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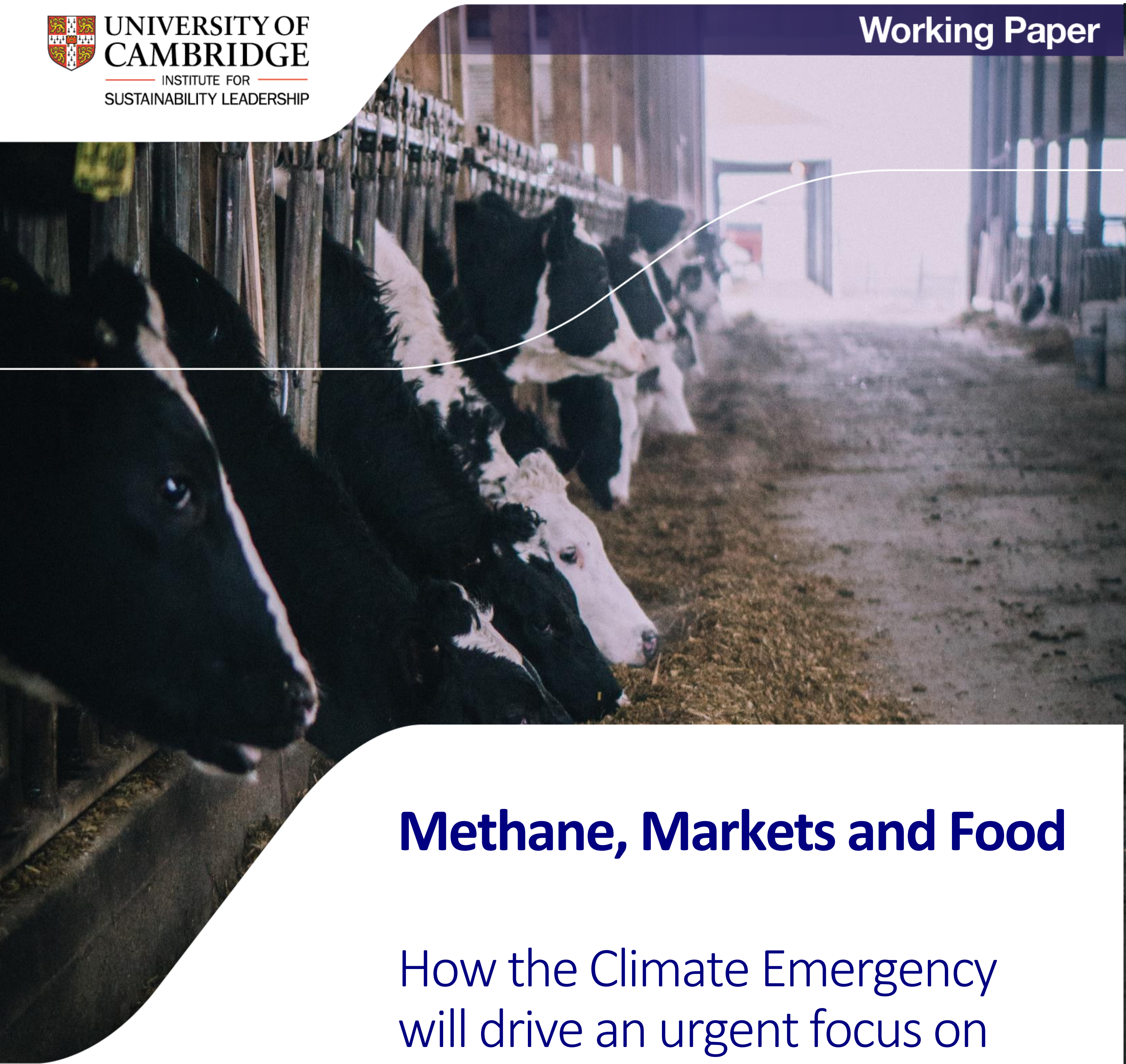

Methane, Markets and Food

How the Climate Emergency will drive an urgent focus on methane and what this means for the food and agricultural industries

The University of Cambridge Institute for Sustainability Leadership

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Contents

Executive Summary

This paper argues we are at the start of the most profound shift in the climate debate in 20 years. We argue we will now see:

- The arrival of the climate emergency into public consciousness, driven by increased severity and frequency of extreme weather events and concern about irreversible climate tipping points.
- A resulting shift to a focus on 'rates of warming' in addition to 'level of emissions'.
- A recognition that even dramatically accelerated CO_2 emission reductions won't reduce the rate or warming in the required time frame.
- Therefore, an intense focus on methane, with action needed in the next decade.

The market impacts could be profound with:

- Intense pressure on methane intensive industries to rapidly reduce emissions in the next decade.
- Mitigation measures required across all methane intensive sectors – Fossil energy, waste and food and agriculture, to hedge against rapid emission reduction failure in any one sector.
- The high likelihood of policy, pricing and incentives to drive methane mitigation measures.
- A resulting market disruption to the food and agricultural industries with a battle between new disruptive technologies and adaptive incumbents for the multi-trillion-dollar market opportunity.

The Climate Emergency

Faced with the threat of irreversible tipping points, humanity will choose to urgently reduce the rate of warming - with the most viable approach being to dramatically reduce methane emissions in the next decade.

The Recognition of Climate Change as a Genuine Emergency

The underlying driver of all action on climate change is the science. While it's debated and at various times denied or resisted, it is in the end the key. Within the science it is the IPCC reports which synthesise the collective scientific evidence. The latest IPCC (2021, 2022) reports were unequivocal:

- Our climate is changing.
- We're suffering severe consequences decades earlier than predicted.
- Physical impacts will continue to worsen.
- Abrupt and irreversible change in vital natural systems is increasingly likely.
- And critically – due to the lag between action (emission reduction) and impact (reduced rate of warming) - we're running out of time to act.
- IPCC Working Group ll Co-Chair Hans-Otto Pörtner summarised the findings of the latest reports as follows, "The scientific evidence is unequivocal: climate change is a threat to human wellbeing and the health of the planet. Any further delay in concerted global action will miss a brief and rapidly closing window to secure a liveable future" (IPCC, 2022b).

Given the scientific conclusion, by any interpretation we now face a climate threat that can accurately be described as an emergency. An emergency not in a rhetorical sense (as it has been to date) – but as a statement of fact that reflects the magnitude, speed, and intensity of both the threat, and the response required.

This shift to a focus on climate change as an emergency is being sharpened by an unprecedented surge of extreme weather events globally[i]. Climate scientists describe the severity of these events as "off the scale", compared with what atmospheric models forecast (Hook et al., 2021). This is due to the unprecedented frequency and intensity of the events, and their occurrence at far lower global temperature increases than expected[ii]. The resulting social, biophysical and economic losses observed are significant, triggering many experts to warn that even the 1.5°C 'safe' temperature increase aligned with the Paris Agreement, may be insufficient to prevent 'catastrophic threats', in particular - tipping points (Ripple et al., 2021).

A tipping point is a threshold where small changes in one of Earth's systems could shift that system to a new state, with irreversible and large-scale consequences for human and ecological systems. The IPCC advise that the probability of this low-likelihood, high impact outcome increases with higher global warming and that these dangerous thresholds are closer than once thought (IPCC, 2021). They conclude:

"The worst is yet to come...." ..... "Life on Earth can recover from a drastic climate shift by evolving into new species and creating new ecosystems...Humans cannot" (IPCC, 2021b; France24, 2021) [iii].

Examples of potential Earth system shifts from warming land and sea temperatures include:

- Runaway loss of ice sheets, that accelerate sea level rise.
- Forests and other natural carbon stores such as permafrost releasing their stores (CO_2, CH_4, NO_x) into the atmosphere, accelerating warming.
- The destabilisation of ocean circulation systems which are critical for heat transport between regions.

Increasing concern, is evidence that key tipping points are interconnected across biological systems[iv] - therefore if one were triggered, it could have cascading effects on others, making their occurrence both more likely and of higher impact (Lenton et al., 2019; IPCC, 2022).

The reason this possibility is so critical, and why it frames this paper's assumptions about the market response, is that without dramatic change to our warming rate in the next decade, the likelihood of these tipping points being crossed will significantly increase.

Achieving this requires an increased focus on methane reduction.

Why A Climate Emergency Response requires an intense focus on methane as well as CO_2

As the climate emergency worsens[v], an accelerated reduction in fossil fuels and CO_2 emissions – essential for ultimate climate stability – will not by itself have significant impact on reducing the risk of runaway climate change (Ripple et.al, 2021). Credible science argues that even if we stopped emitting CO_2 today, the lag time to any measurable reduction in the rate of warming means little result before 2050 if we do not also abate other greenhouse gases (GHGs), such as methane and nitrous oxide[vi].

Given we already face tipping points[vii] where we could lose control of the climate (including melting ice sheets, thawing permafrost and slowing jet streams), we now need to consider both:

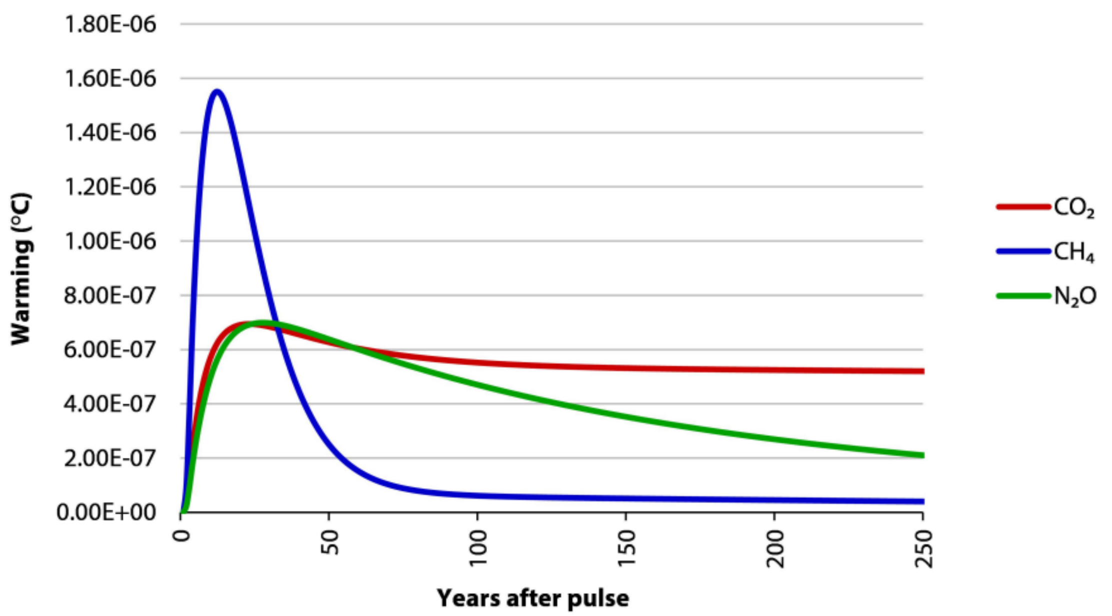
1. The *level* of warming, which is proportional to the accumulation of GHGs in the atmosphere. CO_2 is the key long-term determinant of how hot the earth will get and for how long it will stay that hot. Current warming levels are linked to the historical (since preindustrial levels) accumulation of CO_2 followed by methane (CH_4) which is shorter-lived but has a stronger warming effect.
2. The *rate* of warming, which is proportional to the level of GHG emissions and is the key to the likelihood and timing of climate change accelerating out of our control. Abating short-lived but strong-warming gases such as methane is the key to manage the rate of warming and thus the fastest route to reducing the risk of triggering irreversible tipping points.

Critically, methane reduction will also help off-set a perverse impact of phasing out coal (Harvey, 2021). The end of coal use is a key element of all emission reduction pathways – but doing so temporarily increases warming. This is because sulphur particles emitted by coal burning temporarily deflect sunlight and thereby mask the true extent of warming. Stopping coal use will lead to this sulphur falling out of the atmosphere, which will mean warming already primed in the system will be released.

Our ability to quantify to what degree methane abatement can influence the rate of warming in the atmosphere is today imprecise, though the science is rapidly developing. However, based on the evidence we have, it is clear it is the best pathway to curb current rates of warming. For instance, Severinsky and Sessoms (2021) found that reducing radiative forcing by 0.63W/m^3 would require a 0.3 GT reduction in methane compared to a 930 to 980 GT of $C0_2$. In the absence of valid fast carbon capture and storage technologies and geoengineering solutions along with the physical constraints on rapidly completing the energy transition, methane abatement buys us time.

Unlike CO_2 which warms for around a century, methane does its warming early on – in around a decade. During this time, it is very potent. While methane is often reported as having 28 times more warming impact than CO_2, this is when the two are compared over 100 years. Over 10 years – the timeframe the IPCC tells us we have[viii] – methane is 90-115 times more potent[ix].

Figure 1: A comparison of the climate responses from a one off 1 $MtCO_2e$ pulse of CO_2, CH_4 and N_20. Methane achieves its warming early on. Source: CCC (2020).



Troublingly, atmospheric concentrations of methane have more than tripled since pre-industrial times (NOAA/GLM, 2022) and are increasing now faster than any time since the 1980's (UNEP, 2021), with 2020 seeing the biggest one-year jump on record (NOAA, 2021). The causes of the recent spike are unclear but could include: leakage from natural gas and oil; emissions from landfill; increased output from thawing tundra/permafrost and methane-producing microbes in wetlands and the guts of livestock being spurred by rising temperatures; or, a combination of human-caused and natural forces (Turner. et.al, 2019; Katz, 2021). Researchers describe this tend as “dangerously fast” (Tollefson, 2022).

Whatever the causes, this observed increase makes the methane issue more urgent, due to the uncertainty about its potential to exacerbate systemic risks. As a result, the recognition of methane’s importance is rapidly being established:

- The May 2021 UNEP Global Methane Report acknowledged methane as the most “powerful lever in reducing near-term warming” and the only plausible way of reducing warming in the next 20 years (UNEP, 2021).
- A July 2021 assessment of ‘planetary vital signs’ signed by more than 13,900 scientists warned “Because of the limited time available, priorities must shift toward immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane” (Ripple, 2021).
- In August 2021, Senior Director of the Special Presidential Envoy for Climate Change in the US, Rick Duke announced “Methane is the next crucial, fast, climate-stabilization prize. There's simply nothing that comes close for securing our near-term climate future, buying us crucial time to decarbonize energy and to develop advanced options like negative-emissions technologies” and “by far the top priority short-lived climate pollutant that we need to tackle to keep 1.5˚C within reach” (Simon, 2021).
- In September 2021 the European Union and the United States formed an agreement, the Global Methane Pledge, to cut global methane emissions 30% by 2030 (EC, 2021).
- On 7 October 2021, Fatih Birol, Executive Director of the IEA, warned “At a time when we are constantly being reminded of the damaging effects of climate change, it is inexcusable that massive amounts of methane continue to be allowed to just seep into the air from fossil fuel operations’’ (IEA, 2021).
- By its launch at COP 26 in November 2021, more than 100 countries had signed the Global Methane Pledge (US Department of State, 2021).

It is now clear that without deep cuts in methane emissions *this decade*, the Paris Agreement's goal of limiting (or restoring) warming to 1.5°C may be beyond reach[x] and we may face runaway climate change.

The Role of Methane

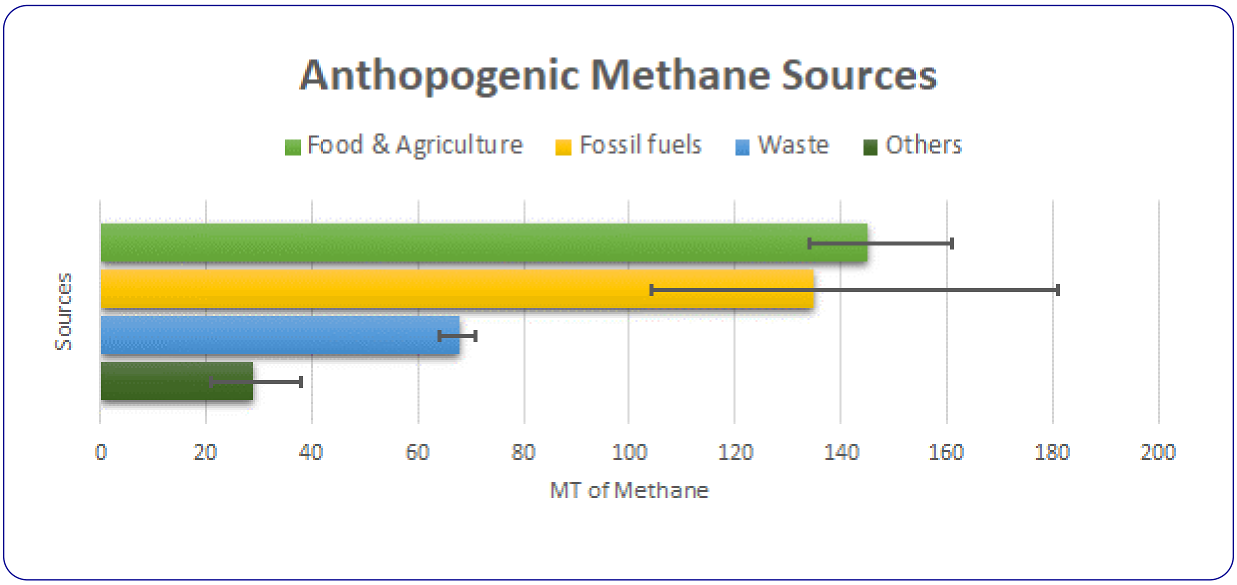
To understand how to drive change, and to forecast how change will occur, requires an analysis of how markets shift in response to social pressures.

If we conduct such a market framed analysis, we can conclude that reducing methane emissions in the next decade is most likely to occur in the food and agriculture sectors – not, as most forecast, in the fossil fuels or waste sectors.

Who's Responsible for Anthropogenic Methane Emissions?

The Global Methane Assessment produced by the Climate & Clean Air Coalition (CCAC) together with the United Nations Environment Programme (UNEP), provides the most recent detailed analysis of current methane emissions, their sources, impacts and benefits of mitigation. Using data from Jackson et al. (2020), their analysis finds that about 60% of methane emissions come from 'anthropogenic' sources (energy, waste and agriculture), and 40% are 'natural' (wetlands, lakes and rivers, natural geological sources, volcanoes & termites)[xi]. From 'anthropogenic' sources, agriculture accounts for ~40% of methane emissions, fossil fuels ~35% and waste ~20%. The remaining comes from mixed sources including burning of wood as fuel, biofuels and bushfires.

Figure 2: Global sources of methane emissions. Source: Data from Jackson et al. (2020)



<u>Food and Agriculture</u>

In the agricultural sector, livestock emissions from manure and enteric fermentation (gas from ruminant animals such as cows, sheep and goats) represent around 32%, and rice cultivation (flooded rice field create the perfect environment for methane emitting bacteria) around 8% of global anthropogenic methane emissions.

Fossil fuels

Globally, fossil fuels account for 35% of anthropogenic methane emissions – of this oil and gas account for 23%, and coal mining 12%.

A large proportion of methane emissions from coal, oil and gas extraction, production and distribution are referred to as 'fugitive emissions' because they are incidental to the desired production process, for example leakage from pipes or wells or seeping from old coal mines.

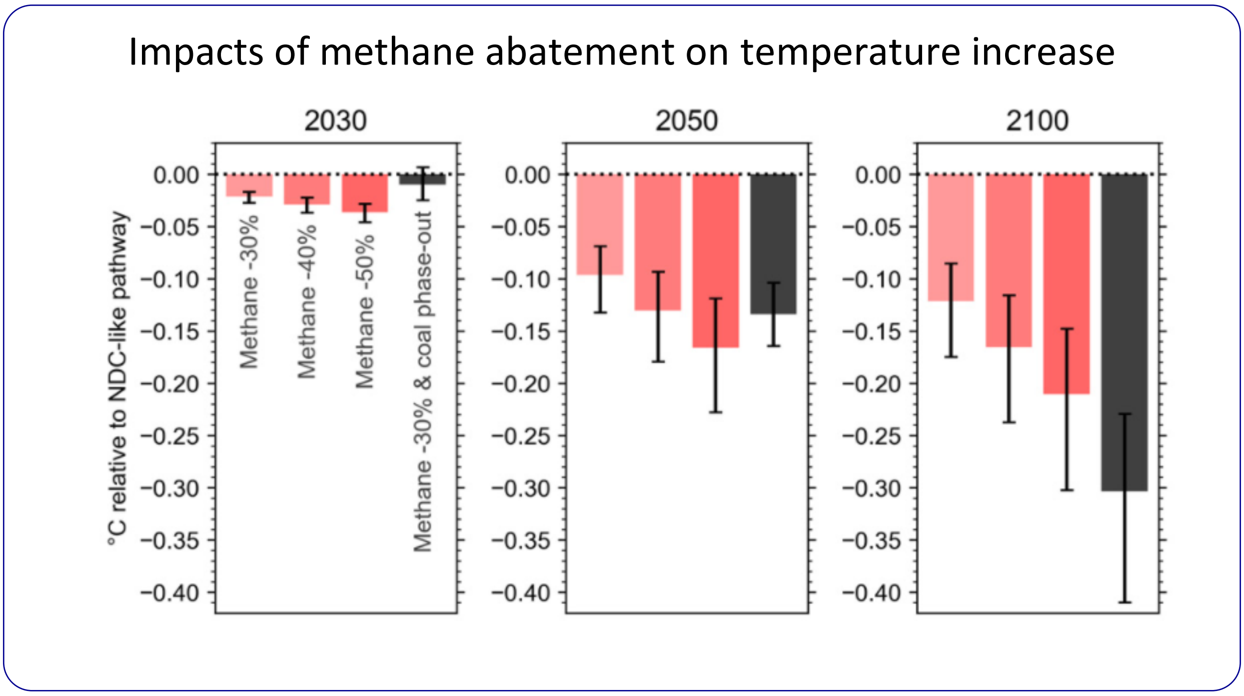
Waste

In the waste sector, landfills and wastewater make up about 20% of global anthropogenic methane emissions (as organic waste in landfill and wastewater decomposes, the microorganism that do this release methane).

Where is the Greatest Opportunity for Methane Reductions in the Next Decade?

Ultimate success in the context described in this paper, will be dependent on which measures can be executed within the next 10 years, which according to the science, is the critical timeframe for slowing the rate and level of warming. Thanks to the short atmospheric lifetime of methane, strong methane emission reductions in the short term (between 2020 and 2030) can generate a significant impact on limiting the global mean temperature increase (see figure 3 below).

Figure 3: Impacts of short-term methane emission reductions on global mean temperature increase in 2030, 2050 and 2100. Methane emission reductions are assumed to increase linearly between 2020 and 2030 and then stop, keeping methane emission levels constant after 2030. Red bars show the response to the methane emission cuts, while the black bar shows the response to coal phase-out on top of a 30% methane reduction (CB, 2021).



Most analyses argue the greatest opportunity for methane reduction is in the fossil fuels and waste sectors[xii]. While management of methane within agriculture is also addressed, mitigation potential in this area is perceived to be limited by lack of technological solutions and reliance on cultural and behaviour change.

This paper concludes that this primary focus on improving fossil fuel energy and waste to reduce methane emissions is flawed. This conclusion is based on:

- There now being a different context - an emergency response necessitating actions to slow the rate of warming within 10 years.
- Analysis of how methane reductions would be achieved in a market economy and the capacity to do so.

As is explored in some detail in sections below, it is this second point that is key to understanding the actions with the highest likelihood of *being* delivered. This is different to an analysis of how action *could* be delivered, which tends to focus on the biggest theoretical opportunity.

With over 30 years of evidence demonstrating how social, market and political change has been delivered - or failed to be - on climate and sustainability questions, society has a great deal of evidence of reality. This understanding needs to frame our approach to what can be achieved in methane reduction and how to drive it.

Choosing the wrong approach may cost us another decade which, given the scientific evidence on risk, would be extremely high risk for global stability.

A Primary Focusing on Fossil Fuels for Methane Reduction May Not Deliver the Required Reduction and Should Not be Relied Upon

The disruption of the energy system is firmly underway with coal, oil and gas being challenged by increasingly competitive renewable alternatives. Completion of this disruption is still however 20-30 years away (IEA, 2021d), as net-zero targets are only expected to be reached by mid-century (IPCC, 2018). This means that the energy transition will not deliver the required methane reductions. So, the pathway for methane reduction, if we choose to focus on emissions from fossil energy, falls on fugitive emissions, with the IEA assessment finding that 75% reductions in the fossil fuel sector could be achieved by 2030 (IEA, 2021c).

There is no question that these reductions *could* theoretically be delivered. However, given the importance of this task and the short timeframe for delivery, we must examine the level of certainty before relying on fugitive emissions to achieve the bulk of the methane reductions the science tells us is required.

There are three key reasons to exercise caution when assessing this likelihood:

1. <u>Methane reduction will require regulation and/or pricing at a global scale.</u>

More than 70% of methane emissions coming from the oil and gas sector can be abated with existing technologies and around 45% can be abated at no cost (as the captured gas has value;

IEA, 2021c). Despite this, methane emissions from the oil and gas industry have continued during decades when the industry was highly profitable and valued. Given this, we can assume the industry, which is now shedding profit and value, will not address this without strong policy and aggressive regulation.

Methane policy and regulation (compliance mechanisms) and the operating systems of oil and gas production chains (how companies choose to manage their methane) vary greatly from country to country, state to state and business to business. To achieve meaningful methane emission reductions, coordinated regulation and incentives (such as pricing), will be required if we are to drive action at a global scale.

History has demonstrated that acceptance and deployment of emission reduction mechanisms at a national scale is complex and slow (especially when vested interests are at play). At a global scale it is even more so (Gills and Morgan, 2020) [xiii]. We are now 30 years on from the first attempt at a coordinated international emissions reduction approach, still without success.

2. The fossil fuel industry is supremely skilled in delay.

For over 30 years the fossil fuel industry has skilfully and strategically delayed action on climate change (Brulle and Roberts, 2017) despite clear warnings, citing economic loss, job protection and energy security as justification. Powerful lobbyists and interest groups are well established, influential and continue to dissuade and delay policy makers from creating the regulation and pricing necessary to drive emission reductions (Brulle, 2014)[xiv]. With declining value and accelerating job losses being symptomatic of the industry's instability, it seems inevitable they will again succeed in delaying strong methane regulation.

3. Methane abatement is a low value business proposition in a declining industry.

While temporary macroeconomic conditions will drive short-term rebounds in demand and commodity pricing, overall, the outlook for the fossil fuel industry is increasingly uncompetitive (IRENA, 2021) and capital constrained (Olson and McFarlane, 2021), with high debt ratios (Williams-Derry et.al., 2020), falling asset values (Mercure et.al., 2018), volatile commodity prices (WEC,2022), and failing consumer and investor sentiment (Bond and Butler-Sloss, 2021)[xv]. This is happening in a market where the accelerating energy transition will keep putting pressure on demand, accelerating these trends (IEA, 2021d). It is effectively an industry in terminal structural decline, meaning there will be strong commercial resistance to investing in abating their methane emissions. The only way past this would be aggressive pricing or regulation. With the industry focusing on preserving value and profits in an unstable market, methane abatement will be strongly opposed and is likely, based on historic experience, to succeed.

The reasonable conclusion from this is that - in the context of the climate emergency demanding speed - *a primary* focus on energy for methane reduction carries big risks. The cost benefits and ease of methane abatement from fossil fuels is not in question, it should undoubtedly be pursued as one strategy for methane reduction. However, it should not be at the cost or dismissal of an intense parallel focus on the alternative approaches in food and agriculture.

Waste is Important but not Material in a 10-year Timeframe

Unlike fossil fuels, the responsibility for managing emissions from waste is largely disconnected from the production chain (e.g., solid commercial and residential waste managed in landfill; wastewater managed in treatment plants). This highly distributed system, largely managed at a municipal level, can promote waste reduction, diversion and sorting and flare or convert methane to energy on site. This is being done, but like fossil fuels, it is not guaranteed to occur at the scale or in the timeframe required, without coordinated regulation and pricing and major redirection of government funds. Greater and faster opportunity lies in systems and technologies that prevent the production of the waste in the first place – this falls back on forestry, agricultural/food systems and the industries that use their outputs (Balcombe et al., 2018). Therefore, this sector should certainly be pursued as strategy for methane reduction but cannot be relied upon for a result in the next decade.

The Agri-Food Disruption

The food and agricultural sectors are the largest source of methane emissions and are primed and ready for rapid and exponential change.

This will cause major market disruption and result in large wealth creation and considerable social and environmental benefits – including dramatic methane reductions.

The Assumption that Changing the Food System is Slow is Now Wrong

With fossil fuels and waste put forward by most strategies as the primary target for methane reduction, opportunities in food and agriculture are de-prioritised with the assumption that change in this sector is slow, difficult and incremental.

Three key assumptions drive this perception:

1. That there is limited potential to address the food and agricultural sectors' methane emissions through technology change (compared to the case of renewables replacing coal).

2. That changing food consumption patterns through the market will be slow, as it will require overcoming strong consumer and cultural resistance to change.

3. That changing policy in food and agriculture is politically difficult due to the widespread influence of 'big agriculture' and the 'farm lobby'.

These assumptions have resulted in food and agriculture's role in tackling the methane emergency being perceived as limited to gentle change, with commensurately slow and incremental emission reduction impacts. Strategies focus on farmer and consumer behaviour change such as reducing food waste and loss, improving livestock management and the adoption of healthier diets, such as lower meat and dairy consumption in rich countries. They assume farmers, consumers and companies' impetus to act will be largely based on a sense of responsibility or 'doing the right thing'.

These assumptions are outdated and no longer valid. As a result, the actions suggested for methane reduction in agriculture are flawed for three key reasons.

- Firstly, they assume change is an option – that despite the evident harm the current food system causes and its' inadequacies and vulnerability to climate change, it will persist as there are no viable alternatives. This is wrong. The food system is broken. It is up against real limits and is no longer fit-for-purpose. That means change is inevitable - the only question is when and how.

- Secondly, they are all based on key assumptions about technology, consumer attitudes and market driven change that are outdated.

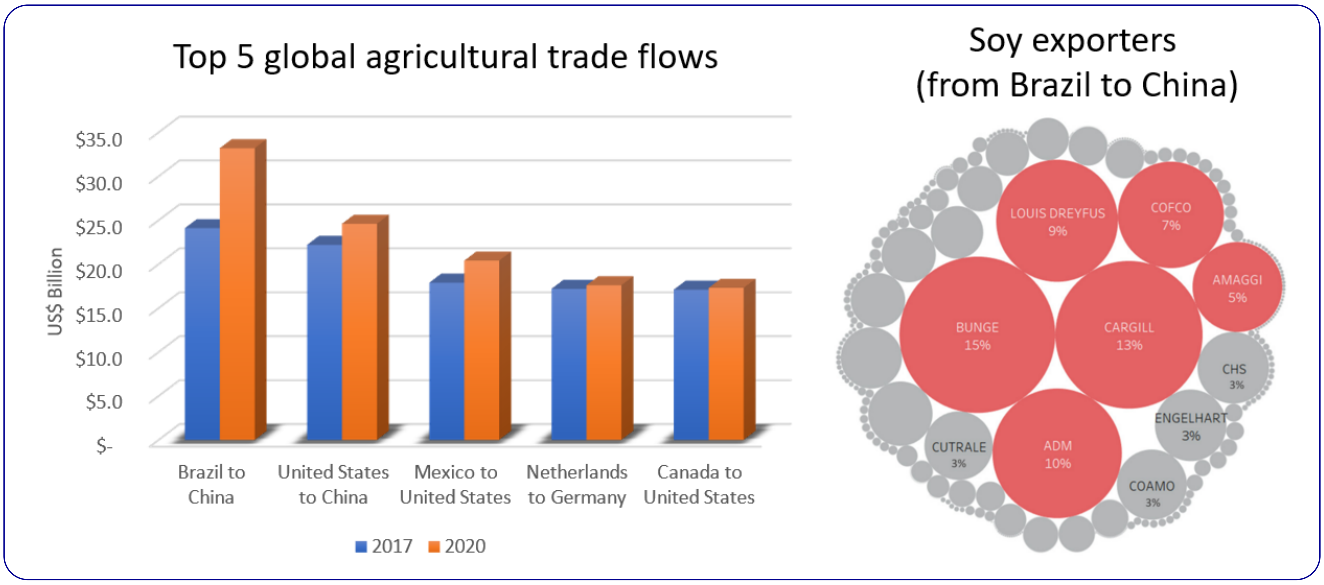
- Thirdly, action driven by 'responsibility' won't deliver the result required. They will lead to incremental reductions in methane emissions and subsequent warming rates, which are inadequate and illogical for a climate emergency focus.

The outdated assumptions are, in summary, based on the belief that while the proposed responses are clearly inadequate and we would all 'like to do more', they are unfortunately 'the best we can do'. The evidence shows that this approach is wrong for several reasons, described in the next sections of this paper.

Change in Our Food and Agricultural Systems is Inevitable – Based on Economics

Modern food and agriculture is a complex global system of sophisticated markets and industries, controlled by a small number of actors in the fields of production (industrial agriculture), processing (food manufacturing) and retail (supermarkets and food service). This food, produced through intensive and consolidated agriculture, is then predominantly manufactured into low cost, high energy, long-life, processed, and packaged foods, which are distributed through food service outlets or supermarkets, then sold to consumers at low prices. Figure 4 shows the case of soy trade between Brazil and China, which is the largest bilateral agricultural trade in the world (US$ 23.2 billion in 2020, 70% of the total agricultural export from Brazil to China). More than 70% of this market is dominated by 10 companies. This is not to criticise this system but to note the reality of it, because this is what provides the framing context for any analysis of how it will change.

Figure 4: (Right) Top five global agriculture trade flows in 2017 (blue) and 2020 (orange). Around 70% of the exports between Brazil and China correspond to soybean trade. They reached US$23.2 billion in 2020 (US$ 20.9 billion in 2017), representing the largest single international agricultural trade worldwide (data from Chatham House (2022)). The Transparency for Sustainable Economies initiative found that more than 70% of the soy exports from Brazil to China between 2013 and 2017 was concentrated in only 10 companies (left figure, from TRASE (2019).

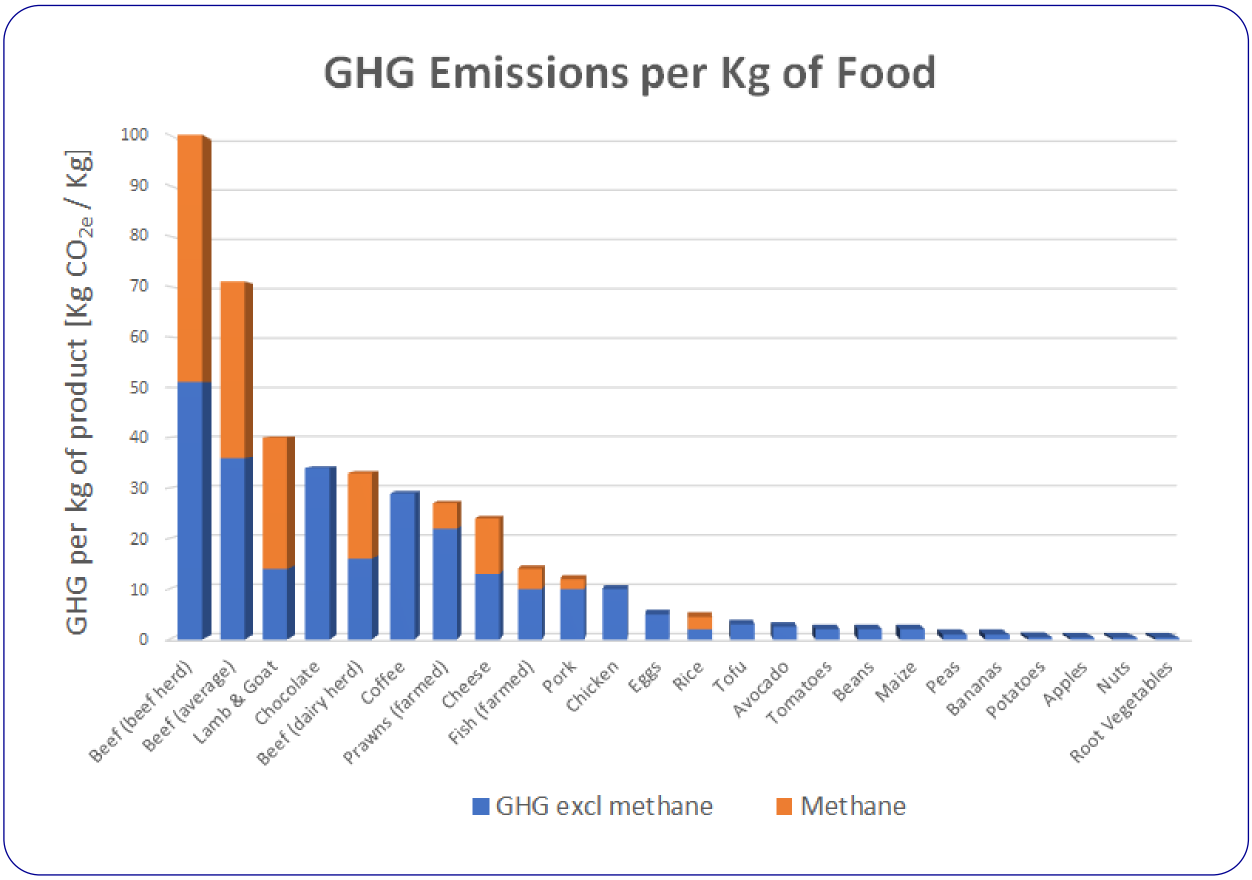


The key driver of this system is industrial agriculture, an idea originally conceived as a "panacea for a fast-growing world" (UNEP, 2020). Industrial agriculture allows for the large-scale, intensive production of crops and animals with a primary focus on production efficiency. Synthetic fertilisers, chemical pesticides, intensive[xvi] high yield monoculture cropping and livestock practices [xvii], high density and expansive land use and an emphasis on energy-dense (vs nutrient dense) 'affordable' food crops, have come to typify this system.

While productivity gains have been undoubtedly successful, they have also come at a steep cost: contaminated and depleted land and water[xviii], an increase in animal pathogens[xix] and zoonotic disease[xx], antibiotic resistance[xxi], lowered immunity[xxii], human disease and abnormality from chemical exposure and ingestion[xxiii], an epidemic of obesity and chronic disease[xxiv] and inequality driven by the disproportionate control that industrialised agriculture and corporate buyers have over small holder farms[xxv].

While the global proportion of people suffering from hunger has currently decreased, and this is to be celebrated, the proportion of people malnourished has increased. This is due to the increase in food availability being dominated by low-cost, energy rich foods that provide calories, but lack the essential nutrients required for healthy development and immunity[xxvi] . The unintended toll on society, the environment and poverty, creates economic costs in the range of $3 trillion (UNEP, 2020) to $12 trillion each year (Food and Land Use Coalition, 2019).

Figure 5: Greenhouse gas emissions from food, separating short vs. long-lived gases. Adapted from Ritchie (2020) - with data sourced from Poore & Namecek (2018)



Climate extremes now threaten these gains in productivity and hunger reduction. Weather extremes are now occurring simultaneously, with cascading impacts that are difficult to manage. These have affected productivity in *all* agricultural and fishery sectors (IPCC, 2022), and exposed millions of people to acute food and water insecurity, especially within vulnerable population in Africa, Asia, Central and South America, on Small Island States and in the Arctic (IPCC, 2022b).

The point of describing this is not to argue it should change. It is to establish that it is simply not possible for this current model to keep growing. This is a market and economic reality not a moral judgement. Therefore, the supply of nutrition through food must grow substantially to meet growing global needs[xxvii], making dramatic change in the food system *inevitable*.

At the September 2021 UN Food System Summit, convened to review and transform "the entire spectrum of food", it was concluded that "while food systems are contributing up to one third of greenhouse gas emissions, up to 80 per cent of biodiversity loss and use up to 70 per cent of freshwater… It is possible to feed a growing global population while protecting our planet" by changing to sustainable food productions systems that overcome these challenges (UN Secretary-General Antonio Guterres, 2021).

Central to this change – and the likely place it will start given the pressing need to reduce rates of warming - are those parts of the food system that also contribute most agricultural emissions of methane – the livestock industry, particularly beef and dairy (see figure 5).

This is not a 'should' argument but a 'likelihood' one, based on a market and economic analysis that beef and dairy is where the issues of food system change, resource constraint, new technology development and the climate emergency have the most market synergies. Therefore, it is here where the biggest market impact is likely to occur and where the race between savvy and adaptable incumbents and new disruptive technologies begins.

Technological Solutions are Ready to Disrupt Industrialised Agricultural and Food Markets. The Process Could be Accelerated and Managed but it Does Not Need to be Initiated.

There is growing consumer pressure and policy maker support in a number of developed countries to move away from predominantly animal based diets for health, nutritional, ethical and environmental reasons[xxviii]. In developing countries also, there is equal pressure and support both locally and globally, to find a new approach for delivering health and nutrition. With three billion people globally unable to afford a healthy diet, these nutrition solutions must also be resilient to conflict, climate extremes and economic volatility – the key drivers for the current food security and malnutrition crisis (UN Secretary-General Antonio Guterres, 2021).

In response, this has seen a rapid acceleration of interest and investment in 'alternative' proteins (plant-based, cell-cultivated, insect and fermented protein). There has been a 3-fold increase in investment from 2019 to 2020 (Nunes, 2021), and projected increase in market share from the current 2% to 11-22% by 2035, with Europe and North America forecast to reach 'peak meat' as early as 2025 (Witte et al., 2021). Such a rate of growth could trigger disruptive market responses – a sentiment reiterated in the latest IPCC report which claimed alternate protein sources for human food and livestock "may be highly disruptive to existing value chains…(and) have considerable potential for sustainably delivering protein for food and feed" (IPCC, 2022).

Consider ground beef, which accounts for more than 40% of beef consumed in the US - the world largest consumer of beef (Schulz, 2021; Davis and Lin, 2005). Separate analysis conducted by Tubb & Seba (2019) and CE Delft (2021) modelled that by 2030, production costs of cell-cultivated ground meat are capable of falling to $5.66 - $10/kg, compared to $1.2 mill per pound retail in 2013 and $6,000 per pound in 2017 (Purdy, 2017). This would give it the economic capacity to compete with significant portions of the current market.

The technological disruption in food and agriculture is largely not driven by 'new' technologies, but 'enabling' technologies that allow us to do things we've been doing for centuries, like fermentation, but do them smarter, faster and better. Examples include:

- c16 Biosciences, who are brewing palm oil using similar techniques to brewing beer – reducing the pressure on the $61 billion palm oil industry and its environmental impacts.

- Veramaris, an Omega-3 oil produced from a single-celled marine algae. Used as animal feed, especially in aquaculture, this product reduces the need for unsustainable fishing practices that utilise wild caught fish to produce fish oil.

- Solar Foods, who are producing protein rich flours from soil bacteria fed by air and Nature's Fynd who also produce protein flour, this time from a microbe found in Yellowstone National Park which was found to be a complete protein source containing nine essential amino acids, dietary fibre, calcium, and vitamins.

- EverSweet™,a stevia sweetener product produced through commercial-scale fermentation facilities, using less land and other resources, and producing less waste than processing of the stevia plant.

- Good Meat which produces meat from cultivated animal cells, sells its Chicken Bites to consumers in Singapore. The meat which can be grown in just 4-6 weeks claims to emit 92% fewer carbon emission and use 95% less land that traditional means of production.

These technologies are leveraging big data, digital capacity and biotechnology then applying them to micro-organisms and animal cells. This approach has the potential to drive transformational market and social changes in food production and agriculture. Critically, these enabling technologies follow a 'Wright's / Moore's Law' like process of acceleration, so we can reasonably assume the pace of change will accelerate[xxix].

It is easy to dismiss such new technologies as 'interesting but niche', 'just in the lab and not yet commercial', or, when they do reach the market, to assume they are marginal due to higher costs, the lack of serious capital backing or consumer acceptance. Incumbent companies often do this - as the fossil fuel and auto industries did for renewables, battery storage and electric cars. This tendency is one of the reasons incumbents often fail to respond in time, an issue we explore below.

Keeping this in mind, the critical drivers to note in the above examples, which are just a small sample of what is occurring around the world, are:

- The involvement of large global companies with the capital, credibility and market access needed to rapidly grow new businesses and rapidly scale up.

- The involvement of these large companies as the owners and developers of new approaches, not just as venture investors in start-ups[xxx].

- That many of these products are in the mainstream B2B market today and being taken up by customers[xxxi].

- That consumer acceptance of new food technology is increasing, especially amongst younger consumers[xxxii].

An analysis of these technologies and their capacity to drive market disruption is available from RethinkX in their report 'Rethinking Food and Agriculture 2020-2030 (Tubb and Seba, 2019).

They argue the process will follow a similar path to the disruption already underway in energy and transport, but in this case the viable alternative is the ability to produce protein and other foods through fermentation and cultured cells. They believe these technologies will target the industrialised meat and dairy industries that supply inputs to the corporate food industry. Because their market is Business to business (B2B), it is price and supply sensitive, rather than being consumer dependent. They argue this could result in the US cow population falling 50% by 2030 with these 'alternative' proteins becoming 10 times cheaper than today's animal proteins by 2035.

If this occurred, they conclude that net greenhouse emissions from traditional agriculture could reduce emissions (predominantly methane), from the sector by 45% by 2030 and be on course for 65% reductions by 2035. Lands previously used to produce animal foods could become a major carbon sink and be used to enhance biodiversity protection.

The work by RethinkX is a bold forecast and a bullish view of the way technology and markets accelerate. It may well be wrong, as technology forecasts often are. But it could also be right. If it is, it demonstrates that animal agriculture is unprepared for the transition to a sustainable food system. Concerns about the industry's lack of preparedness is a sentiment reiterated in a December 2021 report by FAIRR (Ramachandran et.al., 2021), an investor network representing over $46 trillion in assets under management, focusing on ESG risks in the global food sector.

It is important to note that the above analysis on the potential for technology disruption does not yet incorporate the central premise of this paper – that a climate emergency will trigger an urgent focus on methane reduction. If society does decide to act on methane these technologies can facilitate this and thereby make agriculture and food the central focus of such action.

How Disruptive Market Transformations Generally Unfold.

What these new technologies show is that we may be facing a disruptive and transformational change process, akin to solar and batteries tipping the coal – and soon oil and gas industries – into a state of permanent structural and market decline. Therefore, we need to understand how disruptive market change occurs.

Market transformation is rarely a simple case of 'out with the old and in with the new'. This is particularly the case in this area, where the global market structure of the food system is the key to understanding how it might unfold.

Market change is triggered when pressure grows for a new approach, incumbents feel the threat of change, then choose to dismiss it, or to embrace it and adjust their performance. How drastic the adjustment required, and the culture of the affected incumbent businesses, are key to whether incumbent players navigate the transition successfully or are replaced. We have considerable evidence from historical disruptions[xxxiii] to understand how this tends to occur.

In the auto industry for example, Tesla captured the market because incumbent car companies were too conservative to see, or to act on, the opportunity electric cars presented, and because of the way markets value incumbents differently to disruptors.

Tesla did not 'discover' the electric car, they simply took it to scale with a clever business strategy facilitated by improved and cheaper enabling technologies like software, control systems and batteries. Critically, they also generated enormous investment support and excitement, which then resulted in market valuations that enabled them to invest in moving to scale, even while an unprofitable, high-risk company.

In this example, it is important to note that the market adjustment required was not truly disruptive – it was essentially the same product with a different engine. Recognising this, the incumbent car companies that were at first caught out, are now racing to catch up and many may succeed.

Adjustment in other sectors however, have proved far more complex. In the case of coal, oil and gas, the *cultural* and *market* adjustments required to survive their disruption are very challenging.

- From a cultural perspective, these industries have been so powerful and such as crucial part of the economy and social progress for so long, it has developed a culture of 'immortality'. "*We are so important to society and so needed, we can't imagine the world without us in it*". Part of this historical view is accurate - the modern world was in fact built on the back of fossil fuels. However, in business terms, such a culture creates the risk of strategic blind spots and a failure to see the market turning until it's too late.

- From a technological perspective, global energy systems also face a 'technological lock-in'. The strong incumbent position of coal, oil and gas in different sectors of the economy implies that most of the energy processes existing today require fossil-fuel based technologies to work. Whilst the transformation of those processes is changing at accelerating pace, the longevity of capital stock, added to the capital-intensive nature of the energy assets, makes the rate of change of the energy sector slower than other sectors. There is, however, an important caveat here: as the low-carbon transition unfolds, the replacement of fossil fuel-based assets is expected to accelerate. The growing demand for low-carbon assets is being matched by an equivalent increase in production, fostering economies of scale and productivity improvements. Consequently, low-carbon technologies are becoming more competitive, which is increasing sales, productivity and further cost reductions. This self-reinforcing mechanism can be seen clearly in the market evolution of solar PV and wind energy, which is increasing exponentially, as shown in "Learning from the solar and wind disruption" section below.

- From a market perspective the changes required in fossil fuels are also very complex due to very different market structures. The differences – in competence, culture and market structure - between a coal or oil company and a solar or battery company are fundamental. Fossil energy is dominated by large, long life, slow moving, physical assets feeding into large corporate customers managing centralised systems - whereas solar and batteries are in a fast-moving technology business focused on a distributed system, which includes many retail consumers and crosses over into synergies with the auto industry. In terms of business culture and market structure, the new energy economy has more in common with an iPhone than a coal mine.

Based on economic history it seems likely many incumbents in the energy sector will fail and be replaced – as evidenced by what is today increasingly looking like a market death spiral[xxxiv].

The food and agricultural sectors have many similarities - but also some very important differences.

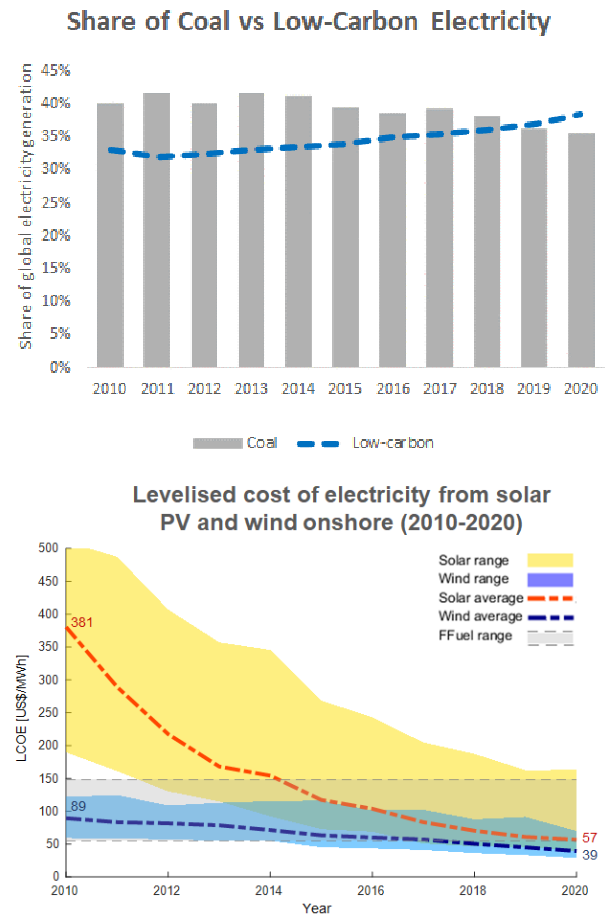
Learning from the solar and wind disruption

The case of coal versus renewable electricity is a telling example of an ongoing global disruption driven by the uptake of low-carbon technology. How you analyse the numbers, and the monitoring of key indicators, is however critical to understand and prepare for what is coming.

Indicator 1: Change in market share, not current market share is indicative of disruption.
According to figures from the International Energy Agency, coal is by far today's dominant energy resource for power generation. In 2020, its share of global electricity generation surpassed 35%. By contrast, the share of wind and solar PV electricity during the same year were 6% and 3%, respectively (IEA, 2021d). This massive size difference, however, is not an accurate indicator of where the market is heading. Figure 6 (top) shows the share of coal-based electricity (grey bars) and low-carbon electricity (blue dashed line) between 2010 and 2020. Coal-based power consumption is still growing, but its market share is shrinking, as it is steadily losing ground to low-carbon electricity.

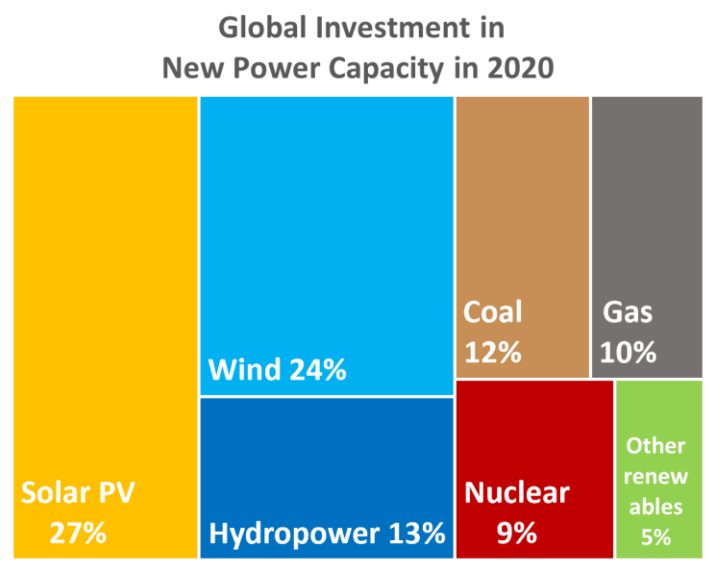
Indicator 2: Declining costs indicative of accelerating opportunity for market takeover.
One of the main drivers of this changing market share is the exponential decline in the levelised cost of solar PV and wind electricity, shown in figure 6 (bottom).

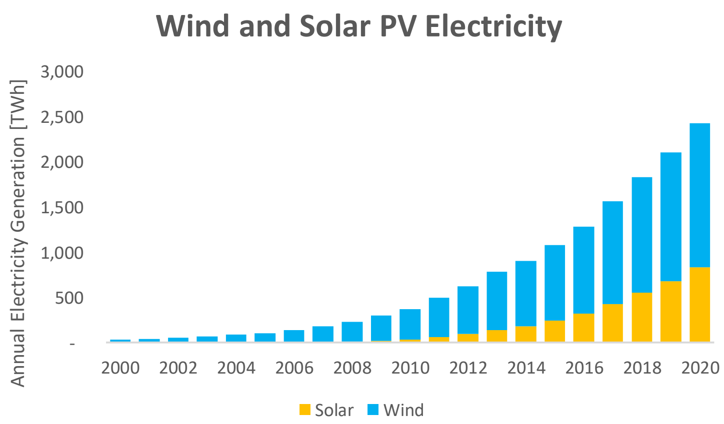
Figure 6. Top: Share of coal-based electricity (grey bars) versus the share of low-carbon electricity (blue dashed line). The low-carbon electricity includes the following technologies: hydropower, solar (PV and CSP), wind (onshore and offshore), bioenergy, geothermal, marine and nuclear. Data from IEA (2021d). Bottom: Evolution of the levelised cost of electricity for solar PV (yellow/orange) and wind onshore (blue) between 2010 and 2020. Data from IRENA (2021b).



Indicator 3: Global investment in new technology indicates a market shift is underway.
On the investment side, the disruption is clearer: Solar PV and wind are capturing an increasing share of the global investment in new power capacity, while the relative investment in coal is declining. As shown by figure 7 (top), in 2020 solar PV and wind captured 27% and 24% of investment in new power capacity, respectively, while coal only captured 12%. As a result, we are seeing an exponential increase in the amount of solar and wind electricity being produced, as shown by figure 7 (bottom).

Figure 7. Top: Global investment in new power capacity, by technology, in 2020. Adapted from REN21(2021). Bottom: Annual wind and solar PV electricity generation between 2009 and 2020. Data from IEA (2022).





How Will the Food and Agricultural Industries Fare in a Disruptive Transition?

Food and agricultural markets are now facing similar pressure as the fossil energy sector faced 20 years ago. In this case from:

- The growth in alternative proteins including plant-based milks and meat replacements in the short term and transformative new technologies in the medium term akin to the entry of renewables into the energy market in the early 90's, especially solar PV and wind energy.

- Changing consumer and policy maker attitudes regarding health and nutrition comparable to concerns about the effects of pollution from cars, power generation, gas exploration and coal mining on human health, well-being and the right to clean air and water.

- Concerns about the traditional industries' environmental impact and emissions.

- With all these as the baseline, food and agriculture now face the potential for a methane emergency response accelerating transformation, as the fossil energy sector faced with a focus on reduction in CO_2 to address the climate emergency.

Unlike the coal vs solar and wind example described above however, the process of transformation in food and agriculture is more nuanced. The race for market confidence and market share will be 'won' by whomever adjusts faster to address these concerns.

The growth in alternative proteins and milks (Nunes, 2021), (that consumers perceive to be more healthy and environmentally friendly), is already driving dairy and beef companies to take action to reduce their emissions, as they realise their new 'competitor' has an advantage in this area (Global Dairy Platform, 2021; Phillips, 2021). The threat of market loss and consumers' turning, thereby creates a market for technologies that reduce enteric methane emissions from livestock – with advanced feed additives for example reducing methane output by 30- 90%[xxxv].

The adjustment required here is not dissimilar to electric vehicles. Like changing the engine, they need to change feed and production practices to reduce emissions. If this can deliver a significant emission reduction result, investment in new animal feed and updating farm management practices is a relatively achievable adjustment given other business fundamentals remain the same.

Another important consideration in understanding the market outcomes from disruption in agriculture and food, is that the structure of the market is adaptable.

Agricultural production is based on a market demand driven product volume, with the ability to shift production relatively quickly. By contrast, fossil fuels' market is defined by providing energy to power long-life assets - cars, houses, industrial processes, and factories. We shop and consume food every day - we change cars and build houses and factories over decades. The slow rate of change in the energy sector is linked to the longevity of its capital stock (in the supply and the demand side), as well as the fact it is a capital-intensive sector (Gallagher et al., 2012). Those characteristics do not necessarily apply to the agri-food sector.

To put it simply, if people consume less beef and dairy but more plant-based products one year, farmers will breed less cows the very next year. If consumers demand lower methane beef and dairy, practices can be changed, and technology applied within a few years[xxxvi]. Both responses will reduce methane emissions virtually immediately and the rate of warming soon thereafter.

A decline in beef and dairy consumption, or, the added cost of reducing methane within beef and dairy production, will still involve broad economic change and potential losses as well as social impacts during the transition, but at a much lower scale than fossil fuels. For the broader economy, costs would be more than offset by the economic benefits of methane reductions[xxxvii].

Farmers in many countries are incredibly adaptable and are adept at responding to market shifts. We are already now seeing growing focus on regenerative farming in response to the growing market for food produced this way (Lane, 2021). In countries like New Zealand we saw large and rapid conversions to dairy from other types of farming, as the profitable market opportunity for dairy became clear. So, change could accelerate quickly for both adaptable producers of traditional meat and dairy as well as their alternatives.

As such, the ‘prize’ in the race to win market confidence, is yet to be decided. It will be determined by the speed of the strategic response by the incumbent players and by their new disruptive competitors and investors. This will determine the speed and scale of the market disruption.

Consumers will not be the only determinant of how the disruption will unfold

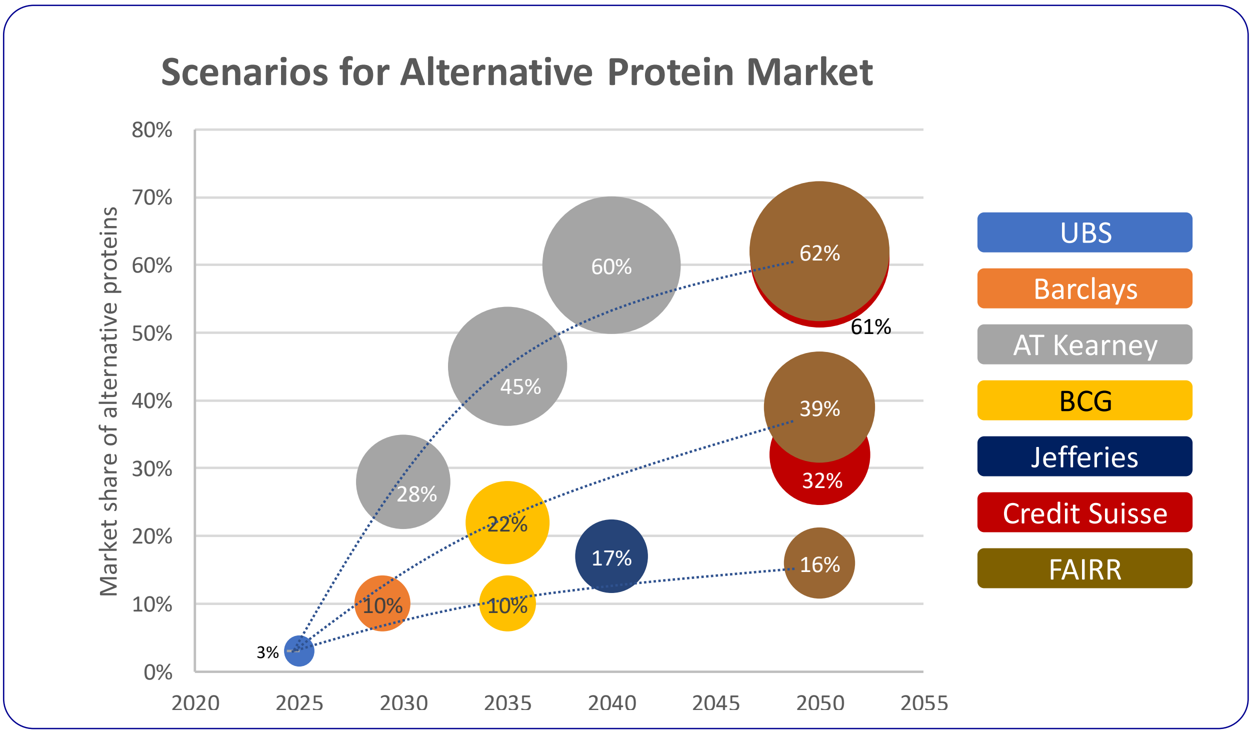
Our perception of the agri-food industries is very different to the reality. Many see market change as slow and incremental because it is focused on consumer acceptance of new technologies – that if consumers do not like the taste of plant-based milk or the idea of lab grown meat then the market will not shift enough to drive disruption. This disruption however, will not only accelerate through a business to consumer interaction.

The disruption is likely to be largely triggered by a business-to-business interaction focused on key ingredients such as ground beef for burgers, ground chicken for nuggets, milk solids, palm oil or sweeteners. These can be supplied via cellular and fermentation production and their use will not be primarily based on consumer acceptance but on corporate supply chains. These supply chains are focused on supply reliability, cost and customisation and the ability to confidently label products as higher nutrition delivered with decreased emissions, lower resources input and better animal welfare outcomes. This is how market change accelerates.

It’s not that disruptive change is ever easy. It is often very difficult for those involved. However, the societal context shows countless examples in economic history of such adjustments not only being successfully navigated but unlocking enormous economic opportunity. We’re learning this with cheaper, cleaner and more accessible renewable energy and we have seen it in countless other market and technology shifts. There is no reason to believe that food and agriculture will be any different.

A 2019 report by the Food and Land Use Coalition that examined the costs of transitioning to a sustainable food system found that while the transition cost would be $300-$350 billion annually, it would deliver a net yield of $5.7 trillion annually by 2030 (Food and Land Use Coalition, 2019). This figure represents an enormous economic opportunity for both disruptors and adaptive incumbents (such as small-scale and regenerative farms), who successfully navigate the transition. Figure 8 below shows some of the market share projections for the alternative protein sector. They start at around 3% by 2025 (UBS) and by 2050 they are expected to be between 16% and 62%, according to different scenarios from FAIRR and Credit Suisse.

Figure 8: Scenarios for alternative protein markets from different sources. Adapted from FAIRR (2021).



As was the case earlier in the auto and energy sectors, the technological and market innovations in the food and agricultural sectors are today largely being dismissed as 'niche' by most incumbent players. Yet among some investors and Fast Moving Consumer Goods (FMCG) majors, they are rapidly gaining traction and attracting very substantial investment[xxxviii]. Coupled with a global focus on food security and nutrition, our food systems are arguably primed for a similar disruption to the auto and energy systems.

Of critical significance to this is that our current food system is broken. Changing it is not a 'nice to have' that we should choose because it's 'the right thing to do'. It simply cannot grow due to physical limits in the rapidly changing ecosystem on which it depends. These include the direct impacts of climate extremes, soil and water on food production (IPCC, 2022) and the indirect but related impacts of issues like deforestation, ocean acidification and desertification. Yet demand for nutrition and food is growing and so production volume must expand.

As a result, the question is not ‘can we change our food system’ as though this is a moral or ecological choice. The question is how we will manage the inevitable decline or collapse of our current food system and its replacement with one that is more fit for purpose.

The Future of the Agri-Food Sector

There is enough evidence from other economic disruptions, including some underway today, to forecast how this is likely to unfold across the economy.

"*The viability of our societies depends on leaders from government, business and civil society uniting behind policies, actions and investments that will limit temperature rise to 1.5 degrees Celsius*".

This statement from UN Secretary General Antonio Guterres in response to the IPCC's 6th assessment is a powerful call to action. Many market participants however, will read such a statement and consider it an important social, political or moral question rather than a market one. In business terms, this is a potentially fatal mistake.

The rapid response he refers to will happen – because we have no choice. And it will translate into disruptive market change - because nothing else will deliver the required result.

The global economic and social system is a complex set of interacting parts, yet certain trends and behaviours are clear.

- Pressures in the system are applied and build over time - with science, activism, policy, investor and consumer attitudes all playing a part.

- When there is enough pressure for policy to be applied (or price competitive options to relieve the pressure), we switch to action. The market then starts to deliver the change required. Changes in the socio-technical landscape put pressure on exiting technological regimes, creating windows of opportunity for niche innovations (Geels, 2002).

- While the market change starts in 'niches', it then builds to rapid growth and turns exponential. Technologies become aligned and stabilise in a dominant design. Then momentum starts to build. The innovations that started in niches then permeate and transform the socio-technical regime, becoming the new incumbent (*ibid.*).

- New approaches and technologies don't become dominant just by taking market share. The historical evidence shows that transformative technologies create entire new markets, shifting the system to a new state (something called a 'phase transition'). In the energy sector, for instance, innovations such as the steam engine or electricity enabled a lot more innovation than just replacing horses and candles. Similarly, new agri-food technology will unleash significantly more than low-carbon hamburgers and milk.

As in any other market disruption, the reality is that many agri-food companies will not survive. Their current business will not be viable in the future the science says we're committed to, and the change they would need to make to successfully navigate the disruption is beyond them.

This is not a moral assessment but a market one, based on the evidence of the energy transition and many other disruptions. It is how markets work.

However, for those companies and investors that can embrace the pressure and navigate the transition, this disruption is an enormous opportunity[xxxix], in the same way that the low-carbon transition is a great opportunity for energy firms.

But the market clock is ticking. The climate emergency and the risk of irreversible tipping points will combine to catalyse the prioritisation of methane reductions, with profound implications for business. The brunt of the impact will be felt by the fossil fuel and agricultural sectors. In broad terms, this is all fairly predictable based on our experience of market change in the energy and transport transition now well underway.

This leads to our concluding forecast for the food and agricultural industry.

Agricultural and Food Systems

The pressure on the agricultural and food industries to manage emissions will approximate the pressure on fossil fuels seen a decade or two ago, but will accelerate faster, as the stakes are higher and public sentiment will demand it.

Farming practices, especially industrial agriculture will be scrutinised and demonised, as activists, investors and policy makers shift their focus - now with an emergency mindset.

We will see NGOs (Greenpeace, 2020), IGOs (IPCC, 2020) and governments (Dimbleby, 2021) shift to focus on big industrial agriculture and food emitters like JBS, Tyson, Cargill, Dairy Farmers of America and Fonterra. Data and information on these companies will be carefully curated to create a narrative that likens the actions of these organisation with those of the energy transition 'villains' such as the GRAIN (2018) pre-pandemic study, which claimed these food and agriculture majors produce more emissions in one year (when combined) than Exxon or Shell or BP.

The entire food system will be scrutinised to find solutions for the task of providing a stable and climate resilient supply of calories and nutrients to a growing population, using less resources, with minimal waste and low emissions. In response, consumers, will further reduce consumption of the most polluting foods and seek-out lower emission alternatives (Smithers, 2018).

Industrial scale operations that fail to adapt could face decline or collapse, as costs[xl] and consumer expectations increase, and public and government support and subsidies decline - redirected to more sustainable farming and protein production[xli].

While there is much to learn from the energy transition, the disruption in the food system will be very different due to the different market structures.

Out of necessity and with the market engaged, solutions of all types will boom. This will include new protein (Leger et.al, 2021), cleaner protein (Tubb and Seba, 2019), smart (Walter et.al., 2017) and sustainable farming practices (UCS, 2017), emissions reduction technologies (Beef Central, 2021b) and plant-based food (Credit Suisse, 2021). Investors will pile into the rapidly growing space (Nunes, 2021), joined by large global FMCG companies like Nestlé (Nestlé, 2021) and Unilever (Unilever, 2020) which will respond swiftly to avoid losing market-share to disruptors. And because the capital and consumer structures allow it, this market change will accelerate rapidly, as we see already emerging today (Witte, 2021).

There will be a unifying theme of reducing the methane intensity of food and agriculture, but the actual activities will be diverse and will compete for market progress. Examples will include:

- Actions that reduce methane emissions within livestock farming such as food additives and farming process changes. The faster the current industry can reduce its emissions, the slower that new alternatives will take market share.

- Actions that leverage whole-system land and livestock management, to promote soil carbon, emission reduction, regenerative farming and sustainable resource use, supported by consumer demand for quality sourcing. As the public demonisation of livestock farming accelerates, this niche of sustainable farming will seek to differentiate from industrialised agricultural practices and will gain market share and premium pricing by doing so.

- Governments will rally to guide the disruption to minimise negative impacts. Policy will both encourage the social benefit of a more sustainable food system (and the resulting methane reduction) and minimise the negative social consequences of disruption – with a renewed focus on protecting people not business.

- There will be reductions in the consumption of animal products and particularly livestock with beef and dairy feeling the greatest impact. This will create the market for differentiated producers like those above, but it will also drive faster market growth in plant-based milks and protein.

- Critical to this will be the engagement of global FMCG companies, partnering with competitive disruptors, with their billions of dollars spent on marketing accelerating consumer attitude change making it self-reinforcing. As consumers are voters, this will also influence policy change.

- Coming in behind these ‘ready to go’ solutions will be rapid growth in investment in the ultimately most disruptive new technologies in the food ingredients area, particularly cell-cultivated meat and dairy and fermentation-based approaches to protein production. These new technologies will ultimately dominate the market[xlii] but whether they do so in 10 years, or not for 30 years, will be determined by the response of the current players.

Just as in the energy transition, incumbent players will use arguments about livelihoods and culture to delay action. However, unlike the energy transition, they will be resisted by a growing number of market players that stand to win, as a new regime emerges by a shift in technology, markets and environmental awareness. Critically in this example, compared to the energy one, is that these winners already exist today and include large established players like global FMCG majors that carry as much influence as agribusiness majors.

Value will flow into the economy from disruptors in agriculture and food, displacing or surpassing losses from the collapse of incumbent players.

The market, as always, will adjust to protect itself. As in a casino, ‘the house always wins’.

Conclusion

Shifting our mindset from pain to gain, and from fear to courage.

Climate change is now a real emergency. Every day the evidence mounts that we face irreversible tipping points that, if we pass, may eliminate our options to have an impact. What's at stake here is not 'the environment' but the future of the economy, our society and a stable human civilisation.

We are today controlling the earth's climate but doing so without awareness or a plan to manage the impacts. We now need to shift to managing it deliberately and safely. To do so, we must:

1. Continue to cut CO_2, but now more urgently, to ensure the long-term result, and

2. Intensively focus on cutting methane to slow warming and ensure a viable long term.

We have 10 years or less to get this job done. Not to start the process, but for methane emissions to have been significantly cut and the rate of warming to have slowed. The science is clear. Speed is paramount.

While rapid and significant methane emission reductions could be achieved by focusing on fugitive emissions from fossil fuels, the nature and current state of the industry, coupled with the leverage they hold over policy makers, carries the risk that meaningful reductions may not be achieved within this timeframe.

We should therefore pursue all available options to reduce methane emissions and rates of warming – our best available option for reducing the risk of runaway climate change.

In the 1-to-10-year time frame, the greatest opportunity lies in food and agriculture. Nostalgia attached to food systems of the past distracts many from the actual nature of our current food systems – which are mostly part of large-scale industrialised market system. This nostalgia feeds the perception that technological innovation and behaviour change is slow, limited by political considerations and consumer acceptance and necessarily incremental in impact. The evidence tells a different story. It shows the potential for enormous disruption and opportunity, with action already underway which could now be accelerated with deliberate policy and market action.

To embrace this, perhaps what is needed most is a change in perspective. Kingsmill Bond and Sam Butler-Sloss from Carbon Tracker eloquently describe this change as one to 'gain not pain' (Bond and Butler-Sloss, 2021). They argue the old logic of climate mitigation assumed that the necessary solutions pose a burden, are a collective action problem and that costs to individual countries or businesses are far greater than benefits. That is a story of individual pain for collective and distant *gain*.

In 2021, we have an overwhelming amount of evidence showing that this is just wrong. Mitigating climate change is no longer an expensive collective action problem; it is a technology revolution with enormous wealth-generating and redistributive potential. Given the economic implications of the ongoing low-carbon transition, the framing of climate action as economically detrimental to those pursuing it is a poor description of strategic incentives (Mercure et al, 2021). As Bond and Butler-Sloss put it, the pursuit of gain will "breed co-operation and competition, shift capital flows from the billions to the trillions and mobilise the wit and will of humanity at a speed necessary to avoid climate chaos" (Bond and Butler-Sloss, 2021).

This is the reality of our context in 2021. Climate change, water security, population growth and food and nutrition insecurity are driving the need for disruption. Consumer sentiment and demand, accelerating investment and rapid advancements in technologies and sustainable farming practices are driving the *how*.

Importantly for methane, market and technology developments have the potential to deliver transformational change, with dramatic reductions within 10 years. Add to this the rapid growth of investment in alternate proteins, and on-farm practices that reduce and capture emissions, and the agricultural and food sectors present our best chance of achieving the methane reductions and reduction in the rate of warming required to stave off runaway warming.

To achieve this, we need to understand it is social, political and moral pressure that triggers the change but markets that deliver it. We need both and we need them both urgently.

We clearly still have the opportunity to achieve a safe climate and a prosperous civilisation. The only question is whether we decide to pursue it.

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[i] For example: Record shattering fires in Australia and the US that are starting earlier in the year and are so big they create their own weather (Edwards, 2019); Flooding in China where a year's rainfall fell in a day (Shepherd, 2021), and heatwaves in the Northern US & Canada where temperatures hit 49°C.

[ii] Director of the Earth System Science Centre at Penn State University, Michael Mann explains that "..current models underestimate the magnitude of the impact of climate change on extreme weather events" and that while the actual warming of the planet is "in line with climate model predictions from decades ago, the rise in extreme weather is exceeding the predictions" (Hook et al., 2021).

[iii] These quotes are from the draft report from the IPCC Working Group II's, *AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability*, released to AFP in June 2021 following its Second-Order review (IPCC, 2021b; France24 2021). The IPCC advised that this leaked version of the report was circulated for review by governments and experts in January 2021 and not yet approved. These quoted did not appear in the approved report released on February 28, 2022 they were original statements from the authors (IPCC, 2021b).

[iv] Lenton et.al (2019) describes the interconnectedness and potential for cascading impacts between the Amazon Rainforest, Arctic Sea Ice, Atlantic Circulation, Boreal forests, Coral Reefs, Greenland Ice Sheet, Permafrost, West Antarctic Icesheet, and the Wilkes Basin.

[v] Ripple et.al (2020) assessed a series of 'planetary vital signs' to identify trends that potentially pose a catastrophic threat to humanity. A 2021 update of this research, which tracked 31 of the vital signs over the subsequent 2 years, found 18 of the 31 have now registered new record lows/highs, indicating increased destabilisation and threat (Ripple et.al, 2021). The authors and more than 13,900 signatories call for transformative change to stay within planetary boundaries and protect life on Earth.

[vi] Durwood Zaelke, president of the Institute for Governance and Sustainable Development and a lead reviewer for the IPCC explains that the burning of fossil fuels like coal emits CO_2, but also sulphur particles that deflect incoming energy, and thereby have the effect of masking warming. As a result, "Defossilisation will not lead to cooling until about 2050…Cutting carbon dioxide will not lead to cooling in the next 10 years, and beyond that our ability to tackle climate change will be so severely compromised that we will not be able to run on. Cutting methane gives us time" (Harvey, 2021).

[vii] Recent (2020/21) research papers demonstrate that we are nearing or have crossed critical tipping points in the Earth system, including melting of the West Antarctic (Hulbe, 2020) and Greenland (Boers and Rypdal, 2021) icesheets (critical to sea levels and oceanic and atmospheric circulation), warm-water coral reefs (critical ecological, cultural and economic resource; Goreau and Hayes, 2021), the Amazon rainforest (critical carbon sink; Staal et al., 2020), melting permafrost (massive methane store which if released would rapidly increase warming; Schuur, 2019) and the slowing Gulf Stream (or AMOC; Caesar et al., 2020) which stabilises temperatures in Western Europe.

[viii] In October 2018 the IPCC advised that by 2030 we need to have made massive, unprecedented changes to emissions intensive industries to avoid catastrophic climate change (IPCC, 2018b).

[ix] Estimation based on figure 6 from Balcombe et.al (2018).

[x] The 6th Assessment Report of the IPCC (2021) found that averaged over the next 20 years, global temperature is expected to reach or exceed 1.5°C of warming unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions - "Strong, rapid and sustained" reductions in short-lived climate forcers like methane would "limit the warming effect". The Global Methane Assessment report from UNEP (2021) found that methane emissions would need to be cut 45% by 2030 to avoid the worst effects of climate change (a deeper and faster reduction than the IPCC (2018) target of '35% or more by 2050', that would limit global warming to 1.5°C with no or limited overshoot). Professor Drew Shindell, who chaired the UNEP's Methane Report reiterated this with the statement, "Methane mitigation is one of the most significant climate actions the world can take in this decade" (Hook, 2021).

[xi] The distinction between 'natural' and 'anthropogenic' methane sources is becoming less clear, with human activities at risk of disrupting the behaviour and functioning of the 'natural' methane cycle. For example: warming land surface temperatures are unlocking organic soil carbon (which breaks-down to methane) from thawing permafrost (Biskaborn et al., 2019), while warming ocean temperatures have the potential to destabilise huge stores of methane stored in marine clathrates (there is limited evidence of this occurring as yet; Ruppel and Kessler, 2016). Research also suggests that warming will trigger increased methane release and decreased up-take, due to changes in the balance of microbial communities (both methanogens which produce CH_4 and methanotrophs that remove CH_4 and convert it to CO_2), across many ecosystems (Zhu et al., 2020).

[xii] The UNEP (2021) Global Methane Assessment examined analysis by US EPA, IIASA, IEA and a review by Harmsen et al (2019) to identify methane mitigation potential against a 2030 baseline. All analysis found the greatest total emissions mitigation potential in fossil fuels, followed by waste (with the exception of Harmsen) and lastly agriculture. As a percentage of projected baseline emissions, the mitigation potential in both fossil fuels and waste far exceeded agriculture.

[xiii] As described by Gills and Morgan (2019): "Consider the context for what the Kyoto Protocols initially achieved: 5 years to agree that targets should exist (1992–1997), another 4 years to agree actual targets (2001), another 4 years to initialize targets (2005) and another 3 years before the process of reduction began for some of the more technical mechanisms and components of the targets (2008), and this for a process to be formally completed by 2012 – i.e. 20 years after the beginning of the process".

[xiv] A financial analysis conducted by Brulle, R.J (2014) found that between 2002 and 2010 the 'climate change counter movement' received ~$900 million per annum in funding from vested fossil fuel interests.

[xv] Fossil fuel stocks have been consistently derated since the Paris agreement, while the price of renewable stocks has doubled in the two years to 2021. 2021 has also seen a disconnect occur between fossil fuel commodity price (which has surged) and share prices (which have fallen). Bond and Butler-Sloss (2021).

[xvi] Between 1970 and 2011, livestock increased from 7.3 billion to 24.2 billion units, worldwide, with about 60 per cent of all agricultural land used for grazing (UNEP, 2020). Agriculture consumes 70% of freshwater extraction (Gladek et.al., 2017) and drives 80% of deforestation and 70% of biodiversity loss (FAO et.al., 2021).

[xvii] Biodiversity International (2017) found three-quarters of Earth's food supply draws on just 12 crops and five livestock species.

[xviii] Agriculture accounts for 70% of freshwater extraction globally and is the main factor in the degradation of inland and coastal waters globally, while nitrate from fertiliser application the most common chemical contaminant in the world's groundwater aquifers (FAO et.al., 2017). Land degradation is worsening worldwide, undermining the well-being of 3.2 billion people. The unsustainable management of croplands and grazing lands (which now cover more than 1/3 of the Earth's land surface), is the most extensive driver (IPBES, 2018).

[xix] Intensive livestock farming can produce genetic similarities within flocks and herds. This makes them more susceptible to pathogens and, when they are kept in close proximity, viruses can then spread easily among them. Intensive livestock farming can effectively serve as a bridge for pathogens, allowing them to be passed from wild animals to farm animals and then to humans. (UNEP, 2020)

[xx] Zoonotic disease is an infectious disease that has jumped from a non-human animal to humans. Clearing forests and killing wildlife to make space for agriculture and moving farms nearer to urban centres destroys the natural buffers that protect humans from viruses circulating among wildlife (UNEP, 2020). Increasing demand for animal protein, unsustainable agricultural intensification and climate change are among the human factors affecting the emergence of zoonotic diseases. 60 per cent of known infectious diseases in humans and 75 per cent of all emerging infectious diseases are zoonotic. COVID-19, Ebola, SARS, the Zika virus and bird flu all came to people by way of animals. UNEP and International Livestock Research Institute (2020).

[xxi] Antibiotics are commonly used to accelerate livestock growth. Over time, microorganisms develop resistance, making antimicrobials less effective as medicine. According to the World Health Organization, antimicrobial resistance "threatens the achievements of modern medicine" and may precipitate "a post-antibiotic era, in which common infections and minor injuries can kill." (UNEP, 2020).

[xxii] Since 1940 agricultural drivers were associated with >25% of all infectious diseases that emerged in humans. While modern agriculture has been effective in reducing hunger, its production and distribution leaves billions deficient in one or more crucial micronutrients (iron, Vit B_{12}, Vit A), with significant effects on defence against disease. The widespread use of antibiotics and anti-parasitics (which has driven microbial resistance) and the use of pesticides and fertilisers (which can act as immunomodulators and endocrine disruptors) have also had notable direct effects on human immunity. Meanwhile, the redistribution of fresh water sources for irrigation and dams, urbanisation and globalisation, biodiversity loss, soil degradation, water pollution and increased contact with livestock and wild animals associated with agriculture, have increased the spread of pathogens and human exposure to them globally. (Rohr et.al. 2019)

[xxiii] Chemical fertilizers and pesticides are used to increase agricultural yields. Humans may be exposed to these pesticides through the food they consume, resulting in adverse health effects. Some pesticides have been proven as endocrine disruptors potentially affecting reproductive functions, the incidence of breast cancer, growth and development in children, and immune function. (UNEP 2020).

[xxiv] Industrial agriculture produces mainly commodity crops for use in inexpensive, calorie-dense, and widely available foods (processed foods). Consequently, 60 per cent of all dietary energy is derived from just three cereal crops – rice, maize, and wheat. Although this has effectively lowered the proportion of people suffering from hunger, this calorie-based approach fails to meet nutritional recommendations, such as those for the consumption of fruits, vegetables and pulses. The popularity of processed, packaged, and prepared foods has increased in almost all communities, triggering a global rise in preventable diseases like heart disease, stroke, diabetes, and some cancers. (UNEP, 2020).

[xxv] Land inequality is the difference in the *quantity* and *value* of land that people have access and rights to. It is important as rights to land provides the water, food and natural resources required to sustain life – withholding of these rights is central to declines in democracy, climate resilience, health security, unemployment and gender and intergenerational justice. Since the 1980's, land inequality has steadily increased. Today, the top 10% of the rural population control 60% of agricultural land value while the bottom 50% control just 3% - largely due to land acquisition by large-scale agricultural interests in poorer countries. The concentration of more land, into fewer hands, serves the interest of corporate agribusiness and their investors (who are often disconnected from the land), who demand industrial models of agricultural production that employ fewer and fewer people and export, rather than locally consume, the produce. Inequality now threatens the livelihoods of an estimated 2.5 billion people involved in small-scale agriculture. (Guereña and Wegerif, 2019 & ILC and Oxfam, 2020).

[xxvi] Food that is affordable to the poor is energy-dense but invariably nutrient-poor. Micronutrient deficiencies may impair cognitive development, lower resistance to disease, increase risks during childbirth and, ultimately, affect economic productivity. The poor are effectively disadvantaged both as producers and consumers. (UNEP, 2020).

[xxvii] Total global food demand is expected to increase by 35-56% between 2010 and 2050. Van Dijk et.al (2021)

[xxviii] In the UK, 1/3 of consumers have stopped or reduced their meat consumption and there has been a 4-fold increase in veganism, citing animal welfare, health and climate concerns as drivers (Smithers, 2018). The UK Government's Climate Change Committee has concluded that meat consumption needs to be reduced 20-50% by 2050, while the National Food Strategy urges the government to bring this date forward to 2030 (FarmingUK, 2021).

[xxix] While studying airplane manufacture, Theodore Wright found in 1936 that the production cost per unit declines as cumulative production increases, a process called 'learning-by-doing' or 'Wright's Law'.. Using a similar principle, in 1965 Moore extrapolated that computing would dramatically increase in power, and decrease in relative cost, at an exponential pace (the doubling of the number of transistors in a circuit every 2 years) – this is Moore's Law. Enabling technologies relevant to the disruption of the food system which have followed exponential growth include:

- The rapidly declining cost, and increasing speed, of DNA sequencing (reading) and synthesis (writing) - the first sequencing of the human genome required 13 years and US$3 billion; today, it takes a week and US$600 (Xun, 2019).
- Machine learning allows scientists to identify ideal DNA configurations for products or processes and analyse complex biological processes with far greater speed and accuracy than ever before - we now have the technology to annotate a database of 100 million proteins in less than two days using a single computer (Scwartz, 2018).
- AI and robotics mean we can test millions of potential versions of new food ingredients simultaneously, to identify the best combination for desired traits - allowing scale-up and production to happen at a greater speed and scale.

- The rapidly declining cost and increased speed and capacity of computing makes everything faster and cheaper – in 2000 the cost of computing was $50m per teraflop. Today, a GPU for machine learning costs less than $60 per teraflop (Seba, 2017).
- The cost of Precision Fermentation has rapidly improved – in 2000 it cost around US$1mill per kg, in 2019 it fell to around US$100 per kg and is predicted to reach $10 per kg by 2025 (Tubb and Seba, 2019).

[xxx] For example:

- DSM combine expertise in biotechnology and fermentation to produce such products including: Veramaris® algal oil (a JV with Evonik); EVERSWEET™ sweetener (a JV with Cargill) and life's™ OMEGA algal oil, as well as a number of ingredients to support improvement in plant based protein and meat alternatives (DSM, 2022a; DSM, 2022b).
- Cargill is leveraging new technology and innovation in formulations to produce ingredients that support the production of plant-based products. They also hold substantial investments in cell-cultivated meat companies Memphis Meats and Aleph Farms (Cargill, 2020; Cargill, 2022).
- Nestlé is investing in both plant based and cell-cultivated protein technologies (Nestlé, 2021; Morrison, 2021).
- Tyson, the largest meat producer in the US recently released its own plant based hamburgers and sausage, to directly compete with Beyond Meat, of which it used to own a 6.5% stake prior to its IPO in 2019 (Polansek, 2021).

[xxxi] For example, rennet which is used to produce cheese was originally derived from the stomachs of calves, then microbes. Availability, animal rights concerns and inferior performance led to precision fermentation being used to produce pure chymosin, the active ingredient in rennet. Since its approval for use in food production in 1990, fermentation-produced chymosin is now used in more than 90% of cheese produced in the US. (Tubb and Seba, 2019).

[xxxii] A recent survey of US and UK consumers found that 85% of under 39s and 75% of older generations were willing to try cell-cultivated meat – on average, these respondents expected that cultivated meat could account for 40% of their future meat intake (Szejda, 2021). This consumer survey echoes the findings of a 2019 research survey of food experts that predicts by 2040, 60% of meat will be cell-cultivated or plant based, not derived from slaughtered animals (Carrington, 2019).

[xxxiii] In 1942 Austrian Economist Joseph Schumpeter coined the term 'creative destruction'. Based on his observations of the market he described this process as "process of industrial mutation that incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one." This essentially argues that for innovation to be deployed, the old system must be destroyed to free up the necessary energy and resources for the transition. (Kropp, 2021).

[xxxiv] See: Gilding, P (2018b) Why Incumbents Fail – and What That Means for Sustainability; Gilding, P (2018c) Will 1.5 Degrees Trigger a Death Spiral for Oil and Gas; Gilding, P (2018a) Disruptive Markets – What Sustainability Really Means for Business; Gilding, P (2020) COVID-19 and the Death of Market Fundamentalism.

[xxxv] Results from recent feedlot trials (Beef Central, 2021b), have shown that the feed additive *Bovaer* (active compound 3-NOP) developed by Dutch company DSM, was found to reduce emissions in feedlot beef cattle by 90% and 30% in dairy cows, with no negative impacts on animal performance .
FutureFeed, which uses *asparagopsis* seaweed, is also showing similar results. While feedlot trials are still underway, steers who have received the seaweed additive have demonstrated methane reductions of 80-98% (Beef Central, 2021a).

[xxxvi] Grubler (2012) examined the early stages of the energy transition to identify key learnings to aid a smoother transition towards sustainability. This research provides valuable insight into how the transition towards a more sustainable food system may unfold. One of the main constrains of the energy transition is the timescale involved in the process, which tends to be in the order of decades. Moreover, as the complexity of the system increases, the underlying uncertainty on the speed of both renewable uptake and fossil fuel decommissioning increases. As both the timescales for change and complexity within the food system are smaller within the food system, this is a key indicator that the speed in which transition could occur in this system could be greater than most anticipate.

[xxxvii] UNEP (2021) found that reducing methane emissions 45% by 2030 would avoid 0.3°C warming, and prevent 255 000 premature deaths, 775 000 asthma related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of crop losses globally. The global monetized benefits for all market and non-market impacts would approximate US$ 4,300 per tonne of methane reduced.

[xxxviii] A 2021 Report by FAIRR (FAIRR, 2021) who tracks 25 leading global retailers on protein transition found that 7 of the 25 (28%) global food retailers and manufacturers now have targets to expand their alternative protein portfolio, up from

zero in 2018. Best performers include Unilever, Conagra, Nestle and UK retailers Tesco and Sainsbury's. In the first 6 months of 2021 a record $506 million was invested in cultivated meat – including a collaboration between Nestlé and Future Meat Technologies announced in July.

[xxxix] This is evident in the energy sector with NextEra Energy surpassing Exxon in market cap in October 2020; clean supermajors Enel, Iberdrola and Orsted now worth more than comparable oil majors (Eckhouse et.al., 2020) and Goldman Sachs projecting that spending on renewables will overtake spending on oil and gas in 2021 (Winck, 2020). At the same time fossil energy has been the worst performing sector in the S&P 500 for more than a decade (Olson and McFarlane, 2019), and the most profitable company in the world, Saudi Aramco's planned IPO in 2020 (predicted to be the largest in history) was scaled back due to lack of interest from private investors and valuations coming in lower than expected (Ambrose, 2019).

[xl] Climate impacts will disproportionately impact industrial agriculture due to 'industrial amplifiers' that reduce their resilience to extreme weather, increasing losses and costs (UCSUSA, 2019).

[xli] Calls for explicit farming subsidies (~$700 bn per annum) to be redirected to sustainable food production, and for the industry to be accountable for the $3 to $12 trillion per annum in hidden environmental and social costs, would have profound impacts on the viability of industrial agriculture. (Food and Landuse Coalition, 2019 & UNEP, 2020)

[xlii] A common criticism of this thesis is that consumers will not accept novel cell-cultivated protein. What needs to be understood is that this disruption will not accelerate from a business to consumer interaction. The disruption will be a business-to-business interaction whereby key ingredients (ground beef for burgers, ground chicken for nuggets, milk solids, palm oil or stevia), will be supplied via cellular and fermentation production with increased supply reliability, nutrition, customisation and decreased emissions, resources input, animal welfare issues, distribution and costs.