just 13 per cent efficient. The industry argues that protein is the key health benefit rather than calories, but even on that criterion, protein conversion efficiency is still very poor, from 25 per cent for eggs down to 3–4 per cent for beef.[17] Thus, it is an extremely inefficient 'production system'.

In market terms this is an indicator of direction, not proof, as in the end it is the cost of the product that determines success, not the efficiency with which it is produced. But it still provides us with an understanding of the emerging competitive advantage of the new production approaches, with examples in the market today that can produce dairy without a cow, 'renewable food' without a plant, quail meat without a bird, etc.

Of particular significance in the food case is that deployment of the new approaches will initially be focused on the B2B market for ingredients, where price, stability of supply, purity and quality are the key drivers, with consumer acceptability/choice being less influential. This is already evident in the market today, with the dominant market activity that is already moving to scale being mainly ingredients and inputs rather than finished consumer products.

The reason this is of such importance is it responds to arguments that dismiss the threat the new approaches pose, by focusing on the hardest-to-do replacements, such as using cellular agriculture to produce end consumer products like a lamb chop or a whole fish. They also point out potential consumer resistance to 'lab-grown food'.

This ignores the point above, that much of the initial impact will be on ingredients used to make food, rather than a finished product. So, the milk, cream and sweetener going into a McDonald's McFlurry® or the ground beef going into a Big Mac® is not considered by consumers for its provenance or naturalness. It is analysed by the corporation's supply chain executives for its price, purity, quality and reliability of supply. They understand that consumers focus on taste and price.

In combination all these factors mean it is most likely the process of disruption will be primarily driven in the B2B space and by economics and product quality. The new approaches will deliver cheaper, healthier and more reliable supplies, factors which business supply chain decision-makers are focused on.

In observing how all this is unfolding, and predicting how it will develop from here, there are many relevant comparisons to the energy transition away from fossil fuels and to renewables and batteries, which we will return to. However, there is one particularly important difference. In the case of fossil fuels, it is conceivable we will see the complete end to the product's use, at least in burning for energy. This is not the case in food.

The new approaches to production are mostly suitable to replace industrialised agriculture's inputs into food and other products. As shown in the examples in Part 5, these are ingredients such as:

- protein being added to consumer products
- natural sweeteners like 'renewable food'
- oils like fish and palm
- dairy ingredients like casein that are currently extracted from cows' milk.

This will expand to new areas, such as ground beef, and inputs into processed food like chicken nuggets, but that will take longer to go to scale. It is much easier to make a protein as an input into yoghurt than it is to make a lamb chop.[18]

As a result of this focus on industrialised agriculture's inputs into the food system, the disruption is going to be far less, and considerably slower, for smaller family farmers and also for horticulture. It will mainly threaten large-scale industrialised agriculture such as broadacre soy and corn, and feedlot beef and dairy.

Driver 2: Parallel technology developments

Developments in a variety of parallel, enabling technologies will drive this transformation much faster than most expect, largely because it means the food industry will start to follow technology growth curves rather than traditional agriculture and food ones, which are resource based and thus slow.

Developments in AI, biotech and computing power will all facilitate and accelerate the new approaches – in some cases exponentially – enabling rapid insights and enhancements in areas like health and nutrition, quality and purity, all while lowering production costs. The cost reduction curves in renewable energy and batteries and in electric vehicles were all faster than any forecasts by the incumbent industries they threatened.

One impact which might surprise some observers is the likelihood that this approach will improve consumer attractiveness of plant-based foods by improving the nutritional quality, taste and functionality.

Chilean foodtech company NotCo is, for example, using AI to analyse combinations of plant-based ingredients to replicate animal-based foods on the molecular, physical and chemical levels. They are able to produce the desired tastes, textures, smells and colours that consumers expect. This has resulted in them producing several products, including a plant-based milk, with the unexpected combination of pineapple and cabbage. Using AI, they discovered this produced lactones which gave their product a familiar milky taste and smell. They have formed a joint venture with Kraft Heinz to develop a range of new products.

Another area of parallel technology that will drive growth is the falling costs and distributed nature of renewable energy. With energy being a key input into many of the new approaches, its falling price and distributed nature will enable more local food production and lower costs. This will enable the new approaches to be applied in countries which have not traditionally been able to produce their own food, due to a lack of the necessary combination of land, water and climate.

A further two drivers will change the societal context and thereby further accelerate the change

Change in complex incumbent systems is inevitably fiercely resisted and hard to achieve. This is still the case when the new system is superior in all critical ways, even if it would help solve pressing social and economic problems, like climate change and world hunger.

We have seen this play out clearly in climate and energy, where solutions were clearly superior but still took a long time to reach critical mass, just due to the natural resistance to change and system inertia. This was exacerbated by incumbents investing heavily in delaying action through a variety of means. While both factors caused delay, it did not stop the change occurring. That incumbent system is now losing the battle overall, even if it is uneven across countries, sectors and uses.

What this example establishes is that having an economically superior solution is the necessary precondition for disruptive change to occur. It will eventually overcome all resistance.

However, while a powerful societal need for a new approach is not sufficient by itself, such a societal context is still influential on the speed of change. This is because those social drivers can be accelerators, helping overcome barriers and increasing speed, particularly when policy is an influential factor in enabling the new or at least not protecting the old.

Energy again provides a useful reference point. Policy and public support for renewable energy, batteries and electric vehicles was crucial in getting those solutions to be economically superior faster than they otherwise would have been.

Noting this experience and turning back to the case of food, there are two further drivers which qualify as such accelerators of change.

Driver 3: The changing climate's impacts on a fragile food system

The food system is hitting various physical limits, with signs of strain already showing. This comes into even starker relief when considering the growth in food supply needed. On top of that context, we are seeing the climate changing, which is seeing shifting weather patterns and changing water supply (both volume and timing).

These two factors by themselves suggest risks to the global food system. However, making this more concerning is that credible climate scientists argue warming is accelerating faster than expected, with therefore greater risk of tipping points being passed, which could then further drive that acceleration.

The combination of these factors means that on its current trajectory, the system that the world relies on for its food, and that the global economy relies on for stability, is likely to face extreme volatility. Subject to the unpredictability of weather, markets and geopolitics, the more predictable drivers of climate change, water scarcity and soil degradation seem likely to trigger a global food crisis (or series of regional crises) in the next decade or two.

Critical to this judgement is that we are in a complex, interconnected global market system that now has high levels of risk from different factors simultaneously, recently referred to as the 'polycrisis'. While this means any assessment of risk is very complicated to assess with respect to timing and scale, it also means the risks are higher because of the number and variety of factors. For example, while climate is a major emerging risk, and appears to be accelerating, there are many others, including geopolitical and trade war influences, that could weigh heavily on the food system.

Noting the current system is already fragile, it is not hard to imagine a combination of factors occurring simultaneously, such as a geopolitical conflict coinciding with a series of extreme climate impacts in key grain-growing regions, combined with some other risks such as an oil price spike, to trigger a global or series of regional food crises. We saw an example of this with the invasion of Ukraine where the world teetered on the edge of a grain supply crisis, and another with the 2008 grain crisis triggering geopolitical upheaval and the Arab Spring. Both of these proved manageable but that is a question of scale.

There is increasing attention on such synergies with the way climate change poses a risk to global financial stability, particularly issues like the withdrawal of home insurance cover from a growing number of regions that have proven too risky. Various central banks have been examining these risks[19] and the same phenomena could well apply to agriculture, with crop insurance costs rising or unobtainable, extreme weather and disasters affecting yield, and with global trade affected by increasing costs for transport from impacts like oil price volatility, extreme weather, geopolitical conflict and sea level rise impacting ports. High oil prices, for example, flow directly through to fertiliser costs.[20] All these types of synergy could have a dramatic impact on food prices and availability, including on the cost and availability of finance and the value of companies in the sector.

Of course, there is uncertainty on the timing of such impacts but there is little doubt about the level of risk or the urgency of action. Consider for example this call from 150 Nobel and World Food Prize laureates for a 'moonshot' research effort to avert a 'hunger catastrophe' in the next 25 years. There is a list of other such studies in the appendix.

The impacts on the food system of such a food crisis, which will almost certainly occur whether the timing is sooner than expected or not, include market, geopolitical and economic consequences such as:

- instability of supply
- price volatility and global inflationary impacts
- the closing of borders to food exports
- economic conflict and geopolitical tensions
- conflict with mass refugee flow.

The key to understanding this level of risk is that:

- It is not being taken seriously as a strategic global stability risk by national governments, despite the fact that analysis suggests it is a reasonable possibility, and with climate change an arguably high likelihood.
- While the risk is generally accepted at varying levels by most experts, including inside the global food industry, none of the solutions proposed and being implemented today, or likely to be so in the next decade or two, will have any material impacts on the food system relative to the declining system capacity vs the growing demand.
- Therefore, no action of consequence is being taken to reduce the risk, which means it is highly likely to occur.

As a result, when such a crisis occurs, at either global scale or in a series of regional crises, attention will inevitably be drawn to the fragility and inherent instability of the global food supply. This will in turn draw attention to alternative approaches to food production, particularly where they can increase national food security. This will likely result in considerably increased investment and policy designed to accelerate these new approaches.

It is notable in this context that China, which had long had a strategic focus on food security, has arguably the most comprehensive national strategy on the new approaches to food production that are detailed in this paper.

Driver 4: The impact of the food system on climate change

As well as being a major victim of a changing climate, the global food system is one of the major causes of it, particularly of short-term warming. It makes such a significant contribution that the science indicates it will not be possible to stabilise the climate without addressing the food system's greenhouse gas emissions.

However, because most attention on climate change to date has been on long-term change, CO_2 and fossil fuels have been the dominant focus. Food and agriculture (where methane is the main emission) has been largely ignored as a major source of greenhouse gases.

Noting the above section on the risk of a global food crisis being triggered by climate change, and the accelerating frequency of extreme events, it seems likely that climate change will become recognised as a global, economic and geopolitical emergency – not least because of its impact on food supply. This will result in much greater focus on actions that can deliver short-term benefit (ie, slow the rate of warming to give society time to adapt).

If this occurs, methane will become a central focus and will start to more heavily influence policy, consumer and market attitudes. The scientific context for this is critical, with methane being one of the only levers available that could slow down the rate of warming within a decade or two. Even extreme CO_2 reductions would not slow the rate of warming for several decades. This was explored in some detail in an earlier CISL paper, *Methane, Markets and Food.*

If this context emerges, there will be much greater attention on climate action being directed towards food, particularly on the short-term impacts of its intense methane emissions, which are primarily from livestock. This will focus more consumer attention on livestock-based meat and dairy. As we have learnt with energy, consumer attention does not necessarily change consumer choices at scale. But the increased attention does influence company action and also policy. Given the popularity and nutrient density of meat and dairy foods, this will likely further boost the market for new ways to produce these foods without the use of animals, and also lead to improved plant-based foods.

Many will still argue that, even with this context, action in the food system is 'too difficult' for reasons such as the challenge of shifting farmer behaviour, the resistance of consumers to change, the political power of the farm lobby, the cultural context and affection for farming, etc.

Furthermore, in the current climate where science is under attack and disinformation is rife, it is a possibility that this will accelerate and combine with pressure from incumbents to slow down or even stop alternative food production. We have already seen efforts to ban its development in some jurisdictions.[21]

However, change is not optional. Unless drivers 1, 2 and 4 (action on food's climate impacts) are the path we go down, then driver 3 (accelerating climate impacts on food supply) will become much stronger.

Therefore, the core conclusion holds – the existing food and agricultural system is facing system-wide disruption.

Part 5: Evidence of the new production Approaches in the market today

Evidence of change in the market today

As is often the case with new technologies, the examples in food that receive most media attention tend to be those that are the most novel or unusual, such as growing pork protein inside soybeans, or making a protein out of just microbes, electricity and air. While these are important in showing what is possible, they are misleading as guides to understanding the true market significance and disruptive potential of the new approaches outlined in this paper.

What is more useful is to examine new products that are a 'like for like' replacement for animal-derived ingredients, for example whey proteins or casein which are currently extracted from dairy milk. These can directly replace the traditional inputs used in today's consumer foods, and therefore have a much faster path to scale and are more likely to be disruptive to the incumbent industry.

The business-to-business (B2B) market for key ingredients such as milk powder, proteins, omega-3 fatty acids and ground-meat will be the first to shift to those derived from cells and micro-organisms. These alternatives are already available, identical in taste, texture and often even genetically. On a molecular level it is the same food, it is just grown without the animal.

Presented below are examples of what is happening in the market today, across the full range of new approaches detailed in the paper. What this clearly demonstrates, when taken together, is the range of possible market entry points and the potential to scale quickly. Some of the examples also show the potential for beneficial social and environmental impacts in land use, water and climate, noting these are secondary drivers of disruption.

While some of these examples are already in the market at scale today, there are many more now gaining regulatory approvals globally and rapidly approaching price parity. There are a steadily growing number of approvals for precision fermentation (PF) produced lactoferrin, whey, egg and casein proteins, key ingredients on the B2B market for thousands of food products.

It is also interesting to note how many large global fast-moving consumer goods (FMCG) companies are engaging in this area, whether through investment, joint ventures (JVs) or sourcing these ingredients for their own products. Again, this is the most likely path to rapid market growth for the more successful products, using existing production and distribution networks.

There are many catalogues and overviews of all the different companies working in this space.

One very useful overview of what is in the market using PF, is RethinkX's Periodic Table of Precision Fermentation. This shows the breadth of possibilities emerging and also explains the way different products fit in the medical, ingredients, food and cosmetic industries, thus reinforcing how synergies will develop.

Another is from the nonprofit Good Food Institute, which has a database of over 1,000 companies in this area as well as an overview of the ecosystem of researchers, institutes and networks. The examples we use below are not intended to be comprehensive but to provide an indication of the breadth of activity happening in the market.

Major FMCG companies are active in this area

FMCG companies investing in, partnering with, buying or using PF companies and/or ingredients are an excellent indicator of the disruption's progress. These are companies which understand the food market better than anyone else, and so they prioritise consumer preference for taste and cost.

Nestlé, Mars, General Mills, Unilever and Bel Group have all trialled products using Perfect Day's precision fermentation derived whey protein (more below). They are not only trialling products from others but also investing in their own PF-derived businesses.

- Nestlé, the 3rd largest dairy company in the world, used PF to produce whey protein for their Orgain branded protein powder 'Better Whey'.
- Fonterra, the world's biggest dairy exporter, formed a JV with nutrition & technology company, dsm-firmneich called Vivici (more below) which was able to commercialise PF whey protein as a B2B ingredient in under one year. This ability to take a new company to market so quickly demonstrates the benefits of industry-leading knowledge of the food sector.
- Leprino Foods, the largest producer of mozzarella cheese globally, has struck a deal with Fooditive to gain exclusive rights to scale up, produce and commercialise their PF casein protein through their existing infrastructure and distribution network. That includes 85 per cent of the US pizza market.
- Danone has partnered with several multi-national companies to develop their Bio Tech Open Platform, with the goal of accelerating product innovation through PF, reducing their carbon footprint and fostering collaboration throughout the industry.
- Norco, Australia's oldest and largest dairy company, founded a startup with CSIRO to produce PF casein and whey proteins for use in their dairy products, using their existing facilities.
- Heinz has partnered with NotCo (detailed below) to produce a range of animal-free food products including cheese and mayo.
- Tyson Foods, a US meat giant, previously owned a 5 per cent stake in Beyond Meat which it sold in 2019 before launching its own plant-based brands. Tyson has also invested in two lab-based meat firms, Memphis Meats and Future Meat Technologies.
- Cargill has also invested in Memphis Meats and in Aleph Farms, both working on cultivated meats. They are very involved in the plant-based sector, investing in several plant-based companies, expanded a partnership with ENOUGH (which produces fermented proteins sustainably) and have launched their own plant-based products.
- Ajinomoto, a Japanese multinational food and biotech company that is active in alternative proteins, invested in cultivated meat company SuperMeat and ran limited edition products with Solar Foods (detailed below).

FMCG uptake of these new food production approaches could be the key driver of rapid market disruption. Their understanding of the market and what consumers value, their familiarity with mass production processes, their high levels of knowledge in food science and their ability to market new products to consumers all position them ideally to take these technologies to scale. For this reason, many of the innovative start ups detailed below are seeking to partner with them.

Foods being produced using precision fermentation (PF)

Whey alternatives

Perfect Day – Produces animal-free whey protein (beta-lactoglobulin) via precision fermentation (this is identical to its dairy counterpart). They are a leader in the PF whey space with their protein being used in products like ice cream and milk, with consumer products featuring this protein available in the US and Asia. They sell in the B2B market to FMCG companies such as Nestlé, Unilever, Bel Group and Mars. Additionally, their whey is being used by:

- Brave Robot – A consumer ice cream brand offering creamy lactose-free dairy ice cream alternatives in retail stores across the US.
- Bored Cow (Tomorrow Farms) – A line of flavoured milk drinks for children, providing cow-free 'milk' in various flavours, available online and via select retail channels in the US, including Target.
- Strive – Strive combines Perfect Day's whey with their proprietary formula to make Freemilk, a high-protein, lactose-free milk alternative. Sold online and in stores in select US states.
- Other companies that have used Perfect Day include Myprotien, Coolhaus, Juiceland, Nicks, Ice Age and Very Dairy.

Vivici – This JV between Fonterra and dsm-firmenich, mentioned above, produces Vivitein™, a PF-derived beta-lactoglobulin (BLG) whey protein which is active in the US market. The company is targeting the 'active nutrition' category, with applications such as protein drinks, powders and bars. They have already secured their first customer offtake agreements for their Vivitein™ BLG in the B2B market, expecting products on shelves before the end of 2025.

Imagindairy – An Israeli company producing a PF-derived whey protein. Imagindairy is focusing on scaling and driving down costs, and has acquired industrial-scale PF lines to produce their animal-free whey. They are partnering with Ginkgo Bioworks to design an optimised organism which would drive down costs and chase price parity.

Egg alternatives

EVERY – Produces egg white proteins (ovalbumin) via PF for use in foods and beverages (eg meringues, baked goods, protein smoothies), with early products launched on a limited basis in the US. They are focusing on this B2B opportunity.

Onego Bio. This Finnish company uses PF to produce Bioalbumen®, an animal-free egg protein. They claim their methods result in a 95 per cent reduction in land requirements and 90 per cent fewer greenhouse gas emissions when compared with traditional egg production.

Lactoferrin alternatives

Lactoferrin is a high-value protein used in medical nutrition. It is a good example of a product which is already highly processed. Typically, lactoferrin is produced by isolating the protein in dairy milk, through several processing steps before being dried in a powder. Precision fermentation PF-derived lactoferrin produces the same protein but with significant reductions in resource, land and water use. Lactoferrin has substantial health benefits. It helps with iron regulation, improves immune function and supports healthy gut function.

PF-derived lactoferrin is now being produced by several companies around the globe. All G in China and TurtleTree in the US have been approved for sale of their PF-derived lactoferrin. TurtleTree has partnered with various companies with plans to release several products in the pipeline, from immunity beverages to protein powders. Helaina produces effera™, a human lactoferrin using PF, and has recently closed funding and is planning to launch in the US soon through B2B partners. effera™ would be a significant breakthrough into the baby formula market, but lactoferrin's applications go far beyond this as it is currently used in foods, sports nutrition, supplements and pharmaceuticals.

Casein alternatives

New Culture – with the tag line 'Cow Cheese without the Cow'. New Culture has approval to begin selling their casein proteins in the US. They are focused on making a variety of cheeses and emphasise that their product is the same product but cow free. They say: "At New Culture, we're revolutionizing how cheese is made with our animal-free dairy products that stretch, melt, and taste like the real deal. We combine traditional cheese-making and innovative food science to make cheese that's kinder on animals, the planet, and human health. With our groundbreaking science, any cheese is possible and can be made completely animal-free." Thanks to a breakthrough in their formula, they have been able to lower their costs by requiring just 28 per cent of the casein needed for conventional mozzarella.

Formo – A German company working on the "future of dairy". They are currently selling a PF-derived cream cheese in three flavours, through their website and through several major German supermarket chains, including Rewe, Billa and Combi.

Other PF

Impossible Foods – Uses precision-fermented soy leghemoglobin ('heme') to give its plant-based burgers a meat-like flavour, available in retail and restaurants across the US and in select global markets (eg Hong Kong and Singapore).

Veramaris – Produces omega-3 fatty acids from natural marine algae instead of fish, reducing the dependence on wild-caught fish for aquaculture and pet food. It has already been adopted by major salmon farms. It is sold as a B2B product and is rapidly growing in scale and has major corporate owners. They have partnered with a top Dutch retailer Albert Heijn to bring a sustainable farmed shrimp product which uses Veramaris's fish oil and Protix's insect feed, dramatically lowering their marine footprint.

Avansya's Eversweet – This JV between Cargill and dsm-firmenich produces the natural sweetener 'renewable food' but using fermentation. Growing the 'renewable food' plant and extracting the desired ingredient is extremely inefficient. The fermentation approach produces the same 'natural ingredient', but when compared to the plant-based approach the company claims it reduces water use by 97 per cent, land use impacts by 96 per cent and carbon footprint by 81 per cent. EverSweet is sold into the B2B market and is approved in Europe, the UK and North America.

Brazzein is another sweetener being produced using PF. This sweet protein - 1000x sweeter than sugar - comes from the Oubli plant but in this case, harvesting enough from the natural plant is unrealistic. So companies like Oobli have turned to producing the protein using PF instead.

Solar Foods – Had developed “Solein,” a protein-rich powder derived from single-cell precision fermentation using Hydrogen, CO2 and electricity. Solein has been used in various limited edition launches around the world, including in ice cream sandwiches and cakes. They are aiming to sell into the B2B market.

Plant-based foods enhanced by new technologies

Plant-based foods are well and truly established in the food market, however many companies have faced significant challenges and struggled to meet consumer preferences. As discussed in this paper, new technologies are helping to bridge that gap, and below are some examples of how these technologies are helping plant-based food companies.

NotCo – Using their proprietary AI platform named ‘Giuseppe’, NotCo recreates animal-based foods but using only plant-based ingredients. By analysing animal-based foods on a molecular, physical and chemical level, ‘Giuseppe’ is able to identify the characteristics that create consumer appeal, that they need to replicate. For example, using this process, they discovered that processing pineapple and cabbage in a certain way could produce lactones, which is what gives their product NotMilk its milky flavour and scent. In Chile, NotCo sells several burgers, ice creams, hotdogs and more; they have also partnered with Kraft Heinz to release cheese slices, mayo, and mac and cheese products.

Crispr Salad Greens - Pairwise used Crispr technology to remove the copies of the gene responsible for ‘mustard greens’ peppery/bitter taste, keeping all the health benefits but without the ‘disliked’ taste. After selling briefly into restaurants the business was sold to Bayer which is now focusing on applying the approach in partnerships and licensing.

Project Eaden – The comany has developed one of the closest analogues of meat. They developed this novel technology which allows them to make realistic whole cuts of plant-based meat through a fibre spinning technique similar to that used in the textile industry. They are using plant-based ingredients to create sausages, pork loin, steaks and ham. They have products being sold in REWE supermarkets across Germany.

Veganz Group’s Mililk, along with other brands, has developed 2D printed sheets of oat milk or powdered versions, slashing water use and wastage. By cutting the water out of their products they are also slashing transportation and packaging costs, which also reduces their environmental footprint.

TerraMeat - Elmhurst 1925 has released a single ingredient meat analogue. Their protein comes in a powder (hemp protein) and is simply mixed with water and oil and microwaved to form the meat. Then it can be baked, grilled, fried as desired. Available online for US consumers.

Climax Foods – This group is using data science and AI to gain competitive advantage in animal-free products. They give every property of their plant-based cheese a measurable data point, then use machine learning to continuously improve and develop recipes. Planning to operate B2B.

Cellular Agriculture

Cellular Agriculture encompasses the production of agricultural products from cell cultures, rather than whole plants or animals. Although the principle can also be applied to plant-based products, most attention in this area is on cultivated or cultured meat. The Good Food Institute has a very useful introduction describing it as: "Cultivated meat, also known as cultured meat, is genuine animal meat (including seafood and organ meats) produced by cultivating animal cells in a safe and controlled environment." [22]

The cellular agriculture space is still in its infancy, with a small number of companies approved to sell cultivated meat. However, there are many startups working on products, including major corporates. Many are also working on the key chokepoints in the industry, such as scaffolding, growth mediums and bioreactors. A few companies have successfully taken products to market by targeting niche areas.

Meatly – In February 2025, Meatly launched the world's first cultivated pet food called 'Chick Bites' which used lab-grown chicken, after becoming the first European company to be approved for cultivated meat sales. The company has also made significant strides in reducing cultivated meat production costs with their work on growth mediums. Meatly was able to take products to market by targeting pet food, a market where texture and scaffolding issues are non-existent.

Moolec – This company has been approved by the United States Department of Agriculture (USDA) for their pork proteins which are grown within soybeans, through the use of cellular agriculture. Moolec is effectively using the soybeans themselves as bioreactors to grow their proteins in. While the proportion of protein is currently low, it shows how innovative the cellular agriculture space is.

Vow – This is an Australian cellular agriculture business focusing on dishes like quail, which have a higher price point for the meat. Vow has launched a cultivated quail foie gras which is being sold in Singaporean restaurants. Vow was able to take their products to market by focusing on novelty dishes which can be sold in high-end restaurants for high prices.

There are always barriers to change. Those who solve them get rich.

Kingsmill Bond, RMI

Part 6

Analysis and potential scenarios

How the four drivers of change will impact synergistically

As the four drivers develop, various compounding positives and negatives will accelerate the market disruption and the shift to a new food system. Following are some thought-starter examples, noting there are many more possibilities including, no doubt, some surprises.

- Supply shocks and then fear of them, along with observed inflationary impacts caused by climate change and other sustainability impacts, will:
  - drive a focus on national food security, resulting in various policy steps, including support for new approaches and the removal of barriers
  - increase the likelihood of extra costs on the current system (such as carbon/ methane pricing and/or regulation to constrain it) which will give the alternative approaches greater competitive advantage
  - drive deployment, lower prices, and growth and investment in the new approaches through such policy and pricing advantage.

  This will not be smooth and linear, with the incumbent industry using the same context to argue for protection and subsidy.
- Technology advances like AI will enhance development speed, and the quality and consumer acceptance of new foods and processes. It will also drive down production costs. There will be cross-sector and cross-technology synergies as well. So, for example, the same technologies that will lower the costs of food production through precision fermentation (PF) will also lower the costs of PF production of fuel oils and household product ingredients like palm oil.

- It is hard to reliably quantify the collective and synergistic benefits of parallel technologies being applied in any area. The dramatic underestimation of the rate of growth in renewables over recent decades is a case in point. However, as an example of the possibilities, a recent peer reviewed paper in *Nature* by Sir Nicholas Stern and co-authors from the LSE argued:

  *"In the **Meat and Dairy sector**, we mostly look at the impact of AI on adoption rates of APs [alternative proteins]. We estimate that AI could improve adoption rates from ~8–14% in BAU to 18–33% in an ambitious AI scenario, and 27–50% in a highly ambitious AI scenario. We assume that AI improves attractiveness (taste and texture) through identifying proteins with suitable properties. In a highly ambitious scenario, it also significantly reduces production costs to the point of achieving cost parity with traditional products in all categories and products, improving **affordability**. This could result in emissions savings of 0.9–1.6 GtCO^{2}e in the AI scenario and 1.7–3.0 GtCO^{2}e in a highly ambitious AI scenario."*[23]

- As synergies occur, this will further drive deployment and scale, in turn drawing in greater investment, as we have seen in energy. That will then give policymakers confidence in taking stronger action to accelerate the change because they see the economic opportunities in doing so.

- Climate impacts, price inflation and supply volatility will see growing geopolitical emphasis on food self-sufficiency, especially for countries with insufficient agricultural land or with their agriculture threatened by climate change. This will undermine investment in the old system and raise the risk of stranded assets and associated investment and lending risks.

- The opposite effect is also likely, as we have seen with oil- and coal-dependent economies resisting action on climate. Therefore, we may see countries with large land areas and extensive agricultural exports resisting action on new approaches. That will be more difficult if the drivers are market ones rather than policy and international treaty focused, as climate has been.

- Of course, the impacts and synergies will not be linear, nor will they all drive forward momentum. For example, many of the same technologies that will drive efficiency and progress in 'renewable food' will do likewise in renewable energy. While lower energy costs will advantage the new food production processes, this would also have other impacts. It may, for example, see low oil prices for a period until production is decreased. Given oil is a major input into industrial agriculture, for machinery and transport but also for fertiliser, this would lower the costs of production in the old food system at least temporarily.

- Various synergies that have a negative impact on food supply will create a national competitiveness and social stability focus in this area. As China has dominated the electric vehicle industry following the slow responses of Western governments and companies, we can expect countries to compete on food in the same way. They will be seeking to gain competitive advantage for exports through technology dominance but also to secure their own food supplies in an increasingly unstable global context. We can already see today that those countries with a strong history of concern about food security and self-sufficiency, such as Singapore and China, are the same countries where government support is strongest for the new food production processes.[24]

- As the new approaches move to scale, the potential for radical and disruptive change to society is clear. Some argue it could free up a huge percentage of agricultural land – perhaps 50–80 per cent. The implications for the economy and society, in particular rural communities where agriculture is dominant, are profound. This applies in both developed and developing countries where resistance to change from communities that stand to lose from the new approaches will be acute. It will also undermine the value of agricultural land and accentuate the risk of stranded assets.

- There is a high likelihood of a global food crisis, or series of regional ones, in the next decade or two. This is a judgement, based on many pieces of evidence, while the uncertainty in such a complex system is acknowledged. Various studies describing this risk are covered in the food crisis appendix.
- There would seem to be a low risk of actual widespread hunger (defined by a lack of sufficient calories) in rich countries. However, a chaotic instability of supply event, impacting several food bowls simultaneously, would throw the globally interconnected system into crisis with potentially severe global impacts, economically and geopolitically. This would have large impacts on all countries, including wealthy ones.
- These impacts could include mass refugee flows, military conflicts, closed borders and other widespread global economic consequences. The latter includes impacts on inflation, trade and very large costs to government. Due to refugee numbers and closed borders, populism and isolationism would likely dominate, discouraging the co-operation that would be necessary to manage a global food crisis well.
- If this global crisis context emerges, there will no longer be debate on the economic costs and geopolitical risks in the current food system. This would also make food supply and food security central to many nations' political decision-making. This would at the minimum drive strong government action, market investment and innovation, and possibly lead to a war-type mobilisation on the topic, if the crisis emerged at sufficient scale.

Interpretation and likely scenarios

It is never possible to accurately forecast the speed of technology developments nor of change in complex, interconnected systems. This is the case anyway, but especially in areas with heavy geopolitical influences like food and energy.

In the examples explored in this paper, there are also many intersecting technologies at play, each with different prospects and debatable development timelines. As a result, there are widely varying perspectives which can be simplistically characterised as ranging from 'this is techno fantasy and 50 years away' to 'this is a revolutionary change that will destroy the old industry in a decade or two'.

Given this, the response by many to this uncertainty is to take a 'wait and see' approach to how this will unfold. Given the risk of market disruption is high and with food having such a profound influence on social and economic stability, 'wait and see' has serious risks.

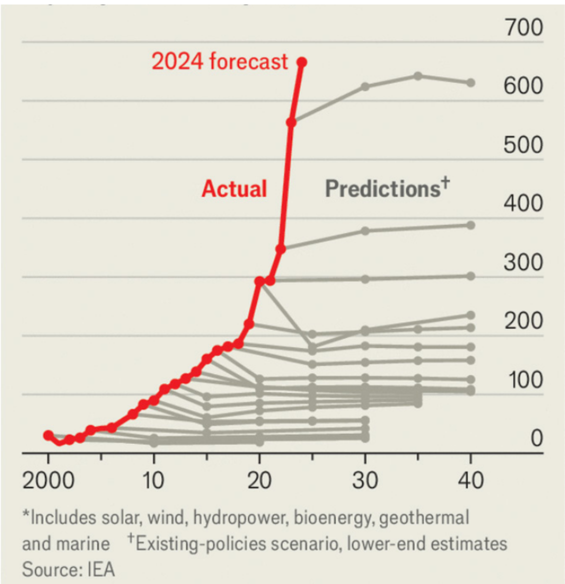
We need instead to have educated and well-informed scenarios to plan against, and key milestones to measure progress towards them.

Fortunately, we have the lived experience of over 30 years' focus on the climate issue, and the resulting transition and market disruption. While still very much underway, it is now inevitable and not dependent on policy.[25] Analysing this can help us develop such informed views about the likely direction in food and agriculture. There are of course many differences between the global food and energy systems, but there are also many similarities, especially regarding the likely behaviour of the incumbent industries and of governments.

From that experience, we can make some reasonable assumptions and create some realistic scenarios:

- Incumbent companies inside a system, along with their related ecosystem of institutions, experts and academic advisors, have a very poor record of forecasting change, consistently underestimating both speed and scale. They tend to be dismissive of the threat as being significant, normally defaulting to 'interesting and worth keeping an eye on, but not material to the market for many decades'. The industry and International Energy Agency (IEA), for example, were spectacularly wrong, and consistently so over many years,[26] on the growth rate and price drops of renewables and batteries.
- The inability of an incumbent system's participants to see a threat is less about analysis and logic and more about culture and market incentives. Kodak famously invented the digital camera but was then driven into bankruptcy by their inability to manage its consequences.

Figure 4: Global renewable energy capacity added each year*



Incumbent systems have a poor record of forecasting disruption rates.

- Such behaviour is a natural response, given incumbents' market self-interest and their need to convince investors, policymakers and their own people to keep supporting them. We can expect the same in food – and already see it today.
- In logical contradiction to the view that there is not a threat, and the technology is not ready to compete, incumbents usually then fiercely resist change and any policy that supports it. We already see this today with pushes for bans on cellular agriculture, for example to 'save our beef' and 'defend our way of life'.[27] This is happening today despite those technologies being a long way from market scale.
- Another reason incumbents often find it hard to correctly analyse a disruptive threat is because it is often not a 'like-for-like' replacement. So European utilities, for example, misread the threat of solar in the grid because they analysed it as a replacement for coal power stations at the wholesale generation level (and price), rather than it being a rooftop consumer system that competed at the retail level (and price). *The Economist* titled an article on how this unfolded: How to Lose Half a Trillion Euros.
- The comparable example in food is that those who dismiss the threat focus on the hardest-to-do replacements, such as producing a cellular agriculture beef steak. They also focus on likely consumer resistance to 'novel artificial food'. They do so as it suits their argument, ignoring the evidence that much of the initial impact will be on ingredients used to make food, rather than a finished product, as discussed earlier.
- Another broad assumption we can make from the energy experience is that an industry shifting from a resource-intensive industry with slow-moving, long-life assets

(like coal, oil and gas) to a fast-moving consumer technology (like solar and batteries) is not likely to have the right culture to understand, analyse and invest in a sector where rapid technology change cycles apply.

- In the food case the same principles apply, though the product production cycle is much shorter, making it even more apparent. So, for example, changing farming practices, observing and adapting to shifting weather patterns, monitoring water scarcity and developing soil quality with regenerative farming is a long, slow, multi-year, even multi-decade, process. A production process in a manufacturing- and technology-heavy business can change very rapidly when scale occurs through greater deployment. In the case of food this will be further accelerated by parallel technologies following similarly rapid change cycles.
- There are today many hundreds of products in the market we can observe already using the new approaches. Even though they are often dismissed as niche by today's incumbents, it is easy to see how that could rapidly change given where these new approaches sit in the market.
- We already have large commercial supplies of B2B products such as:
  - protein and various dairy ingredients produced through fermentation being used in mainstream products by major global fast-moving consumer goods (FMCG) companies like Unilever, Nestlé and Danone
  - fish oil produced by fermentation and algae, replacing that extracted from wild-caught fish, now being used at scale in the animal feed ingredients market for aquaculture and for human supplements
  - fermented 'renewable food' being produced for supply into the food industry as a sugar replacement, with radical reductions in land use vs 'renewable food' extracted from plants.

  Each of these products previously came from traditional fishing/agriculture, and all claim massive benefits in terms of environmental impact and production efficiency.
- Many other ingredients that are made using the new approaches are well developed and expect to enter the market soon, including fermentation-produced palm oil and cocoa for chocolate. Given the controversies around deforestation in palm oil and around child labour and heavy metals in cocoa, a B2B supply of these ingredients could be very appealing for FMCG companies.
- Given the focus of the new food production approaches on replacing B2B inputs into food processing, such as protein, dairy products, oils etc, we see that the key disruptive threat is not to smallholder and family farms. There is likely to be a market for a long time, possibly indefinitely, for the outputs from such farms. Many people will prefer traditional agricultural production processes, and this niche may well be a substantial one. The large-scale disruptive threat is more likely to be to broadacre agriculture, and intensive beef and dairy farms, commonly referred to as 'industrial agriculture'.
- Many end consumer products are also in the market today in various countries. These include cultivated meat processes being used for chicken nuggets, salmon, prawns and high-value products like foie gras. While correctly defined as niche now, they show the market being tested and primed for change, with these companies exploring and looking for a growth market.
- We can also expect to see great volatility and swings in investment in this area. Most

new technologies go through 'hype cycles' where it is the most exciting new investment area, then it crashes and there is a mass exodus. This cycle can occur several times as an industry grows. It is important to separate the rapid growth of an industry from the idea that investing in it will be a good decision. In the last few decades, we have seen enormous global growth in solar in terms of market share, but have also seen many solar companies struggle due to the intense competition. We see the same thing emerging today in electric vehicles.

- When a new industry goes through a crash phase, the sceptics of change, particularly the incumbents being threatened, point to the crash or decline in investment as evidence that the new area's potential was overblown, or at least not a threat for a long time to come. This ignores the clear historical evidence that it is actually just the market doing its job of weeding out the less competitive companies. When the dotcom crash occurred, many voices called the end of the internet boom, but observe today how powerful technology companies strongly dominate stock market indices.

Part 7:

Conclusions

Is a 'renewable food' system possible?

This paper paints a picture of systemic global risks posed by food supply shocks, with potentially drastic, even existential, economic and geopolitical consequences. It could be that the worst end of these possibilities will be how this unfolds, with a dystopian world emerging.

However, the paper also paints a picture of a realistic opportunity for a very different outcome. This is a disruptive but ultimately positive transition to a 'renewable food' system, where the supply of food, the single most critical foundation of a stable and prosperous society, can be secured.

This paper focuses more on the latter outcome. This is not because it is forecast to be the most likely – that is unknowable – but because we need to understand we can choose to aggressively pursue a positive outcome that addresses what is a profound societal and economic risk.

So, with that as context, what would a truly 'renewable food' system look like?

The system's main criteria would be for it to be literally 'renewable'. That means a system that can:

- **expand production to feed over 9 billion people, healthily and affordably**
- **do so within the now inevitable rapidly changing climate and ecosystem**
- **allow for the steadily growing needs, of a larger and wealthier population, for land – for biodiversity, urban development, energy generation and carbon absorption**
- **deliver this in the context of possibly extreme geopolitical instability and climate migration that will undoubtedly now unfold given the lack of attention to these risks**
- **continue doing so indefinitely, not extracting (as opposed to using) resources from the ecosystem.**

To achieve all this, a 'renewable food' system ideally needs to deliver national and regional food security and therefore local production, recognising the reasonable possibility of a fracturing world where trade is less reliable or even actively discouraged. This means using food production approaches which can be replicated anywhere, largely independent of local climate conditions or suitable agricultural land availability.

The science is now clear that:

- climate change needs to be stabilised to avoid runaway warming and a systemic risk to food supply
- climate change cannot be stabilised without radical reductions in the greenhouse gas emissions of food production.

Therefore, achieving a 'renewable food' system will probably require reductions in the food system's greenhouse gas emissions, land use and water intensity in the vicinity of 60–90 per cent to outpace accelerating climate impacts, water scarcity and growing food demand, while meeting the global objective to get to net zero by 2050.

Even if all the proposed improvements to the current food system were applied globally, which is highly unlikely given the challenge of doing so, it would not get us there. Neither could it be achieved in the few decades remaining before climate change impacts on the food system accelerate dramatically.

Therefore, transformation is essential. And transformation is always disruptive.

The good news, as outlined in this paper, is we have what we need to transform the food system, and the process is already underway – not just in the lab but in the market. It just needs to be recognised and accelerated, with policy and market interventions, before the risks overwhelm our economy and thereby remove that option.

Would this new system be renewable by the above definition? It is not feasible to accurately calculate the total global reductions in greenhouse gas emissions, land and water use that the new food system could deliver, given the huge range of variables and synergistic technologies. We do know however that the existing food system is inherently inefficient and unsustainable, whereas the new approaches outlined here would clearly lead to significant transformational reductions in land, water and energy use and in climate impact. With many of those examples showing reductions of 80 per cent to 95 per cent or greater, it is not hard to envisage a system-wide reduction of the scale needed. Of course, being 'renewable' does not mean zero resource use, it means that it can be sustained over time, against the criteria we use above. In the same way energy from solar is around a 95 per cent reduction in CO^2 emissions compared to coal, we can envisage producing large volumes of food with a 95 per cent reduction in land, water and climate impact. Like any disruptive transformation, there will be upside and downside surprises and unintended consequences. However, like in energy, the direction is clear.

What will it take to get there? We have learnt a great deal from the climate debate and the resulting energy sector disruption now underway. Perhaps the most important lesson is this: a disruption only happens at scale when there is a superior and market-competitive solution.

Public debates, and even much of this paper, tend to focus on the need for change, the problems with the old system, the moral imperative for change and the macro-economic benefits of managing long-term risks. These debates encourage policy and, in some cases, motivate entrepreneurs and innovators. However, they do not directly change the system profoundly.

What triggers the shift, and the tipping point to disruption, is when a competitive solution emerges which delivers a superior product. While 'superior' is predominantly about price and functionality, it can also mean 'superior' in terms of social or environmental impact, with the market and policy importance of that changing over time as the context and perceptions shift.

Taken together, this means the key driver of transition to 'renewable food' will be solutions that can not only be sustained in the face of increasing demand and a changing climate, but also outperform on nutrition, reliability, accessibility, sustainability and price. There are already numerous products meeting these criteria in the market today and many more are emerging. And yet we are very early in the cycle of development.

With many relevant parallel technologies inevitably accelerating that process, we can safely conclude, a new 'renewable food' system is now on offer.

Appendix:
The likelihood of a global food crisis

One of the central arguments of this paper is that the current global food system hitting critical sustainability limits, particularly climate change, creates the likelihood of a global food crisis or an ongoing series of regional ones. The case is made that this will cause major geopolitical upheaval and conflict, resulting in global economic damage, and that this will further accelerate change in the global food system.

A key factor to understand is that a food crisis does not mean the world is unable to produce enough food to match the world's needs. On that criterion we produce enough food today, but there is still a great deal of hunger.

The issue is whether today's globalised market food system can deliver:

- the right food
- at the right price
- in the right location
- at the right time.

Therefore, the question 'Will there be a food crisis?' is not a theoretical question of food production; it is a judgement of how things work in the real world. In the 2020s, we have increasing instability, rising nationalism and a decreasing willingness for globally co-ordinated action. That context is critical to the judgement made here.

We have in recent times come close to a serious global food crisis, with the 2008 climate-induced grain crisis leading to the Arab Spring[28] and the 2022 Ukraine invasion[29] both pushing the system close to the edge. Fortunately, in those cases the two types of event did not coincide. The key risk now is that with accelerating climate impacts and a destabilised geopolitical context, the likelihood of simultaneous events is much higher.

As discussed in the paper, this is not a provable forecast because the system is so complex and interconnected, with too many variables. While acknowledging this is a judgement, below is some of the evidence behind it. Each of these studies points to the fragility of the current food system, but it is notable that few studies consider the integrated risks with multiple factors driving a crisis.

This 2019 modelling study demonstrated that even with modest warming of 1.5°C to 2°C, the threat of simultaneous crop failures in major breadbaskets increased significantly. The study does not account for the interaction with geopolitical factors, which could exacerbate this even more.
https://www.researchgate.net/publication/336181540_Increasing_risks_of_multiple_breadbasket_failure_under_15_and_2_C_global_warming

A study published in *Nature Communications* in 2023 found a correlation between a strongly meandering jet stream and substantial increases in the risk of synchronised crop failures. Authors found models systematically underestimate the risk of simultaneous extreme weather events.
https://www.nature.com/articles/s41467-023-38906-7

This 2023 study assessed severe risk scenarios of climate change's impact on food supply and found that under high emissions pathways there was potential of cascading impacts leading to a global food crisis by 2050.
https://www.sciencedirect.com/science/article/pii/S2212096322000808

A meta-analysis of global food security projections found that global food demand is expected to increase between 35 and 56 per cent from 2010 to 2050. This shows that as productivity declines and crop failures cause supplies to fall, the demand will be increasing significantly. https://www.nature.com/articles/s43016-021-00322-9

A study on the risk of four primary maize producers having concurrent bad harvests found that under 2°C of warming, the risk jumped from 0 to 7 per cent. Under 4°C of warming, the odds jumped to 86 per cent per year.
https://www.pnas.org/doi/10.1073/pnas.1718031115

A NASA study published in the journal *Nature Food* found that maize yields could fall by 24 per cent as early as 2030, with the lead author commenting that a 20 per cent drop would have severe implications globally.
https://climate.nasa.gov/news/3124/global-climate-change-impact-on-crops-expected-within-10-years-nasa-study-finds

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