CONSTRUCTING SUSTAINABLE TECHNOLOGIES

The Case of Synthetic Biology

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Abbreviations

A-LCA	Anticipatory Life-Cycle Assessment
BIS	Department for Business, Innovation, and Skills
CME	Coordinated Market Economy
CSA	Constructive Sustainability Assessment
CSR	Corporate Social Responsibility
CSS	Country-Specific Sector
CTA	Constructive Technology Assessment
ELSA	Ethical, Legal, and Social Aspects
GHG	Greenhouse Gas
GMO	Genetically Modified Organism
HMDA	Hexamethylenediamine
ISO	International Organization for Standardization
KTN	Knowledge Transfer Network
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LCM	Life-Cycle Management
LCSA	Life-Cycle Sustainability Assessment
LCT	Life-Cycle Thinking
LME	Liberal Market Economy
MSP	Minimum Selling Price
NOTA	Netherlands Office for Technology Assessment
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
RAE	Royal Academic of Engineering
RRI	Responsible Research and Innovation
RTFO	Renewable Transport Fuels Obligation
SBLC	Synthetic Biology Leadership Council
SBRC	Synthetic Biology Research Centre
SDGs	Sustainable Development Goals
SHDB	Social Hotspots Database
SHI	Social Hotspot Index
SLCA	Social Life-Cycle Assessment
STI	Science Technology and Innovation
TA	Technology Assessment
TEA	Techno-Economic Analysis
TIP	Transformational Innovation Policy
TRL	Technology Readiness Level
UN	United Nations

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Abstract

Governing the emergence of technologies in society is a complex endeavour, one that has been much studied yet remains without satisfactory answers. Given the urgent sustainability challenges faced by society and the significant role that science, technology, and innovation are expected to play in tackling them, the desire to exert control on emerging technologies is more pressing than ever.

While a considerable volume of relevant research has been undertaken on this issue drawing from a range of academic disciplines, philosophical positions, and methodological traditions, much of it takes place in silos, precluding holistic insights. This thesis takes an interdisciplinary, mixed-methods approach to ask how emerging technologies can be governed in line with the sustainability needs of society. Empirical insights are derived from the emerging technological paradigm of synthetic biology.

Four journal-style research papers make up the body of the thesis. The first paper develops a conceptual framework for Constructive Sustainability Assessment (CSA) which aligns analytical sustainability assessment approaches with technology assessment and responsible research and innovation. CSA provides a means through which the sustainability implications of new technologies can be evaluated early in their development. In the second paper, CSA is operationalised as part of an industry-based action research study in the field of synthetic biology. The synthetic biology-enabled production of bio-based nylon is found to provide potential benefits in terms of greenhouse gas emissions but have detrimental impacts in terms of several other environmental and social aspects. This paper demonstrates how the CSA approach can shed light on the impacts of new technologies at an early stage and potentially feed these findings into company decision-making. The third paper explores the barriers and opportunities revealed through testing CSA in the context of a company and discusses how the Silicon Valley-style business practices employed could be better aligned with sustainable development. Lastly, the fourth paper draws on the policy mix literature to investigate the role that sustainability has played in policy interventions supporting synthetic biology in the UK. While the sustainability agenda has played an important role in making the case for government support, this has failed to translate into policy development and implementation.

At the core of the thesis is the argument that while controlling new technologies will always be challenging, approaches such as CSA can help. The findings also suggest that we should avoid taking the sustainability potential of new technologies at face value. Furthermore, greater clarity is needed from those promoting new technologies concerning promised sustainability benefits while mechanisms are also needed for citizens to more clearly specify their sustainability priorities. Finally, three sets of recommendations are identified for research, policy, and practice: i) to critically assess the sustainability of emerging technologies, ii) to specify sustainability claims and needs, and iii) to reshape the socio-technical landscape for sustainable technologies.

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Dedication

To Mum and Dad,

Something *constructive.*

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And finally, thanks to Hans Zimmer et al., for providing the soundtrack.

Chapter 1: Introduction

> *"Can we control our technology - can we get it to do what we want and can we avoid its unwelcome consequences?" (Collingridge, 1980, p. 11)*

How to control our technology remains to this day one of society's most pressing yet least adequately answered questions. Its apparent intractability can be put down to what Collingridge (1980) described as the "dilemma of control" (Figure 1.1). The dilemma states that, on the one hand, early in the development and diffusion of a particular technology, knowledge of its impacts is inherently limited. On the other hand, by the time a technology has developed and become embedded in society to the extent that its implications have become apparent, flexibility to exert control over technological trajectories has been lost as a result of lock-in. This suggests that the rational governance of technology in societally desirable directions is inherently problematic, although Collingridge himself was at pains to emphasise that this did not make governance efforts entirely futile, calling for a "theory of decision-making under ignorance" and emphasising the need to make decisions which are "reversible, corrigible and flexible" (ibid., p. 12).

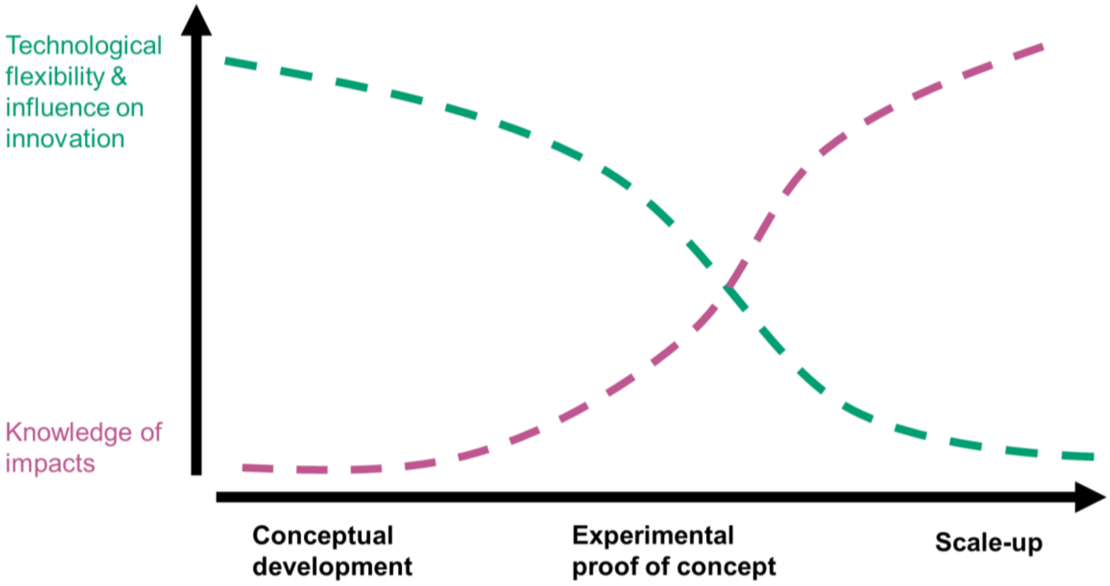

Figure 1.1: A graphical representation of the Collingridge dilemma (Source: Authors elaboration based on Collingridge, 1980).

Collingridge's important contribution sits within a broader literature which seeks to understand how technologies emerge and become embedded within society.[1] From this literature, we can understand the process of emergence to be shaped through social actions and choices alongside

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[1] This body of literature is highly interdisciplinary in origin and includes research that can come under many overlapping titles, notably: science and technology studies (STS); innovation studies; science policy, and innovation studies (SPIS); and science, technology, and innovation studies/policy (STIS/STIP) (Fagerberg & Verspagen, 2009; Martin, 2012; Martin et al., 2012; Soete, 2019).

technical features and therefore technologies can be considered, to varying extents, socially-constructed (Bijker et al., 1987; Jasanoff, 2004; Latour & Woolgar, 1979). Meanwhile, the negotiation of joint visions and expectations regarding future science and technology by a range of actors can play an important role in mobilising resources, thus becoming self-fulfilling prophesies in enabling new fields of science and technology to emerge (Borup et al., 2006). More broadly, technological innovation[2] is a complex, non-linear process that is best viewed from a systems perspective (Hughes, 1987; Kline & Rosenberg, 1986). Thus, understanding the interactions and flows of information between networks of actors at different levels (national, sectoral, and regional) can help to explain the outcomes of innovation (Edquist, 1997; Freeman, 1995; Lundvall, 1992). Finally, the socially embedded nature of technology and technological change can be further drawn-out through a focus on socio-technical systems and the sets of rules and norms (i.e. “regimes”) that maintain their stability (Geels, 2004). Building on this, the multi-level perspective (MLP) enables an explanation of how (socio)technical change occurs through attention to the dynamics and interactions between the three levels of *niches*, *socio-technical regimes*, and the wider *socio-technical landscape* (Geels, 2002).

The above-described theories of innovation and technological change tell us that, in line with Collingridge, there is unlikely to ever be a simple answer to how to control technology. Yet, this has not precluded many decades of efforts to, both implicitly or explicitly, grapple with, alleviate and manage the tensions implied by the Collingridge dilemma and to try and avoid the “unwelcome consequences” of technology (Collingridge, 1980, p. 11). These efforts have arisen both from theory and practice, and often through a combination of the two. One particular family of governance and technology assessment approaches includes constructive technology assessment (Schot & Rip, 1996), anticipatory governance (Barben et al., 2008), value-sensitive design (B. Friedman, 1996), midstream modulation (Fisher et al., 2006), and upstream engagement (Wilsdon & Willis, 2004). These frameworks have a common focus on the need to consider and anticipate possible future impacts at an early stage while remaining open-minded and responsive to new knowledge and developments as they emerge. Most recently, the concept of responsible research and innovation (RRI) has enabled efforts in this direction to coalesce somewhat around a common, albeit ill-defined, concept (Ribeiro et al., 2017; Stilgoe et al., 2013). Returning to the systems perspective, a growing body of complementary research in the areas of transformational innovation policy (TIP) and sustainability transitions has focussed more explicitly on the directionality of innovation and how the wholesale transformation of socio-technical systems can be brought about (Köhler et al., 2019; Schot & Steinmueller, 2018; Weber & Rohracher, 2012). Correspondingly, there has been increasing attention from policy-makers concerning how to intervene in innovation systems to help find solutions to societal “grand challenges” (Edler & Fagerberg, 2017; Mazzucato, 2018). Clearly, Collingridge’s desire to control and direct technological change towards societally desirable ends, and the fundamental challenges this brings, remain pertinent and active avenues for research and policy (Genus & Stirling, 2018; Ribeiro et al., 2018).

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[2] See the definitions (Section 1.3) for a brief clarification on the relationship between science, technology, and innovation.

Meanwhile, the need to control our technology has become ever more pressing with growing awareness of the sustainability challenges facing society. These challenges span economic, environmental, and social dimensions and demonstrate an inextricable link between people and planet (UN, 2012). In response, the sustainable development agenda attempts to maintain the earth's biophysical health within planetary boundaries (Rockström et al., 2009) while also achieving a minimum acceptable standard of life for all. Yet, at present, we are achieving neither of these (O'Neill et al., 2018). A key issue remains that while there is general agreement that human societies are operating unsustainably and on some broad high-level objectives in the form of the Sustainable Development Goals (SDGs) (UN, 2015b), exactly what a sustainable society would look like and which pathways to take are unavoidably political issues and subject to contestation[3] (Scoones et al., 2020).

The role of science and technology in this agenda is a complicated one. Many contemporary sustainability problems were created and embedded through processes of technological change. Since the industrial revolution, world population, per-capita consumption, and non-renewable resource extraction have all grown markedly putting considerable pressure on the earth's ecological and social systems (Schot & Kanger, 2018; Steffen et al., 2015). Nonetheless, given the role that technology plays within society, it also has an integral part to play in the potential resolution of these problems (Cervantes & Hong, 2018; UNCTAD, 2018). For technologies to assist a transition to a more sustainable society and avoid undesired consequences, there is a need to gain knowledge concerning their sustainability implications and to use this knowledge in the governance of technological change. This is a necessity that faces the unavoidable realities of the aforementioned Collingridge dilemma.

In recognition of the need for greater understanding and knowledge to inform and guide efforts towards sustainable development, a multi-disciplinary range of researchers under the broad umbrella of sustainability science have sought to address knowledge gaps and better understand the dynamic relationships between society and the environment (Kates et al., 2001; Nakamura et al., 2019). Within this, many methods and approaches for modelling and assessing sustainability have been developed and deployed (Maas et al., 2020; Patterson et al., 2017; UNEP/SETAC, 2009; Weyant, 2017). Both the environmentally focussed life-cycle assessment (LCA) and the broader life-cycle sustainability assessment (LCSA) framework (that attempts to integrate social and economic dimensions) seek to evaluate the sustainability implications of products, policies, or plans and provide a potential avenue to "link science to actions" (Sala, Ciuffo, & Nijkamp, 2015, p. 317). Owing to their fairly advanced methodological development, there is considerable interest in the use of these tools to support an evidence-based approach towards the SDGs (Sala, 2021; Sonnemann et al., 2018; Weidema et al., 2020). With respect to new and emerging technologies, this requires the development of more forward-looking, anticipatory approaches to assessment than have typically been employed previously and the development of methods that

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[3] At an international level, this is illustrated by the Paris Agreement where, while there was agreement on the goal of keeping global warming to 1.5 degrees (UN, 2015a), individual nations' pledges fail to achieve sufficient or equitable emissions reductions (Anderson et al., 2020; Watson et al., 2019).

can better grapple with high levels of uncertainty and ambiguity (Kühnen et al., 2019; Wender, Foley, Hottle, et al., 2014).

While valuable, it is also important to recognise that there are fundamental limitations to the extent that analytical assessment approaches can inform sustainable development. The modern world is characterized by unpredictable, extreme, discontinuous events rather than incremental change (see Taleb, 2007). This reality is in tension with the desire to assess and therefore rationally inform sustainability trajectories. More fundamentally, the concept of sustainability raises as many subjective as objective questions, particularly concerning what should be developed, what should be sustained, and with what relative prioritisation (Scoones, 2016). There are many potential “ends” for sustainable development, and a plurality of pathways to reach those ends which can invoke a widely variable role for (new) technologies (ibid.). Thus, while expert-based analytical approaches have an important role to play in achieving sustainable development[4], these approaches cannot on their own provide answers to sustainability questions and over-reliance on them risks artificially ‘closing down’ options (Stirling, 2008a). Ultimately, questions of how to tackle urgent sustainability challenges have to be answered by society, with a diversity of sciences, both natural and social, helping to facilitate, inform and light the way.

1.1 Research questions

This research is motivated by the contemporary challenge of sustainable development with an underlying aim of trying to tackle, grapple with, and where possible answer these urgent problems faced by today’s societies. At a high level, the research problem is similar to that described by Collingridge – how can we exert control on technologies at an early stage of development given inevitable uncertainty over their impacts and implications? As already described, this is not the first attempt to tackle this problem and hopefully will not be the last. While this thesis does not propose a grand theory, it demonstrates novelty in the way it tackles the Collingridge dilemma and hopefully makes some progress in responding to this decades-old problem. To this effect, attention has been directed towards two specific dimensions of the wider problem.

The first dimension is focussed on assessment. It recognises that while there are many methodologies and approaches available to integrate the assessment of sustainability into the governance of emerging technologies, this work tends to take place in silos. Given the nature of sustainability challenges, which raise questions that are relevant to both the social and natural

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[4] The role of science and the special status it has often enjoyed as the authoritative voice of objective truth has been expansively critiqued by philosophers and sociologists of science who argued that scientific knowledge, like all knowledge, is socially constructed (Kuhn, 1962; Latour & Woolgar, 1979). In this thesis, I subscribe to the “third wave” perspective put forward by Collins & Evans (2002) which argues that there can be a nuanced place for science as an appropriate and moral way to inform (but not make) decisions where scientific expertise is put explicitly at the service of democratic societies. This defence of scientific values as a key feature of a democratic society, while acknowledging the considerable limitations to scientific knowledge, can be termed “elective modernism” (Collins & Evans, 2017).

sciences, there is considerable value to be gained from a more integrated approach (Forsberg et al., 2016). This leads to the first research question:

> *Research Question 1: How can complementary approaches from distinct academic disciplines be integrated to enable the sustainability implications of emerging technologies to be assessed at the early stages of development?*

The second dimension is focussed on governance. The insights provided by better assessment of sustainability at early stages can only lead to societal benefit if the governance structures are in place for those insights to feed into technological development. The inevitable uncertainty and ignorance which pervades the emergence of new technologies make this problem both pertinent and challenging. The second research question can therefore be expressed as follows:

> *Research Question 2: How can sustainability considerations be better embedded at multiple levels in the governance of emerging technologies?*

In line with these research questions, this thesis proceeds with the hypothesis that, while the Collingridge dilemma will always limit our ability to rationally control technology, it can be partially alleviated. This can be approached from two angles. Firstly, we could improve our capacity for assessment to reduce uncertainties and rationalise the available knowledge such that it can inform technology trajectories at an early stage. On the other hand, we could also improve our approaches to policy and governance in a way that more systematically integrates societal imperatives such as sustainable development. This work sets out to explore, demonstrate, and reflect upon how this can be achieved by integrating knowledge from a range of disciplines and from both theory and practice.

1.2 Research approach

This section covers the key areas of introductory background and context which are needed to understand the approach taken in the thesis. First, the empirical setting of synthetic biology is introduced. Following this, the philosophical position of critical realism that underpins the thesis is briefly discussed followed by a description the overarching methodological logic of action research and the implications for positionality. A practical overview of the research process is then provided.

1.2.1 Empirical setting

This thesis draws empirical insight from the field of synthetic biology, an emerging technological paradigm that has developed over the past two decades. It brings together advances in several areas - notably the increasing ease of sequencing and synthesising DNA, new molecular biology techniques such as CRISPR-cas9, and the use of computation and automation – to enable the redesign as well as *de novo* assembly of biological systems (Endy, 2005; RAE, 2009). This represents a more engineering-inspired and application-orientated approach to biological research which can trace its roots back to the emergence of systems biology in the 1990s (Cameron et al., 2014). A 2009 report by the Royal Academy of Engineering defined synthetic biology as follows:

> *"Synthetic biology aims to design and engineer biologically based parts, novel devices and systems as well as redesigning existing, natural biological systems."* (RAE, 2009, p. 6)

More recently, e*ngineering biology* has become an increasingly popular way to refer to this field of study (EBRC, 2019; RAE, 2019). In this thesis, the two labels are considered to be broadly synonymous. The term synthetic biology has been primarily used to maintain consistency.

The genetic "toggle switch" and the repressilator, both reported at the turn of the Millennium (Elowitz & Leibler, 2000; Gardner et al., 2000), might be considered the first truly synthetic biological systems and therefore a sensible starting point for the field. The first dedicated synthetic biology conference (SB 1.0) took place at MIT in 2004 and from then on research funding and output increased markedly (Shapira et al., 2017). Activity has been generally concentrated in a relatively small number of large economies with research funding overwhelmingly led by the US accompanied by significant investment from the European Union, China, the UK, Germany, Japan, Canada, and South Korea (ibid.). In line with the application-focussed nature of synthetic biology (Endy, 2005), there has been considerable interest in the commercialisation of research discoveries from synthetic biology with Artemisinin production in yeast by Amyris an early example (Paddon et al., 2013). Over recent years, commercial activity has accelerated as applications mature with synthetic biology companies now able to attract substantial equity investment (Cumbers et al., 2020).

Synthetic biology should not be considered a commercial sector in itself, rather, it can be understood as a platform technology that opens up capabilities that could have an impact on a wide range of existing sectors (Bueso & Tangney, 2017). Notably, its implications are often framed in terms of sustainability and many of the applications that synthetic biology enables can be linked to the SDGs (Table 1.1; French, 2019). For some, this is part of a new "bio revolution" where the biological sciences are becoming a much more important and broader source of innovation, helping to tackle many of the problems faced by contemporary societies (Chui et al., 2020). This vision aligns with the growing policy interest in what has become known as the bioeconomy[5] - a wide variety of nations, including the UK and US, have published dedicated bioeconomy strategies (German Bioeconomy Council, 2018; HM Government, 2018; NASEM, 2020). A common idea behind many of these strategies is that through a renewed focus on the bioeconomy, with strategic investment and cross-sectoral coordination, we can realise more sustainable and circular production and consumption patterns for food, chemicals, energy, and materials (Teitelbaum et al., 2020).

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[5] Though specific definitions of what is encapsulated in the bioeconomy concept vary, a widely used definition is that from the Global Bioeconomy Summit in 2015: "the knowledge-based production and utilization of biological resources, innovative biological processes and principles to sustainably provide goods and services across all economic sectors" (Global Bioeconomy Summit, 2015). In the US, the bioeconomy has been defined in a somewhat narrower way: "The U.S. bioeconomy is economic activity that is driven by research and innovation in the life sciences and biotechnology, and that is enabled by technological advances in engineering and in computing and information sciences." (NASEM, 2020).

Application area	Example Applications	Principle SDG Associations
Industrial Biotechnology	• Microbial cell factories to expand the use of bio-based production for speciality and commodity chemicals (National Research Council, 2015). • Biological routes to existing and novel materials such as plastics (Hatti-Kaul et al., 2020; Le Feuvre & Scrutton, 2018). • On-demand production of small molecules (Casini et al., 2018).	• Responsible Production and Consumption • Climate Action • Life on Land • Life Below Water
Environmental biotechnology	• Bioremediation - using biological systems to detect, take up, degrade and/or valorise environmental pollutants and waste (such as plastics) (Blank et al., 2020; Rylott & Bruce, 2020). • Biological systems for the removal and sequestration of atmospheric greenhouse gases (DeLisi et al., 2020).	• Climate Action • Clean Water and Sanitation • Life on Land • Life Below Water • Responsible Production and Consumption
Food & Agriculture[6]	• Engineered crops with improved yields and efficiency. • Reduced fertiliser usage through engineering nitrogen-fixing plants and microbes. • Foods with modified and optimised nutrient content. • Alternative (meat free) protein sources (Tze, 2019). • Plants as a production platform for biochemicals and pharmaceuticals (Tschofen et al., 2016).	• Zero Hunger • Clean Water and Sanitation • Climate Action • Life on Land • Life Below Water • Responsible Production and Consumption
Health & Medicine	• Personalised and targeted therapies (Pedrolli et al., 2019; Sun et al., 2019). • New diagnostics for disease (Amrofell et al., 2020; P Teixeira & Fussenegger, 2019). • Speeding-up vaccine development (Charlton Hume et al., 2019). • Discovery and production of new drugs (Romanowski & Eustáquio, 2020).	• Good Health and Well-being
Energy	• Engineering of bioenergy crops to increase photosynthetic efficiency and improve cell-wall composition (Markel et al., 2020; Ort et al., 2015). • Engineered microbes and enzymes for more efficient breakdown and conversion of biomass into biofuels (Jiang et al., 2018; Lillington et al., 2020). • “Third-generation” biorefineries producing biofuels from carbon dioxide using light, chemicals (e.g. hydrogen), or electricity as an energy source (Z. Liu et al., 2020).	• Affordable and Clean Energy • Climate Action • Responsible Production and Consumption

Table 1.1: A summary of potential application avenues enabled by synthetic biology and their links to the UN SDGs. (Source: Author’s synthesis based on categorisation developed by the EBRC, 2019).

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[6] For a recent review of synthetic biology’s impact on this application area, see Roell & Zurbriggen (2020).

Synthetic biology and the idea of a rejuvenated bioeconomy are accompanied by many highly optimistic visions of what this will deliver for society, largely framed in terms of sustainability, an example of what some term “promissory rhetoric” (Petersen & Krisjansen, 2015; Schyfter & Calvert, 2015). These ambitions are not without justification given the pressing need for more sustainable alternatives to fossil fuels and the intuitive benefits of deriving products from biomass (or even carbon dioxide) in terms of greenhouse gas (GHG) emissions, particularly when it comes to replacing the portion of the oil barrel which can’t easily be electrified, such as chemicals and materials as well as aviation and shipping fuels (OECD, 2018b; Saygin et al., 2014). It is in this area of application, which is often referred to as *industrial biotechnology*, that this thesis primarily focusses on with particular attention to the sustainability promises that accompany it.

Yet, these promised benefits don’t always stack-up to scrutiny, and the optimistic visions are not always shared. When it comes to promises of environmental benefits, issues of indirect land-use change experienced with first-generation biofuels tell us that anticipated GHG emission reductions aren’t always realised in practice (Searchinger et al., 2008). Furthermore, the production of chemicals from biomass rather than fossil-fuels often show worse impacts for other environmental impact categories such as eutrophication (Escobar & Laibach, 2021; Ögmundarson et al., 2020; Weiss et al., 2012). More fundamentally, while it is difficult to find robust and consistent estimates of biomass availability (OECD, 2018a), it seems clear from available analyses that the supply of *sustainable* biomass to meet the growing demand for energy, chemicals and materials is likely to be a major constraint on what the bioeconomy can deliver sustainably (Daioglou et al., 2019; Jones & Albanito, 2020; Piotrowski et al., 2016; Ros et al., 2012).[7]

Synthetic biology’s emergence has also raised social issues that are highly pertinent for achieving a holistic view of its sustainability implications. One key concern is how to ensure a fair distribution of costs and benefits with technologies being predominantly developed and owned in the global north but often exploiting the natural resources and biodiversity of the Global South (Asveld et al., 2019; French, 2019). Meanwhile, if biomass production to feed the growing bioeconomy competes for land with food production this can drive-up food prices, disproportionately impacting the world’s poorest citizens (Naylor et al., 2007). Provision of biomass for biotechnology applications can also have detrimental impacts for rural communities and small-holding farms through disruption to employment patterns, land ownership, land-use rights, and the cultural traditions of farming communities (Raman et al., 2014; van Dam et al., 2010). More broadly, the field raises questions around the place of humans in nature and the level of precaution which should be taken when modifying and manipulating biological systems, individual answers to which fundamentally comes down to differing worldviews (Asveld et al., 2014, 2019).

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[7] The development of microbial cell factories that can directly fix carbon dioxide offers a promising opportunity to finally decouple bio-based production from its ecological footprint (Z. Liu et al., 2020). However, this relies on major technological barriers being overcome and potentially the provision of vast quantities of renewable electricity and/or hydrogen (The Royal Society, 2017).

In summary, synthetic biology represents a technological platform with the potential for wide-ranging impact and relevance for sustainable development. These promised benefits are accompanied by controversy and contestation and this has led to interest from a range of actors (including NGOs, governments, companies, and researchers) in how best to proceed responsibly. This is perhaps most aptly demonstrated by the efforts in the UK in particular to institutionalise an RRI approach in government-funded synthetic biology initiatives (Macnaghten et al., 2016; Owen et al., 2021). Nonetheless, there remain considerable knowledge gaps concerning the field's sustainability implications. As the field continues to develop and focus increasingly turns to application and scale-up, there is a need for continued critical consideration of the field's wider (sustainability) implications and its overall *directionality*[8]. By grounding the research in this particular empirical case, it has been possible to engage in the complementary exploration of the research questions posed earlier, while also seeking to intervene in and support actors in the field of synthetic biology to better integrate sustainability considerations into policy and practice.

1.2.2 Philosophical position

Research, and particularly social science research, is approached from a broad range of philosophical and methodological angles (Guba & Lincoln, 1994). This thesis is grounded in critical realism (Archer et al., 1998). Three core concepts characterise this position – ontological realism (that a reality exists independently of our knowledge of it), epistemological relativism (that our knowledge of the world is fallible and socially constructed), and judgemental rationality (that it is possible to rationally prefer certain explanations of the world). Causality is understood through three hierarchically organised domains consisting of underlying structures and mechanisms (the Real), the events that these mechanisms generate (the Actual), and the events that we actually observe and experience (the Empirical) (Bhaskar, 1975).

Critical realists tend to focus on generating knowledge about underlying causal mechanisms through a process of retroduction (abductive reasoning) where "we take some unexplained phenomenon and propose hypothetical mechanisms that, if they existed, would generate or cause that which is to be explained" (Mingers, 2006, p. 23). This leads to provisional explanations of the world, a pragmatic approach to knowledge generation that is summed up by Sayer (1992): "Our knowledge of the world is fallible and theory-laden. Concepts of truth and falsity fail to provide a coherent view of the relationship between knowledge and its object. Nevertheless, knowledge is not immune to empirical check and its effectiveness in informing and explaining successful material practice is not mere accident" (p. 5). By extension, and given an underlying commitment to realism, it is possible to have normative dimensions to our knowledge, and, albeit cautiously, make statements concerning the *ought* as well as the *is*. Values and facts are not neatly separated, and thus value-statements can be opened up to a degree of empirical investigation or explanatory critique (Gorski, 2013). As a result, Bhaskar widely argued that far

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[8] The issue of directionality is recognised to be of central importance for transformational change towards more sustainable socio-technical systems (Weber & Rohracher, 2012).

from being neutral, “explanatory social science necessarily has emancipatory implications” (Bhaskar, 1979, p. 61).

In terms of methodological approach, critical realism goes some way to reconciling the divide between typically quantitative positivist and typically qualitative interpretivist approaches (Sovacool et al., 2018). Methods tend to be mixed and are chosen based on the research question being explored. The differences in methods are compatible through a position often termed critical naturalism (Bhaskar, 1979). This involves accepting that a realist approach is, in theory, equally applicable to social and physical systems while acknowledging that the study of social systems is challenged through issues of agency, a lack of universality, their inherently open and interactive nature, difficulties in measurement, and the fundamentally self-referential nature of social science research (Mingers, 2006). These characteristics render such systems more amenable to interpretative understanding. As Bhaskar puts it: “…the *predicates* that appear in the explanation of social phenomena will be different from those that appear in natural scientific explanations and the *procedures* used to establish them will in certain vital respects be different too (being contingent upon, and determined by, the properties of the objects under study); but the principles that govern their production will remain substantially the same” (Bhaskar, 1979, p. 22).

1.2.3 Methodological logic and positionality

Tackling the “how can” research questions posed earlier lends itself to action research. Action research emphasises the role of the researcher in taking action in real-life settings, and the diversity of approaches can be described as “intervention”, “collaborative”, and “insider” research (Eikeland, 2011). In modern times it can be traced back to the works of Collier (1945) and Lewin (1946). Lewin is widely attributed as saying: “in order to understand something you have to change it”. Action research allows the investigation of research questions relating to “what is happening here?” and “how do I change/improve it?” (Whitehead & McNiff, 2011). The research process typically involves iterative cycles of "problem identification, diagnosis, planning, intervention and evaluation of the results in order to learn and plan subsequent interventions" (Cassell & Johnson, 2006, p. 784). This continuous and iterative process is commensurate with a critical realist commitment to retroduction and emancipatory action (Houston, 2014). This approach has also enabled me throughout the research to be responsive to changing situations, new opportunities, and the evolution of my own knowledge and understanding.

Within this broader action research approach, mixed methods were used to probe the research questions from multiple angles and domains, in line with the philosophical position described previously. The research has been highly interdisciplinary and has involved a pragmatic approach to methodological choices. Methods employed have included traditional social science methods such as semi-structured interviews, workshops, documentary analysis, and surveys while also utilising tools and approaches derived from the natural sciences such as LCA and techno-economic analysis (TEA). The specifics of the methods used are described and justified in greater detail within each of the journal format papers that make-up the body of the thesis.

It is helpful at this point to briefly consider the question and possibility of generalisation. Generalising findings from the primarily qualitative research employed in this thesis can be challenging and fraught with limitations. Certainly, it is not generally the aim to derive statistical "sample-to-population" generalisations here but there are two other routes through which the findings from this thesis can be used to derive tentative generalizations (Firestone, 1993). The first is through naturalistic generalization, which relies on the idea that other researchers reading case study descriptions can identify parallels and similarities to their own experiences and research, thus enabling the potential for the transfer of insights to other contexts (Melrose, 2012). The second is that of analytic generalization whereby the researcher seeks to generalize back from empirical findings to broader ideas and theory. Yin (2018) describes two potential grounds to base analytical generalization from case study findings: "…(a) corroborating, modifying, rejecting, or otherwise advancing theoretical concepts that you referenced in designing your case study or (b) new concepts that arose upon the completion of your case study" (ibid., p. 38). The analytic generalisation pursued in this thesis is typically focussed on the former approach rather than the latter.

Finally, the positionality of the researcher, while always relevant, becomes particularly pertinent in the kind of collaborative, action-oriented research undertaken in this thesis where the researcher quite purposefully intervenes in the system in which they study. According to Rowe (2014): "Positionality refers to the stance or positioning of the researcher in relation to the social and political context of the study—the community, the organization or the participant group." (p. 2). A common way to conceptualise positionality in this context is the insider-outsider dilemma (or continuum, see Herr & Anderson, 2012). In this thesis, I have sought to assume a position of both an insider and an outsider, occupying "the space between" (Dwyer & Buckle, 2009). As an active contributor to biological science research (see Matthews & White, 2019; Muller et al., 2020), I can be described as an insider. This position helped to facilitate access to participants and data. A degree of specialist understanding was also essential to enable research in these highly technical and jargon-heavy empirical contexts. Despite these benefits, it also raises questions and tensions regarding the impact of researcher subjectivity (Rooney, 2005). To manage these issues, the research involved iteration between periods of intense interaction and collaboration punctuated by periods of more removed reflection and analysis. This involved complementary use of more traditional research methods such as documentary analysis, surveys, and interviews, helping to preserve the ability to take a critical, outsider perspective on the field of study, allowing the introduction of perspectives and knowledge not otherwise considered and helping to avoid "going native". The approach taken positioned me as a critical (outside) but constructive (inside) voice to the field of study.

1.2.4 Research process

The research for this journal format thesis took place over three and a half years between September 2017 and January 2021 with empirical data collection taking place in the US and UK (see Appendices A.1 and A.2). The first six months were primarily focussed on undertaking training courses and reviewing academic literature while the latter half of the first year shifted attention to research design, establishing collaborations, piloting methods, and developing the conceptual basis for the thesis. In particular, it was during this time that the *Constructive Sustainability Assessment* (CSA) framework was first elaborated. The CSA framework was written-up as a journal paper in the autumn of 2018, submitted to a journal in March 2019, and published in May 2019. During its development, the CSA framework was presented and discussed in numerous fora (see Appendix A.2), as well as being tested through a practical case study.

From July 2018 to April 2019 the first period of concerted data collection was undertaken focussed on a collaboration with a leading synthetic biology company in California, USA (hereafter referred to as the case company). As the proposed research involved human participants, ethical approval was sought and received from the Alliance Manchester Business School Panel (Appendix A.3). The case study involved applying the CSA framework in practice, working collaboratively with the researchers and company employees. Data was collected primarily through workshops and surveys as well as a small number of follow-up interviews. During this time, to enable the CSA process, desk-based sustainability assessments were undertaken which involved the use of analytical methods such as techno-economic analysis (TEA) and LCA. To support this work, the SustAssessR codebase was developed for carrying out sustainability assessments using the R statistical programming language (Matthews, 2019; R Core Team, 2021). The case study results were written-up in the Spring of 2019 and published in December 2019.

The research was interrupted for three months between the 22nd July and 22nd October 2019 complete a UKRI internship at the Government Office for Science[9]. This internship was undertaken for experience and career development, rather than as a research or data-collection opportunity. However, the internship did provide insight into the world of policy-making, particularly science and innovation policy.

On returning to PhD research, I reflected on where to take the research next. The research up to this point had focussed predominantly on Research Question 1 and had been relatively successful in addressing it through the development and application of the CSA framework. Yet, the case study had raised questions concerning the feasibility of embedding sustainability assessment approaches like CSA within existing governance arrangements for emerging technologies, as well as the role of policy in this. It was therefore decided that the remaining period of the PhD would be best spent focusing on Research Question 2. There were two parallel avenues to approach this.

Firstly, during the company case study, the utility of the CSA framework had been discussed and explored with employees which had provided rich insights concerning where they did and didn't feel that they were able to actively embed sustainability considerations in their operations. It was decided to unpack and develop these findings into the third paper of the thesis. The data analysis and drafting process for this paper took place between October 2019 and November 2020.

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[9] https://www.gov.uk/government/organisations/government-office-for-science

The second avenue was to investigate the role that sustainability has played in the promotion of synthetic biology in the UK. This involved building on the network of contacts and a deepening understanding of the UK synthetic biology ecosystem that had been developed over more than two years of engagement with the field. A research design utilising an exploratory case study approach was developed and grounded in the innovation studies literature. Ethical approval was sought and received in February 2020 (Appendix A.4). Data (documentary evidence and interviews) was gathered throughout the first half of 2020, with some inevitable disruption due to the COVID-19 pandemic. Data analysis and writing-up then proceeded throughout the remainder of 2020.

1.3 Definitions

It is helpful at this early stage to clarify definitional issues regarding some of the key concepts used in this thesis.

Science, Technology, and Innovation

While Science, Technology, and Innovation are often referred to collectively within the STI acronym, it is appropriate to break this down and identify the important distinctions between the concepts, how they interrelate and in what context they are used in this thesis.

Taking first *science* and *technology*, in theory, they can be neatly distinguished by the systematic process through which knowledge can be generated (science) and the practical application of knowledge (technology). This thesis is mostly concerned with the latter, and as a result, there is relatively little reference to “science” specifically. However, it is also important to recognise “the complex intertwining of science and technology that marks the modern world” (Nelson, 1992, p. 350). It would be incorrect to say that all of the knowledge that underpins technology is derived from the sciences (much of it being gained incrementally through its application and use). However, it is fair to say that in modern societies a considerable portion of technological change is science-based and most fields of technology have accompanying fields of science that feed into and interact with them (Narin et al., 1997; Nelson, 1992).

This thesis often refers to the concept of *emerging technologies*. What makes a technology emergent is not easily defined, although Rotolo et al. (2015) identify five common features mentioned in definitions: “(i) radical novelty, (ii) relatively fast growth, (iii) coherence, (iv) prominent impact, and (v) uncertainty and ambiguity” (p. 1827). As previously described, the emergence of new technological fields is also often accompanied by somewhat extravagant visions and promises regarding its perceived impact and benefits which play an important role in shaping and enabling their emergence (Borup et al., 2006; Schyfter & Calvert, 2015). Thus, one additional feature might be added to that list: *hype*.

Increasingly, we have seen the use of the term *innovation* to encapsulate a broader perspective with a less explicit science and technology focus (Fagerberg et al., 2012; Fagerberg & Verspagen, 2009; Martin, 2012). Schumpeter famously described innovation as “new combinations” of knowledge and resources and viewed innovation as the implementation of new ideas as distinct from their invention (Fagerberg et al., 2012; Schumpeter, 1934). Focussing on innovation as opposed to science or technology specifically allows the consideration of non-scientific knowledge and non-technological combinations and helps to emphasise the complex, dynamic, and social processes through which these new ideas and combinations emerge and diffuse (Kline & Rosenberg, 1986).

Predominantly, this thesis employs the terms *emerging technologies* and *innovation*, remembering that the former can be considered an important object of study within broader innovation processes and systems (Hekkert et al., 2007; Rotolo et al., 2015). At times, the STI acronym is also employed, particularly when considering the wider policy landscape. Which terms are employed depends on the particular level and object of analysis and the different literature being mobilised. This pragmatic approach was necessary given the range of terms used, often interchangeably, in the literature. However, every effort has been made to achieve internal consistency within each paper of this journal format thesis.

Sustainability

The sustainability agenda can trace its roots to long-established debates about the potential limitations to the human exploitation of nature (e.g. Malthus, 1798). The latter half of the 20th Century saw the publication of many influential works on the subject such as Carson's *Silent Spring* (1962), Hardin's *Tragedy of the Commons* (1968), and the Club of Rome report *The Limits to Growth* (Meadows et al., 1972). The 1987 Brundtland report, as well as proposing a detailed strategy for sustainable development, laid down what remains the most widely used definition:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* (Brundtland Commission, 1987)

There have been numerous subsequent attempts to build on and provide further specification on what *is* sustainable development (Kates et al., 2005). One approach has been to explicitly distinguish between what is to be developed from what is to be sustained (National Research Council, 1999). Meanwhile, the triple-bottom-line approach of economy, society, and environment has sought to broaden the attention of businesses away from the single bottom-line of profit to also consider value creation for people and planet (Elkington, 1997). Breaking down sustainable development into a set of high-level goals to be achieved has been an approach taken at the UN level with the millennium development goals and their successor, the seventeen SDGs (UN, 2015b; United Nations General Assembly, 2000). Indicators take this one step further towards a concept that can be explicitly measured, with examples such as ecological footprint and the human development index (HDI) (Strezov et al., 2017). Kates et al. (2005) delineate two further ways to conceptualise sustainable development. Firstly, the indicators, goals, and definitions described above "are all expressions of values" (ibid., p. 16) while the Earth Charter explicitly proposes a set of values and principles[10] to guide a more sustainable society (Earth Charter

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[10] The four high-level pillars or principles laid down were: respect and care for the community of life; ecological integrity; social and economic justice; and democracy, nonviolence, and peace (Earth Charter Commission, 2000).

Commission, 2000). Finally, it can be conceptualised in terms of its practice, whether that be in terms of the social movements (early examples being Friends of the Earth and Greenpeace formed in 1969 and 1971 respectively), institutional initiatives (notably at the UN), or the efforts within many domains of science and technology to address sustainability challenges (Kates et al., 2005).

The idea of sustainability is central to this thesis, yet it remains an idea with a vague and varied definition. Indeed, this lack of definition is an important feature of the concept in enabling many different actors, agendas, worldviews, and value-systems to come together behind a single idea and is something that is actively discussed in this thesis (Kates et al., 2005). Therefore, a clear and specific definition would be unsuitable, although it is important to clarify that when sustainability is referred to in this thesis it is in reference to this broader sustainable development agenda and discourse, rather than a generic reference to the ability to sustain something.

One final aspect worth clarifying is the distinction and connection between sustainability and sustainable development, described eloquently by UNESCO:

> *"Sustainability is often thought of as a long-term goal (i.e. a more sustainable world), while sustainable development refers to the many processes and pathways to achieve it (e.g. sustainable agriculture and forestry, sustainable production and consumption, good government, research and technology transfer, education and training, etc.)."* (UNESCO, n.d.)

As this thesis considers both the long-term goal of sustainability and the pathways to achieve it, both terms are widely employed.

1.4 Thesis structure and contribution

The thesis is presented in a journal format with the body (Chapters 2-5) consisting of four journal-style papers (Figure 1.2). Two of these have already been published in peer-reviewed journals. It is possible to read this thesis as an iterative cycle of action research and this section presents the subsequent chapters of the thesis as such, using the stages of *problem identification*, *diagnosis*, *planning*, *intervention*, and *evaluation* (Cassell & Johnson, 2006).

Chapter 2 derives from a manuscript published in the journal *Sustainable Production and Consumption* (Matthews, Stamford, et al., 2019). The chapter seeks to *identify* and *diagnose* the problem – the need for sustainability assessment approaches that can align social science and natural science approaches – and then articulates the theoretical, conceptual, and methodological details of a possible *intervention* strategy called Constructive Sustainability Assessment (CSA). The CSA approach embraces methodological pluralism in line with a critical realist research paradigm, matching theory and method to mechanism. The novelty of the CSA framework is found in the way it aligns deliberative governance approaches such as RRI and analytical sustainability assessment methodologies such as LCA.

Chapter 3 derives from a manuscript published in *Scientific Reports* (Matthews, Cizauskas, et al., 2019). Co-published with industry collaborators[11], it reports on the application of CSA in an industry context and the first published sustainability assessment of bio-based nylons 410 and 510.[12] In the context of action research, this chapter represents an *intervention*. This paper presents detailed sustainability assessment results, providing empirical insight into some of the sustainability trade-offs involved in transitioning to bio-based production methods. It also demonstrates how CSA can be utilised in practice to provide actionable insights for innovators at the early stages of technological development.

The results of this intervention are more broadly *evaluated* in Chapter 4. In this paper, the barriers to the case company taking action on sustainability are explored and unpacked with particular attention to how the nature of the sustainability concept and the systemic context in which the company operates influence, obstruct, and potentially redirect efforts towards sustainability. The possibility of greater alignment of the Silicon Valley model of business operation employed by the company with sustainable development is explored.

Chapter 5, the fourth and final paper of the thesis, presents the results of an exploratory case study investigating the role that sustainability has played in the promotion of synthetic biology in the UK. Empirical data from interviews and documentation is used to probe where sustainability considerations have (and haven't) been embedded. This chapter can be thought of as the initiation of a new cycle of action research, focussed on *problem identification* and *diagnosis*, building on some of the obstacles encountered during the previous interventions. The paper analyses how expectations of improved sustainability played a role in policy processes and considers how these have been rationalised within the policy strategy and instrument mix, identifying the manifestation of transformational failures[13] in this case.

Finally, Chapter 6 sets out the overarching contributions and conclusions of the thesis. The implications of the CSA framework for our understanding of the Collingridge dilemma are first explored. The validity, usability, and transferability of CSA are then considered, identifying some outstanding limitations and suggesting avenues for future research. Next, the findings of the thesis are integrated to develop a tentative framework for the societal alignment of emerging technologies towards sustainable development. Lastly, the implications of the thesis more generally for how we should understand the sustainability potential of emerging technologies are discussed. The limitations and potential for further research are then considered. Finally, three sets of recommendations are offered for research, policy, and business: i) to critically assess the sustainability potential of emerging technologies, ii) to specify sustainability claims and needs, and iii) to reshape the socio-technical landscape for sustainable technologies.

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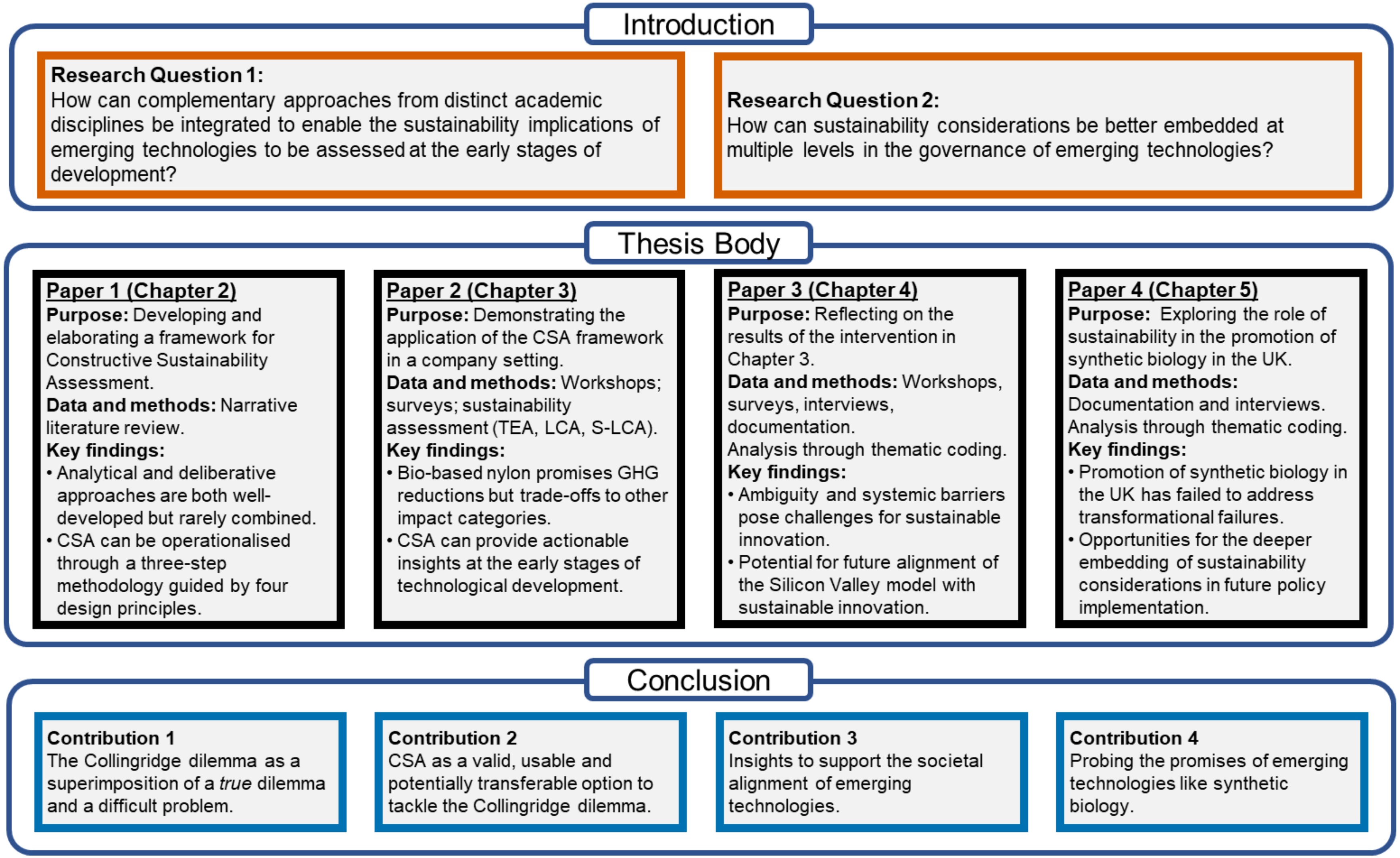
[11] I was the first author of this paper and led all the key activities in developing the paper including conceptualisation, data collection and analysis, and manuscript drafting.

[12] A recent review in Nature Sustainability (Ögmundarson et al., 2020) searched for articles on the subject between 2003 and 2018 and found no previous LCA studies for the key precursor 1,5-pentanediamine (referred to as cadaverine in Chapter 3). The chemicals company Evonik Industries has carried out LCAs for biobased polyamide 1010 and partially bio-based polyamide 510: https://www.vestamid.com/en/products-services/VESTAMID-terra/ecologic-benefits.

[13] See Weber & Rohracher (2012).



Research Question 1:
How can complementary approaches from distinct academic disciplines be integrated to enable the sustainability implications of emerging technologies to be assessed at the early stages of development?

Research Question 2:
How can sustainability considerations be better embedded at multiple levels in the governance of emerging technologies?

Paper 1 (Chapter 2)
Purpose: Developing and elaborating a framework for Constructive Sustainability Assessment.
Data and methods: Narrative literature review.
Key findings:
- Analytical and deliberative approaches are both well-developed but rarely combined.
- CSA can be operationalised through a three-step methodology guided by four design principles.

Paper 2 (Chapter 3)
Purpose: Demonstrating the application of the CSA framework in a company setting.
Data and methods: Workshops; surveys; sustainability assessment (TEA, LCA, S-LCA).
Key findings:
- Bio-based nylon promises GHG reductions but trade-offs to other impact categories.
- CSA can provide actionable insights at the early stages of technological development.

Paper 3 (Chapter 4)
Purpose: Reflecting on the results of the intervention in Chapter 3.
Data and methods: Workshops, surveys, interviews, documentation. Analysis through thematic coding.
Key findings:
- Ambiguity and systemic barriers pose challenges for sustainable innovation.
- Potential for future alignment of the Silicon Valley model with sustainable innovation.

Paper 4 (Chapter 5)
Purpose: Exploring the role of sustainability in the promotion of synthetic biology in the UK.
Data and methods: Documentation and interviews. Analysis through thematic coding.
Key findings:
- Promotion of synthetic biology in the UK has failed to address transformational failures.
- Opportunities for the deeper embedding of sustainability considerations in future policy implementation.

Contribution 1
The Collingridge dilemma as a superimposition of a *true* dilemma and a difficult problem.

Contribution 2
CSA as a valid, usable and potentially transferable option to tackle the Collingridge dilemma.

Contribution 3
Insights to support the societal alignment of emerging technologies.

Contribution 4
Probing the promises of emerging technologies like synthetic biology.

Figure 1.2: A summary of the thesis structure and content.

Chapter 2: Aligning sustainability assessment with responsible research and innovation: Towards a framework for Constructive Sustainability Assessment

This chapter is based on a manuscript of the same name that was published in May 2019 in the journal Sustainable Production and Consumption:

Matthews, N. E., Stamford, L., & Shapira, P. (2019). Aligning sustainability assessment with responsible research and innovation: Towards a framework for Constructive Sustainability Assessment. Sustainable Production and Consumption, 20, 58–73. https://doi.org/10.1016/j.spc.2019.05.002

The manuscript was co-authored with the doctoral supervisors Philip Shapira and Laurence Stamford. The thesis author led all stages of producing the manuscript including conceptualisation and drafting.

Abstract

Emerging technologies are increasingly promoted on the promise of tackling the grand challenge of sustainability. A range of assessment and governance approaches seek to evaluate these claims, but these tend to be applied disparately and lack widespread operationalisation. They also face specific challenges, such as high levels of uncertainty, when it comes to emerging technologies. Building and reflecting on both theory and practice, this chapter develops a framework for *Constructive Sustainability Assessment* (CSA) that enables the application of sustainability assessments to emerging technologies as part of a broader deliberative approach. In order to achieve this, we first discuss and critique current approaches to analytical sustainability assessment followed by deliberative social science governance frameworks. We then develop the conceptual basis of CSA – blending life-cycle thinking with principles of responsible research and innovation. This results in four design-principles – transdisciplinarity, opening up, exploring uncertainty, and anticipation – that can be followed when applying sustainability assessments to emerging technologies. Finally, we discuss the practical implementation of the framework through a three-step process: a) formulate the sustainability assessment in collaboration with stakeholders, b) evaluate potential sustainability implications using methods such as anticipatory life-cycle assessment, and c) interpret and explore the results as part of a deliberative process. Through this, CSA facilitates a much-needed transdisciplinary response to enable the governance of emerging technologies towards sustainability. The framework will be of interest to scientists, engineers, and policy-makers working with emerging technologies that have sustainability as an explicit or implicit motivator.

2.1 Introduction

While aggregate economic growth and urbanisation continue at a global level, conveying improved opportunities, health, and quality of life for many, this is occurring at the expense of the environment with the costs and benefits of development unevenly distributed (UN, 2012). Recognition of these problems has led to the emergence of sustainable development as a dominant paradigm to mobilise governance and policy responses, defined by the 1987 Brundtland report as follows:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Brundtland Commission, 1987)*

Through the United Nations (UN), multiple attempts have been made to bring about coordinated international efforts towards sustainable development. Of particular note are the 17 Sustainable Development Goals (SDGs) which span a range of environmental, social, and economic areas (UN, 2015b).

With the pressing challenge of sustainability, there is a growing focus on how emerging technologies could provide potential solutions to sustainability challenges (UNCTAD, 2018). Recent examples include synthetic biology, nanotechnology, and artificial intelligence. Disruptive scientific and technological developments are anticipated in these domains which can be viewed in terms of Kuhnian style "paradigm shifts" (Kuhn, 1962) as well as Schumpeterian examples of "creative destruction" (Schumpeter, 1942). The field of sustainability transitions suggests that disruptive innovation is essential in order to displace existing socio-technological regimes but that the transition to more sustainable modes is as much a social as a technical one, requiring an understanding of issues such as lock-in and path-dependency that exert powerful exclusion effects on new entrants (Kemp et al., 1998; Markard et al., 2012). Furthermore, new and disruptive technologies are often accompanied by a promise of improved sustainability (French, 2019), yet they can also create new problems and can result in inequitable distribution of costs and benefits (Balmer & Martin, 2008; van den Belt, 2013; Yuste, 2017). Thus, the sustainability promises associated with emerging technologies cannot be taken as an assumed fact; rather, critical evaluation is required, from both technical and social points of view, ideally at the early stages of development.

Recently, there has been a policy drive towards developing technologies that contribute to sustainable development, an example being the European Commission's eco-innovation initiative (EC, 2013a). At the same time, policy (reflecting public concerns) increasingly seeks for emerging technologies to be governed in a manner that is in line with societal priorities, encapsulated within the concept of responsible research and innovation (RRI) (EC, 2013a; SBRCG, 2012; Stilgoe et al., 2013). Linking these two aspects is the aspiration for innovations and technological change to be directed towards tackling societal "grand challenges", including the pressing need to transition to a more sustainable society (von Schomberg, 2013).

To align emerging technological fields with desired societal and sustainability outcomes requires knowledge concerning the sustainability impacts of technologies to be made available at low technology readiness levels (TRLs) in research, proof of concept, and testing phases. The concurrent application of sustainability assessments to emerging technologies as they emerge could allow technological advances to be taken forward sustainably. However, in the early phases of technological development, the data is neither known nor available to carry out established environmental assessments of an innovation. Yet, by the time the technology has developed, such that this data is available, much developmental flexibility has been lost as lock-in and path-dependence sets in. This challenge is often referred to as the Collingridge dilemma (Collingridge, 1980). Furthermore, such assessments require clear underlying definitions of sustainability and sustainable development, as well as a grasp of what society wants and needs from emerging technologies. The latter is also particularly uncertain during the early stages of development.

While early technological development that is concurrent and iterative with sustainability assessment is inherently problematic, we suggest that there are ways to navigate through this complexity. Assessment approaches from a variety of fields have been developed with the aim of generating knowledge to guide emerging technologies. These originated as analytical and expert-based assessment routines but have increasingly been augmented with more qualitative, deliberative, and participatory approaches to assessing and governing emerging technologies developed in the social sciences (Stirling, 2008a). We argue that both the deliberative and analytical approaches are complementary and aim to deconstruct the distinctions between them to develop a conceptual framework for *Constructive Sustainability Assessment* (CSA). By "constructive", as we will discuss in subsequent sections, we mean inclusive processes of dialogue, interaction, and consideration of diverse groups in technological design and deployment. CSA grounds the state-of-the-art in sustainability assessment within deliberative methods to allow for the more open and mutually beneficial evaluation and governance of emerging technologies.

We start by discussing both analytical sustainability assessments and deliberative governance approaches. We then explore their potential complementarity, developing four principles of CSA that can guide the application of sustainability assessments to emerging technologies. Finally, we outline a practical, three-step methodology to operationalise CSA.

2.2 Assessing sustainability

Although numerous analytical approaches to assessing sustainability have emerged in recent decades (such as energy/exergy analysis and carbon/ecological footprinting), typically with a focus on environmental sustainability, the most widely applied and comprehensive methodology is that of life-cycle assessment (LCA) (Patterson et al., 2017). LCA was first developed in the 1970s, with a focus on reducing resource depletion and environmental damage (Klöpffer, 1997). A series of concerted efforts in the 1990s resulted in International Organization for Standardization (ISO) standards for LCA and the now widely familiar underlying structure for LCA studies shown in Figure 2.1 (Guinée et al., 2011; ISO, 2006b, 2006a).

The LCA approach is underpinned by "life-cycle thinking" (LCT). LCT involves broadening the perspective when evaluating products and processes such that flows and impacts are considered throughout the life-cycle from "cradle-to-grave"[14] (Azapagic, 2010). Taking a life-cycle perspective when evaluating sustainability seeks a holistic consideration of all possible impacts of a product, aiming to avoid temporal or geographic burden-shifting and unexpected impacts. With the concern that the continued growth of production and consumption is pushing the earth to its biophysical limits, it is hoped that applying a life-cycle approach can help to achieve more sustainable patterns of consumption and production (Azapagic & Perdan, 2014).

Recently, LCA has undergone further infrastructural and methodological development. New approaches have emerged such as hybrid, economic input-output, and anticipatory LCA (Wender, Foley, Hottle, et al., 2014). There have also been developments in LCA databases (e.g. Ecoinvent, U.S. LCI Database) and software tools (e.g. OpenLCA, Brightway2) to open up the application of LCA to a broader spectrum of practitioners (Finnveden et al., 2009). Several life-cycle impact assessment (LCIA) methodologies have been proposed and improved upon (e.g. ReCiPe, CML), incorporating an enhanced understanding of pollutant pathways, ecosystem, and human health impact mechanisms, and, in some cases, differing value systems. Attention has been raised to the issues of scale-up and its effect on LCA results with approaches put forward to better take into account scaling effects (Piccinno et al., 2016; Shibasaki et al., 2006; B. Simon et al., 2016). Using highly-aggregated datasets with limited primary data, screening-level LCA studies have been deployed to allow hotspot identification during preliminary product development (Gasa & Weil, 2011; Upadhyayula et al., 2017). At the same time, the importance of handling and propagating uncertainty has been increasingly recognised, with sensitivity and uncertainty analysis forming key steps in many LCA studies (Finnveden et al., 2009; Gargalo, Cheali, Posada, Carvalho, et al., 2016).

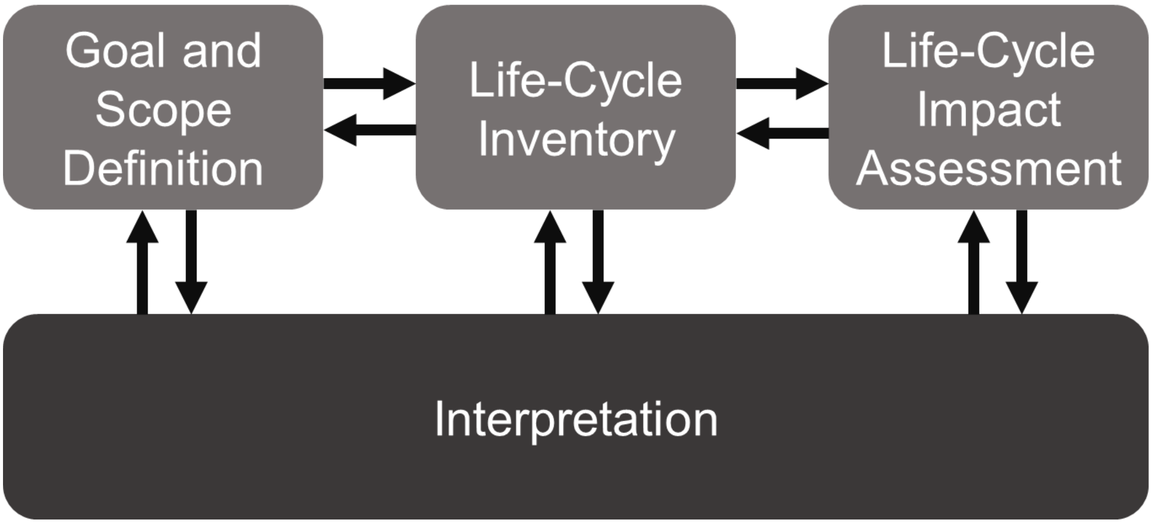


Figure 2.1: The ISO standards structure for an LCA (Source: ISO, 2006).

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[14] "Cradle-to-gate" and "gate-to-gate" are also common variants with different system boundaries, chosen as appropriate for the system under study.

2.3 Emerging challenges for analytical sustainability assessments

2.3.1 New responsibilities

Sustainability is progressively becoming an influential and crucial topic and an area of societal concern. As a result, sustainability assessments are increasingly employed by firms and governments who are applying life-cycle thinking to promote more sustainable decision-making (Sala et al., 2016; Sonnemann et al., 2018; UNEP/SETAC, 2008). Sala et al. (2015) conceptualise sustainability assessment as a tool for operationalising sustainability science and a systematic approach through which the SDGs can be achieved. This highlights an evolving view of what sustainability assessment can and should be mobilised to do, with an increasing focus on utilising analytical sustainability assessments to inform decision-making and governance to help facilitate transitions to a more sustainable society (Sala et al., 2015; Sonnemann et al., 2018).

Applying analytical assessments to emerging technologies is an area of particular promise as they represent technologies that have not yet been entrenched by path dependency and lock-in. Although there is debate about how emerging technologies can and should be defined (Rotolo et al., 2015), these are broadly technologies that are still “in-the-making” (Latour 1987). This creates opportunities for assessment where knowledge or information that can be generated at the early stage of development has a greater potential to influence subsequent development and associated impacts. Early analytical assessments can be important in influencing the promises, commitments, and expectations of emerging fields which in turn shape the technological facts and objects that are created (Borup et al., 2006). Thus, the way in which early analytical sustainability assessments are carried out, framed, used, and communicated becomes an even more crucial consideration and responsibility. To take up these roles and responsibilities, analytical sustainability assessments must address several challenges, as outlined below.

2.3.2 Broader notions of sustainability

Demonstrated by the wide remit of the UN’s SDGs, contemporary notions of sustainability span far beyond environmental considerations and biophysical limits to consider social and economic dimensions (Azapagic & Perdan, 2014; Grunwald & Rösch, 2011; UN, 2015b). To accommodate this, there has been a call within the sustainability assessment community to “broaden the scope” of LCA (Jeswani et al., 2010; Weidema, 2006). Life-cycle sustainability assessment (LCSA) tackles this by taking a three pillars approach to sustainability assessment, combining LCA with life-cycle costing (LCC) and social life-cycle assessment (SLCA) (Finkbeiner et al., 2010; Kloepffer, 2008; UNEP/SETAC, 2011; Zamagni et al., 2013).

However, of the three components of LCSA, neither LCC nor SLCA has reached the level of method development or standardisation seen for LCA. LCC has long been applied alongside LCA (Norris, 2001) and while a code of practice has been developed to align it with LCA (Swarr et al., 2011), LCC lacks consensus over how it should be applied or, indeed, whether it is a relevant part of LCSA at all (Jørgensen et al., 2010; Wood & Hertwich, 2013). SLCA, on the other hand, represents a younger and less consistent concept. Guidelines were laid down by UNEP/SETAC almost 10 years ago with an update recently published (UNEP/SETAC, 2009, 2013; UNEP, 2020). Progress has also been made to address data shortages, for example with the development of the social-hotspots database and PSILCA (Benoît Norris et al., 2012; Ciroth & Eisfeldt, 2016). However, while the literature surrounding SLCA is growing rapidly (Petti et al., 2016; Ramos Huarachi et al., 2020), the lack of standardisation has been a persistent issue (Arcese et al., 2016; Grubert, 2016; Kühnen & Hahn, 2017; Russo Garrido et al., 2016).

The inclusion of social impacts brings increased challenges to the field of analytical sustainability assessment. Assessing social aspects greatly increases levels of subjectivity and requires a move away from the positivist epistemology used in LCA and LCC. It is therefore increasingly agreed that if (S)LCA is going to robustly grapple with the social dimension within sustainability assessments then there is a need to embrace the role of the social sciences (Azapagic & Perdan, 2014; Grubert, 2016; Iofrida et al., 2018; Sala et al., 2013). Qualitative approaches applied in the social sciences can assess social impacts for which no quantitative metric can be fully or readily derived but this is epistemologically inconsistent with traditional environmental LCA which applies a positivist approach reflecting the engineering paradigms it developed within (Iofrida et al., 2018). At the early stages of technological development, the assessment of environmental and economic aspects may also benefit from employing these more qualitative approaches given the high levels of uncertainty. As a result, future sustainability assessments will necessitate a multi-paradigm approach to marry different epistemological positions under a single framework (Lang et al., 2012). This represents a fundamental challenge.

2.3.3 The limitations of analytical approaches

Sustainability assessment methodologies, such as LCA, might provide a means through which the sustainability promises of emerging technologies can be evaluated and unexpected impacts identified at low-TRLs such that certain technological trajectories can be avoided or impacts mitigated. However, typically, LCA approaches rely on detailed and specific data from throughout the life-cycle of processes and products that are already in the market (Cherubini et al., 2009; Spath et al., 1999; Vink et al., 2003; A. G. Williams et al., 2006). In recent years, an increasing volume of research has attempted to conduct LCA on products at low TRLs, such as nanomaterial production, graphene, biofuels, and carbon capture and utilisation (Arvidsson et al., 2014; Cuellar-Franca et al., 2016; Gavankar et al., 2015; Hischier & Walser, 2012; Rajagopalan et al., 2017; Wender, Foley, Prado-Lopez, et al., 2014). While it appears that the existing underlying framework for conducting LCA is appropriate for emerging technologies, there is no well-established approach to the use of LCA under such circumstances (ISO, 2006a, 2006b; Klöpffer et al., 2006). Furthermore, these analytical approaches face a number of limitations:

- No assessment can ever be fully objective. LCA studies involve subjective judgements relating to system boundaries, data sources, allocation, impact assessment, and aggregation. Subjective decisions, assumptions, and limitations are an inherent feature of any modelling approach, particularly when new methods are being developed. While the ISO standards for LCA provide guidance on transparency by clearly setting out the “goal and scope” of any assessment (ISO, 2006b), a great deal of “black-boxing” still occurs, and there is little guidance on how these subjective decisions should be made.

- The use of Monte Carlo simulations and probabilistic comparisons can enable the high parameter uncertainty experienced at low-TRLs to be propagated and explored (Wender, Foley, Prado-Lopez, et al., 2014). However, this uncertainty is not always communicated in the results, with many studies still attempting to present simple, aggregated results, which can be misleading for policy-makers (Stirling, 2008b). Moreover, the ISO standards for LCA do not explicitly detail the need, method, or communication of any formal uncertainty analysis.
- It is inevitable, particularly for emerging technologies, that some aspects will not be responsibly measurable: at some threshold of statistical uncertainty, the existing analytical methods for handling uncertainty becoming insufficient (Hetherington et al., 2014). However, while a quantity or aspect being unknown or unmeasurable does not make it any less significant, a purely analytical assessment would simply omit it as a known unknown.
- Unknown unknowns are prevalent when assessing emerging technologies with limited available data and knowledge. Previous technologies promoted on the grounds of (environmental) sustainability have proved to have questionable sustainability performance once further information comes to light: a notable example being first-generation biofuels and bio-based plastics when indirect land-use change is taken into account (Piemonte & Gironi, 2011; Searchinger et al., 2008).
- An unavoidable constraint is that of limited resources, in terms of skills, time, and/or money. The application of complex analyses during periods of rapid technological development will inherently involve tough choices with respect to the allocation of resources, potentially leading to incomplete assessments (Peace et al., 2017).

A final caveat is more fundamental. Definitions of sustainable development hinge around concepts of intergenerational equity and of maintaining quality of life now and in the future by working within our biophysical limits. However, while these biophysical limits represent phenomena that can be measured against, the kind of world and society that should be maintained within those limits is a subjective and value-laden judgement (de Vries & Petersen, 2009). Furthermore, the role and relevance of sustainability assessment tools in informing the broader field of sustainability science and guiding the path to sustainable development is essentially dependent on the worldviews and values of those individuals and stakeholders concerned (Asveld & Stemerding, 2016). Depending on differing views of knowledge and of nature, the ways in which sustainability assessments would be interpreted, or indeed whether they are relevant at all, may differ markedly (Asveld et al., 2014; de Vries & Petersen, 2009; Hofstetter et al., 2000). Thus, analytical approaches on their own will never be sufficient to fully address societal concerns surrounding emerging technologies.

These issues should not be construed as a critique of analytical sustainability assessments themselves, which frequently yield valuable and robust quantitative findings that can inform sustainability-minded governance and decision-making. On the contrary, the field of analytical sustainability assessment has progressed and developed considerably in response to the new challenges it faces as it is increasingly tasked with helping to deliver a more sustainable society. Rather, the problem lies in the way in which analytical approaches are employed and communicated. All too often, analytical approaches like LCA are asked to answer specific sustainability questions yet when it comes to the concept of sustainability and subjective decision-making, there is only so much that an analytical perspective can inform. In all cases, but particularly for emerging technologies, employing purely analytical approaches yields a substantially incomplete picture.

To address these challenges, we suggest that the field of analytical sustainability assessment must continue to evolve and progress, operationalising a more transdisciplinary approach, engaging in active dialogue with stakeholders to position sustainability assessments within broader societal contexts, and considering how sustainability assessments can be pragmatically applied to explore rather than answer sustainability questions and communicate this within sometimes-restrictive industry and policy contexts. Such changes are already well underway and will result in a methodology almost unrecognisable from the early roots of LCA. Sustainability assessments must continue to expand from their analytical roots and draw upon the experiences and approaches of other fields, particularly those that deal with the challenges of assessing and governing emerging technologies, such as technology assessment and deliberative governance frameworks.

2.4 Technology assessment and deliberative governance

2.4.1 From Technology Assessment to Responsible Innovation

The formal elaboration of technology assessment (TA) arose in the latter half of the 20th century, reflecting an aim of “reducing the costs of trial and error learning” (Schot & Rip, 1996, p. 251) by anticipating potential social and technical problems associated with emerging technologies. A key event in this movement was the establishment in 1972 of the Office of Technology Assessment (OTA) by the US Congress, with further TA offices formed in Europe such as the Netherlands Office for Technology Assessment (NOTA, now the Rathenau Institute). The emergence of TA reflected, explicitly or implicitly, an anticipation of what is now known as the Collingridge dilemma (noting that the emergence of TA precedes Collingridge’s 1980 book) (Nordmann, 2010).

While early forms of TA were critiqued as too expert-based (van Lente et al., 2017), there was an early recognition of the “heavily entangled” nature of technology and society and therefore that assessments can never be truly objective or value-free (Bijker et al., 1987; A. M. Lee & Bereano, 1981). Subsequently, there were efforts to engage with broader stakeholders to facilitate the co-production of emerging technologies. An early example was constructive technology assessment (CTA), pioneered by NOTA in the 1980s–1990s (Schot & Rip, 1996). CTA aims to inform decision-making surrounding technologies by anticipating impacts while taking a constructive approach, where “design criteria” for technologies are developed in an open and inclusive process, helping to facilitate societal alignment of emerging technologies (Ribeiro et al., 2018;

Schot & Rip, 1996). CTA focusses on bridging gaps between technological actors and wider society by facilitating interactive workshops and other “bridging events” which can provide spaces for anticipation and reflexivity (Rip, 2018). These events may help to reduce and actively manage uncertainties surrounding impacts and societal responses.

The development of CTA marked a key shift in focus away from government- or parliament-centred forms of TA focussed on informing policy, towards more distributed approaches (A. M. Lee & Bereano, 1981). CTA laid the groundwork for subsequent developments such as real-time technology assessment, anticipatory governance, and RRI (Guston, 2014; Guston & Sarewitz, 2002; Stilgoe et al., 2013). Such approaches are characterised by a closer relation to the development of technology itself, emphasising distributed responsibility for technological development amongst a wide variety of actors. These changes reflect an increasing recognition of the potential problems, as well as benefits, created by emerging technologies alongside a fundamental reframing of technological innovation away from the view of research and development as an intrinsic public good (Schot & Steinmueller, 2018; van Est, 2017). Thus, these frameworks exist in a new context, one where there is a desire to actively shape future socio-technological systems towards tackling societal grand challenges such as sustainable development (Fleischer & Grunwald, 2008; Kemp et al., 1998; Nordmann, 2010). For convenience, we shall refer to this family of approaches as “deliberative approaches”, recognising their common emphasis on multi-stakeholder deliberation and goal of opening up discussions around emerging technologies (van Lente et al., 2017).

Reflecting a growing public policy drive for emerging technologies to tackle societal grand challenges, attempts have been made more recently to further institutionalise deliberative governance approaches within technological R&D projects to foster responsible innovation (Owen et al., 2021; Roco et al., 2011; von Schomberg, 2011). In the United States, two social science research centres were incorporated within the National Science Foundation’s nanoscale science and engineering research programme leading to the development of real-time technology assessment and anticipatory governance approaches that attempt to tackle the Collingridge dilemma by leaving “…that relationship between governing decision and quality of knowledge in productive tension” (Guston, 2014, p. 227). An aim was to provide instruments to enable the co-construction of emerging technologies towards societal needs using widespread public engagement, participatory scenario development, and integration of social and natural scientists within research environments, distributing responsibility throughout a variety of actors in technological development (Barben et al., 2008; Guston, 2014).

Meanwhile, in Europe, RRI has been incorporated into research programmes at both the European and national levels (EC, 2017; Owen et al., 2021). One influential framework advocates for the embedding of principles of anticipation, inclusion, reflexivity, and responsiveness into the research and innovation process (Stilgoe et al., 2013). The core elements of this framework were adopted by the UK’s Engineering and Physical Sciences Research Council (2019). Inclusion reflects the increasingly recognised need to engage relevant stakeholders early, to ensure the appropriate social values are considered in technology development (Delgado et al., 2011; Wilsdon & Willis, 2004). Responsiveness emphasises the importance of being able to modulate trajectories as knowledge of impacts and stakeholder values develops. A critique of precursors to RRI was the lack of institutionalised responsiveness, performing more observatory roles instead (Zwart et al., 2014). Reflexivity refers to a level of self-awareness within the institutions, governance structures, and actors that are involved in scientific developments, and involves being open-minded to one's own assumptions and framings (Stilgoe et al., 2013). Finally, anticipation is a process of "capacity building" through the generation of technology visions and imaginaries, drawing from anticipatory governance (Guston, 2014).

2.4.2 Limitations and challenges of deliberative approaches

While deliberative approaches have flourished conceptually, challenges in operationalisation persist. CTA is described as having a "diffuse and emerging character" (Schot & Rip, 1996, p. 252) while RRI has been described as a "mobilising concept" (Ribeiro et al., 2017). Such frameworks may be effective in bringing together interdisciplinary academic perspectives but there is also a distinct lack of clear and practical methodological guidance. Another issue has been that funding for social science research into specific emerging technologies has historically followed several years after the initial natural science funding commitments and on a much smaller scale, limiting the scope for assessments to be carried out and alternative perspectives included (Guston, 2014).

Furthermore, while public engagement is a fundamental feature of the deliberative governance approaches we have described, the role of public participation in assessment processes is still one of contestation. While much of the recent literature, coupled with policy commitments along the same lines, emphasises the need for public participation in science and technology through engagement with assessment and appraisal activities, there is little agreement on when and how this should take place (Delgado et al., 2011; Stilgoe et al., 2014). "Upstream engagement" activities can be particularly challenging in terms of identifying relevant stakeholders and implementing appropriate participatory activities while avoiding artificial framing and closing down of discussions (Brandt et al., 2013; Lang et al., 2012; Wilsdon & Willis, 2004).

The move towards more participatory and deliberative methods for assessing and governing emerging technologies, as part of a more open-ended and democratic approach, could be seen as an alternative to analytical, expert-led approaches. However, particularly in the case of emerging technologies, there are similar risks relating to the framing of the engagement activities which could bias the outcomes, potentially towards instrumental goals. In the case of nanotechnology, it has been claimed that engagement tended to close down discussion and failed to question the linear, determinist view of technological progress (Delgado et al. 2011).

Participatory approaches are pitched as democratising technological development as a means to achieve societal alignment (Ribeiro et al., 2018). However, others suggest that the idea of representing all members of "society" is highly problematic, and practically impossible (van Lente et al., 2017). Furthermore, sustainable development is underpinned by a consideration of the wants and needs of future generations alongside those in the present (Brundtland Commission, 1987). Therefore, employing participatory approaches to guide sustainable technological development may risk prioritising present generations over future generations who cannot represent themselves.

These criticisms notwithstanding, we do not argue that increased participation of citizens and the use of deliberative approaches in technological development processes are unimportant or ineffective. Indeed, such approaches are vital and need to be enhanced to better align technological development with societal goals and needs. The capacity of public engagement to include marginalised voices and contribute to the co-construction of technology should be welcomed. Still, the use of public engagement does not preclude many of the issues of power, representation, legitimation, and framing that pervade analytical approaches (Stirling, 2008a). As Stirling et al. (2008) articulate, the important distinction is not between participatory and analytical approaches, but between “opening up” and “closing down” of technological options, with current approaches tending to close down. Insincere, narrowly framed, and poorly executed engagement is arguably more of a risk than no engagement at all, as it grants the assessment the perceived trust and legitimation of a participatory approach. If improperly used, engagement can act as a smokescreen, and risks being used for instrumental purposes.

More practically, while deliberative governance approaches have demonstrated the utility of participation and deliberation in order to integrate alternative forms and frames of knowledge into early technological development, they often pay little attention to the complementary role that more expert-based analytical assessments might play. According to Grunwald (2007), the combination of explanatory knowledge (such as from analytical assessment) with orientation knowledge (such as derived from participatory approaches) is essential to enable informed, action-oriented knowledge production to help achieve sustainable development. Thus, while the original rejection of purely expert-based assessment approaches may have been well-justified, a more nuanced view of their potential complementarity is required to generate the necessary interdisciplinary knowledge to guide the sustainable development of emerging technologies. We seek to improve the quality and social utility of RRI and related governance approaches, moving away from viewing RRI and other deliberative approaches as substitutes for analytical sustainability assessments (and vice-versa), and towards exploring how they can complement one another.

2.5 Towards a Constructive Sustainability Assessment

For emerging technological developments to be taken forward sustainably, and to deliver on the promises they are promoted upon, there is a need to evaluate the sustainability of technologies as they emerge, requiring the management and tackling of issues relating to uncertainty conceptualised within the Collingridge dilemma. We have so far made the case that neither participatory nor analytical approaches to assessing and governing emerging technologies towards sustainability are in themselves sufficient to do this. Available approaches to do so tend to close down discussions and can lead to narrow framing of the sustainability concepts, questions, and priorities.

We emphasise the complementarity between the analytical and deliberative approaches discussed. Indeed, to fully grapple with the inherently subjective and value-laden concept of sustainability, to assess social impacts, and to introduce participatory methods to help relate sustainability assessment outputs to their broader societal context, there has been a clear and repeated call for greater inclusion of social science methods, theories and perspectives within sustainability assessment frameworks like LCA as part of a transdisciplinary approach to sustainability science (Azapagic & Perdan, 2014; Iofrida et al., 2018; Sala et al., 2013; Thabrew et al., 2009).

While participatory approaches have thus-far evolved along separate streams from analytical sustainability assessment, there now exist the necessary drivers to facilitate productive cross-fertilisation. The call from many authors to embrace the social sciences' role in sustainability assessment is gaining momentum, while the growing number of fields and disciplines attempting to tackle sustainability issues provides the necessary academic groundings to tackle the many dimensions that make up the complex challenge of sustainable development. Furthermore, although similar spaces still need to be established more widely in industry (Flipse et al., 2014), the institutionalisation of social science research within emerging technology research programmes such as those relating to synthetic biology and nanotechnology provides spaces to facilitate the necessary interdisciplinary research (Balmer et al., 2015; Pansera et al., 2020). Within these spaces, alignment with analytical assessments could act as an inroad for more deliberative approaches to engage with and influence the trajectories of emerging technologies. Talking about data and quantitative models, such as can be generated from LCAs, can help social scientists to communicate with natural scientists in their “language” and therefore makes the research and knowledge that is subsequently (co-)produced relevant, understandable, and persuasive.

Building on a small but burgeoning literature, we now aim to blend these different approaches into a coherent framework for *Constructive Sustainability Assessment* (CSA) through which the necessary interdisciplinary assessments can be operationalised. CSA builds on theoretical underpinnings and frameworks from both the social and natural sciences (see Table 2.1). Conceptually, we draw mostly on frameworks for deliberative governance situating CSA close to technological development (Table 2.2), emphasising the importance of deliberative and discursive approaches informed by explanatory knowledge generated through analytical assessments to enable informed and incremental decision-making under uncertainty (Grunwald, 2007). CSA can facilitate the exploration of socio-technical scenarios in interactive workshops to enhance reflexivity through anticipation and learning (Schot & Rip, 1996). Grounding analytical assessments within deliberative governance can thus help to achieve the “reflexive sustainability assessment” called for by Fleischer & Grunwald (2008, p. 896). This enables an iterative process of informed experimentation which provides crucial opportunities for learning in support of sustainability transitions (Luederitz et al., 2017).

We now articulate the CSA framework through four core design principles which capture the complementarity between analytical sustainability assessments and participatory and deliberative approaches, distilling the conceptual links between the two areas of study. This gives a theoretical underpinning to CSA which is grounded in both the social and natural sciences.

2.5.1 Design principle 1: Transdisciplinary approach

The sustainability challenges faced by society (e.g. climate change, water and food scarcity, equitable economic development) fundamentally span social and natural domains (Kates et al., 2001; UN, 2015b). Analytical sustainability assessment can help to evaluate emerging technologies in relation to the biophysical limits of the earth, in terms of ecosystem and human health as well as resource scarcity. However, even given knowledge of their impacts, the governance of emerging technologies to maximise well-being is a question that requires a societal response (de Vries & Petersen, 2009). Therefore, CSA requires the integration of analytical knowledge with knowledge of sustainability goals and criteria (Grunwald, 2007).

In attempting to marry social science and natural science theories and practices, engaging in deliberative activities alongside analytical assessments, CSA builds on the fact that research is increasingly undertaken as part of multi- or trans-disciplinary teams (Gibbons et al., 1994; Leydesdorff & Etzkowitz, 1996). Applying these transdisciplinary approaches, where knowledge is co-produced through an interactive and integrated approach across numerous actors is a fundamental challenge and requires grappling with the differing backgrounds, academic vocabulary, methods, and epistemological positions held by the researchers and societal actors involved.

2.5.2 Design principle 2: Opening up perspectives

A challenge to both analytical and deliberative approaches is that they tend to close down discussion and promote a linear view of technological development. If emerging technologies are to be aligned to societal needs, it is essential to integrate a wider range of perspectives in the assessment process and in the formation of expectations which shape future technological developments (Borup et al., 2006). A way to initiate this is for assessments to actively engage with the viewpoints of a wide range of stakeholders. This requires sustainability assessment practitioners to move out of their “ivory towers” and engage with societal actors (Wiek, Farioli, et al., 2012).

CSA is fundamentally stakeholder focussed, not least because the users of the assessment (e.g. decision-makers in the public and private sectors) are considered integral stakeholders. CSA requires the inclusion of a wider range of perspectives and values in the assessment process than typical analytical assessments allow, maintaining an open discussion of possibilities and interpretations. Engaging with a range of stakeholders is one approach to open up discussions but any attempt at widespread societal engagement activities must be done thoroughly and comprehensively, a challenge that will be further explored later.

Aspect	Traditional LCA	LCSA	RRI, CTA, and anticipatory governance	Anticipatory LCA	SfSA	CSA
Discipline	Natural sciences	Natural sciences (mostly)	Social sciences	Interdisciplinary (but mostly natural sciences)	Interdisciplinary	Interdisciplinary
World-view	Typically follows a hierarchist, “controlled nature” worldview	Typically follows a hierarchist, “controlled nature” worldview	Can handle differing worldviews	Typically follows a hierarchist, “controlled nature” worldview	Can handle differing worldviews	Can handle differing worldviews
Perspective	Retrospective	Mixed	Anticipatory	Anticipatory	Solution-focussed	Anticipatory
Handling of uncertainty	Largely ignored	Increasingly acknowledged and reported	Embraced and acknowledged	Embraced, propagated, and rationalised	Unclear	Embraced, propagated, and rationalised
Opening up or closing down options?	Closing down	Closing down	Opening up (in theory)	Closing down	Closing down	Closing down and opening up
Sustainability aspects	Environmental focus	Can span environmental, economic, and social aspects	Typically focusses on social aspects of emerging technologies	Environmental focus	Can span environmental, economic, and social aspects	Can span environmental, economic, and social aspects
Sustainability definition	Assumed/ prescribed	Assumed/ prescribed	Open	Assumed/ prescribed	Determined through deliberation	Determined through deliberation
Standardisation	Established (ISO 14040/14044)	Increasing (e.g. SLCA guidelines)	Some (e.g. AIRR and AREA frameworks)	In development	Seven step approach	Standard approach at a high-level, flexible application

Table 2.1: A comparison of selected technology assessment and governance routines with CSA (Source: Authors’ elaboration).

Framework	Definition	Novelty	Core principles	Contribution to CSA
Constructive technology assessment *(Schot & Rip 1996)*	"A notion of shared responsibilities for managing technology in society, with all actors working toward the CTA goals of learning, reflexivity, and anticipation." (Schot & Rip 1996)	Inclusion of a broad range of actors in the design of technologies.	• Reflexivity • Co-production • Modulation and learning • Anticipation.	• The use of bridging events. • Inclusion of a broader range of perspectives.
Anticipatory governance *(Guston 2014)*	"A broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible" (Guston 2014)	Closer link to the process of technological development.	• Anticipation • Foresight • Engagement • Integration	• Integration of natural and social sciences. • Taking an incremental approach to governance.
Responsible research and innovation *(Stilgoe et al. 2013)*	"Taking care of the future through collective stewardship of science and innovation in the present" (Stilgoe et al. 2013)	Greater attention to normativity. Innovation to tackle grand challenges.	• Anticipation • Reflexivity • Inclusion • Responsiveness	• Directing innovation towards "normative anchor points" (Von Schomberg 2011) • Importance of embedding reflexivity and maintaining responsiveness.

Table 2.2: A review of selected deliberative governance frameworks and their conceptual contribution to CSA (Source: Authors' elaboration).

2.5.3 Design principle 3: Exploring and communicating uncertainty

Assessing sustainability at low TRLs involves dealing with inevitable data gaps, normative ambiguities, and unknown unknowns that are unresolvable at such an early stage of development (Hetherington et al., 2014; Olsen et al., 2018; van de Poel et al., 2017). Inspired by a recently developed anticipatory LCA (A-LCA) approach, CSA takes a prospective and anticipatory approach to sustainability assessment, embracing uncertainty as a fundamental feature of the assessment (Wender, Foley, Hottle, et al., 2014; Wender, Foley, Prado-Lopez, et al., 2014).

Crucially, while A-LCA focusses on exploring issues of statistical uncertainty using Monte Carlo simulations and probabilistic comparisons, this tackles only one of the many sources of uncertainty (list adapted from van de Poel et al., 2017):

- Parameter and scenario uncertainty;
- Uncertainty surrounding unknowns (both known and unknown) and rebound effects; and
- The subjectivity inherent when considering societal priorities, values, and worldviews.

CSA extends A-LCA to consider and embrace non-statistical uncertainties through the participatory exploration of scenarios, alternative viewpoints, and unknown unknowns. Crucially, CSA acknowledges that uncertainty is a fundamental feature of assessing, evaluating, and governing emerging technologies, but also asserts that within the available uncertain data and information there is a great deal of knowledge that can be extracted to inform decision-making. Indeed, rather than see uncertainty as a limitation, it should be viewed as an opportunity. High levels of uncertainty, as well as reflecting our limited knowledge, also reflects the existence of flexibility and open design options that can be explored (Grunwald, 2007). However, it is imperative when handling uncertainties that they are propagated throughout the process and that those using results are aware of their limitations. Uncertainties, unknowns, and unmeasurables must be communicated so as not to give misleading certainty which could result in uninformed and detrimental governance (Stirling, 2010).

2.5.4 Design principle 4: Anticipation of futures

In focussing on the assessment and governance of emerging technologies, CSA takes a forward-looking, anticipatory approach to sustainability assessment. Through anticipating and reflecting upon plausible future impacts, CSA facilitates capacity building such that organisations and individuals are better prepared for future challenges and developments, improving responsiveness (Guston, 2014). This allows for the Collingridge dilemma to be actively managed, ensuring that technological actors are well equipped to respond rapidly as new information becomes available (Stilgoe et al., 2013).

With the broad scope of platform emerging technologies like synthetic biology and nanotechnology, life-cycle tools offer opportunities for the exploration of the specifics and complexities of individual applications (Ribeiro & Shapira, 2018). Thorstensen & Forsberg (2016) articulate SLCA as a tool for anticipation at the level of specific products, allowing the systematic study of social sustainability issues, and operationalisation of RRI. According to Wender et al.

(2014b), life-cycle tools enable an approach which: “systematically and iteratively explores uncertainties across the life cycle of an emerging technology to prioritize research with the greatest potential for environmental improvement and contributions to responsible innovation” (p. 10536). Helping technological actors to view and understand the variety of avenues and possibilities available and their wide-ranging implications helps to open up governance approaches, questioning current technological expectations and commitments, and promotes governance that promotes informed experimentation and “directed incrementalism”, preserving developmental flexibility for longer (Grunwald, 2007).

2.6 Constructive Sustainability Assessment in practice

A step-wise approach to carry-out stakeholder grounded sustainability assessments has previously been outlined by Zijp et al. (2016) in the form of Solution-focussed Sustainability Assessment (SfSA). By blending state-of-the-art modelling alongside deliberative methods such as workshops and qualitative evaluation as part of a transparent and participatory sustainability assessment, SfSA utilises sustainability assessment to explore solutions to supposedly “wicked” sustainability problems (ibid.). CSA has a similar structure, but while SfSA starts with a sustainability problem and searches for solutions, CSA starts with emerging technologies and probes the promises of sustainability they are promoted upon. Thus, CSA aims to open up discourse and explore options, rather than explicitly search for solutions.

A typical application of CSA would be within or by an organisation, and in this respect, CSA has strong similarities to life-cycle management (LCM), which aims to provide a toolkit for organisations to integrate sustainability into management decisions (Hunkeler et al., 2003). However, LCM provides little guidance on the practicalities of carrying out sustainability assessments within organisations, remaining largely conceptual (Bey, 2018). While CSA does provide practical guidance, it is also not restricted to organisational contexts, and could easily be applied at higher levels, for example, to evaluate and inform national or international policies (see Section 2.7).

This section refers to the assumed role of the “CSA practitioner(s)” who would facilitate the CSA process. A three-step process (Figure 2.2) is deployed to operationalise the design principles outlined in the previous section. This begins with the *formulation* of the sustainability problem, which informs and guides the subsequent *evaluation* process, where the sustainability of the technology/product is assessed relative to the sustainability concept and priorities identified during problem formulation. Finally, the *interpretation* stage involves deliberative reflection and discussion of the results to identify outcomes, actions and, priorities for further study.

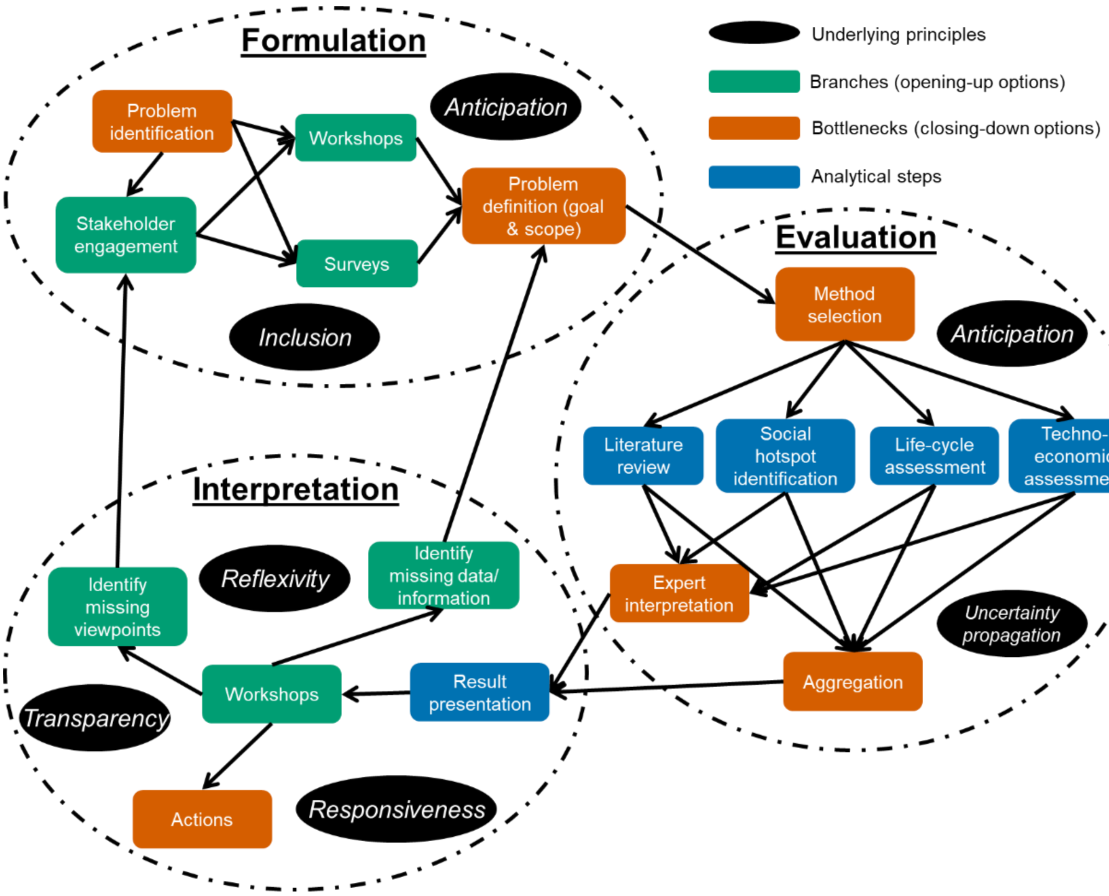

Figure 2.2: The methodological approach to CSA (Source: Authors' elaboration).

Stage	Mobilised Concepts, Principles, and Frameworks	Methodological toolkit
Formulation	Co-construction; inclusion; ISO goal & scope definition	Stakeholder mapping; literature review; interviews; surveys; workshops; focus groups
Evaluation	Anticipation; inclusion; ISO life-cycle inventory; ISO life-cycle impact assessment	Life-cycle assessment; social life-cycle assessment; Life-cycle costing; EIO modelling; hybrid LCA; screening LCA; up-scaling LCA; expert consultation; literature review; early-stage metrics; surveys
Interpretation	Value-sensitive design; reflexivity; responsiveness	Workshops; focus groups; interviews; surveys; consensus conferences; citizen juries

Table 2.3: A suggested toolkit for CSA.

It is intended that CSA should be carried out in a cyclic or iterative manner to allow continuous constructive assessment and an incremental and adaptive governance approach (Lindblom, 1959). Figure 2.2 represents this diagrammatically. Stages such as method selection and data interpretation are key steps of the assessment process in that they allow possibilities to be explored and promises to be probed but also tend to lead to the closing down of options (represented by orange boxes in Figure 2.2). Combining them with more open-ended methods such as workshops allows the process to be reopened and alternative viewpoints (re)considered (represented by green boxes in Figure 2.2). Thus, the cyclic and continuous nature of the process is essential, not only to allow the inclusion of new knowledge which is likely to improve over time and allow incremental governance but also to counter the tendency of evaluations and assessments to lead to gradual closing down. The following sections articulate the three CSA steps in more detail. A suggested methodological toolkit is provided in Table 2.3.

2.6.1 Step 1: Formulation

2.6.1.1 Stakeholder identification and engagement

Despite the requirement in the ISO LCA standards that the application, aims, audience, context, use, and technical scope of the study are clearly defined in the “Goal and Scope Definition” stage, there is little guidance as to how this should be determined and there is no mention of stakeholders (ISO, 2006b). If these subjective judgements are made solely by LCA/CSA practitioners, the subsequent assessment will be framed relative to the sustainability visions and values of the practitioner (Freidberg, 2018). We propose that in a CSA process, the goal and scope definition phase is precluded by deliberative activities with stakeholders through workshops and surveys. This ensures that the subsequent sustainability assessment can be framed more broadly and inclusively as well as being made more explicit.

Mathe (2014) considers there to be four different kinds of stakeholders relevant for sustainability assessments: method users, result users, those affected by the impacts (beneficially or detrimentally), and those with input into methodological issues. Taking Mathe’s classification, CSA practitioners should consider themselves stakeholders, as both method users and potentially methodology developers. This is in line with a more constructivist view of the role of the researcher. Other stakeholders involved should include result users, and potentially, impacted groups. In recent years, a growing number of stakeholder and public dialogues have taken place surrounding emerging technologies, particularly synthetic biology, the results of which can allow the inclusion of a greater variety of stakeholder viewpoints (Bhattachary et al., 2010; Castell et al., 2014; Schmidt et al., 2009; Stilgoe & Kearnes, 2007) in addition to new initiatives for engagement and dialogue (e.g. Climate Assembly UK, 2020). Stakeholder engagement can also be broadened over time as societal interest increases or resources become available.

2.6.1.2 Deliberation

Sustainability assessments should not be framed in terms of “what we can measure” and instead start with “what matters”. Then, one can analyse what can be reasonably analysed and provide transparency about what cannot be reasonably measured or evaluated at the time. To achieve this, CSA advocates undertaking deliberative activities that allow the sustainability concept employed to be discussed and clearly specified (Zijp et al., 2016). This also provides a space to reflect on what the stakeholders would like to achieve from the process. Engaging stakeholders who will use the outputs of the study at this early stage can advance their understanding of the sustainability assessment process, improving engagement and trust as well as building capacity. We suggest the following aspects to be considered at this stage:

- Identification of potential technological futures and scenarios of interest.
- Clarification of the object, level, and system boundaries of analysis.
- Discussion of the sustainability concept. The UN SDGs may provide a “normative anchor point” for this discussion (UN, 2015b; von Schomberg, 2011).
- Exploration of the worldviews of the stakeholders, in particular how they perceive nature (Asveld et al., 2014; Hofstetter et al., 2000).
- Discussion of data sources as well as the interpretation and presentation of outputs to ensure that the subsequent results are understandable, useful, and seen as legitimate by stakeholders (von Geibler et al., 2006; Zijp et al., 2016).

The answers to these normative aspects of the sustainability assessment will vary in each application of the CSA framework, and the validity and utility of the problem formulation that results will be inherently dependent on the stakeholder perspectives included. Carrying out this process and outlining the assumptions and subjective elements that underpin the study improves transparency and legitimacy.

2.6.2 Step 2: Evaluation

2.6.2.1 Method selection and the place of life-cycle methods

The effectiveness of the CSA process is underpinned by a period of evidence collection where the sustainability implications of the object of analysis are assessed. The formulation stage guides CSA practitioners in undertaking this evidence collection. However, picking appropriate methods from the many available remains a key challenge and an area where closing down might occur, particularly when resources are limited and the use of streamlined methods such as scanning LCA might be required (Peace et al., 2017; Wangel, 2018). The use of such approaches should be transparently reflected upon and communicated alongside the results, acknowledging any limitations.

Previous studies have highlighted the need for a case-by-case approach to evaluating emerging technologies, advocating situated and context-specific evaluation (Ribeiro & Shapira, 2018). Thus, the CSA framework does not prescribe specific methods or how they should be applied, particularly considering that the perceived utility and validity of different approaches will depend on stakeholder worldviews (Asveld & Stemerding, 2016). However, the methods used should be consistent with the overarching principles of CSA and make appropriate use of previous methodological developments and state-of-the-art.

In most cases, particularly when applying CSA to specific products, it is anticipated that life-cycle tools will fulfil this evidence-gathering role. LCSA provides a useful methodological framework to follow, as it allows the consideration of all three pillars of sustainability (Finkbeiner et al., 2010). Furthermore, the application of life-cycle tools such as LCA and SLCA at low-TRLs provides a means through which uncertainties can be rationalised and future impacts anticipated and explored (Thorstensen & Forsberg, 2016; Wender, Foley, Hottle, et al., 2014). For particularly early-stage studies there are various challenges, especially surrounding process scale-up, and several alternative approaches are available, as discussed by Broeren et al. (2017). Such challenges introduce uncertainty, which is discussed below.

2.6.2.2 Handling uncertainty

A central challenge is how uncertainty is handled and propagated. Uncertainties concerning data and knowledge should be duly acknowledged and propagated into the empirical evaluation while assumptions, exclusions, and limitations should be systematically recorded for presentation alongside the results. Existing LCA tools already possess methods for this and many databases include qualitative or quantitative uncertainty scores (Ciroth et al., 2016). To handle parameter uncertainty, Monte Carlo simulations have been utilized in a number of recent studies (Baral et al., 2018; Gargalo, Cheali, Posada, Carvalho, et al., 2016; Pérez-López et al., 2018). This allows uncertainties relating to input parameters to be propagated throughout the modelling process and be reflected in the resulting LCIA where error bars or probabilistic comparison methods like discernibility can allow transparent interpretation (Mendoza Beltran et al., 2018; Wender, Foley, Prado-Lopez, et al., 2014). Spreading further along the uncertainty continuum, more qualitative aspects of uncertainty are reached as discussed in previous sections. The application of deliberative and participatory social science approaches helps to open up discussion surrounding these uncertainties, encouraging reflection on the limits of knowledge and increasing awareness of other stakeholder perspectives (Ribeiro et al., 2016).

At the early stages of technological development, there are likely to be many sustainability aspects that cannot be fully evaluated due to high uncertainty, lack of knowledge or data, no available methods, or simply a lack of appropriate skills or resources. It is crucial, that while these “unmeasurables” are not empirically evaluated, it is crucial that they are not discarded either, and that these unknowns are recorded and propagated to the interpretation stage for further deliberation.

2.6.3 Step 3: Interpretation and informed decision-making

2.6.3.1 Consolidating and presenting the results

The interpretation stage is arguably the most important stage of CSA. How the results of assessments are consolidated and presented to stakeholders represents a key bottleneck where the risk of closing down is high (Figure 2.2). While aggregation and weighting involve subjective judgments and discards complexity regarding trade-offs and uncertainty, it is also challenging for non-technical stakeholders to understand the meaning and significance of raw sustainability assessment results, and thus there is a tension between understandability and robustness

(Peace et al., 2017). Indeed, where life-cycle methods are already utilised to inform decision-making there are fears that the inherent subjectivities and uncertainties embedded within these methods may not be properly understood or reflected in the decisions taken by stakeholders who desire crisp answers to fuzzy sustainability questions (Sonnemann et al., 2018). Furthermore, even if the limitations, uncertainties, and qualitative results of the assessment are presented, quantitative results presented in graphs, tables, and diagrams will be easier and faster for decision-makers to understand and interpret, with the danger that they are unfairly prioritised in decision-making.

With CSA we recommend taking a pragmatic approach. A certain degree of aggregation to more understandable “mid-points” or “end-points” may be appropriate, although how this is carried out and the value judgements involved must be made explicit. Where uncertainty levels are extremely high, one option is to focus on using analysis results for hotspot identification rather than articulating results in absolute terms. Employment of innovative presentation techniques, for example, the use of practical hands-on activities or diagrammatic presentation approaches can also help to alleviate these issues.

2.6.3.2 Deliberation

More fundamentally, the challenge is not just in how the results are presented, but in how the empirical results are used and mobilised. CSA is not intended to give fixed answers to sustainability questions. Rather, it explores a set of possibilities and potential impacts (Olsen et al., 2018). To achieve this, we advocate a deliberative interpretation approach more appropriate for the inherent uncertainty and subjectivity of the sustainability concept. While this makes the process more complicated and does not result in clear-cut results, it reflects the true nature of the outputs and allows the propagation of uncertainty directly to decision-makers. Using deliberative activities like workshops to re-engage stakeholders allows empirical results gathered in the evaluation phase to be related to the formulation stage that they engaged with. During these deliberative activities, the following aspects should be reflected upon:

- The meaning and significance of the results, including any unexpected results or significant hotspots. While the CSA practitioner will need to explain the results and ensure that stakeholders can make judgements based on an informed understanding of how the results were generated, the stakeholders themselves should be encouraged to derive their own interpretations.
- CSA practitioners should be clear about, and encourage reflection upon, the limitations of the evaluation results and encourage discussion of what the results can tell us and what they cannot. This can lead to the identification of important gaps and unknown impacts that could be investigated in future CSA cycles.
- Discussion of how differing worldviews might impact the interpretation of the results, and how this might lead to other societal stakeholders coming to different conclusions, helping to encourage reflexivity (Stilgoe et al., 2013). If a stakeholder takes a *vulnerable nature* worldview it can render uncertain, early-stage sustainability assessments almost irrelevant (Asveld & Stemerding, 2016). This process can be aided by the three different

archetypes (hierarchist, individualist, egalitarian) used in the ReCiPe impact assessment methodology (Hofstetter et al., 2000; Huijbregts et al., 2017).

- To encourage responsiveness, the stakeholder participants should be asked to identify potential recommendations or actions, either to be taken now or responses that may become appropriate in the future, should possible but uncertain outcomes become clearer. This step provides opportunities to initiate value-sensitive design (B. Friedman, 1996).

2.6.3.3 An open and continuous process

During the process of applying CSA, there are various stages at which narrow framing and closing down may occur prematurely (Figure 2.2). To address this, the interpretation stage represents an opportunity to re-open the process by considering ambiguities, uncertainties, and alternative interpretations. The interpretation stage should not in any sense be considered an end-point. The process should remain open and continuous in order to be responsive to new information and developments, supporting an incremental approach (Lindblom, 1959). By setting out recommendations for further evaluation, the interpretation stage can act as the formulation stage for future rounds of CSA. This helps to ensure continuous evaluation and deliberation, feeding information into governance and decision-making as soon as it becomes available.

2.7 Options for operationalisation

So far, we have put forward a primarily conceptual exposition of CSA. Future research will necessitate the operationalisation of the framework in practice to enable further elaboration and refinement. CSA is designed to be continuous and iterative to enable it to be applied at a variety of stages of development and in different institutional contexts. While CSA would ideally be operationalised as early as possible in the development of emerging technologies, it could also be introduced to already well-developed technologies where it can help to re-open the governance process. Furthermore, where an LCA has already been undertaken, a CSA framework could be introduced at the interpretation stage rather than the formulation stage to open up discussion and explore options for further evaluation.

In Figure 2.3 we provide some suggested avenues and stages for operationalisation overlaid on our graphical elaboration of the Collingridge dilemma. During the initial stages of emergence, foresight, horizon scanning, and public dialogues are already widely undertaken, and CSA does not seek to replace these. Similarly, when a technology is well-developed and diffused, the opportunities for CSA to have an impact are minimal. The areas where CSA application is most pertinent is between these two stages, bridging the well-known “valley of death”. This is where the crucial design decisions are taken and experimentation occurs, so this is where knowledge of sustainability implications can be most pertinent.

Many emerging technologies are initiated in research environments. Operationalising a CSA process at this early stage will maximise the potential to influence research trajectories before lock-in becomes apparent. Furthermore, the trend of embedding RRI and related frameworks within natural science research programmes provides an entry for CSA activities to being carried out (Karinen & Guston, 2010; Owen, 2014). Scientists should be engaged in the formulation process to inform the evaluation stage with subsequent deliberative interpretation workshops allowing the exploration of anticipated sustainability implications informed by available data. This provides opportunities for sustainability considerations to be integrated into emerging technologies at an early stage. Inviting broader stakeholders (e.g. non-governmental organisations, industry figures, regulators, members of the public) to participate in formulation and interpretation workshops would help to broaden the sustainability perspectives considered and facilitate shared agenda-setting. CSA could thus provide operationalisation to RRI by enabling improved anticipation of impacts, the inclusion of different viewpoints, responsiveness to changes, and reflexivity on the part of technological actors (Stilgoe et al., 2013).

Meanwhile, the scale-up and commercialisation of emerging technologies is typically driven by firms. Firms developing technologies that promise sustainability benefits increasingly engage with consultants to carry out analyses like LCAs to back up such claims and promises. Building on this already established interest in sustainability assessment, the engagement of firms in the formulation stage of CSA would enable their sustainability claims to be made explicit. These claims can subsequently be critically evaluated, providing firms with an opportunity to demonstrate a more substantive commitment to sustainability by proactively incorporating sustainability considerations into the design of their products through deliberative interpretation.

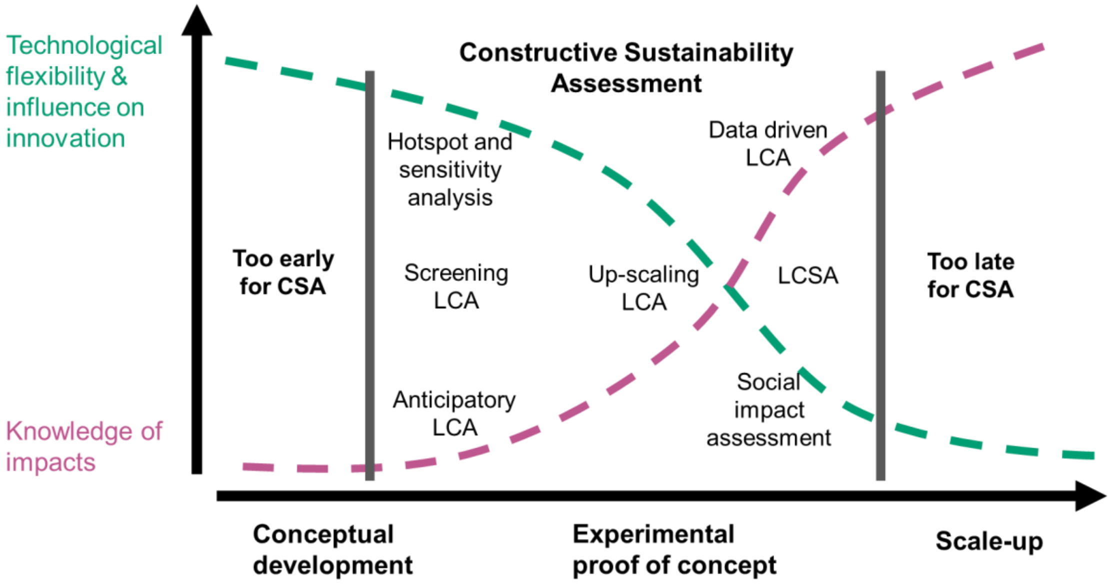

Figure 2.3: The Collingridge dilemma of social control for emerging technologies with options for CSA operationalisation overlaid (Source: Authors' elaboration based on Collingridge, 1980).

Perhaps the most promising avenue for operationalisation is broadening out from the limited environments of research institutes or firms to implement CSA within communities. This would bring added challenges in structuring the process but would also reflect the fact that large-scale sustainability transitions will require socio-technical shifts as well as technological fixes (Markard et al., 2012). Engaging a wider range of societal actors would help to situate the governance of emerging technologies towards sustainability within their broader context, linking technological developments with the overarching need for sustainable consumption as well as sustainable production.

2.8 Conclusion

This chapter began by outlining and critiquing current approaches to assessing and governing emerging technologies. Analytical assessment methods such as LCA represent well-established and powerful tools for the evaluation of sustainability promises, systematically probing assumptions and frequently revealing unexpected results. In recent years, substantial progress has been made in reshaping these tools to grapple with new and ambitious demands such as the need for a more anticipatory viewpoint and to consider broader notions of sustainability. However, they still fail to grapple with many of the normative dimensions of sustainability and the uncertainties of emerging technologies. LCAs are too frequently employed in isolation to answer complex sustainability questions which they are ill-equipped to answer. We believe the power of analytical approaches like LCA is maximised when they are grounded within a broader deliberative framework.

We have also explored deliberative frameworks such as RRI which offer an alternative, more qualitative, and reflexive perspective. These approaches offer opportunities to open up discussion and support an incremental approach towards the sustainable development of emerging technologies, although they do not replicate the quantitative information that analytical sustainability assessments can generate. High-level frameworks for RRI exist, such as the UK EPSRC’s framework (Owen, 2014), but the practical application has been lacking at low-TRLs. We argue that combining these frameworks, with a dedicated period of evidence and data collection using tools like LCA, can offer enhancements.

Thus, rather than simply comparing and contrasting deliberative and analytical approaches, we have developed a “third way” in the form of the CSA framework, which emphasises their mutual complementarity. Analytical sustainability assessments are powerful tools for evaluating emerging technologies, however, when used in isolation they can be deeply flawed. By grounding them within a deliberative and participatory approach the assumptions and ambiguities of analytical approaches can be explored and made explicit. Furthermore, we argue for the importance of context, with analytical methods enabling the exploration of the specific sustainability opportunities and implications relating to emerging technologies and their applications. Based on this, the balance of different methods and of participating stakeholders should intrinsically be linked to the context and specificities of the emerging technology in question.

The grand challenge of sustainability, perhaps the greatest challenge facing society, is highly complex. It involves problematic trade-offs that necessitate a systemic perspective. With emerging technologies, governance under high levels of uncertainty is required (Collingridge, 1980). To tackle this challenge requires the asking of complex questions to which there will not be simple answers. Therefore, rather than provide unrealistically clear solutions, CSA involves exploring options and rationalising uncertainties while encouraging reflection on assumptions as well as alternative framings and perspectives. CSA emphasises the importance of maintaining an open discourse on emerging technologies while also engaging in the critical evaluation of promises and expectations. This maintains the two in productive and continuous tension in the search for incremental and constructive governance of emerging technologies. While CSA does not solve Collingridge's dilemma, it actively tackles it through a continuously responsive process.

Through its four core design principles and three-step methodology, CSA provides a means to operationalise RRI for emerging technologies through the anticipatory and deliberative application of sustainability assessments. In doing so, CSA represents a means through which the emerging technologies can be governed actively and iteratively from an early stage in order to realise the sustainability benefits they promise. Its capabilities and utility are maximised when applied early. Thus, resources and funding for assessments must be provided earlier, in parallel, or ideally before significant resources are committed to the emerging technologies and before the onset of path dependency and lock-in. Moreover, while CSA provides a route, it cannot provide the underlying incentives for sustainable development. In relation to emerging technologies, the promise of sustainability is frequently ambiguous, mobilised all too often for instrumental means. The widespread operationalisation of CSA and related frameworks would inform and enable real moves towards sustainability, although doing so will require substantive commitments to such processes by government, research organisations, industry, and non-governmental groups.

Chapter 3: A Constructive Sustainability Assessment of bio-based nylon

This chapter is based on a manuscript published in December 2019 under the name of "Collaborating constructively for sustainable biotechnology" in the journal *Scientific Reports*:

Matthews, N. E., Cizauskas, C. A., Layton, D. S., Stamford, L., & Shapira, P. (2019). Collaborating constructively for sustainable biotechnology. Scientific Reports, 9, 19033. https://doi.org/10.1038/s41598-019-54331-7

The manuscript was co-authored with the doctoral supervisors Philip Shapira and Laurence Stamford as well as two industrial collaborators: Carrie A. Cizauskas and Donovan S. Layton. The thesis author led all stages of producing the manuscript including conceptualisation, data collection, data analysis, and manuscript drafting and editing.

Abstract

Tackling the pressing sustainability needs of society will require the development and application of new technologies. Biotechnology, emboldened by recent advances in synthetic biology, offers to generate sustainable biologically-based routes to chemicals and materials as alternatives to fossil-derived incumbents. Yet, the sustainability potential of biotechnology is not without trade-offs. Here, we probe this capacity for sustainability for the case of bio-based nylon using both deliberative and analytical approaches within a framework of *Constructive Sustainability Assessment*. We highlight the potential for life cycle CO_2 and N_2O savings with bio-based processes but report mixed results in other environmental and social impact categories. Importantly, we demonstrate how this knowledge can be generated collaboratively and constructively within companies at an early stage to anticipate consequences and to inform the modification of designs and applications. Application of the approach demonstrated here provides an avenue for technological actors to better understand and become responsive to the sustainability implications of their products, systems, and actions.

3.1 Introduction

Recognising the growing call for more environmentally, economically, and socially responsible societies, emerging technologies are increasingly promoted on the promise of sustainability benefits. Synthetic biology, a sector that integrates engineering principles and computational approaches with advances in biological techniques, is often advocated as an example of a field that is widely developing more sustainable solutions (Bueso & Tangney, 2017). By enabling biological routes for the production of a wide range of fuels, chemicals, and materials from biomass, synthetic biology could displace existing fossil-based production routes with renewable alternatives (EC, 2018; SBRCG, 2012). Given their potential, it would seem appropriate to harness such technologies to help deliver greater sustainability (French, 2019).

However, sustainable development is a complex challenge, presenting issues that span both social and natural domains and which have characteristics of interrelatedness, uncertainty, and incommensurability (Grunwald, 2007). The UN’s Sustainable Development Goals (SDGs) articulate but hardly simplify this complexity, outlining seventeen broad and interrelated goals (UN, 2015b). Concepts and practices of sustainability remain subject to diverse interpretations. As a result, while there is increasing recognition of the urgent need for wide-ranging sustainability transitions, there remains limited agreement on how this should be undertaken and what this should achieve.

How can we navigate through this complexity and promote the sustainable development of emerging technologies? A growing sustainability literature emphasises the need for an open-ended approach characterised by experimentation and learning; this body of literature also recognizes that traditional, top-down “command and control” management and policy approaches to solving such problems are insufficient for robust decision-making under conditions of uncertainty (Diaz Anadon et al., 2015; Etzion, 2018; Grunwald, 2007; Schot & Geels, 2008).

Yet, experimentation with sustainable technologies is not simply an exercise in the random sampling of solutions - it must be informed by evidence and supported by continuous, iterative cycles of evaluation and learning (Grunwald, 2007). This necessitates the acquisition of knowledge on the sustainability performance and implications of emerging technologies, as well as on the criteria against which they should be judged. Such a process involves evidence gathering from multiple domains and transdisciplinary knowledge generation (J. Liu et al., 2019). To be salient, such evidence must be acquired and integrated into technological design at the early stages of technological development to inform key design decisions before lock-in is established and before further downstream development, when change is difficult or costly (Collingridge, 1980). This requires the gathering of evidence when very limited data is available.

Evidence gathering and experimentation are further complicated by the fact that emerging technologies like synthetic biology are developed and applied largely by and within companies. Traditionally, the role of a company is to maximise financial return while complying with its legal and contractual responsibilities. Companies are also constrained to working within existing systemic frameworks, such as the agricultural sector that provides fermentation feedstocks. Concepts such as the triple-bottom-line expand this view, and a growing literature explores how companies can simultaneously achieve benefits for people, planet, and profit (Adams et al., 2016; Boons & Lüdeke-Freund, 2013; Carrillo Hermosilla & Del Rio Gonzalez, 2009). However, this outlook potentially restricts experimentation with sustainability-orientated innovations to those that are compatible with (short-term) profit (Dyck & Silvestre, 2018). A possible solution is found through promoting responsible research and innovation (RRI) (van de Poel et al., 2017). RRI provides a framework through which companies might assume greater responsibility for the impacts of the innovations they generate, both positive and negative (van de Poel et al., 2017). However, in addition to exploring a (re)distribution of responsibilities for innovation amongst companies and other technological actors (such as governments, regulators, and civil society organisations) (von Schomberg, 2013), research is needed to strengthen the capacities of companies to engage with the complex socio-technical systems within which they operate (Geels, 2002).

Clearly, governing and promoting emerging technologies in such a way that they can contribute to sustainable development is no simple endeavour. In this chapter, we demonstrate how a constructive approach to assessing sustainability can productively grapple with these challenges through a) close collaboration between interdisciplinary researchers and technology actors (in this case, a biotechnology company); b) the application of life-cycle assessment methodologies at the conceptual design stage under high uncertainty; and c) the use of deliberative workshop formats to consider sustainability concepts and implications and explore options.

3.2 The case for Constructive Sustainability Assessment

Members of our group have previously outlined a Constructive Sustainability Assessment (CSA) approach to navigating through the complexity of assessment and governance of emerging technologies towards sustainability (Chapter 2; Matthews, Stamford, et al., 2019). Conceptually, we draw on frameworks for deliberative and constructive technology assessment and governance to articulate four key design principles for constructive sustainability assessment:

- Design principle 1: Mobilise transdisciplinarity to allow knowledge generation across multiple domains and integration of findings into decision-making.
- Design principle 2: Implement tentative and incremental governance in order to keep technological options open (Kuhlmann et al., 2019; Stirling, 2008a).
- Design principle 3: Propagate and explore uncertainty as a core feature of the assessment exercise.
- Design principle 4: Anticipate potential future impacts of emerging technologies in terms of sustainability.

A methodological framework for operationalising these design principles follows a three-step approach (Figure 3.1). The *formulation* stage involves deliberative workshops and evidence gathering involving stakeholders. The results of these activities inform the sustainability assessments subsequently undertaken during the *evaluation* process utilising established methods such as life-cycle assessment (LCA). In a subsequent *interpretation* stage, the results of the process are then discussed and elucidated during further workshops to deliberatively explore the implications of the results.

CSA is designed to be broadly applicable to emerging technologies and a range of production systems wherein differing analytical approaches may be utilised during the *evaluation* stage within a consistent methodological framework. The approach is also designed to be flexible and scalable according to the time and resources available, such that it could be applied by various technological actors and organisations of differing sizes from start-up to multinational. Here, we demonstrate the operationalisation of CSA in the context of a relatively young (~6 years old) biotechnology company still developing internal practices and processes as well as exploring new markets. Our study's test company is also involved in developing diverse and interdisciplinary projects and products across multiple scales, presenting an appropriate laboratory for developing and testing CSA methods. Many of the company's employees have been involved in several different projects at different times during company growth, at different points of scale-up, and across different product types, giving the study a diverse cross-section of industry experiences.

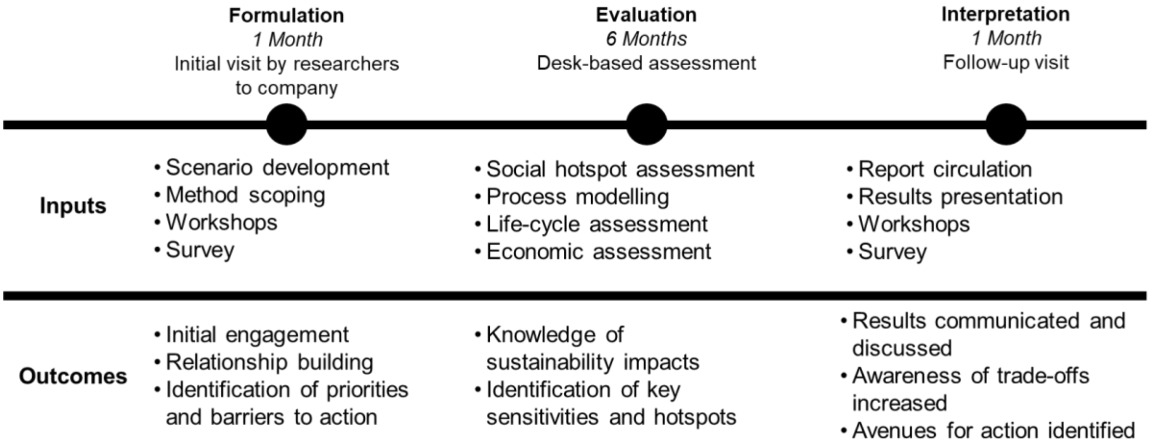

Figure 3.1: Overview of the CSA process undertaken for this study.

We recognise that techno-economic analyses (TEAs) are already employed by companies to evaluate the economic feasibility of processes. In biotechnology, early application of TEAs is increasingly recognised as important to integrate downstream industrial-scale considerations into the design phase, thereby facilitating smoother scale-up (S. Y. Lee & Kim, 2015). TEA and CSA both require prospective analysis of anticipated applications, grappling with uncertainty issues to ensure timely acquisition of knowledge. TEA provides a framework for carrying out prospective modelling. CSA expands the scope to consider additional environmental and social parameters while, through its constructive approach, embedding the practice within the management and social structures of the company.

3.3 Methods

This study followed the methodological approach for Constructive Sustainability Assessment (CSA) outlined in Chapter 2. In this case study, we completed one cycle of CSA. This involved three stages: *formulation*, *evaluation,* and *interpretation*. The study received ethical approval from the Alliance Manchester Business School ethical review panel (Appendix A.3).

3.3.1 Formulation

During the *formulation* stage, we conducted four, hour-long workshops that engaged a total of twenty company employees from four departments (Table B.1). N.E.M. facilitated all workshops. The workshops explored the following topics:

- What does it mean for a product to be sustainable? What aspects matter?
- In terms of sustainability, what sources and types of information are useful and influential?
- What kinds of data and presentation formats are preferred?

During the workshops, participants were asked to electronically submit answers to the question: “What characteristics would a sustainable biotechnology product have?” The answers were cleaned to combine similar terms and used to produce the word cloud in Figure 3.2.

In addition, we circulated a survey electronically to all company employees and received 137 full responses and 16 partial responses. The company had ~500 employees at the time of surveying. The survey covered the following topics:

- The significance of different aspects of sustainability for the biotechnology sector.
- Preferred data sources.
- Personal sustainability motivations.

Text and notes from the survey and workshops were coded and analysed and, based on these outputs as well as discussions within the team, we developed the subsequent *evaluation* stage. This involved primarily the selection of indicators, methods, and scenarios.

3.3.2 Evaluation

In consultation with company employees, we selected cadaverine and putrescine as bio-based targets of interest as they can be used as precursors to make useful chemicals and materials such as nylons. The goal of the *evaluation* stage was to assess the sustainability implications of using bio-based cadaverine and putrescine for the production of nylon compared to fossil-based alternatives (nylon 66). The scope of the study is articulated individually for each of the assessment stages.

3.3.2.1 Social assessment

This study made use of the social hotspot risk mapping tool, an online interface to the social hotspots database (SHDB) which provides data on social risks to the resolution of a country-specific sector (CSS) (Benoît Norris et al., 2012). This database uses more than fifty indicators, both quantitative and qualitative, to characterise five social categories. The results for each social category can be aggregated for a CSS using the social hotspot index (SHI) (Benoît Norris et al., 2014). This involves assigning a risk level based on indicator values following which a weighted sum is calculated which is then normalised against the maximum possible weighted sum for that CSS, with a maximum score of 100. The mathematical formula for this is shown below (source: Benoît Norris et al., 2012):

$$SHI_{cat} = \sum_{T=1}^{n}(R_{avg} \times W_T) \,/\, \sum_{T=1}^{n}(R_{max} \times W_T)$$

SHI_{cat} = Social hotspot index for a category
T = Theme (e.g. risk of child labour)
W_T = Weight assigned to the theme (1.5 or 1.0)
R_{avg} = Average risk across the theme
R_{max} = Maximum possible risk for a theme (all issues very high)

In this study, we modelled two different CSS for each geographical scenario, one for the relevant feedstock production and a second using the *Chemical, rubber, and plastic products* sector as a proxy in the absence of a specific sector for biorefineries, in line with the approach followed in a previous similar study (Valente et al., 2017). The main results presented are aggregated SHI results.

3.3.2.2 Integrated cost and environmental assessment

We carried out anticipatory cost and environmental assessment using an integrated modelling framework developed specifically for this study called SustAssessR (Figure B.1; Matthews, 2019). All modelling was undertaken using the R statistical programming language (R Core Team, 2021).

We developed the process model for cadaverine and putrescine production by building on a previously published process from Kind et al. (2011); this model involves fermentation followed by downstream processing and work-up through centrifugation, solvent extraction, and distillation (Figure B.2). We added process steps for the handling of excess biomass and waste “cake” with two versions of the process model to reflect different waste handling scenarios:

- Integrated: Waste cake sent for incineration (modelled as municipal incineration).
- Non-integrated: Waste cake burned in the combustor, yielding process steam.

3.3.2.3 Model parameterisation

We determined the stoichiometric yield trade-off between biomass and product per glucose via flux balance analysis using the *E. coli* genome-scale model iML1515 (Monk et al., 2017). We used the stoichiometric outputs as inputs for an in-house built fermentation model utilizing mass balance first principles. The fermentation model used common fermentation conditions for the host organism to simulate key performance indicators such as titre, productivity, and yield and we simulated several scenarios, including different product yields, organism uptake rates, and time switches between the growth of biomass and product formation. The results inferred raw material requirements, such as sugar and nitrogen, and were used for determining the downstream material flows for a plant with an output of 100 kilotonnes per year. For the solvent extraction step, we assumed the solvent load requirement based on information from the literature (Krzyzaniak et al., 2013).

With the exception of the distillation steps, we derived steam and electricity requirements of key process steps from the BREW project generic approach (Patel et al., 2006). We modelled the heat required for distillation of compounds as the sum of the theoretical sensible heat required to raise the temperature of the compound to its boiling point and the enthalpy of vaporization, all divided by an estimated distillation efficiency (Cavaletto, 2013):

$$E_{heat} = \left(c\Delta T + \Delta H_{Vap}\right) / Eff_{Dist}$$

c = sensible heat
ΔT = change in temperature
ΔH_{Vap} = enthalpy of vaporisation
Eff_{Dist} = efficiency of distillation

This is a similar approach to that taken in the BREW project's "generic approach", but now taking into account sensible heat and more conservatively factoring-in efficiency.

3.3.2.4 Uncertainty propagation

We represented parameters with probability distributions to account for uncertainty. Uncertainty distributions were derived from published ranges of values where possible. Where only single figures could be found, we took a conservative approach, constructing a triangular distribution with the published figure as the modal value, and maximum and minimum values corresponding to double and/or half the published figure. To propagate the uncertainty, we employed a Monte Carlo approach with 10,000 iterations using pseudorandom variables to sample from the specified uncertainty distributions. Scenario uncertainty (e.g. waste handling, geographical location/feedstock, energy source, nitrogen source) was also propagated by sampling from these discrete distributions of possibilities. All parameters and their associated distributions are outlined in Table B.2.

3.3.2.5 Life-cycle assessment

We conducted a life-cycle assessment (LCA) in line with the ISO standards following an attributional approach and a cradle-to-gate system boundary (Figure B.3) (ISO, 2006b, 2006a). Foreground mass and energy flows were derived from the process modelling described above. The primary background data source was the Ecoinvent v3.3 (Ecoinvent, n.d.) database as implemented in the Gabi LCA software (thinkstep, n.d.). We carried out impact assessment using ReCiPe 2016 under the hierarchist perspective[15] (Huijbregts et al., 2017). We calculated climate change impact excluding biogenic carbon dioxide and applied a credit for carbon dioxide embodied in the product (Pawelzik et al., 2013).

The sources and names of background data used in this project are outlined in Table B.3. The energy source (for steam and electricity) was randomly varied between biomass and grid (electricity grid/natural gas) for each Monte Carlo run. We chose municipal solid waste incineration as the most appropriate proxy for waste treatment, in the absence of data concerning the specific composition of the waste cake generated. In the absence of a specific background dataset for biomass combustion, we chose data for softwood combustion as a proxy for combustion to generate heat due to its similar water content. In line with the US National Renewable Energy Laboratory (NREL) modelling, we assumed evaporation to be effective at

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[15] Egalitarian and individualist perspectives for cadaverine and putrescine production are also provided in the supplementary information of the published article (see Matthews, Cizauskas, et al., 2019).

reducing the water content to 60% (Davis et al., 2013). The construction of the fermentation plant was taken into account using Ecoinvent v3.3 data for a bioethanol fermentation plant scaled according to the number of fermenters required as determined in the process model.

We modelled different feedstocks from three geographical locations (Table B.4):

- Glucose and xylose generated from corn stover in the U.S.
- Glucose from corn starch, also in the U.S.
- Sucrose from sugar beets in France.
- Sucrose from sugarcane in Brazil.

Data for sucrose from sugarcane (Brazil) and sucrose from sugar beets (France) was sourced from Ecoinvent v3.3. For the production of corn starch and corn stover, we used data from the US Life Cycle Inventory (LCI) Database (NREL, 2012). For the processing of corn starch, we used an LCI from Renouf et al. (2008) (Table B.5), while we sourced corn stover processing data from the NREL 2017 sugars model (NREL, 2018) and the corresponding 2015 report for emissions data (Table B.6) (Davis et al., 2015).

We wanted to identify key hotspots and sensitivities, thus, we first calculated results for the production of cadaverine and putrescine monomers where the functional unit was 1kg of monomer production. To allow comparisons between monomers in their polyamide context, we considered four different polyamide usage scenarios (nylon 66, nylon 46, nylon 410, nylon 510; see Figure 3.5A); we compared these on a “like-for-like” mass basis due to their generally comparable physical properties (Kind et al., 2014). For such cases, the functional unit was 1kg of nylon. The data sources for each of the monomers are provided in Table B.7. We sourced an LCI for fossil-based Hexamethylenediamine (HMDA) production from published literature and adapted it with global scale background data from Ecoinvent v3.3 (Table B.8) (Dros et al., 2015; Ecoinvent, n.d.). We used data from thinkstep for sebacic acid production from castor bean and from Ecoinvent 3.3 for fossil-based adipic acid production (Ecoinvent, n.d.; thinkstep, n.d.). For the climate change impact of adipic acid production, we randomly varied the value selected for each Monte Carlo run between the Ecoinvent v3.3 value (assuming 80% N_2O abatement) and a sensitivity case (assuming 98% N_2O abatement) as modelled by Aryapratama et al. (2017). This takes account of variability in the N_2O abatement strategies of the incumbent production process.

We derived the steam and electricity requirements of nylon 66 manufacture from the Plastics Europe ecoprofile for all nylon types as preparation of nylons using adipic acid and sebacic acid occurs under similar conditions (Estes & Schweizer, 2011; PlasticsEurope, 2014). We assumed that the polymerisation site was located relatively close to monomer production (within the same country/state) and so the transportation distance was modelled accordingly as a uniform distribution between 100 and 400km. Full LCIs at unit-process and aggregated level, life-cycle impact assessment (LCIA) results for monomer and nylon production, and hotspot results for monomer production are provided as Supplementary Datasets 14-18 accompanying the published manuscript (Matthews, Cizauskas, et al., 2019).

3.3.2.6 Minimum selling price calculation

We calculated the minimum selling price (MSP) as the minimum price needed to make the net present value (NPV) of the project zero over its lifespan. We assumed a minimum acceptable rate of return (and therefore discount rate) of between 10 and 24%. The lower figure was chosen as an industry-standard while the higher figure reflects the high-risk nature of the project (Davis et al., 2015; Gargalo, Cheali, Posada, Gernaey, et al., 2016). We calculated the relative contribution of different cost elements using the methodology outlined in Figure B.4 with economic assumptions guided by the literature, NREL models, and the BREW project (Table B.9) (Davis et al., 2015; Gallagher et al., 2005; Gargalo, Cheali, Posada, Gernaey, et al., 2016; Patel et al., 2006). We determined prices and costs from a range of sources with a decision hierarchy that guided this process (Table B.10). The distributions used are outlined in Table B.11 (Davis et al., 2015; Gargalo, Cheali, Posada, Gernaey, et al., 2016; Tsagkari et al., 2016); all figures are in 2014 US$ due to data availability constraints. Capital cost was estimated based on a published figure for an advanced biorefinery (Tsagkari et al., 2016). This figure, $149 million in 2011 for a 33 kilotonne biorefinery, was scaled to 100 kilotonnes using a scaling exponent of 0.836 (Gallagher et al., 2005) and the CEPCI index to convert to 2014 US$. The cost was then scaled using the same exponent according to the number of fermenters required as determined in the process model.

We fully integrated the MSP model with the process model and life-cycle assessment described above. The model integrated the outputs from the process model with uncertain parameters pertaining to economic and cost assumptions. We annualised the capital cost to a capital charge using a similar approach to the aforementioned calculation of the minimum selling price whereby the charge was set at a level that would make the NPV of the capital investment zero at the end of the project.

3.3.2.7 Sensitivity test

To test the sensitivity of the model to individual parameters and their relative influence on the results we varied each parameter individually throughout its range while holding all others steady to determine which parameters were most influential. We employed a multi-start methodology to take into account how individual parameter influence might vary across the parameter space (Rakovec et al., 2014). For each parameter investigated, we re-ran the analysis (with 1000 iterations) starting in different regions of the parameter space each time. We selected the starting location at random based on the specified probability distributions described previously.

3.3.3 Interpretation

The *interpretation* stage centred around a set of six workshops involving 32 company employees across various teams (Table B.1). In advance of the workshop, we circulated a summary sheet to all participants along with a detailed report of results. The results reported in this chapter represented a slightly updated version of what was presented to stakeholders reflecting the iterative and continuous nature of the process. However, the key implications and conclusions have not changed. N.E.M. facilitated all workshops. At the start of the workshops, N.E.M. made a short (~10 minute) presentation of results. Subsequently, the following topics were discussed:

- Discussion of results: What do you think of the results? Are they as expected? Were there any unexpected results?
- Making decisions: How could the results be used? Do they change how you might make decisions?
- Future work: Where do we need more information and clarity? What are the priorities for further analysis and data collection?

For wider engagement of internal stakeholders, N.E.M. also presented results and project context at an hour-long, company-wide internal seminar. We then electronically circulated a summary report and survey. In the survey participants were asked:

- What they thought of the results of the assessment.
- What impact the results had on the way they think about the sustainability of bio-based processes.
- What they thought about the application of frameworks like CSA in the biotechnology industry.

Results of these engagements were coded and analysed in Nvivo 12 (QSR International, 2018) to identify emergent themes.

3.4 Results

3.4.1 Formulating the assessment

To operationalise and illustrate our CSA approach, we established a transatlantic collaboration consisting of a biotechnology company developing fermentation products across multiple scales and uses, and a team of university researchers. The company wanted to better understand the sustainability implications of the bio-based products they develop in engineered microbes. The university researchers were interested in developing new approaches to assess sustainability that could grapple with its subjective nature and generate findings that could be responsibly integrated into decision-making. Underpinning this team was its transdisciplinary nature (Design principle 1 of CSA) spanning the social and natural sciences, with skills including molecular biology, business and management, sustainability and environmental science, responsible innovation, and ecology.

A key feature of the collaboration was the embedding of academic researchers within the company from where they could understand and engage with industry stakeholders and carry out more situated assessments (Ribeiro & Shapira, 2019). This began with the *formulation* stage of the assessment, in which internal stakeholders (company employees) were engaged through a survey and workshops (see Methods) to discuss questions of what sustainability in biotechnology meant to them and what data formats were useful and informative (see Figure 3.3 for emergent themes).

We first sought to clarify the sustainability concept employed by the internal stakeholders, exploring the characteristics they felt that a sustainable biotechnology product should have

(Figure 3.2). Discussions and responses on this topic initially focussed on environmental aspects, particularly on the potential of biotechnology applications to reduce greenhouse gas (GHG) emissions and combat climate change. Being “renewable”, “non-toxic”, and generally “low environmental impact” were also characteristics frequently highlighted as being considered sustainable.

While the initial focus was clearly on environmental impacts, broader notions of sustainability were widely discussed. Beyond tackling climate change (SDG 15) and improving the health of global ecosystems (SDGs 13 & 14), eliminating poverty, hunger, and poor-health (SDGs 1,2,3,6,7), and sustaining employment and economic growth (SDGs 8,9,11) were also seen as areas where biotechnology applications could make positive contributions (Table B.12). However, the results also highlighted consensus among internal stakeholders that promoting equality, peace, and justice (SDGs 4,5,10,16) was likely to be an effort outside of the influence and capabilities of an individual company. These initial results informed assessments in the subsequent *evaluation* stage and demonstrated the utility of internal stakeholders’ perspectives for broadening the focus. As such, they may represent an often-untapped method of encouraging a more open and deliberative approach to innovation within companies (Design principle 2 of CSA).[16]

While internal stakeholders were keen that the products they developed should yield sustainability benefits across a broad range of dimensions, they also highlighted the need for economic viability; financial constraints ultimately frame the extent of integration of broader elements. This discussion highlighted the importance of undertaking analysis of costs alongside environmental and social assessments, and so we added minimum selling price (MSP) to the subsequent *evaluation* phase as a key parameter.

The *formulation* stage included a discussion of methodological aspects to ensure the outputs of the *evaluation* stage were salient for stakeholders. This also allowed the researchers to understand the backgrounds and expertise of the various internal stakeholders. For example, there were markedly differing levels of exposure to quantitative methods across employee departments, emphasising that the results of the *evaluation* must be presented in a manner that all can understand. Stakeholders also highlighted the importance of sensitivity testing, the use of “real-world” data where possible, and clear articulation of all assumptions. Overall, the *formulation* stage of the CSA approach demonstrated a number of important outcomes:

- Engaging those who might act upon results in the assessment process early-on, achieving trust in and commitment to the process.
- Clarifying the sustainability concept employed by internal stakeholders, providing a normative reference point for subsequent assessments.
- Mobilising the viewpoints of internal stakeholders to expand sustainability perspectives.
- Elaborating, at an early stage, perceived opportunities and barriers to actions that might be taken to promote sustainable biotechnology at an early stage.

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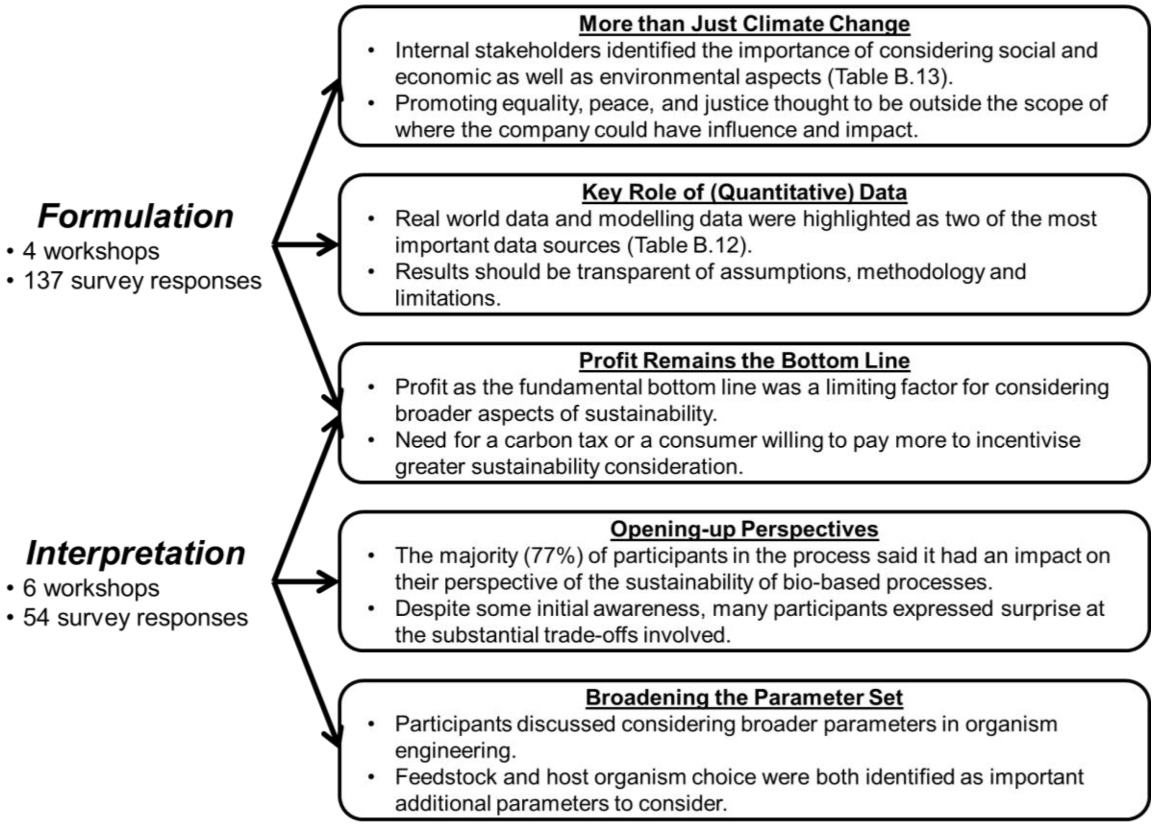
[16] This point is further elaborated in Chapter 4.



More than Just Climate Change

- Internal stakeholders identified the importance of considering social and economic as well as environmental aspects (Table B.13).
- Promoting equality, peace, and justice thought to be outside the scope of where the company could have influence and impact.

Key Role of (Quantitative) Data

- Real world data and modelling data were highlighted as two of the most important data sources (Table B.12).
- Results should be transparent of assumptions, methodology and limitations.

Profit Remains the Bottom Line

- Profit as the fundamental bottom line was a limiting factor for considering broader aspects of sustainability.
- Need for a carbon tax or a consumer willing to pay more to incentivise greater sustainability consideration.

Opening-up Perspectives

- The majority (77%) of participants in the process said it had an impact on their perspective of the sustainability of bio-based processes.
- Despite some initial awareness, many participants expressed surprise at the substantial trade-offs involved.

Broadening the Parameter Set

- Participants discussed considering broader parameters in organism engineering.
- Feedstock and host organism choice were both identified as important additional parameters to consider.

Figure 3.2: Emergent themes from the formulation and interpretation stages of the study.

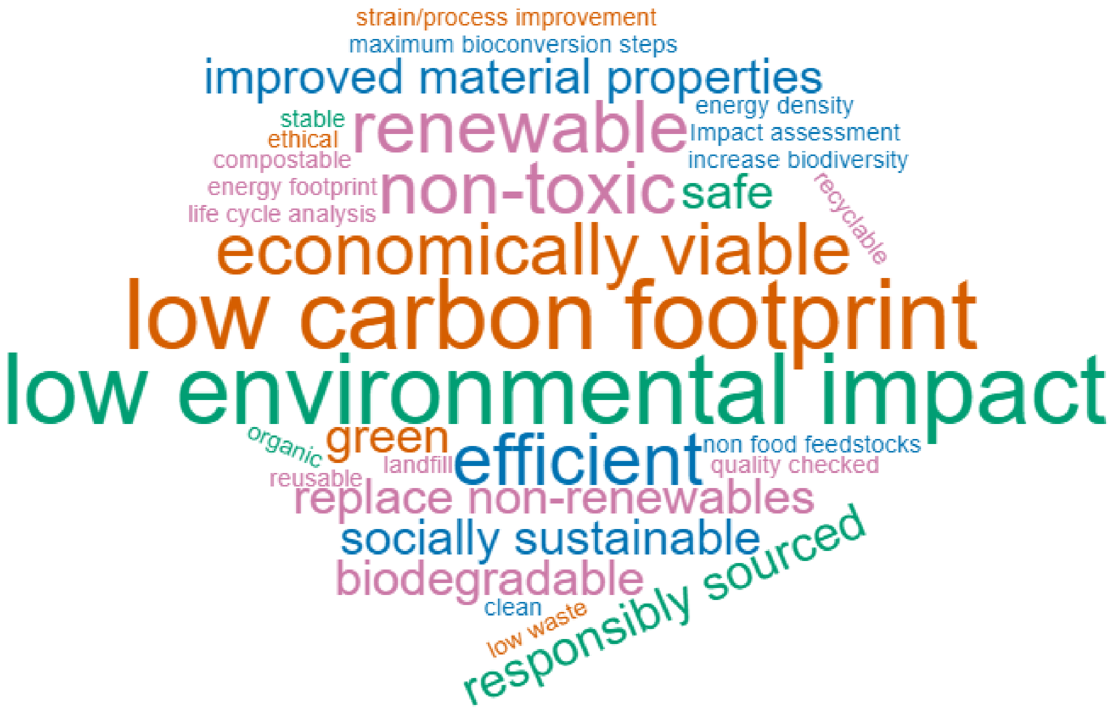


Figure 3.3: A wordcloud generated from responses in the initial formulation workshops to the question: “What characteristics would a sustainable biotechnology product have?”.

- Identifying the relative salience of different methodological tools, data sources, and presentation approaches to diverse audiences.

These activities are essential to ensure the *interpretation* stage of the assessment is relevant to internal stakeholders and actors. The knowledge gained also guides and thus provides legitimacy to the subsequent *evaluation* stage.

3.4.2 Evaluating bio-based nylon sustainability

Evidence collection at the preliminary stages of technology development is crucial to guide informed experimentation with sustainability-oriented innovations. This section reports on the results of the *evaluation* stage in which the sustainability implications of bio-based nylon were anticipated under high uncertainty (Design principles 3 and 4 of CSA).

The monomers used in the production of nylons are, at present, derived from fossil fuel-based sources. Production of adipic acid, used in nylon 66, yields large quantities of the potent greenhouse gas N_2O; one study estimated that adipic acid represents 80% of Chinese industrial N_2O emissions (Li et al., 2014). Given the potentially significant contribution to climate change of adipic acid production, and the importance of nylon as a polymer in a wide variety of applications, biologically-based monomers for nylon production is an area of interest, but without commercial application as yet.

Cadaverine (1,5-diaminopentane) and putrescine (1,4-diaminobutane) are diamines that can be used to derive bio-based alternatives to nylon through polymerisation with dicarboxylic acids (Ma et al., 2017). The biochemical production of both molecules has been demonstrated in *Escherichia coli* (Kwak et al., 2017; Qian et al., 2009). Putrescine can be combined with adipic acid to form nylon 46, while polycondensation of putrescine or cadaverine with sebacic acid (from castor beans) yields nylon 410 or nylon 510 respectively (Estes & Schweizer, 2011). Nylon 510 has been found to have comparable physical properties to the currently predominant nylon 66 and nylon 6 (Kind et al., 2014).

The collaborative approach described in Section 3.4.1 allowed the crucial exchange of data and knowledge to enable and guide the assessment of sustainability implications across social, environmental, and economic criteria (see Methods). In doing so, we followed an approach similar to anticipatory LCA, whereby uncertainty becomes a fundamental feature of the analysis and is propagated and explored throughout (Design principle 3 of CSA) (Wender, Foley, Prado-Lopez, et al., 2014). We considered four feedstock scenarios for sugar production (see Methods).

Due to a combination of constraints from limited data availability and the nature of the issues at hand, levels of analysis had to be tailored to the sustainability pillar investigated:

- **Social:** Biomass and biorefinery sectors were compared to petrochemicals across the geographical locations considered. This was complemented by a literature review of social issues in the biomass sector.
- **Economic:** MSP was calculated for individual bio-based monomers (cadaverine and putrescine).

- **Environmental:** Comparisons were made across four types of nylon – bio-based nylon 510, 410, and 46 compared to fossil-based nylon 66.

3.4.2.1 Identifying social risks at an early stage

We used the social hotspot index (SHI) approach with the social hotspot database (SHDB) to measure potential social risks of bio-based nylon production (see Methods) (Benoît Norris et al., 2012). We calculated the SHI for the country-specific sector (CSS) corresponding to the relevant agricultural sector for each geographical feedstock scenario (Table B.14). We used the *Chemical, rubber, and plastic products* sector as a proxy for biorefineries in the absence of a specific CSS. For all CSS considered, risks to human health and safety were the most significant risks associated with bio-based production, while labour rights and work conditions also represented frequently occurring hotspots (Figure 3.4A, Tables B.15 & B.16). Concerns have previously been raised about poor working conditions in biomass production, such as health issues due to the practice of burning sugarcane tops (Eisentraut, 2010).

The shift towards synthetic biology-enabled bio-based production methods also introduces specific considerations not yet captured in the SHDB. On the positive side, biomass production can lead to investment in local economies and generate local employment. In Brazil, one million people are employed in the sugarcane industry with related improvements in job formality, benefits, and salary (van Dam et al., 2010). However, feedstock production for biotechnology can also result in consolidation of small-holdings and lead to greater mechanisation, disrupting existing land ownership, land-use rights, and employment patterns (ibid.).

The production of biomass for biotechnology can also compete with land for food, driving up global food prices and adversely impacting the world’s economically poorest citizens (Naylor et al., 2007). More recently, there has been increasing focus on biorefineries that make use of waste feedstocks (e.g. corn stover or wheat straw) or lignocellulosic sugars grown on marginal lands (e.g. *Miscanthus*) (Hassan et al., 2018). However, removing these resources can decrease soil-carbon stores by removing straw that would otherwise be recycled, and may adversely affect the economics and culture of vulnerable rural communities (Raman et al., 2015; Ribeiro, 2013; van Dam et al., 2010).

While it is informative to highlight and understand the potential social hotspots of future bio-based products, it is difficult to fully assess cost-benefit trade-offs involved in these disruptive innovations until these technologies achieve widespread adoption, particularly since many of their impacts are likely to be indirect. However, highlighting these issues at the early stage of biotechnological innovation can guide further analyses and data gathering as commercialisation progresses, such as through social auditing of suppliers and commercial partners. These early and ongoing assessments are critical for allowing incremental consideration of social impacts (both positive and negative) during, rather than after, implementation (Design principle 2 of CSA).

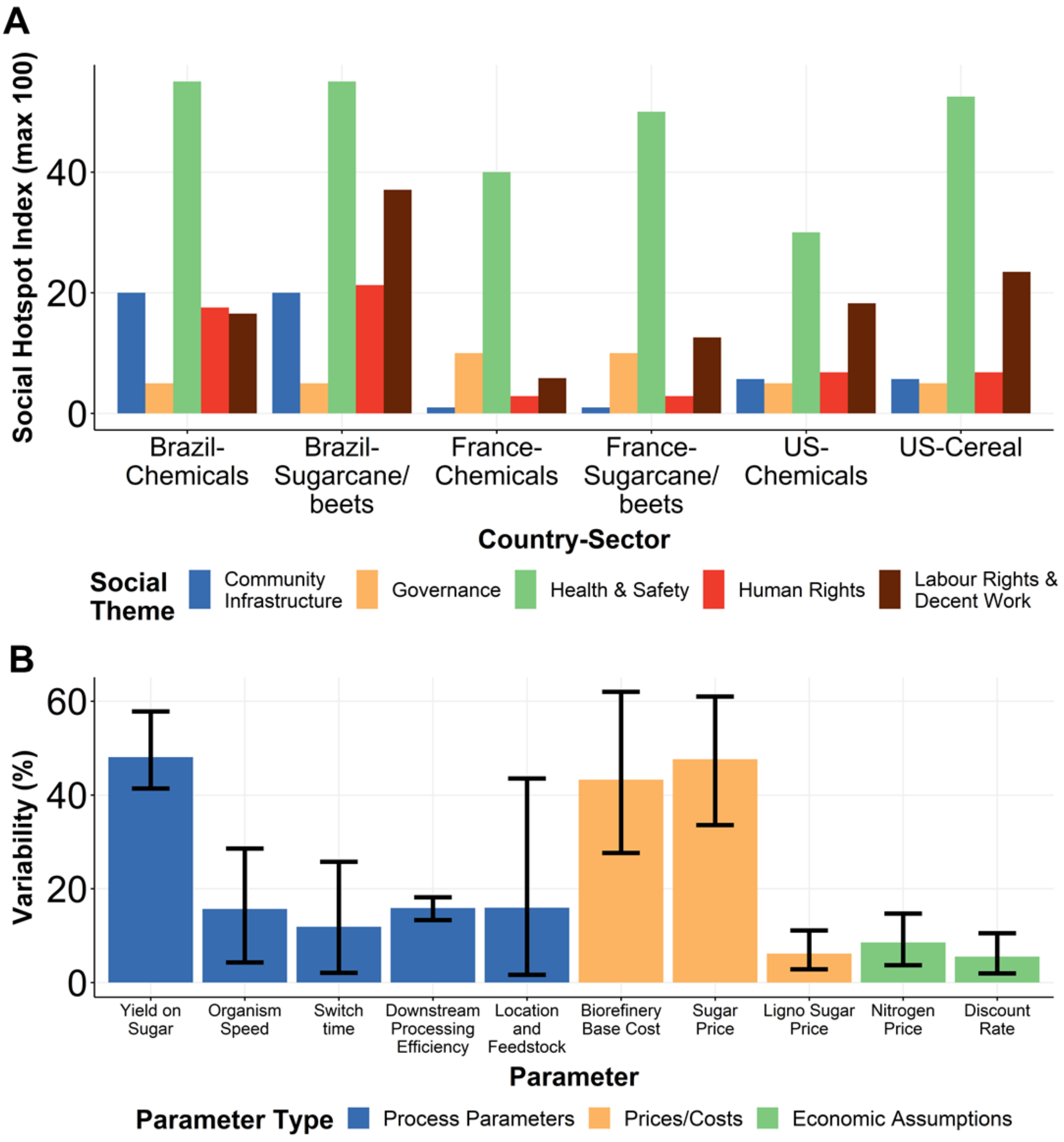


Figure 3.4: Economic costings and social hotspot results. (A) Social hotspots index results for the three geographical scenarios. (B) Key parameters affecting minimum selling price (results for putrescine). Only parameters with an average sensitivity of greater than 5% are shown. Error bars show 95% confidence intervals from multi-start sensitivity analysis.

3.4.2.2 Estimating the minimum selling price

MSP was estimated based on process modelling to determine the potential costs of individual monomer production (see Methods).[17] We estimated an average MSP of \$3.66 per kg for putrescine (range \$1.55-\$8.80) and \$3.67 per kg for cadaverine (range \$1.50-\$9.00). At the lower end of these ranges, which would represent a best case or optimised set of parameters, the MSP is competitive compared with fossil-based feedstocks; for example, a typical adipic acid selling price is 2.09 \$/kg (Davies, 2015). However, it is worth noting the volatility of these markets based on the crude-oil price, a factor that becomes further complicated by the addition of carbon taxes and/or consumer willingness to spend more for sustainable products (the ‘green premium’).

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[17] Full results for the MSP analysis and corresponding sensitivity analysis are provided as Supplementary Datasets 22 and 23 accompanying the published manuscript (Matthews, Cizauskas, et al., 2019).

Global sensitivity analysis using a multi-start approach (see Methods) highlighted the key parameters influencing the results (Figure 3.4B). For putrescine production, the model was most sensitive to the microorganism's yield on sugar with a sensitivity of 48.08% (range 39.20% to 61.60%); this parameter is determined by the efficacy of the microorganism and, therefore, can be engineered. Significantly, the yield represents a core design parameter for companies developing new microorganisms for bio-based production. Similar levels of sensitivity were seen for the capital cost of the biorefinery, at 43.26% (range 22.89% to 69.66%), and the sugar price, at 47.61% (range 24.00% to 70.34%). Sugar price and biorefinery cost are not directly within the control of companies developing the base technology (the microorganism); however, the influence of these parameters highlights the importance of considering both upstream (in terms of feedstock source and type) and downstream processing parameters in sustainability assessments.

3.4.2.3 Highlighting environmental trade-offs

Using the same process model as for the economic analyses, an LCA was undertaken following the ISO approach (see Methods) (ISO, 2006b, 2006a). The functional unit for this analysis was 1kg nylon. Through the combination of published data and the results of analyses carried out in this study (for cadaverine and putrescine), we considered four types of nylon: bio-based nylons 410 and 510, partially bio-based nylon 46, and fossil-based nylon 66 (Figure 3.5A, Table B.7). We found that using bio-based putrescine in the production of nylon 46 resulted in a worse overall climate change impact (more kg CO2 eq/kg nylon produced) in 72.45% of simulations compared to producing fossil-based nylon 66 (Figure 3.5B): on average the impact of nylon 46 was 3.85% higher than nylon 66 (range of -19.57% to 38.49%). This outcome demonstrates the importance of considering how new bio-based chemicals will integrate into existing supply-chains: 1 kg of nylon 46 requires a greater mass of adipic acid to produce compared to nylon 66, which negates the benefits of replacing HMDA with bio-based putrescine. However, bio-based nylon 410 and nylon 510 both showed superior climate change performance (i.e. lower kg CO2 eq/kg nylon produced) in 100% of simulations compared to fossil-based nylon production. We found an average reduction in climate change impact of 64.48% (range of 11.67% to 92.22%) for bio-based nylon 410 and 65.75% (range of 11.75% to 93.05%) for bio-based nylon 510 compared to fossil-based nylon 66.

Most discussions and assessments surrounding bio-based technologies focus on their ability to reduce net GHG emissions and dependence on fossil fuels (Broeren et al., 2017; Hottle et al., 2013; Palmeros Parada et al., 2017). However, such a focus risks shifting impacts towards other environmental areas, particularly those involved with land use and agricultural practices required for biomass production for feedstocks. In this analysis, we considered a wider range of environmental impact categories; our results indicated that bio-based nylons generally had worse impacts across a range of impact categories (e.g. freshwater consumption, land-use, freshwater and marine ecotoxicity, terrestrial acidification) compared to traditional fossil-based production (Figure 3.6A).

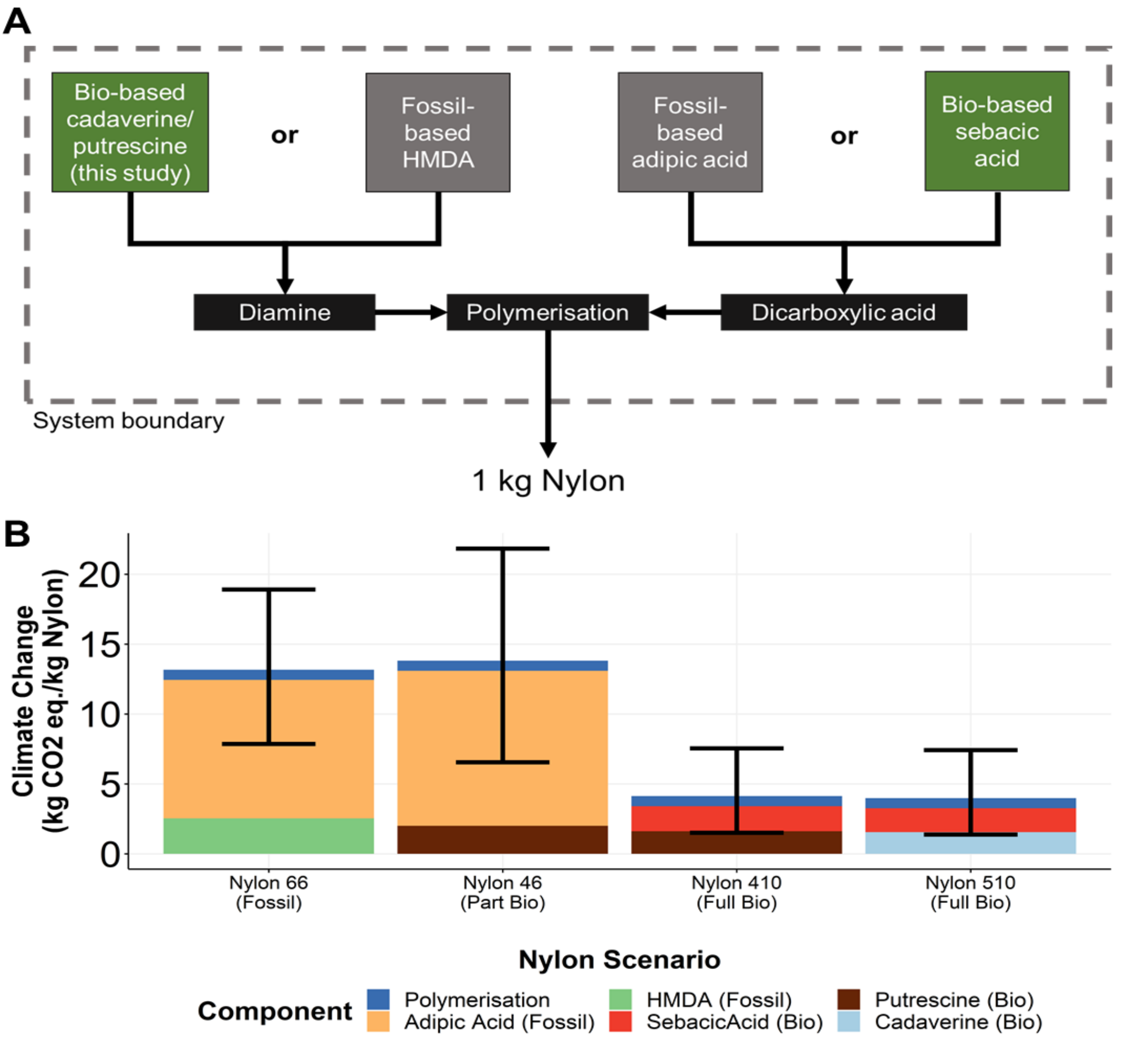

Figure 3.5: Environmental assessment results (1/2). (A) System boundary for nylon comparisons showing how results were combined. (B) Climate change impact results coloured by the relative contribution of monomers and polymerisation. Error bars show 95% confidence intervals from Monte Carlo simulations.

Consistent with design principle 3 of CSA, we present uncertainties clearly in our results. At this stage of analysis, early in the biodesign process, some impact categories contain large uncertainties, leading to somewhat inconclusive results. In other impact categories, we can measure clear differences, demonstrating the utility of carrying out such analyses even at the early stages of product development. Furthermore, far from simply representing incomplete knowledge, uncertainties can also highlight areas in which processes can be improved (Grunwald, 2007). A combination of the hotspot (for influential process stages) and sensitivity analysis (for key parameters) can therefore be highly informative for prioritising efforts to reduce negative environmental and social impacts. In addition, the iterative nature built into the CSA process is designed to both update time-sensitive input data and to reduce algorithmic uncertainties as more data are incorporated into analyses as projects progress.

In our analysis, we identified hotspots in the supply of raw materials such as sugar and nitrogen required by the microorganism, and sodium hydroxide, or another strong alkaline, required for the selected downstream process (DSP) (Figure 3.6B). Our multi-start sensitivity analysis indicated that, while microorganism-specific parameters such as yield and productivity influenced the outcomes of all impact categories, parameters relating to feedstocks and DSP were typically even more influential (Figure 3.6C). The level of waste handling integration in each process examined was particularly important for determining outcomes of ecotoxicity and photochemical ozone-related impact categories. These results are in contrast to our MSP analysis, in which yield was the most influential parameter. This supports the consideration of parameters beyond yield and productivity when developing sustainable microbe-based biotechnologies.

3.4.3 Constructive interpretation

Interpreting sustainability assessment results, such as those presented here from the *evaluation* stage, represents a key challenge. To support the iterative aspect of CSA and promote the constructive exploration and opening up of design options by stakeholders (Design principle 2 of CSA), we pursued a deliberative approach to *interpretation*. We circulated the results of the *evaluation* stage among internal stakeholders through an hour-long company-wide presentation, a summary report, and short (~10 minute) presentations to smaller, departmental workshops in which we then discussed the results. We also distributed a follow-up company-wide survey, similar to our first survey.

Through the deliberative approach, we were able to identify what could be responsibly concluded from the results and for which Table 3.1 provides a summary. The cells of the table encapsulate the results of the analysis described in detail in the previous sections, alongside the key uncertainties, sensitivities, outstanding ambiguities, potential routes forward, and future actions that were discussed and elaborated during the follow-up workshops. The table demonstrates the kind of rich outputs and findings, spanning a broad range of SDGs, which can be generated through this approach. Ambiguities are inevitable when undertaking analyses at this stage of technological development, but they also suggest areas where further cycles of CSA could clarify or elaborate unknowns.

For tackling climate change (Table 3.1, row 1), the use of bio-based putrescene alongside fossil-based adipic acid in nylon 46 should be discouraged. In addressing climate change alongside improving the health of global ecosystems (Table 3.1, row 2), it was clear from workshop discussions that there would be benefits in considering broader parameters when engineering and optimising organisms. Titre is commonly the key parameter against which new microorganisms and strains are evaluated, but our findings highlighted the importance of also considering yield due to its effect on biomass usage. The significance of biomass production for overall sustainability performance also stimulated discussion regarding the use of alternative feedstock. The flexibility of feedstock remains a key issue when the majority of available sources remain first-generation crops that compete with food production. The use of alternative feedstocks such as waste streams could be achieved through the exploration and engineering of different host organisms and strains which can grow on more sustainable and currently available feedstocks.

Key (ReCiPe 2016 Impact Categories)

CC – Climate change, incl. biogenic credit
FD – Freshwater depletion
MD – Metal depletion
FC – Freshwater consumption
FE – Freshwater ecotoxicity
FET – Freshwater eutrophication
HT (C) – Human toxicity (cancer)
HT (NC) – Human toxicity (non-cancer)
PM – Particulate matter
IR – Ionising radiation
LU – Land use
ME – Marine ecotoxicity
MET – Marine eutrophication
POF (Eco) – Photochemical ozone formation (ecosystems)
POF (HH) - Photochemical ozone formation (human health)
SOD – Stratospheric ozone depletion
TA – Terrestrial acidification
TE – Terrestrial ecotoxicity

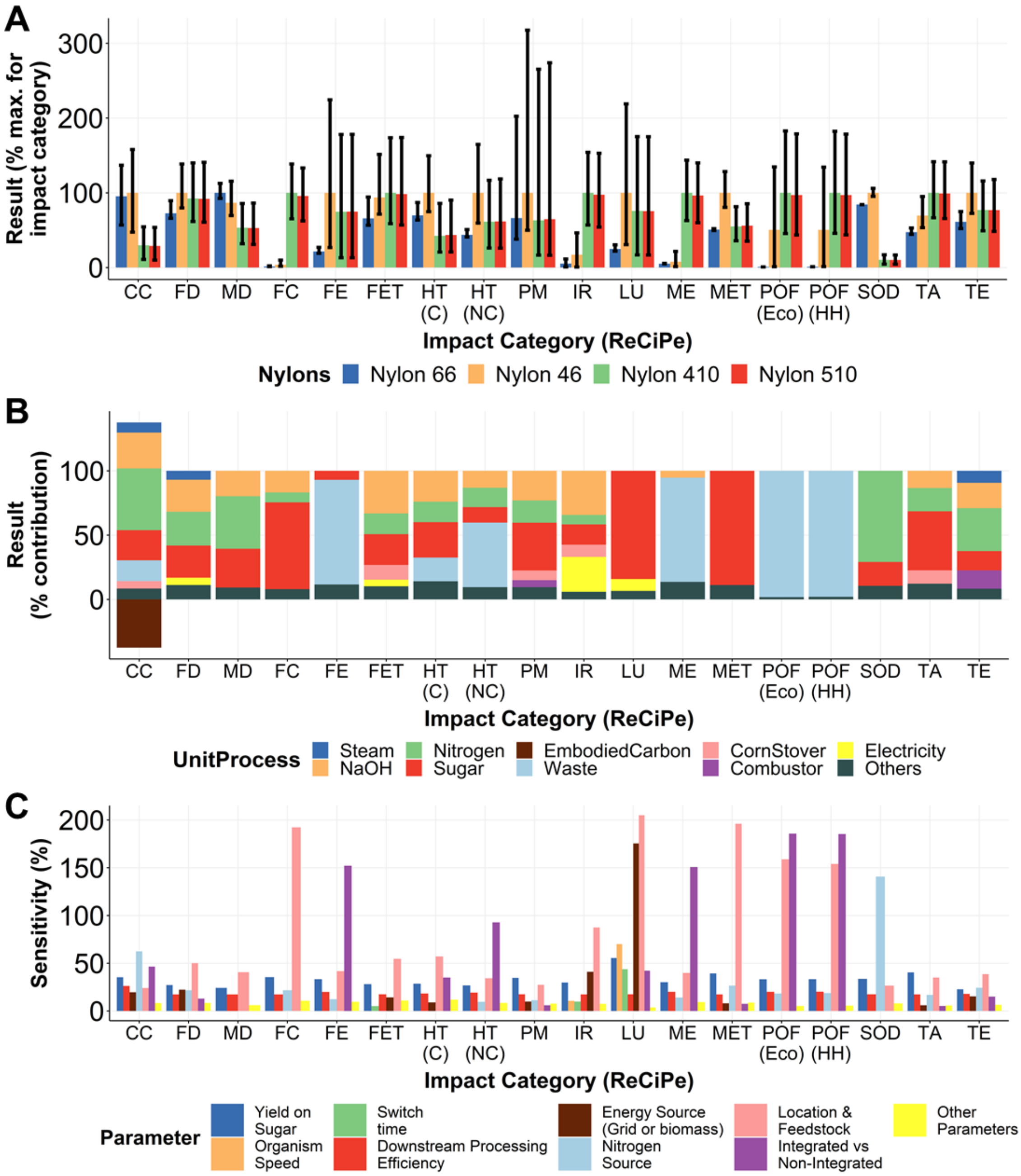

Figure 3.6: Environmental assessment results (2/2). Error bars show 95% confidence intervals from Monte Carlo simulations. (A) Results for all 18 ReCiPe 2016 impact categories across the four nylons considered. Results are normalised by the maximum result for each impact category. (B) Relative contribution of each background or foreground stage to each impact category result (results for putrescine). Stages contributing less than 5% to each impact category are grouped into the “others” category. (C) Influence of parameters on each impact category (results for putrescine). Parameters with an average sensitivity of less than 5% for each impact category are grouped into the “other parameters” category.

Highlighting health and safety risks and potential issues faced by farmers helped us to explore broader social aspects such as poverty, hunger, and poor-health (Table 3.1, row 3). While specific responses to these issues can be more difficult to lock-down given their complex and often macro-level nature, highlighting them at an early stage encourages continued attention through initiatives, such as social auditing of the supply-chain, throughout scale-up commercialisation. Engagement with potentially affected stakeholders throughout the value chain from farmers to consumers may help to further explore the complex social implications of a transition to bio-based manufacturing approaches.

Finally, economic ambiguities (Table 3.1, row 4) are some of the hardest for a company to resolve as they relate to systemic issues that may need to be tackled at a higher level. Deliberation allowed reflection upon how biotechnology companies could tackle these ambiguities given these constraints. The locked-in nature of incumbent fossil-based technologies represents a key barrier to systemic change. In addition to this, the potential benefits of sustainable innovations such as bio-based production relates in a large part to externalities such as GHG emissions. The internalisation of these externalities, such as through a carbon tax paid by those generating emissions, would generate a greater market incentive for sustainable innovation such that the sustainability benefits can become part of a company's core value-offering. However, issues such as carbon taxes are currently subject to active societal debate. Reflective and inclusive dialogue with governments, clients and competitors, regulators, and wider society could be an appropriate route forward (Ribeiro et al., 2018; Stilgoe et al., 2013).

The intention of a CSA process is to question assumptions, open up options, and build capacities in anticipation, reflexivity, and responsiveness for the future (Design principles 2 and 4 of CSA) (Stilgoe et al., 2013). In this study, while awareness of sustainability issues surrounding biotechnology applications varied amongst the internal stakeholders, many participants commented on how the data demonstrated the complexity and trade-offs involved, and that "bio isn't always better". In a follow-up survey, 77% of respondents stated that the CSA process had at least a small impact on the way they "think about the sustainability of bio-based products" (within which 21% indicated a moderate impact and another 21% indicated a significant impact). The use of anticipatory assessments can therefore be successful in questioning the prior assumptions of stakeholders (Figure 3.3) alongside, as discussed above, identifying potential actions and routes forward.

Here, we have carried out a single cycle of CSA focussed on a single application. Wider application and repeated iterations are required to allow further analysis and incremental governance. Internal stakeholders demonstrated an appetite for this and emphasised the utility of starting early and building up the process over time. CSA will also need to align with current business practices. Combining the approaches of TEA and CSA may ultimately be the best approach, by simultaneously anticipating sustainability and commercialisation challenges.

Sustainability Aspect	Evaluation Results	Hotspots	Key Sensitivities	Ambiguities	Potential Actions
Tackling Climate Change (SDG 15)	• Nylon 510/410: Climate change reductions vs nylon 66 • Nylon 46: Climate change increases vs nylon 66	• Biomass (sugar) production • Nitrogen and NaOH • Embodied carbon	• Yield on sugar • Process integration • Nitrogen source	• Future process optimisation • Process parameterisations	• Explore alternative feedstocks • Avoid usage in nylon 46
Improving the health of global ecosystems (SDG 13,14)	• Increased impact across many impact categories including freshwater and marine ecotoxicity	• Biomass (sugar) production • Nitrogen and NaOH • Waste Handling	• Process integration • Geographical location • Yield on sugar	• Future process optimisation • Process parameterisations	• Explore alternative feedstocks • Greater process integration
Eliminating poverty, hunger, and poor-health (SDG 1,2,3,6,7)	• Growth opportunities for rural areas in the Global South • Health and safety risks in the biomass sector	• Health and safety • Labour rights and decent work	• Geographic location	• Many unknown unknowns • How to measure the fair distribution of costs and benefits	• Engage with value-chain stakeholders
Sustaining employment and economic growth (SDG 8,9,11)	• Potential to displace incumbent fossil-based nylons • Highly optimised scenarios may be able to compete with fossil-based incumbents	• Raw material cost • Base capital cost	• Yield on sugar • Sugar price • Biorefinery base cost	• Cost estimates highly uncertain • Future oil price • Possibility of a green-premium or carbon tax	• Reflective and inclusive dialogues to explore options

Table 3.1: A summary of the outcomes of the study as determined through analytical evaluation and deliberative interpretation. Unless otherwise stated, bullet points relate to all bio-based nylon scenarios compared to fossil-based nylon.

3.5 Discussion and conclusion

In this chapter, we demonstrate a collaborative and constructive sustainability assessment applied to bio-based nylon production. Empirically, we find that bio-based nylon alternatives have the potential to yield substantial improvements over petroleum-based analogues in terms of climate change, but show equivocal results in several other environmental impact categories, a result that is consistent with those of other published analyses (Escobar & Laibach, 2021; Narodoslawsky et al., 2015; Weiss et al., 2012). Our results for the current cost of biomaterial production, though uncertain, support the view that while bio-based approaches struggle to compete on a like-for-like basis with established fossil-based incumbent technologies, under optimistic future scenarios favourable economic competitiveness could be seen (Saygin et al., 2014). Parameters such as feedstock choice, yield-per-organism, and level of process integration are identified as promising areas for improving sustainability performance and highlight the need to consider more than simply yield and productivity to achieve sustainable biotechnology development. Socially, results suggest that particular attention should be given to health and safety risks in biomass production, as well as to potential disruption to local employment and cultural practices when producing feedstocks. This is consistent with findings from Valente et al. (2017) in a study of the social implications of future biorefineries.

More broadly, our case study demonstrates a promising operationalisation of the CSA approach (Matthews, Stamford, et al., 2019). Building on the arguments of those who regard internal stakeholders as a potential source of incentives for companies to engage in RRI (Gurzawska et al., 2017), we illustrate the utility of mobilising internal stakeholders throughout the process to open up perspectives and embed RRI principles early in the manufacturing process. Application of CSA in an industry context, while bringing its own challenges, is essential to allow these important players to pursue and experiment with sustainable innovation. We add much-needed empirical evidence to the growing discussions in the literature regarding how companies can align their practices to sustainability goals and embed responsible innovation (T. Brand & Blok, 2019; Lubberink et al., 2017). The case demonstrates how a relatively new company deployed CSA in an attempt to align practices with sustainability goals, gaining experiences and insights that are applicable to future product developments. The approach could also be used by more established companies for enhanced alignment of company practices with sustainability.

Crucially, this (re)alignment needs to be part of a two-pronged, multilevel approach (Geels, 2002). Firstly, companies must consider and manage the impacts of the innovations they create and promote, including both negative and positive effects of products and processes. A CSA approach critically aids companies to understand, anticipate, reflect, and act upon these outcomes. Simultaneously, changes are necessary within the broader market environment within which companies operate to favour truly sustainable innovations. Such rearrangements, including honing feedstock production for greater efficiency and suitability to biotechnology needs, have to be stimulated at a higher level, enabling companies to foresee these challenges and to inform their own and others’ actions so that they can contribute positively to a sustainability transition.

Scaled up, the results of multiple instances of CSA analyses across several industrial stakeholders would create a large body of biotechnology sustainability data and experience that can inform public-private partnerships and policy-makers in efforts to undertake systemic changes not achievable by individual actors. This could be through greater attention to evidence-based sustainability in research funding, design and evaluation, feedstock development and use, modelling, training, regulatory review, and road mapping.

Chapter 4: The role of business in constructing sustainable technologies: Can the Silicon Valley model be aligned with sustainable development?

This chapter is based on a manuscript that has been prepared with the intention of future submission to an appropriate academic journal. The manuscript is co-authored with the doctoral supervisors Professor Philip Shapira and Dr Laurence Stamford. The thesis author led all aspects that contributed to the manuscript and was solely responsible for data collection and analysis as well as manuscript drafting. The two co-authors provided input into the conceptualisation of the project as well as feedback on manuscript drafts.

Abstract

Businesses are increasingly focussing their efforts on developing *sustainable* technological innovations. In doing so, they face obstacles in the systemic nature of innovation processes, the uncertain and ambiguous nature of sustainability, and in reconciling their business model and strategy with social and environmental value creation. This is particularly the case for those trying to emulate the so-called ‘Silicon Valley model’, which prioritises speed to deliver on its ambitious socially significant mission, relies on high-risk venture capital financing, and encourages flexibility and curiosity on the part of employees. This chapter uses data gathered during an action research case study to explore whether this much vaunted model could be better aligned with sustainable development. While, in this case, we find systemic and cognitive challenges to be currently precluding concerted action on sustainability, we also identify opportunities for greater alignment. Changes in the market and financial environment promise to provide new incentives for sustainability while the use of public deliberations such as citizen assemblies could help to reduce ambiguity. Complementary application of approaches like Constructive Sustainability Assessment within companies would allow business models to be more proactively and demonstrably aligned with employee values and ambitious sustainability missions.

4.1 Introduction

The development and application of new technological innovations is widely put forward as a key enabler of sustainable development (Cervantes & Hong, 2018; UNCTAD, 2018). In market economies, businesses play central roles in the development and deployment of these technologies (Kline & Rosenberg, 1986). Consequently, the sustainability agenda and the need for *sustainable* technological innovation implies responsibilities for these businesses that go beyond profit maximisation (cf. Friedman, 1970). Recently, there has been a rise in attention to corporate sustainability, where businesses seek to understand, report on and improve their contribution to sustainable development (Linnenluecke & Griffiths, 2013). Over 12,000 businesses have signed up to the United Nations (UN) Global Compact which aims to rally businesses in support of the Sustainable Development Goals (SDGs), bringing together environmental sustainability with social justice and responsibility (UN, 2015b). In line with this, some businesses now seek actively to pursue sustainable innovation, where “the renewal or improvement of products, services, technological or organizational processes not only delivers an improved economical performance, but also an enhanced environmental and social performance, both in the short and long term” (Bos-Brouwers, 2010, p. 419).

While there may be growing consensus over the urgent need for action, and thus a moral responsibility for companies to actively integrate sustainability considerations into their technology development processes, many barriers and challenges remain (Álvarez Jaramillo et al., 2019; Engelken et al., 2016; Kiefer et al., 2018). To the extent that sustainable development requires the wholesale transformation of socio-technical systems (Schot & Kanger, 2018), such transitions require the underpinning of collective action. This leaves a somewhat unclear role for individual businesses. Meanwhile, the fact that many of the costs and benefits involved in sustainability represent externalities raises difficult questions for how businesses can create and capture value through sustainable business models (Geissdoerfer et al., 2018; van den Bergh, 2010). Finally, the malleable and ambiguous nature of the sustainability concept and inevitable uncertainty concerning the sustainability implications of new technologies collectively pose challenges and dilemmas for individual businesses as to how to operationalise sustainability during technological development (Collingridge, 1980; Kates et al., 2005).

Numerous frameworks have been proposed to help overcome some of these issues such as responsible research and innovation (RRI) (van de Poel et al., 2017) and business transition management (Loorbach et al., 2010). We have previously elaborated a framework for Constructive Sustainability Assessment (CSA) which seeks to grapple with these issues through the use of both analytical sustainability assessment and deliberative governance within an iterative, open-ended, and participatory approach (Matthews, Stamford, et al., 2019). Such frameworks suggest a slower, more precautionary, and deliberative approach to innovation (Reber, 2018; Steen, 2021).

On the other hand, the perceived urgency of contemporary sustainability challenges seems to call for rapid and disruptive innovation (UNCTAD, 2018). In this context, the San Francisco Bay Area is renowned for nurturing start-ups that excel in rapid technological innovation and scale-up, hosting three out of five of the ‘GAFAM’ family of big-tech companies.[18] The idea of the ‘Silicon Valley model’[19] has been used to explain the success of the region. It can be characterised by a focus on rapid growth and innovation; a dependence on venture capital financing; an ambitious, socially significant mission (such as sustainable development); and a people-centric approach that encourages flexibility and curiosity on the part of employees (Steiber & Alänge, 2016c). Yet, while this model receives much praise for exemplifying Schumpeterian ideals of creative destruction (Schumpeter, 1934), its prioritisation of speed and agility appears to be in tension with more precautionary and cautious approaches such as RRI and CSA, which have been put forward as ways to overcome some of the challenges posed by sustainable development for innovators.

This paper sets out to explore these apparent tensions and contradictions, asking whether and how the pursuit of rapid technological innovation and scale-up within a Silicon Valley model could be more aligned with sustainable development. We take as an empirical case a San Francisco Bay Area-based synthetic biology company[20] employing the Silicon Valley model (Steiber & Alänge, 2016c). We build on evidence gathered during an action research case study where the CSA framework[21] was applied collaboratively with the case company. The main aim of this collaboration was to test the applicability of the CSA framework in a business context and the primary results of this have been reported in Chapter 3. This previous chapter demonstrated how the application of the framework was successful in highlighting sustainability trade-offs at an early stage of development and thereby identifying avenues through which the business could pursue more substantive action towards sustainable development. However, cognitive, systemic, and business model challenges seemed set to preclude its broad uptake. Unpacking these challenges here enables us to derive insights for the literature as well as policy-makers and business actors.

We argue that while there are tensions between the rapid growth-focussed Silicon Valley model and sustainable innovation, this much vaunted business approach could be put at the service of sustainable development through changes both internally and externally to individual companies. Importantly, this chapter does not take up a position as to whether the Silicon Valley model should or should not be emulated. Indeed, we have sympathy with many of the very valid critiques of the model (e.g. Audretsch, 2021; Pahnke & Welter, 2019), as will be further discussed. Rather, given the widespread interest in emulating the model, we believe that it is worth considering whether it can be aligned with the demands of sustainable development.

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[18] GAFAM is an acronym of Google (Alphabet), Apple, Facebook, Amazon, and Microsoft. Apple, Facebook, and Google are all based in the San Francisco Bay Area while Amazon and Microsoft are based in Seattle, WA.

[19] Note that the Silicon Valley model is not synonymous with the geographical location which inspired it, as is further clarified in Section 4.2.3.

[20] Alongside Boston, MA, the San Francisco Bay Area represents an epicentre for synthetic biology development, both in the US and globally (Cumbers, 2019).

[21] The CSA framework brings together analytical sustainability assessment with deliberative social science governance frameworks to derive a three-step methodological approach through which innovators can integrate sustainability considerations into the design, development, and scale-up of emerging technologies (see Chapter 2).

The next section proceeds with a literature review outlining the key concepts, ideas, and theories that underpin the paper. Section 4.3 then describes the research approach and methodology before the findings are outlined in Section 4.4. Section 4.5 discusses the implications of the findings before some concluding remarks are offered in Section 4.6.

4.2 Literature review

4.2.1 The multiple challenges of sustainable innovation

Businesses face many challenges when attempting to innovate in a manner that is in line with sustainability development. This literature review starts by identifying and describing three key challenges faced. Next, frameworks and approaches which have been put forward to address these challenges are introduced. Finally, the Silicon Valley Model is conceptualised with consideration given to where there might be tensions with the previously described frameworks.

The first challenge relates to the broad and ambiguous nature of sustainability as a concept, which, while a highly influential concept, lacks consensus as to its specific meaning, with multiple, often contrasting definitions proposed.[22] Bos et al. (2014) conceptualise such 'big words' as ideographs - loosely defined but generally agreeable normative concepts that can have powerful structuring effects. However, these ambiguous characteristics can pose cognitive dilemmas for business managers (see Hahn et al., 2014). In response, innovators can 'articulate alignment' to these broad societal missions by establishing and reaffirming links to the overarching idea and thus legitimising research and innovation avenues (Fujimura, 1987). A consequence of this articulation process can be that once a link between a particular technology and the ideograph in question has been thoroughly established it then becomes black-boxed[23] and is no longer perceived as needing further elaboration (Bos et al., 2014), closing down discussion.[24]

As well as ambiguity over the concept, there is also a lack of clarity concerning how to operationalise sustainability. Its broad nature, spanning social and natural domains (Elkington, 1997), makes the concept difficult to develop metrics for, as some dimensions lend themselves to quantification while others do not. While assessment approaches such as life-cycle assessment (LCA) have been put forward as a means to grapple with this complexity (Sala et al., 2015), there is a limit in the degree to which expert, science-based assessment approaches that tend to be relied upon can provide answers to subjective and values-based questions concerning the impact and desirability of certain technological trajectories (Matthews, Stamford, et al., 2019; Nathan & Coles, 2020). Such questions require shared values to be established before the science can inform the route forward (Sarewitz, 2004). Taken together, these features make it difficult for businesses to operationalise lofty sustainability goals down at a level which are appropriate for

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[22] While initiatives such as the SDGs aim to break down the concept and give more specificity, they remain rather all-encompassing which allows them to support many different priorities and competing conceptualisations (Kates et al., 2005; UN, 2015b).

[23] This process is analogous to the black-boxing described by Latour (1987) with respect to the scientific process.

[24] See Stirling et al. (2008) for a comprehensive discussion of how discussions around science and technology can become closed down.

organisational decision-making. This may help to explain why a lack of resources and expertise, as well as the high cost of implementing assessments, are some of the most frequently cited barriers to SMEs implementing sustainability-focussed initiatives (Álvarez Jaramillo et al., 2019).

The second challenge relates to barriers arising from the systemic character of innovation processes and the systemic contexts within which businesses operate. These include research and development and scaling challenges; technical financial, and market risk; and uncertainty over legal and regulatory incentives (Álvarez Jaramillo et al., 2019; De la Tour et al., 2019; Delmas & Burbano, 2012; Gurzawska et al., 2017).

The systems of innovation approach emphasises that businesses do not operate and innovate in isolation but rather are embedded within complex multi-actor systems (see Lundvall, 1992). The activities of individual businesses are therefore influenced and constrained by their interaction with and interdependence on other businesses (e.g. suppliers, customers, and competitors) as well as investors (public and private), governing authorities and regulators, consumers, and non-governmental organisations (Edquist, 2009). Another key concept is the importance of institutions - the “sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups” (Edquist & Johnson, 1997, p. 46). This perspective helps to avoid the pitfalls of idealised, linear models of how innovation occurs and provides a more realistic and holistic account of innovation characterised by non-linearity, interdependence, and evolutionary behaviours (Edquist, 2009).

The systems approach has been taken forward by sustainability transitions researchers seeking to understand the determinants of stability and change which could then be leveraged to inform policy intervention (Jacobsson & Bergek, 2011; Kanger et al., 2020). Within this literature, the multi-level perceptive (MLP) provides a widely-used framework for understanding the dynamic processes that govern transitions (Geels, 2002). Rather than focus on institutions, the idea of socio-technical *regimes* is used to refer to “the semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems” (Geels, 2011, p. 27). Meanwhile, radical innovations are thought to first emerge through actors such as entrepreneurs occupying *niches* that can provide semi-protected spaces for early development and experimentation (Geels, 2002). However, to bring about transitions, niche innovations have to eventually diffuse and become established. During this process, existing regimes exert selective pressures and are likely to favour those that are more compatible with the logic of incumbent regimes (Schot & Kanger, 2018). Consequently, to enable the emergence of sustainable socio-technical regimes, strategic niche management (SNM) focusses on how to intentionally support experimentation in niches, not simply with new technologies but also with new institutional frameworks, user practices, and networks of actors (Schot & Geels, 2008). However, while these systemic understandings might accurately describe the processes and challenges and provide insightful policy implications (e.g. Kanger, Sovacool, & Noorkõiv, 2020), they provide limited guidance concerning what individual niche actors such as innovating businesses should do.

The third and final challenge is that of aligning business models with sustainability. The business model is of central importance as it "defines how the enterprise creates and delivers value to customers, and then converts payments received to profit" (Teece, 2010, p. 173). This conceptualisation aligns with the traditional view of businesses as profit-maximisation engines[25] but is increasingly in tension with the contemporary repositioning of businesses with broader responsibilities to society and the environment. Correspondingly, there has been considerable research on the subject of sustainable business models which create both monetary and non-monetary value for a broader range of stakeholders, often through the exploration of where the sustainability agenda can be used to generate competitive advantage (Carrillo Hermosilla & Del Rio Gonzalez, 2009; Geissdoerfer et al., 2018). However, while a weakly positive relationship between financial and environmental performance[26] has been reported at the level of firms (Endrikat et al., 2014), the relationship is not well established and remains contested (Boons & Wagner, 2009; Trumpp & Guenther, 2017). This is perhaps not surprising given that many of the costs and benefits involved in sustainability are externalities for individual businesses (van den Bergh, 2010). Consequently, businesses introducing disruptive technologies with new value propositions such as improved sustainability often face the dual challenge of a lack of broad demand for their core value proposition and of their technology being inferior in other respects (such as price) compared to incumbents (Bohnsack & Pinkse, 2017).

Others have more fundamental concerns regarding making the "business case" for sustainability. Dyllick & Hockerts (2020) argue that embedding CSR and corporate sustainability within a business case framing can lead to crowding out of the more fundamental moral and legal rationales. Meanwhile, Henderson (2015) points out that the business case for sustainability is more of a long-term "strategic bet" that in most future scenarios will lead to net benefits for the firm. Thus, while the overall benefits for society of sustainable development and particularly of tackling climate change have been evident for a long time (e.g. Stern, 2007), this does not mean that there will necessarily be an obvious case for individual businesses to take action unilaterally, particularly given issues of externalities and discounting.

4.2.2 Strategies to support sustainable innovation

Numerous frameworks and strategies have been suggested to tackle and overcome the challenges outlined above. In the face of uncertainty and ambiguity, RRI frameworks suggest potential avenues to proceed prudently and embed responsible practices at the early stages of technological development in order to proactively create social and environmental benefits (van de Poel et al., 2017).[27] Yet, applying RRI in business settings remains a relatively new

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[25] Friedman famously stated that "the social responsibility of business is to increase its profits" (M. Friedman, 1970).

[26] Much of the current evidence focusses specifically on the alignment between environmental/ecological performance and economic return, while often excluding the third pillar of social sustainability.

[27] RRI activities can be defined along four dimensions - exploring and anticipating potential future directions and implications of innovation; pursuing inclusive engagement with a broad range of stakeholders; promoting reflection on individual and organisational values and motivations; and responding accordingly to embed insights from these activities in innovation trajectories (Stilgoe et al., 2013).

development. Recent efforts have sought to build on experience in research settings to develop and apply business-focussed strategies (see van de Poel et al., 2020). But others have argued that without a fundamental reframing of how markets operate, there will need to be a pragmatic re-evaluation of some core tenets of RRI to enable widespread operationalisation in industry, particularly concerning the principles of stakeholder engagement and democratic governance (T. Brand & Blok, 2019; Lubberink et al., 2017; Noorman et al., 2017). We have previously outlined a framework for CSA, which provides a methodology to support organisations such as businesses to actively take account of sustainability considerations in their innovation processes (see Chapter 2). This approach draws on RRI as well as other frameworks such as constructive technology assessment (Schot & Rip, 1996), placing analytical assessment approaches such as LCA within a broader iterative and deliberative process which helps to alleviate some, though not all, of the challenges brought by ambiguity and uncertainty in the context of sustainable development (Chapter 2; Matthews, Stamford, et al., 2019).

With respect to systemic challenges, it has been proposed that actors such as businesses can reshape the institutional arrangements that maintain incumbent regimes, but doing so involves assembling multiple forms of power - normative, convening, legal, informational, and financial (see Diaz Anadon et al., 2015). While assembling this power may be challenging, actors can take responsibility by engaging in “institutional entrepreneurship” - developing divergent visions and mobilising other actors to support, achieve, and sustain them (Battilana et al., 2009). Frameworks such as business transition management have also sought to articulate how businesses can go about this.[28] Reflecting the fact that the control of innovation processes is inherently collective and shared amongst a range of actors, a common theme amongst such efforts is the critical role for collaborations and alliances (Kishna et al., 2017; Loorbach et al., 2010; Schaltegger et al., 2018).[29]

To address business model challenges, numerous strategies have been proposed. For example, the lack of a sufficient value proposition from sustainable technologies can be addressed by mitigating inferior characteristics, enhancing superior characteristics, and/or coupling to other products or services (Bohnsack & Pinkse, 2017). Likewise, van Lente & van Til (2008) in the case of nanocoatings describe how improved sustainability of products can be combined with other features such as lower cost or ease of use which serve as “vehicles of sustainability”. However, this strategy is only effective if these vehicles are truly commensurate with sustainable outcomes.

Others have argued for more fundamental changes. Elkington (1997) put forward a triple bottom line framework to account for financial, environmental, and social impacts and outcomes. However, Dyck and Silvestre (2018) refute this approach to SI and propose ‘SI 2.0’ which involves focussing on the active enhancement of socio-ecological wellbeing with financial viability

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[28] Business transition management describes how cycles of strategic envisioning, tactical networking, operational innovation, and reflexive monitoring and evaluation can enable them to become frontrunner businesses in promoting sustainability transitions while also gaining competitive advantage (Loorbach et al., 2010; Loorbach & Wijsman, 2013).

[29] This also aligns with RRI frameworks, early proponents of which emphasised the collective and shared nature of responsibility for the future impacts of innovations (EC, 2013b; Stilgoe et al., 2013; von Schomberg, 2013).

relegated to a secondary, *subservient* necessity. This argument appears to be gaining some traction with the growth of social innovation initiatives such as the B-corps (Stubbs, 2017; van der Have & Rubalcaba, 2016). Similarly, Loorbach and Wijsman (2013) suggest that for commercialisation processes to support more sustainable innovation and contribute towards a transition, sustainability first has to be embedded at the organisational core, entailing the restructuring and reconceptualization of what a company *is* and *does*. These changes require business model innovation to embed a broader and long-term conceptualisation of value in business operations (Geissdoerfer et al., 2018). This can be brought about either through the creation of new companies or through existing companies transforming, diversifying, or acquiring new models (ibid.).

4.2.3 The Silicon Valley model: Can it address the challenges of sustainable innovation?

The responses described above to the previously described challenges of sustainable innovation are heavily implicated in the internal behaviours, operations, and cultures of companies. Similarly, the organisational behaviours and structures of firms are also important determinants of different kinds of technological innovation (Teece, 1996). The Silicon Valley model, named based on the typical characteristics of many highly successful start-ups from the San Francisco Bay Area, represents one such architype of organisational behaviour and structure which is associated with driving radical, disruptive technological innovation of the sort which could play an important role in sustainable development (ibid.). Given the level of interest shown in emulating this model around the world, it is pertinent to explore whether it can be applied in a way that is commensurate with the demands of sustainable innovation.

Before discussing this model further, it is important to clarify two assumptions concerning the conceptualisation presented here. Firstly, the “model”, while closely linked to the business practices often seen in the geographical location of Silicon Valley, is not synonymous with it. Thus, companies following the model do not necessarily have to be based in Silicon Valley while companies based in that region do not necessarily all follow the model. Secondly, this chapter does not profess a normative position as to the overall value of the Silicon Valley model or on whether it should be emulated. Indeed, many different approaches to innovation are found around the world and these are often interdependent on specific local contexts with their particular institutions, priorities, and values (Audretsch, 2021; Pahnke & Welter, 2019). Rather, given the widespread interest in emulating the model (Audretsch, 2021; Casper, 2007a), we believe that it is worth considering whether and how it can be better aligned with sustainable development.

The Silicon Valley model is conceptualised here according to four key features: *speed*, the use of high-risk *venture capital financing*, a *socially significant mission*, and a *people-centric approach*. These features are described below, drawing out potential tensions with sustainable development which are then further explored and elaborated upon in this chapter.

The first feature, *speed*, is possibly the most ubiquitous and the ‘Lean Startup’ methodology is widely employed to try and operationalise this (Ries, 2011). It involves shortening product development cycles through the rapid deployment of Minimum Viable Products (MVPs) which are intended to ‘fail fast’, allowing the company to learn and pivot towards new and better opportunities (ibid.). This approach is widely sought-after and emulated, but this attention to speed can also be criticised as symptomatic of the “tyranny of urgency” (Joly et al., 2010, p. 26) in modern societies which risks undermining more cautious and responsible innovation practices (Steen, 2021). Linked to this, companies following this model often prioritise innovation and fast growth over cost and profitability, particularly at the early stages, which means access to plentiful high-risk *venture capital financing* is a key enabler (Casper, 2007b; Teece, 1996). These kinds of investors are willing to tolerate high levels of financial risk in return for the promise of significant returns on investment if the company is successful in scaling up and diffusing its technology. A consequence of this is a pressure to identify and appropriate private benefit in order to generate this return on investment which risks crowding out attention to broader value creation (Hegeman & Sørheim, 2021).

Third, seeking to address a bold, *socially significant mission* is thought to be a key feature driving the rapid innovation they pursue and helping to underpin a strong company culture (Steiber & Alänge, 2016c). Increasingly, Silicon Valley entrepreneurs and investors promise and target new technologies to address sustainability concerns (Sanderson, 2021). Importantly, having a mission that addresses a socially significant issue does not necessarily mean they will achieve it, as is demonstrated by recent controversies involving firms seemingly employing the Silicon Valley model[30] while the approach has also been implicated in the uneven distribution of economic growth and prosperity in the USA (Audretsch, 2021). Finally, a *people-centric approach* is generally employed which seeks to avoid traditional hierarchical and rigid approaches to coordinating company operations through rules and standardisation, instead emphasising flexibility, freedom, and experimentation on the part of employees accompanied by a relatively flat organisational structure (Steiber & Alänge, 2016c). Steiber & Alänge (ibid.) label companies that follow this model as “startups in large suits” (p. 146) because they seek to maintain the agility of a start-up even when they become very large. Recently, tensions have emerged in this apparent prioritisation of human capital with employees in several large Silicon Valley technology firms protesting at perceived unethical behaviour and demanding more say in what technology the companies develop and how it is deployed (Lavietes, 2018; Tiku, 2018).

More fundamental tensions may well also be at play here. The often much sought-after, though not uncontroversial, financial and business strategies described above are more typically found in the context of varieties of capitalism which align more with liberal market economies (LMEs), associated with low regulation, such as the US (Casper, 2007b; Soskice & Hall, 2001). However, frameworks such as RRI and business transition management which aim to tackle the challenges of sustainable innovation are typically aligned with and were often developed in the context of varieties of capitalism which align more with the coordinated market economy (CME)

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[30] For example, see: https://hbr.org/2019/01/the-era-of-move-fast-and-break-things-is-over

classification (Soskice & Hall, 2001). Such economies, typical of Western Europe, tend to have institutional frameworks that favour more consultative and collaborative business practices (ibid.). Accordingly, attempts to emulate Silicon Valley-style conditions in CMEs have often run into difficulties, in part due to tensions with the wider institutional frameworks (see Casper, 2007a). On the other hand, businesses that prioritise flexibility, dynamism, and fast growth may be impatient to devote time and resource to run sustainability assessments, engage in broad coalitions, or conduct deliberation with wider stakeholders, as is called for by many of the frameworks described in Section 4.2.2 (Matthews, Stamford, et al., 2019; Steen, 2021). This implies that efforts towards promoting more sustainable innovation through more cautious and precautionary models might be in tension with business approaches often thought to support rapid and radical technological innovation.

This potential trade-off would have serious implications for those that position technological innovation as a critical enabler of sustainable development (e.g. UNCTAD, 2018). However, for others, this would be consistent with a view that present preoccupations with technological innovation and novelty are fundamentally incompatible with sustainability needs and that we instead need a focus on bringing about “degrowth” or “responsible stagnation” (Nierling et al., 2018; Saille & Medvecky, 2016). These somewhat fundamental contradictions between different pathways reflect the often underexplored politics of sustainable development (Scoones, 2016).

In summary, multiple factors influence and obstruct the capacity of businesses to truly construct sustainable technologies. These have been delineated here in three broad challenges: i) the ambiguity and uncertainty brought by the sustainability agenda, ii) the systemic nature of innovation processes, and iii) the tensions brought by trying to reconcile sustainability with existing business models. While, as this literature review has outlined, these challenges and obstacles are relatively well characterised and understood, there is a need for greater practical knowledge and strategies for how they might be overcome. We have identified a potential tension between existing frameworks for supporting more sustainable and responsible innovation, which tend to emphasise more precautionary approaches, and the Silicon Valley model. Given the level of interest seen in transferring this model to other contexts (Casper, 2007a; Steiber & Alänge, 2016a), it is particularly pertinent to unpack these tensions and explore whether and how such business practices could be mobilised to construct sustainable technologies. Therefore, this study asks the action-oriented research question of how the pursuit of rapid technological innovation and scale-up within the Silicon Valley model could be more aligned with sustainable development.

4.3 Research approach

To address the research question, this paper analysed data derived from an action research case study involving a single business. While the case study approach is widely used in social science research for descriptive analysis, theory testing, and theory building (Eisenhardt, 1989; George & Bennett, 2004; Stake, 1995; Yin, 2018), single cases have sometimes been criticised for their lack of generalisability and face the accusation of anecdotalism. However, such research has a robust defence as a means of providing the rich descriptions and insights which are necessary for theory development (Flyvbjerg, 2006; Ragin, 1992). Accordingly, rather than seeking statistical generalisation, we pursue what can be described as analytic generalisation, seeking to relate the findings back to the theory presented in the literature review (Yin, 2018). Meanwhile, taking an action research approach allows the translation of theory into practice, working in collaboration with practitioners and stakeholders (Coghlan, 2017). This yields highly contextualised data which allows the development of rich understandings and practical knowledge that cannot be gained by other “at a distance” research methods.

The case study was carried out in collaboration with a globally leading synthetic biology[31] company. Based in California, USA, the company was (and continues to be) actively engaged in developing and commercialising technological innovations in the field of biotechnology. It had received substantial venture capital investment and was growing rapidly throughout the research period from a size of several hundred employees towards a size nearing one thousand by the end of the collaboration. The company broadly emulated the Silicon Valley model of doing business described in the literature review with an emphasis on speed, flexibility, freedom, and experimentation; coordination through an ambitious socially significant mission; and a dependence on venture capital financing (Steiber & Alänge, 2016c). Its primary business model was originally focussed on engineering existing industrial biotechnology organisms to optimise efficiency but subsequently pivoted towards developing novel bio-based products. In both cases its business model was business-to-business, providing its technology platform as a service to other businesses or working through partnerships.

The case study took place between July 2018 and May 2019 during which time a potential product - bio-based[32] nylon - was subjected to a sustainability assessment using the CSA framework (see Chapter 2). This represented the intervention of the action research. CSA provided a framework to operationalise responsible innovation practices, enabling the sustainability implications of emerging technologies to be explored and anticipated, provoking reflection by innovation actors and allowing them to identify avenues for action. This case thereby allowed the applicability of such frameworks to be tested while identifying both barriers for change and opportunities for further development. The precise process, results, and outcomes of the CSA process have been described previously in Chapter 3. The intervention also provoked exploration and reflection on the part of company employees concerning how they could (or could not) take responsibility for the sustainability of their innovations. It is on these reflections and discussions that this paper focusses on.

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[31] Bringing together advances in molecular biology, data science, and automation, the field of synthetic biology promises to enable a more rational, engineering-inspired and application focussed approach to innovation through biology (RAE, 2009). The field is also accompanied by many promises of improving sustainability, such as by providing sustainable alternatives to the use of petroleum, improving the efficiency and reducing the footprint of agriculture, or enabling bioremediation (Chui et al., 2020).

[32] “Bio-based” is a commonly used phrase to describe a product that is derived from biomass typically after conversion or processing.

Date	Activity	Participant/role	Participants	Duration	Data collected
Aug-18	Survey	Company employees	153	NA	Survey Results
Aug-18	Workshop	Development team	4	1 hour	Notes
Aug-18	Workshop	Legal team	4	1 hour	Notes
Aug-18	Workshop	Business Development team	8	1 hour	Notes
Aug-18	Workshop	Manufacturing team	4	1 hour	Notes
Mar-19	Interview	Head of Modelling	1	30 minutes	Notes
Mar-19	Interview	Projects team lead	1	30 minutes	Notes
Mar-19	Interview	Member of the senior leadership team	1	30 minutes	Notes
Mar-19	Interview	Materials development	1	30 minutes	Notes
Mar-19	Interview	Manager of projects	1	30 minutes	Notes
Mar-19	Interview	Business Development	1	30 minutes	Notes
Mar-19	Interview	Materials and Chemical Development	1	30 minutes	Notes
Mar-19	Survey	Company employees	54	NA	Survey Results
Mar-19	Workshop	Development team	5	1 hour	Notes
Mar-19	Workshop	Legal team	6	1 hour	Notes
Mar-19	Workshop	Business Development team	5	1 hour	Notes
Mar-19	Workshop	Modelling team	6	1 hour	Notes
Mar-19	Workshop	Products team	5	1 hour	Notes
Mar-19	Workshop	Manufacturing team	5	1 hour	Notes

Table 4.1: A summary of data collection activities to inform this study (excluding documentary evidence).

Company employees were engaged extensively throughout the course of the research through workshops, interviews, and surveys which generated a large amount of primarily qualitative data (Table 4.1).[33] Protocols for the workshops and interviews as well as survey outlines are provided in Appendices C.1 and C.2. This data was supplemented with documentary evidence which was collected primarily in April and May 2019 and included news reports, publicly available interviews with senior leadership, and information published by the company such as white papers and their website. Together, this data formed a rich picture of how the company engaged with sustainability in its practices.

Quantitative data collected through the two surveys was processed and summarised using Excel and the R statistical programming language (R Core Team, 2021). Quantitative summaries of the survey results are outlined in Tables C.2 and C.3. Qualitative data took the form of documentation, notes, and reflections of the first author[34] from interviews and workshops as well as free-form responses provided in the two surveys. This data was collated in Nvivo 12 (QSR International, 2018) and analysed thematically according to best practices in social science research (Mason, 2017; Nowell et al., 2017).

Data analysis for this study sought to understand the sustainability commitment of the company and its employees and how this translated into the roles and responsibilities they took on. This involved exploring the opportunities and barriers perceived by the study participants in terms of operationalising sustainable practices in their business model and strategy. At first, broad descriptive codes were used to organise the data. These initial codes, namely “barriers”, “roles and responsibilities” and “sustainability commitment”, allowed the data to be organised and enabled researcher familiarity with the data to be established. During this process, mind-mapping was used to develop more specific thematic codes which then guided subsequent rounds of coding. Several iterations between the literature, data analysis, and summarising were then undertaken which led to the thematic organisation presented subsequently in the findings. A summary of themes and their accompanying data sources is provided in Table C.3.

4.4 Findings

This section outlines the primary findings of this study and is structured around three key streams of analysis that emerged from the data. These are each described in turn here, starting with the vision, strategy, and business model employed by the company, followed by an account of the cognitive roadblocks faced in operationalising sustainability. Finally, the systemic context of the company, from the perspective of its employees, is explored. These findings form the basis of the subsequent discussion in Section 4.5.

4.4.1 The vision, strategy, and business model

In line with the Silicon Valley model (Steiber & Alänge, 2016c), the case company put forward an ambitious *socially significant vision* of how their business could contribute to sustainability

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[33] The data collected from these workshops and surveys was also used as part of the results presented in Chapter 3.

[34] All data collection was undertaken by the thesis author.

challenges. This was evident in both internal and external communications and from both the company leadership and more widely in the views of company employees.

According to the company's leadership and mission statement, they wanted to go beyond simply avoiding harm and wanted their technology platform to be used to actively create broader societal and environmental value. The capacity of new biological processes to replace those which at present derive from petrochemicals was seen as a major benefit of new synthetic biology developments and thought to yield substantial benefits, particularly in terms of the renewable use of resources.

This ambitious vision was shared by many of the company's employees. For example, one employee summed up their personal viewpoint of what biotechnology should be about:

> *"The biotechnology sector should be the sector that spearheads our ability to heal the earth." (Survey response, development scientist)*

Such idealistic visions concerning what the biotechnology sector should deliver were not universal. Others commented on their more pragmatic drivers behind their work – such as to do interesting science and create a profitable company. Yet, a survey of employees asking their view on the relative importance of different outcomes from shifting to bio-based chemicals and materials production returned combating climate change and preserving global resources, ecosystems, and biodiversity as the most important (Figure 4.1). Employees also reiterated how the company's attention to sustainability was an important motivator for their work and careers, and therefore wanted to see it actively evaluated and considered in company decision-making, as expressed in this survey response:

> *"I would really like to see [The company] have a meaningful impact on sustainability, and I believe many of our employees buy into this notion and live that ethic. Once I see us making major strategic decisions aligned with that, I'll be fully bought in." (Survey response, desk-based scientist)*

However, when a slightly different question was asked – how important sustainability was for decision-making at the company (Table C.2, Question 6, n=52) – the most common response was "an important consideration among others" (67%, n=35) followed by "background relevance" (27%, n=14). While sustainability might have been perceived by some surveyed employees as an underlying mission of the company, it was also subsidiary to profitability when it came to their commercial strategy and business model:

> *"I think sustainability is an important part of the story that we tell about ourselves, but it's also secondary to business and strategic concerns in [the company's] decision-making." (Survey response, desk-based scientist)*

The underlying value proposition and business model of the company were more overtly evident in more client-focussed statements and publications. Here, the ability of the technology platform to improve the efficiency of existing compounds was a key value proposition and links to the original business model focussed on organism engineering services. Another, mentioned particularly frequently throughout the engagement with the case company and the third most important factor in Figure 4.1, was novelty – the idea that by harnessing the diversity present in nature, materials and compounds with novel characteristics and capabilities can be made available.

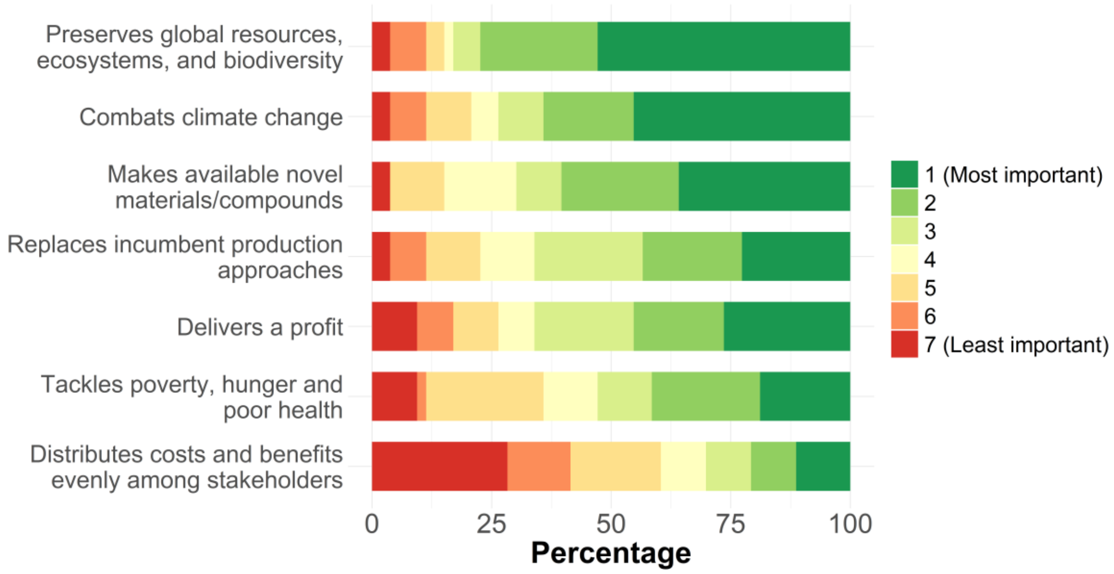

Figure 4.1: The relative prioritisation of different outcomes for bio-based production to deliver according to company employees. The graph summarises the responses given by company employees when asked “In your opinion, to what extent is it important that the bio-based production of chemicals or materials results in the following?” (Source: Survey of company employees, March 2019, see Table C.2, Question 4, n=53).

This need to develop novel products was underpinned by the fact that, particularly being reliant on *venture capital financing*, there was an urgent need to demonstrate a workable business model that could generate returns for investors. Yet, there was a clear perception, as is elaborated further in Section 4.4.3, that sustainability does not pay and that bio-based technologies cannot compete on a like-for-like basis with incumbent petrochemical-based production processes. Thus, just appealing to the *ideograph* of sustainability was not sufficient to legitimise and make the business case for their technology. By appealing to the idea of novelty, which can be seen as another competing ideograph, it established a value proposition that appealed to its customers and thus underpinned a viable business model.

In this case, we saw an attempt to use efficiency and particularly novelty in a way comparable to what van Lente & van Til (2008) have described as “vehicles for sustainability”. This allowed the company and its employees to maintain the underpinning mission of sustainable development, which was especially important for employee motivation as well as for some clients and investors, while also achieving a viable business model.

In addition to this, there was also some acknowledgement in discussions with company employees concerning the potential trade-offs between the profitability of the business model and the underlying vision of sustainability. Several employees tried to rationalise how to manage this trade-off, for example:

> *"Delivers a profit in my opinion is the key behind bio-based production methods catching on and becoming more widespread. Few companies would consider it if it was at great cost. The key is to balance the profitability of these methods with the benefits it provides so that they can simultaneously occur, without the focus shifting towards only profitability." (Survey response, desk-based scientist)*

Others explained how, in the short term, they needed to focus on profitability to develop their technology platform and establish a financially viable company before turning their attention to other priorities. Thus, a focus on novel products would allow them to grow rapidly (at *speed*) from their niche and potentially displace incumbent industries, at which point they would be in a position to more directly address matters of sustainability. The challenge is how to avoid "shifting towards only profitability".

The above-described strategy reflected not just a pragmatic compromise made necessary by a lack of explicit demand for sustainable products, but also a particular viewpoint concerning the role that technological innovation should and will play in enabling a more sustainable society – a commitment to a technology-led transition (Scoones, 2016). This assumption is not without logical support as such innovations could create new markets and disrupt and displace incumbents – both critical mechanisms for enabling socio-technical transitions (Geels, 2004; Mazzucato, 2018). However, technology-led transitions are just one of many transition pathways.[35] The technology-led pathway has also received much criticism, as highlighted in the literature review, from those that see a continued focus on technological innovation as likely to drive further unsustainable growth through rebound effects and continued mass consumption (e.g. Nierling et al., 2018). Furthermore, it is worth noting the pursuit of novelty in this case rather than the direct replacement of existing production processes. Does this run the risk of simply augmenting rather than displacing incumbents, driving increased consumption and thereby increased environmental impact?[36]

These questions and issues will be further explored and unpacked in Section 4.5. Meanwhile, the following subsections will explore what inhibited sustainability in itself being a critical value proposition, focussing on cognitive challenges and the systemic context of the company.

4.4.2 Cognitive roadblocks

As previously discussed, sustainability is an ambiguous and high-level concept with broad and diverse interpretations. Its generally agreeable nature also gives it the power to legitimise innovation trajectories such that it can be beneficial for innovators to establish links between their technologies and sustainability (Bos et al., 2014). In this case, it was possible to see this articulation process in action. The key link involved replacing non-renewable petrochemical-derived products with renewable biomass-derived alternatives. Sometimes, this link was specified

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[35] Scoones (2016) describes four pathways for transformation - "technology-led, market-led, state-led, and citizen-led" (p. 295) - which can be employed in varying combinations.

[36] Note that while bio-based production processes may have a reduced impact compared to incumbents (although not always), the total uncoupling of production from ecological and social burdens is unlikely (Escobar & Laibach, 2021).

further in terms of reduced global warming, and the ability to use milder processes with less toxic waste. Meanwhile, employees also commented on aspects that their technology could not address. In particular, the goals of promoting equality, peace, and justice (encapsulated in SDGs 4, 5, 10, and 16) were typically seen as too big and high-level for the company itself to influence through its technological innovation activities (Table B.13).[37]

In the literature review, we also described how, during this articulation process, the link between a technology and sustainability can become black-boxed, closing down critical consideration (Bos et al., 2014; Stirling, 2008a). Indeed, during engagements with employees at the case company, it was sometimes assumed that bio-based production processes are intrinsically more sustainable than their petroleum-based incumbents. However, it is also well-established that the implications and impacts of new technologies are determined through their interactions with and embeddedness within society rather than purely technical characteristics (Collingridge, 1980). Therefore, technologies cannot be considered inherently sustainable or unsustainable, particularly at the early stage of development when many of these determining interactions have not occurred. Furthermore, specifically for bio-based and synthetic biology-enabled innovations, the potential for trade-offs and undesired impacts has been widely described (Escobar & Laibach, 2021; French, 2019; Matthews, Cizauskas, et al., 2019; Ögmundarson et al., 2020). Critical assessment is essential to validate sustainability claims and minimise unforeseen consequences and burden shifting.

On the other hand, the CSA process which was undertaken collaboratively with the case company through this study and reported in Chapter 3 demonstrated an appetite within the company to engage with this ambiguous concept and critically evaluate the sustainability of their products. For example, during the formulation stage of CSA, there was a chance to explore different conceptions of sustainability. While there were not the resources available or appetite to undertake a broad stakeholder engagement, it was possible to mobilise the diverse viewpoints of company employees who demonstrated a rich and deeply considered view of these issues.[38] This drew upon the *people-centric approach* followed by the company. During workshops, while there was an evident focus on environmental issues, particularly greenhouse gas (GHG) emissions, when discussing what would make a biotechnology product sustainable, much broader notions, including potential social impacts, were also frequently highlighted. The complex and integrated nature of the challenge was also discussed and participants showed broad awareness of potential trade-offs and acknowledgement of the significance of different worldviews.

The subsequent stages of the CSA process involve carrying out evaluations and then interpreting the results to inform future actions and decisions. Here, the broad definition of the concept again brought challenges. Firstly, there was a diversity of viewpoints regarding what sources of data

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[37] This result was previously reported in Chapter 3.

[38] Here, we do not suggest that engaging with company employees was a direct substitute for the inclusion of a broad range of stakeholders, a core tenet of RRI (Stilgoe et al., 2013). Yet directly engaging company employees in this process brought its own benefits, as is further discussed in section 4.5.

were valid for understanding sustainability implications (Table C.1, Question 7). For example, when asked how different sources of information might influence their perceptions of the sustainability of a product, impacted stakeholders were seen as quite influential to some, while others saw them as biased by their own experiences and therefore not influential. Expert viewpoints, alongside real-world and (to an extent) modelling data, were more universally approved of as influential factors.

Additionally, the evaluation stage led to qualitative results across numerous economic, social, and environmental impact categories. Discussion of these results in further workshops as per the CSA framework led to some success in opening up perspectives and identifying avenues for further action (Table C.2, Question 10). Yet, the variety and uncertainty of outputs and the evident trade-offs between different aspects, while potentially accurately representing the nature of the issue at hand, made it somewhat intractable for company employees who found it difficult to translate the findings into clear implications or actions. Meanwhile, when attempts were made towards further aggregation to provide clearer outputs, for example using end-point rather than mid-point LCA characterisation[39], this was not perceived as a valid approach as it involved too many subjective interpretations. This demonstrates a tension between the perceived validity and salience of sustainability data.

Fundamentally, this case illuminated some of the problems faced when an individual company tries to embed sustainability considerations in its operations. There was a desire expressed in workshops for specific, quantitative answers to sustainability questions. Yet, the holistic characteristics of the concept require the integration of different sources of knowledge and expertise from a variety of domains and inevitable subjective trade-offs that cannot simply be resolved through more advanced analytical approaches. They require values-based discussions and deliberations. Taken together, these issues might partially explain why, despite sustainability being an important priority for the company and its employees, this did not necessarily translate into directly informing actions or decisions. In some cases, critical evaluation of claims can seem unnecessary due to a black-boxed link between particular technologies and sustainability. When an evaluation is required, it necessitates grappling with thorny values-based issues that individual companies often do not have the resources, time, or legitimate authority to resolve.

In this case, grappling with these issues was further exacerbated by the company's Silicon Valley-style model of doing business (Steiber & Alänge, 2016c). This approach prioritised experimentation and flexibility to promote innovation and rapid growth. The *speed* at which the company was growing and initiating new projects did not allow sufficient time for the widespread application of more cautious, reflexive, and deliberative processes such as CSA which could enable organisations to grapple with subjective and value-laden sustainability questions.

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[39] Mid-point LCA indicator scores relate to more technical measures such as "kg CO_2 equivalent", while end-points attempt to quantitatively relate them to the final impacts that are trying to be avoided, such as the impact on human health measured in quality-adjusted life-years (QALYs).

4.4.3 The systemic context

The other thematic area which was prominent in the case study was discussions concerning the innovation system within which the company found itself. It was clear that company employees felt that the actions of the company were considerably constrained by this systemic context. From these engagements, it was possible to deduce a map of how they viewed the system around them, which will be elaborated upon in this section (see Figure 4.2).

The case company operated "B2B", primarily using their technology platform to provide services to clients who would then produce products for consumers (Figure 4.2, Point 1). This is not uncommon for developers of emerging technologies, particularly in the case of the platform technologies typical of synthetic biology. However, this dependence on clients constrained what the company felt able to do in terms of integrating wider considerations in their decision-making as most key clients were not primarily concerned with addressing sustainability, a view articulated in the following survey response:

> *"The primary barrier to making it [sustainability] the most relevant [factor in decision-making] is that our primary revenue sources - large companies - are not primarily concerned about sustainability, they are concerned about the bottom line." (Survey response, member of the business development team)*

There were a minority of cases where sustainability was a key driver for a client. However, because of the black-boxing phenomena described in the previous sub-section, simply labelling a product as "bio-based" could often be sufficient to achieve the legitimation and marketing benefit conveyed by the sustainability link. This meant that there was little perceived need to specify or critically evaluate the claims unless a client actively asked for it, perhaps to avoid accusations of greenwashing.

This lack of incentive from clients to actively consider and evaluate sustainability implications aligned with a view that wider societal incentives were also lacking (Figure 4.2, Point 2). There was a widely held perception that consumers were generally not willing or able to pay extra for a more sustainable product (there was no "green-premium"). In addition, the company's technology typically involved genetically modified organisms (GMOs), leading to a concern that even if there were potential environmental and social benefits from the technology, consumer demand might be lacking due to a lack of trust in GMOs. Of course, company employees are also members of society and consumers in their own right (Figure 4.2, Point 3), and as demonstrated in Section 4.4.2, they showed a considerable desire for more sustainable products.[40] The possible implications of this are discussed in Section 4.5.

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[40] For example, when asked "How much more would you be willing to pay for an everyday product if it was considered more sustainable?", the vast majority of employees (92.70%, n=127) stated that they would pay at least some amount more (Table C.2).

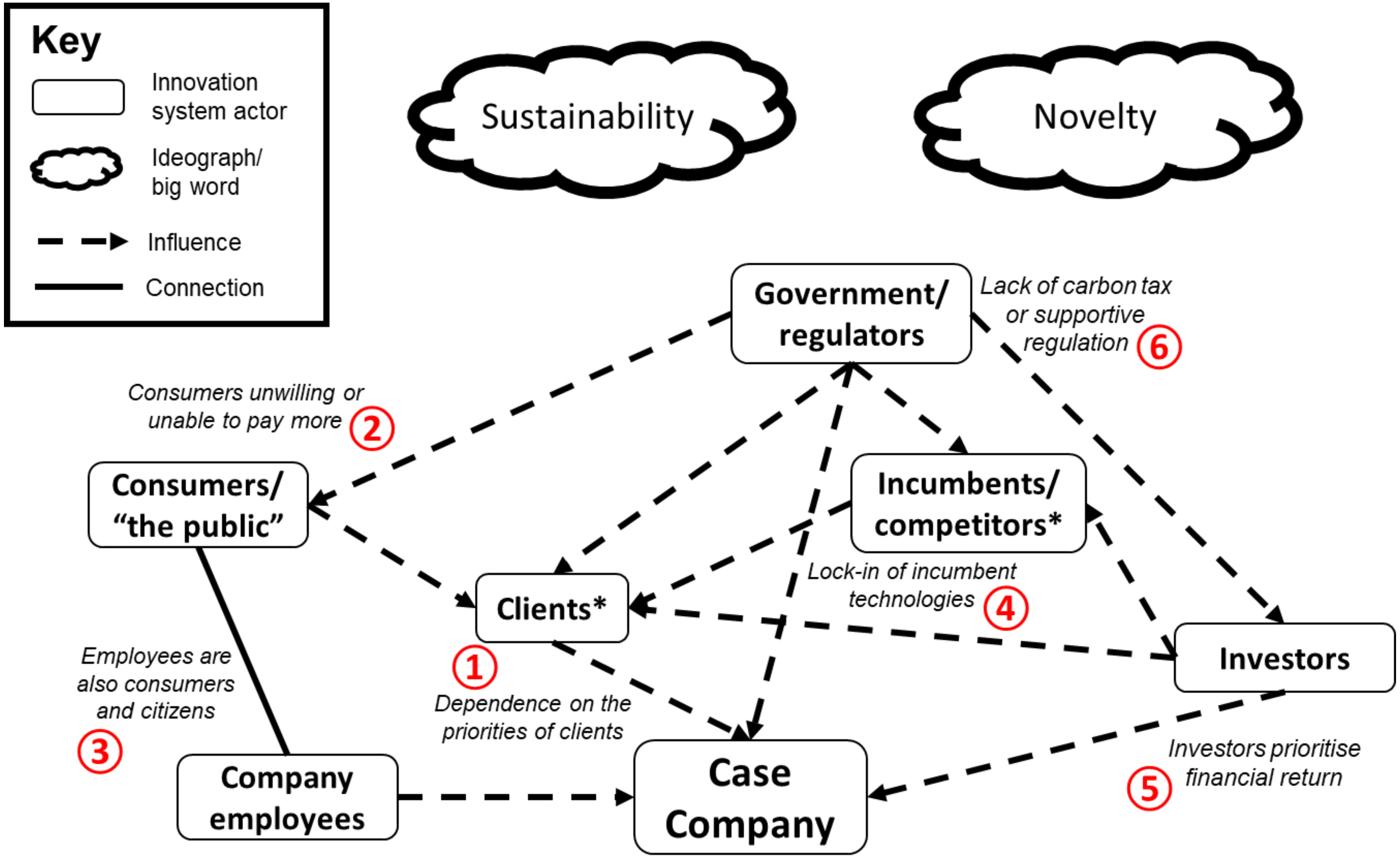

Figure 4.2: A map of the systemic context reflecting the perspective of the company employees. The numbers circled in red provide tags which are referred to in Section 4.4. (Source: Authors elaboration based on engagement with company employees).

**Note that in some contexts clients may also be from incumbent industries.*

On the other side of the perceived lack of incentive from clients and society was the perception that the system was stacked against them (Figure 4.2, Point 4). Industrial-scale production of high-volume commodity products, currently derived predominantly from fossil fuels, involve highly optimised processes often with fully depreciated machinery. More broadly within society, technologies, infrastructures, and institutions were all ‘locked-in’ to fossil fuel-based resource use. In combination, these factors were seen to make it difficult for the company to compete on the key metric valued by clients: price. As a result, while long-term returns may be possible, the level of investment needed to get there made it difficult to persuade *venture capital investors*, who also prioritised financial return (Figure 4.2, Point 5), that bio-based production was intrinsically a worthwhile investment. The high-risk nature of any such investments further reinforces the demand for profit and the single-bottom-line as high-risk investments typically demand a high rate of return. Thus, in the short-term at least, bio-based products needed an additional benefit in order to compete.

A common factor perceived to underpin the lack of demand for more sustainable products and the difficulty in competing with incumbents was the fact that the main benefits of bio-based processes related to externalities in terms of reduced GHG emissions, which are not currently represented in prices. Therefore, they saw themselves as operating on an uneven playing field, which if levelled would broaden the avenues that the company could pursue in terms of developing sustainable technologies. This point was summed up in the following survey response by a company employee:

> *“We're a business and we don't necessarily get paid for producing sustainable products. If there were carbon trading schemes or other methods of capturing the costs of sustainability then it would become a more relevant consideration in decision making.” (Survey response, desk-based scientist)*

The way in which this “levelling” could occur typically involved some form of a carbon tax (Figure 4.2, Point 6).[41] Regulation was also cited as an option, with regulatory compliance an important driver of company and client operation, but lacking for sustainability:

> *“…everything is regulated in this world except sustainability” (Interview response, Member of the Senior Leadership Team)*

In combination, the systemic context that the company employees perceived did not appear to provide the necessary incentives or leave space for consideration and integration of the wider *socially significant mission* of sustainable development. This was confounded by the fact that the case company was reliant on *venture capital finance*, driving an increasingly urgent need to demonstrate that the technology platform could generate returns for investors in the future. From the perspective of many of the company employees engaged in this study, this meant that applying the company’s technology platform with the prime aim of addressing sustainability concerns, which would presumably be the most beneficial option for society as a whole, did not

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[41] It should be noted that a carbon tax focusses on just one of many sustainability dimensions and risks detrimental impacts for the world’s poor if not combined with active redistribution policies (Vogt-Schilb et al., 2019).

provide a financially viable business model in the short-term for the company itself.[42] Instead, the company pursued an alternative value proposition – novelty, as was discussed in Section 4.4.1.

4.5 Discussion

This action research study of a synthetic biology company has sought to build up a rich picture, triangulated from multiple data sources, of how they related and aligned their practices with sustainable development. Despite not being a digital or IT company *per se*, the company in question was in many ways archetypal of the Silicon Valley approach, being venture capital-funded and employing many of the key organisational characteristics (Steiber & Alänge, 2016b). This approach has been successful in enabling the company's rapid growth and the generation of bio-based technological innovations with novel properties providing a value proposition that can potentially compete with and disrupt incumbent petroleum-based industries. The critical question, which this section will consider, is whether this approach is aligned with sustainable development, and what modifications might be necessary to better embed sustainability.

At face value, the strategy for achieving sustainability through the "vehicles" (van Lente & van Til, 2008) of novelty and improved material performance could be judged as a pragmatic solution to the challenges of sustainable innovation, allowing the company to disrupt incumbents and replace petroleum-based production processes with seemingly renewable bio-based alternatives. However, as explained in the findings, this strategy is potentially problematic from the perspective of sustainable development based on the assumptions it involves about the inherent sustainability of specific (bio-based) technologies and its implicit prioritisation of a technology-led transition. The risks described previously in viewing technological innovation as intrinsically beneficial are well established and many frameworks and practices for more proactively and cautiously managing the emergence of new technologies in line with societal needs have been proposed and applied (BSI, 2020; Collingridge, 1980; Frantzeskaki et al., 2012). Given the apparent tensions between these frameworks and the Silicon Valley, "startup in a large suit" approach to innovation, as discussed in Section 4.2.3 and in the findings, we could argue that such business models are simply incompatible with sustainable development and that business practices need to be fundamentally transformed instead, putting sustainability at the core and making financial return subsidiary to social and environmental value creation (Dyck & Silvestre, 2018; Loorbach & Wijsman, 2013). However, we will elaborate here a middle-ground position that we believe could leverage ongoing trends in the market and financial landscape to put the Silicon Valley model at the service of sustainable development. The remainder of this discussion will consider how this (re)alignment can be achieved with reference to the four features described in Section 4.2.3: *speed*, *venture capital financing*, a *socially significant mission,* and a *people-centric approach* (Table 4.2).

Starting with *speed*, this seems to be in the clearest tension with approaches such as CSA because of the time involved in undertaking deliberative and analytical approaches. It can also

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[42] A more proactive approach towards sustainability may also make long-term strategic sense for the company (see Henderson, 2015) but such an approach would require extremely patient investors.

limit opportunities for engagement with wider stakeholders and the formation of alliances and coalitions which can help to address systemic challenges (Kishna et al., 2017; Loorbach et al., 2010; Schaltegger et al., 2018). However, there is also a potential synergy between the agile lean start-up approach used to enable this speed (Ries, 2011) and the requirement of responsiveness – a central tenet of RRI (Stilgoe et al., 2013). The issue at present is that the former is responsive in a financial sense while the latter requires being responsive to the broader needs of society and the environment. On the other hand, policy interventions such as emissions trading schemes and public procurement incentives are increasingly being used to "tilt the landscape" in favour of more sustainable socio-technical systems and could help to bring the two forms of responsiveness into alignment (Kanger et al., 2020; Mazzucato, 2016). This increasing regulation could be seen to undermine the Silicon Valley model, which is thought to thrive within lightly regulated LMEs as discussed in the literature review (Casper, 2007b; Soskice & Hall, 2001). However, these developments mainly involve strengthening existing price-based mechanisms[43] and therefore would not significantly increase the regulatory burden. Still, there is likely to be a limit to which regulation and price-based mechanisms can achieve in the face of uncertainty and contested priorities (Rosenbloom et al., 2020). Therefore, we suggest that complementary use of approaches like CSA will still be necessary to align the Silicon Valley model with sustainable development, therefore necessitating a slightly slower approach. This also brings potential benefits for other key features of the model, as will be discussed.

Feature	Tensions	Opportunities
Speed	• Allows limited time for deliberation and assessment. • Limits capacity for broader engagement.	• Ongoing efforts to tilt the landscape in favour of sustainable technologies. • Streamlining of the CSA approach.
Venture capital financing	• Drives an emphasis on generating financial value.	• The ESG trend in investing emphasises a broader definition of value. • Investors are increasingly likely to demand evidence of sustainability claims.
Socially significant mission	• Scepticism over the authenticity of such missions given recent controversies.	• Implementing CSA provides a mechanism to demonstrate alignment. • Citizen assembly-type activities can provide guidance on the mission.
People-centric approach	• Emerging employee frustration regarding who and what the technologies are being developed for.	• CSA empowers employees and helps to demonstrate alignment of company decision-making with their values. • Employees provide an (albeit limited) source of broader perspectives.

Table 4.2: A summary of the tensions and opportunities for alignment between the Silicon Valley model and sustainable development. The four features are those identified in the literature review (see Section 4.2.3) and mobilised throughout the chapter.

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[43] For example, long-standing emissions trading schemes exist in many areas including the EU, UK, and California

Another feature that seemingly inhibited the company's ability to focus more holistically on sustainable innovation was its reliance on *venture capital financing*. However, partly in response to current and anticipated government interventions such as those described above, as well as the need to maintain legitimacy in the face of existential risks, investing in sustainable companies is increasingly seen as a prudent, if not essential, long-term strategy in preparation for anticipated sustainability transitions (Hegeman & Sørheim, 2021). Consequently, there is a growing trend within the finance and investment community of demanding evidence of broader value creation from investments, often under the auspices of Environmental, Social, and Corporate Governance (ESG) metrics. This brings with it a considerable opportunity for this critical feature of the Silicon Valley model to also become a powerful driver for sustainable innovation as investors seek out companies that can evidence their contribution to sustainable development.

The potential and ongoing changes in the market and financial incentives described above could provide considerable rewards to companies following ambitious, *socially significant missions* in support of sustainable development. However, as discussed in the literature review, controversies involving prominent Silicon Valley companies have raised questions concerning the authenticity of these missions. Therefore, such companies may well find themselves under pressure to demonstrate how they are embedding these missions within day-to-day decision-making. Approaches like CSA provide an opportunity to clearly set out such a mission, evaluate progress towards it, and iteratively incorporate insights to improve alignment, as demonstrated in Chapter 3.

A further incentive to embed such activities within company structures and operations derives from the fourth and final feature of the Silicon Valley model considered here: the *people-centric approach*. Committed employees driven by a strong company culture are thought to play a crucial role in the perceived success of the model (Steiber & Älänge, 2016c). However, recent controversies have also revealed simmering tensions between such companies and their employees, frustrated by a lack of alignment with their values and priorities (Lavietes, 2018; Tiku, 2018). Company employees, who were the main focus of the engagements and data collection efforts for this study, demonstrated a deep and considered understanding of sustainability, including its tensions and complexities. For many, sustainable development was also a key motivator for their lives and careers. Therefore, engaging company employees in approaches like CSA and embedding them within company decision-making offers an opportunity to better align company practices with the priorities and values of employees, as well as sustainability, while in the process improving employee motivation and satisfaction (Aguinis & Glavas, 2019; Gurzawska et al., 2017; Spanjol et al., 2015). Still, such a move is not without trade-offs as it implies implementing a more democratic governance approach within such companies, something which may well bring new tensions (Lubberink et al., 2017).

The changes in emphasis of the Silicon Valley model discussed above and outlined in Table 4.2 might go a long way to tackling the business model and systemic challenges faced by companies trying to innovate sustainably within the Silicon Valley model. These developments could provide incentives for the application of the CSA framework in a business context. Meanwhile, CSA can support companies to actively demonstrate the alignment of their decision-making with sustainability missions as well as their employees’ values. Furthermore, the deliberative workshops at the core of the CSA approach can mobilise internal stakeholders (i.e. company employees) and the increased diversity of viewpoints they bring to help tackle cognitive challenges. This might represent a pragmatic way to open up the innovation process to broader priorities, albeit in a relatively limited manner, while having comparatively low resource and expertise requirements.

However, there is a limit to which internal deliberation can resolve cognitive challenges driven by ambiguity in the sustainability concept, as was discussed in Section 4.4.2. This caused the company great difficulty in rationalising, measuring, and taking action on the grounds of sustainability.[44] If, however, greater specificity could be provided through deliberation and citizen consultations at the national, regional, or sectoral level (e.g. Climate Assembly UK, 2020), this might give innovating companies specific targets to align their missions with by indicating more specifically the relative societal desirability of different innovation trajectories. The corresponding reduction in ambiguity and clearer signals provided would likely enable the streamlining of CSA-type activities by reducing the amount of time needing to be spent deliberating on priorities, trade-offs, and actions. That said, there are likely to be considerable limitations on the degree to which localised consensus regarding sustainability can be realised (Scoones et al., 2020) and to which approaches like CSA can be responsibly streamlined (Stirling, 2010).

Finally, a common theme of many frameworks for responsible and sustainable innovation is a focus on engaging with citizens and collaborating and forming coalitions with other organisations (Kishna et al., 2017; Loorbach et al., 2010; Schaltegger et al., 2018). However, as such an approach is challenging when working at speed and poses considerable tensions for businesses, as discussed in the literature review (T. Brand & Blok, 2019; Noorman et al., 2017), this discussion has focussed on how alignment can be achieved assuming that such broader engagement is largely not present, as was the situation in the case study. If, perhaps facilitated by a slightly slower approach to innovation, companies were able to invite wider stakeholders to engage in internal deliberations or were able to engage with other organisations to formulate collective missions and/or convene citizen dialogues, this would of course be likely to further strengthen the alignment with sustainable development.

4.6 Conclusion

In this chapter, we have described how cognitive, systemic, and business model challenges can obstruct the explicit construction of sustainable technologies by a company, even when this is a core part of their underlying mission. Consequently, we saw in this case how the company employed the additional characteristic of novelty as the key value proposition in its business model, acting as a potential vehicle for sustainability. The success of this approach in enabling sustainability transitions depends on one’s assumptions regarding the necessity of technology for

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[44] This corroborates previous findings that a lack of resources and expertise are major barriers for businesses operationalising RRI and sustainable innovation (see Álvarez Jaramillo et al., 2019; Auer & Jarmai, 2018) and supports the proposition by Hahn et al. (2014) that the ambiguity of the concept poses cognitive challenges for business managers and precludes radical action.

sustainability transitions and the intrinsic sustainability of bio-based processes, both of which are potentially problematic.

The Silicon Valley model employed by the company was heavily implicated in driving these outcomes. In the discussion, we returned to the research question posed in Section 4.2.3 to explore whether and how this model could be more rigorously aligned with sustainable development. We discussed modifications and developments which might enable this alignment. Firstly, changes in the market and financial environment, many of which are already underway, offer to partially resolve some of the systemic challenges faced by providing incentives for companies to embed sustainability considerations more actively in their operations. Secondly, public deliberations could provide greater specificity concerning the ‘wants’ and ‘needs’ of society with respect to sustainability, helping to alleviate cognitive challenges. Thirdly, these developments might provide an opening for the complementary application of CSA-type approaches at the company level which would allow businesses to align their decision-making more proactively and demonstrably with employee values and the overarching company mission.

Admittedly, these changes do suggest a slightly slower and more deliberative approach to innovation in a more regulated economic context, something more in line with what is prescribed by frameworks like RRI and CSA (Steen, 2021). This could be argued to fundamentally undermine the core features of the Silicon Valley model. However, if a streamlined form of CSA were applied, the *speed* penalty may not be all that great. Furthermore, such an approach might help to resolve some of the internal tensions faced by many Silicon Valley companies by helping to better align decision-making with employees’ values and the overarching mission while also creating a model which is robust to an evolving finance and market landscape that increasingly expects demonstrable sustainability credentials. Therefore, we believe that such an approach might enhance rather than undermine the Silicon Valley model.

Finally, we acknowledge that, deriving from a single case study, there is an inevitable trade-off between the depth and richness of the case and the possibility of broad generalisation. However, by positioning our findings within the burgeoning literature on this subject we have been able to elaborate some tentative implications and recommendations. We do not put forward this approach as a rebuttal to other, more planned and structured frameworks for embedding sustainability such as business transition management (Loorbach & Wijsman, 2013). But given the traction that the Silicon Valley model has around the world, we believe that there is value in the discussion presented here concerning how it can be better aligned with sustainable development. We welcome rebuttal or further elaboration by fellow researchers, practitioners, or policy-makers on this matter.

Chapter 5: The role of sustainability in the UK synthetic biology programme

This chapter is based on a manuscript that has been prepared with the intention of future submission to an appropriate academic journal. The thesis author is the sole author of the manuscript.

Abstract

Policy interventions in support of emerging technologies are often justified through their potential to support sustainability transitions. Synthetic biology is one such technology with potential applications across a wide range of sectors with promised sustainability benefits. Over the past decade, the field in the UK has been subject to active policy intervention and support. This chapter explores the role played by the sustainability agenda in policy debates and the policy mix in support of this emerging field in the UK. In this exploratory case study, I describe the processes through which synthetic biology came to be the subject of policy intervention where wider sustainability goals were situated as subsidiary to the commercialisation agenda. Analysis of the policy mix reveals how this has fed through into a supply-side bias with limited consideration given to actively creating or stimulating demand for *sustainable* synthetic biology applications. These features, combined with limited capacity for anticipation and monitoring, are likely to limit the capacity of the field to drive socio-technical transformation due to a lack of attention to policy coordination, reflexivity, and directionality.

5.1 Introduction

There is growing policy interest in the role that science, technology, and innovation (STI) can play in providing solutions to the sustainability challenges faced by society (Cervantes & Hong, 2018; Langhelle et al., 2019; UNCTAD, 2018). Yet, the magnitude and speed of change required alongside the multifaceted and contested nature of sustainable development render this challenge somewhat exceptional (Mowery et al., 2010). Researchers have responded to this from a range of theoretical, conceptual, and methodological perspectives (Hansmeier et al., 2021). One pertinent avenue has been to draw on the literature that explores the processes through which innovation occurs and how technologies emerge and become embedded in society. This carries the hope of appropriating this understanding to (re)direct STI towards desirable ends and has led to the rapid rise of the field of study termed *sustainability transitions* (Köhler et al., 2019). These developments necessitate new framings and approaches to STI policy in order to incorporate the goal of systemic transformation (Schot & Steinmueller, 2018).

The emerging technological paradigm of synthetic biology (also known as engineering biology) is one such area of STI policy interest that has considerable relevance to sustainable development (French, 2019). The applications it enables promise broad impacts across a wide range of sectors, enabling a transition to more sustainable bio-based production (Bueso & Tangney, 2017; EBRC, 2019). It is in part these sustainability benefits that have been powerful in legitimising public and private support. Yet, these benefits are also contested (ETC Group, 2010) and involve difficult trade-offs (Matthews, Cizauskas, et al., 2019).

Synthetic biology has now been the subject of active policy intervention for over a decade across several countries, particularly from national governments (Shapira et al., 2017). In the UK, a considerable programme of support was initiated in 2012 which aimed to nurture a cutting edge synthetic biology community with particular attention to supporting its commercialisation (Clarke & Kitney, 2016; SBRCG, 2012). The programme was also been characterised by a focus on responsible research and innovation (RRI)[45] which seeks to promote anticipation, reflection, and action regarding the broader societal impacts and implication of STI (Macnaghten et al., 2016; Taylor & Woods, 2020).

This chapter seeks to understand the role that the sustainability agenda has played in the promotion of synthetic biology in the UK. I focus on how visions and expectations of improved sustainability have been mobilised within policy processes and how these have been rationalised within the policy strategy and instrument mix. This analysis is guided by insights from the science and technology studies (STS) (Borup et al., 2006), political science (Kern & Rogge, 2018; Kingdon, 1984), and policy mix (Flanagan et al., 2011; Rogge & Reichardt, 2016) literatures. Additionally, I draw on the transformational innovation policy (TIP) literature to explore to what extent the approach to synthetic biology in the UK has addressed transformation failures (Schot

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[45] RRI is often used interchangeably with responsible innovation (RI). While the distinctions between the two discourses have been explored by others (Owen & Pansera, 2019), in this paper I primarily use the term RRI to refer to both overlapping discourses.

& Steinmueller, 2018; Weber & Rohracher, 2012). Together, these literatures provide a framework to guide and structure the analysis, as elaborated in Section 5.2 (Figure 5.1).

Applying this framework to the empirical case of synthetic biology in the UK, I integrate data from a range of sources to enable process tracing (George & Bennett, 2004), as described in Section 5.3. The findings of this investigation, reported in Section 5.4, identify the significant discursive role played by the sustainability agenda and promises of social and environmental value creation in helping to open up and exploit the policy window in 2012. However, this broader vision, which largely became encapsulated within the concept of RRI, was not reconciled with the dominant policy imperatives of commercialisation and financial return. This, alongside an assumption of sustainability, led to a lack of consideration in the resulting policy strategy and instrument mix concerning how to actively create and stimulate demand for *sustainable* synthetic biology applications. As a result, I argue that the approach to synthetic biology in the UK demonstrates transformational failures in terms of reflexivity, policy coordination, and directionality (Weber & Rohracher, 2012).

5.2 Literature review and analytical framework

5.2.1 Emerging technologies, hype, and policy

Emerging technological paradigms are often accompanied by promissory visions and hype that play important roles in enabling and shaping their early development (Grunwald, 2018; Pollock & Williams, 2010). This *promissory rhetoric* put forward by technology advocates can shape the expectations of policy-makers concerning what particular technologies are anticipated to achieve (Borup et al., 2006; Schyfter & Calvert, 2015). Such expectations can lead to the commitment of resources to a field and shape new institutional arrangements, thus becoming performative self-fulfilling prophecies (Petersen & Krisjansen, 2015).

Recently, there has been a growing prevalence of visions concerning how STI can tackle societal grand challenges such as Net Zero and the Sustainable Development Goals (SDGs) (UNCTAD, 2018). This ‘Grand Challenge’ agenda has led to expectations of emerging technologies delivering societal as well as economic benefits (von Schomberg, 2013). In order to legitimise a technological trajectory through its association with broad-brush societal goals such as sustainability, the link has to be *articulated* by breaking down and specifying the goal and explaining how the technologies in question can contribute (van Lente & van Til, 2008). However, in time this association can become *black-boxed* such that the link between a technology and sustainability no longer requires further justification (Latour, 1987).

Expectations are negotiated in a diverse and contested space as part of messy and path-dependent policy processes (Brown & Michael, 2003; Lindblom, 1959). Within these processes, ambiguity is often manifest (Ackrill et al., 2013). The deliberate use of ambiguity can be an important strategy for advocates to achieve alignment in complex political environments (Edler & James, 2015; Leitch & Davenport, 2007). Under these conditions generally agreeable yet vague and malleable concepts such as sustainability can act as *boundary objects*, helping to foster high-level agreement while tolerating a great deal of ambiguity regarding the specifics (F. S. Brand & Jax, 2007; Star, 2010).

To help us understand this messy process we can draw from the policy studies literature. In particular, Kingdon's three streams framework describes how, while the policy stream may evolve with different ideas and propositions in a path-dependent manner, *policy windows* open up only when the perceived problem, policy solution, and the appropriate political backdrop intersect and opportunities for intervention arise (Kingdon, 1984). It has been observed that the policy solution often emerges first followed by a search for an appropriate problem to provide a rationale (Kern & Rogge, 2018). Alignment of the streams within policy windows can be partially articulated by policy entrepreneurs: organisations, actors, or teams who are willing to invest "time, energy, reputation, and sometimes money" (Kingdon, 1984, p. 122) in search of policy change. Advocates for a technology, who often put forward the promissory visions of the future in order to establish positive expectations amongst policy-makers, could be considered key policy entrepreneurs for emerging technologies (Rip, 2006). Depending on the outcome of these processes, a policy window may open up and policy intervention may result.

5.2.2 Policy mixes for innovation

Policy intervention typically takes place through the design and implementation of policy instruments. However, it is important not to consider policies in isolation but rather as part of a mix of instruments that interact over space and time (Flanagan et al., 2011). Furthermore, the nature of the contemporary challenges that STI policies seek to tackle, tending to be complex and systemic, requires concerted action through a mix of policies (Edmondson et al., 2018). Such policy mixes can be realised through packages of *de novo* policies or by 'patching' existing policy elements (Howlett & Rayner, 2013). Resulting mixes can be delineated through a top-down approach, starting from the policy-making processes previously discussed, or from a bottom-up approach, starting from a particular impact domain being studied (Ossenbrink et al., 2019). According to Rogge & Reichardt (2016), policy elements can be broken down into the objectives and plans that underpin the overarching policy strategy as well as the instrument mix itself, each with associated goals, type, purpose, and design features. Collectively, a given policy mix can also be analysed with respect to certain characteristics, notably: "…the consistency of elements, the coherence of processes, as well as the credibility and comprehensiveness of a policy mix" (ibid., pp. 1622-3).

There are many different rationales for intervening in innovation systems and a corresponding diversity of instruments that can be employed.[46] One distinction commonly made is between supply-side and demand-side oriented instruments where a historic tendency to neglect the role of demand-side intervention has been noted (see Edler & Georghiou, 2007). Rogge & Reichardt (2016) divide instruments up further according to their purpose – technology push (i.e. supply-side), demand-pull, or systemic (supply- and demand-side) – and their type – economic instruments (e.g. R&D funding, tax incentives, public procurement), regulation (e.g. standards,

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[46] See Edler & Fagerberg (2017) for an overview of the rationales for innovation policy intervention and a taxonomy of innovation policy instruments.

environmental regulations, IP protection), and information (e.g. training, networking events, foresight). While these classification systems can help to make sense of the wide range of instruments employed, it is also important not to consider them as ‘tools from a toolbox’ because policies are subject to considerable interpretive flexibility depending on the context in which they are applied (Flanagan & Uyarra, 2016).

Finally, when analysing a given policy mix we must also avoid an idealised view of how policy mixes can be designed and coordinated, and of policy-making and policy implementation processes more broadly (Flanagan et al., 2011). New policy instruments and mixes are applied on top of and constrained by the existing policy mix and institutional context and thus policy action is necessarily incremental (Lindblom, 1959). The effect of specific instruments will also be a function of interactions that can take place across time and space (policy, governance, and geographical space) (Flanagan et al., 2011). This complexity has been recognised in *broad* policy mix conceptualisations which emphasise the policy process as an inseparable part of the policy mix alongside the policy instruments themselves while also considering the interactions between policies (Flanagan et al., 2011; Rogge & Reichardt, 2016).

5.2.3 New goals for innovation policy

In the context of pressing grand challenges such as climate change and the need for more sustainable development, there has been a trend towards a more mission-orientated approach to innovation policy, considering how innovation systems can be mobilised to directly tackle these grand challenges (Hekkert et al., 2020; Mazzucato, 2016). In line with this agenda, a growing volume of research has explored how to achieve the radical transformation of socio-technical systems towards more sustainable modes of operation, under the broad grouping of sustainability transitions research (Köhler et al., 2019).

These developments in our understanding of the role of innovation systems introduce new requirements for innovation policy and have led to its reframing for transformational change (Schot & Steinmueller, 2018). This framing marks a considerable departure from previous framings. In the immediate post-war era, the innovation for growth perspective became entrenched, underpinned by the now much-critiqued linear model (Godin, 2006; Kline & Rosenberg, 1986; Nightingale & Coad, 2020). In this context, the primary role of the state was to address market failures by funding basic research to generate new discoveries and drive progress (Bush, 1945). Subsequently, the systems of innovation approach emphasised the significance of interactions, networks, institutions, entrepreneurship, and absorptive capacity in determining the outcomes of innovation (Freeman, 1995; Lundvall, 1992). Increasingly, both of these frames are considered insufficient for nurturing the urgent transformational change now required by society (Schot & Steinmueller, 2018). In the new, transformational innovation policy (TIP) framing, the function of innovation policy instruments is no longer purely to improve innovative capacity but to address “transformational failures” which prevent the alignment of STI with societal and environmental goals and needs (Weber & Rohracher, 2012). Here, I focus on failures in terms of *policy coordination*, *reflexivity*, and *directionality* (ibid.).

As sustainability transitions require concerted changes in multiple areas, and given the deeply embedded nature of present socio-technical systems (Schot & Kanger, 2018), it is generally accepted that *policy coordination* across STI, sectoral, and cross-cutting policies is required (Weber & Rohracher, 2012). Therefore, policies need to go beyond simply supporting and accelerating niche innovations through instruments such as R&D funding and the provision of finance (Kanger et al., 2020). Interventions such as regulation and the withdrawal of subsidies can be used to destabilise incumbents (Kivimaa & Kern, 2016; Turnheim & Geels, 2012) while further demand-side interventions such as the use of public procurement can also help to stimulate demand in application sectors (Edler & Georghiou, 2007). Such policies can also play important roles in articulating broad societal challenges such as sustainable development into more concrete demand for innovations (Boon & Edler, 2018).

While a highly planned approach to governing transitions might be desirable, exerting control on emerging technological paradigms is also acknowledged to be exceedingly difficult if not inherently problematic due to inevitable uncertainty over its development and impact (Collingridge, 1980; Edmondson et al., 2018; Mowery et al., 2010). More fundamentally, there are many different potential pathways and end-points for transitions, within which there may be differing roles for innovation and technology (Scoones, 2016). Therefore, progress towards desired transformations cannot be taken for granted. Instead, there is a need to embed *reflexivity* by putting in place systems for “continuous monitoring and anticipation” (Weber & Rohracher, 2012, p. 1044) such that governance and policy can be appropriately adaptive. The RRI agenda could be considered an attempt to embed these capacities within innovation systems (Stilgoe et al., 2013).

Finally, a critical feature of these new framings of innovation policy is its more explicit attention to *directionality*. In previous systems of innovation framings, the target of policy intervention was a well-functioning and competitive innovation system with less attention to the direction of change[47] (Diercks et al., 2019). Conversely, in the TIP framing, there is a normative expectation that innovation should be actively guided towards realising more sustainable socio-technical systems (ibid.). In line with this, shared visions and expectations need to be established concerning how innovation can address such broader sustainability challenges and needs (Weber & Rohracher, 2012). Within this framing, STI no longer has an intrinsic benefit and instead must be judged by its ability to actively create value in a broad sense (Schot & Steinmueller, 2018), necessitating a focus on social and environmental value creation beyond the traditional focus on financial return (Dyck & Silvestre, 2018). The deeply embedded nature of the present socio-technical systems, reinforced by repeated surges of technological development since the industrial revolution, makes it particularly challenging to shift towards this new, more sustainable directionality with a broader conception of value (Schot & Kanger, 2018). It also means that, if emerging technologies are treated in isolation without explicit attention to their directionality and the kinds of value they

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[47] Although this type of intervention arguably has an implicit directionality towards more innovation, more technology, and more economic growth.

create within the wider economy, they risk being redirected in unsustainable directions by the inertia of incumbent regimes (ibid.).

5.2.4 Analytical framework and research question

The literature discussed above can be organised into a single cohesive analytical framework for this study (Figure 5.1). Policy processes are understood by drawing on insights from both the policy studies and STS literatures (Borup et al., 2006; Kingdon, 1984). The broad policy mix framework put forward by Rogge and Reichardt (2016), is used to complete the policy sub-system, guiding a structured and holistic analysis of policy intervention. Finally, the process and outcomes of socio-technical change require explicit consideration, drawing on the TIP and sustainability transitions literatures, with particular focus on how transformational failures have or haven't been addressed (Weber & Rohracher, 2012). This framework enables the integrated consideration of political processes, policy mixes, and socio-technical change along with their interaction, as has been called for by others (see Edmondson et al., 2018; Meadowcroft, 2011).

Guided by the analytical framework, this study explores the research question of what role sustainability has played in the promotion of a particular emerging technological paradigm (synthetic biology) within a particular national context (the UK). The analysis is particularly focussed on two aspects, represented by the two arrows in Figure 5.1. The first relates to the role played by competing promises and expectations (including that of sustainability) in opening up and exploiting a policy window and how this has translated into the policy strategy and policy mix. The second looks beyond the policy sub-system to probe how the policy mix has been implemented in practice and to what extent this has addressed transformation failures in accordance with the expectations and promises established during the policy process.

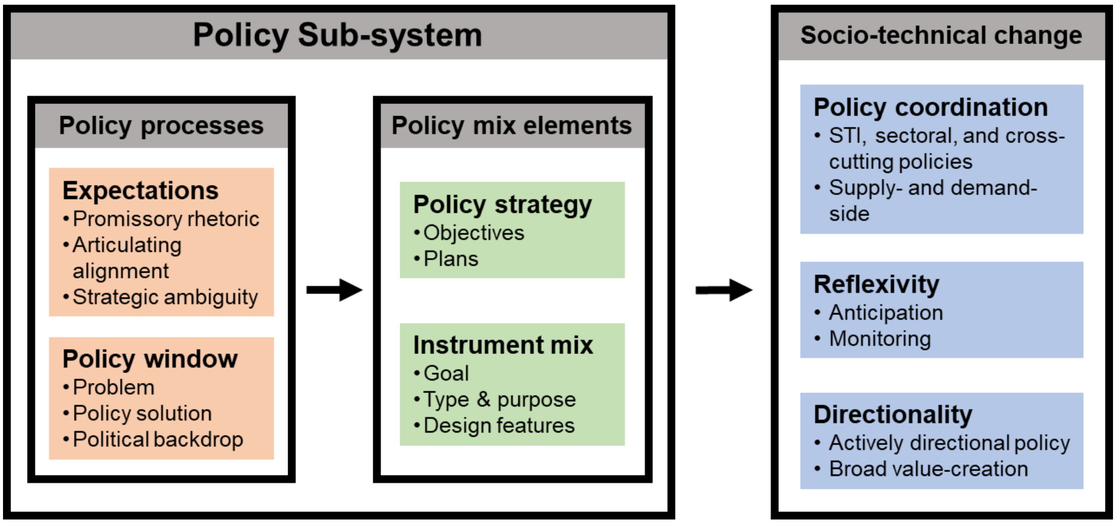

Figure 5.1: The analytical framework for this study. (Source: Author's synthesis drawing on Borup et al., 2006; Kingdon, 1984; Rogge & Reichardt, 2016; Weber & Rohracher, 2012).

5.3 Research approach

5.3.1 Methodology

To operationalise the analytical framework described above, this exploratory case study employs process tracing to chart the causal dynamics which have produced particular outcomes for synthetic biology in the UK (George & Bennett, 2004; Streb, 2010; Yin, 2018). This approach focusses on analysing the “empirical fingerprints” of hypothesised underlying mechanisms and relies on the gathering of large amounts of data from a range of sources to build up a comprehensive picture of a complex process (Beach, 2017).

Two main sources of data were used. Firstly, documentary evidence was gathered from a wide range of sources including policy documents (e.g. roadmaps and strategies), meeting minutes, websites, and news articles. Documentary evidence typically relates to the outcome of policy-making processes and so can give the impression of consensus amongst actors, hiding the messy underlying policy processes (Tansey, 2007). To corroborate findings, fill in gaps, and allow more detailed probing of the processes and rationales that led to specific policy events, semi-structured interviews were undertaken with influential players in the UK synthetic biology landscape. Non-probability purposive sampling was used to select research participants (ibid.). Interviewees were selected based on their involvement in key policy processes such as positions on committees or within organisations. Semi-structured interviews were then conducted based on an interview guide (Appendix D.1). It was critical to be mindful of some of the potential pitfalls of elite interviewing, particularly the fact that interviewees inevitably have their own agendas – as Berry (2002) puts it: “…subjects have a purpose in the interview too: they have something they want to say” (p. 680). By combining analysis of diverse documentary evidence with targeted interviews, this methodological approach enabled triangulation, helping to alleviate the limitations that both these data sources pose when used in isolation.

Due to the COVID-19 pandemic, all interviews were carried out by video call. Nine interviews took place between April and June 2020 (see Table D.1). After each interview, interviewees were sent a short vignette summarising the discussion allowing them to add additional details or correct any misunderstandings. Documentary and interview data were then collated and the Nvivo software was used for thematic qualitative coding, following best practices in interpretive social science research (Mason, 2017; Nowell et al., 2017; QSR International, 2018). Initially, a set of deductive codes were employed to group the documentary data according to the overall analytical framework presented above. As researcher familiarity with the data grew, sub-codes of a more inductive nature were developed. Data analysis proceeded through several iterations between the literature, data analysis, and summarising. See Table D.2 for a summary of data sources, research sub-questions, and resulting themes across the three dimensions.

Finally, to complement the thematic coding described above, tables were produced summarising the key policy documents (Table D.3) and the policies identified (Tables 5.1 and D.4). These tables provided evidence to underpin Sections 5.4.1, 5.4.2, and 5.4.3 of the findings. In support of the findings reported in Section 5.4.4, further analysis and coding of specific subsets of the documentary evidence was undertaken (Tables D.5-D.7). A coding manual for each of the Tables 5.1 and D.3-D.7 is provided in Appendix D.2.

5.3.2 Empirical case – synthetic biology in the UK

The empirical setting for this study was the emerging field of synthetic biology in the UK. Synthetic biology[48] brings together advances in molecular biology and genomics with engineering principles and computational approaches for the development of real-world applications. It can be defined as follows: “Synthetic biology aims to design and engineer biologically based parts, novel devices and systems as well as redesigning existing, natural biological systems” (RAE, 2009, p. 13). In attempting to bridge many well-established fields, it has somewhat fuzzy boundaries. Indeed, some would not consider it a field *per se*, instead viewing it as a particular way of approaching biological research which has implications for a broad range of fields and application domains. In particular, it has implications for the application domains of industrial biotechnology, health and medicine, food and agriculture, environmental biotechnology, and energy (EBRC, 2019). In this chapter, it is viewed as an enabling set of emerging technologies that promise to facilitate the broader spread of biotechnology into new fields and areas not previously accessible, thus having broad societal relevance (Bueso & Tangney, 2017).

The first reports of the ‘repressilator’ and toggle-switch at the turn of the new millennium are often cited as the starting point for the field as the first examples of “genetic circuits that had been engineered to carry out designed functions” (Cameron et al., 2014, p. 382). It is this application of an engineering approach to design, create, and tune biological systems that sits at the core of synthetic biology. Since then, synthetic biology has attracted both scientific and policy interest (Figure 5.2). 2004 saw the first international conference, SB1.0, take place at MIT as well as the first International Genetically Engineered Machine (iGEM) competition for university students (ibid.). It is around this time that the volume of academic articles in the field started to increase (Shapira et al., 2017). The earliest support for the field was most prevalent from US Government sources and funders such as NSF and NIH have continued to dominate the funding landscape (ibid.). Other key funding sources include the national governments of China, Japan, Canada, as well as various European nations and the European Union (ibid.). The UK government has taken an active and fairly interventionist approach and throughout the 2010s put in place a range of policy instruments to support the establishment and development of the field (Clarke & Kitney, 2016).

This study uses the empirical case of synthetic biology in the UK[49] to operationalise the analytical framework described in Section 5.2.4. The reasoning behind choosing to study this case at this time is threefold. Firstly, it represents a platform technology with potentially broad impact,

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[48] Recently, the term Engineering Biology has been increasingly used to describe the field, in particular when it intersects with the industrial domains where synthetic biology enables applications, such as industrial biotechnology. Here, the use of the original synthetic biology description is retained but the two terms are treated as synonymous.

[49] The boundaries of the UK synthetic biology field are inevitably fluid, with research activity and companies spanning national boundaries and many international initiatives and collaborations. However, national contexts remain relevant and it was necessary to draw boundaries in order to enable rich and in-depth analysis within the empirical case.

including in many areas of relevance to the SDGs (French, 2019). Therefore, in terms of the policy mix and sustainability transitions agenda, it provides an opportunity to build the evidence base beyond the energy sector from where the majority of empirical evidence and policy success stories derive (Kern et al., 2019). Secondly, it is an emerging technology where there has been debate concerning its promise and potential while its implications for the environment and society remain contentious. It is instructive to understand whether and how sustainability goals are incorporated into policy design and implementation under such circumstances. Finally, the timing and geographical focus of this study are pertinent in that many of the programmes that kicked off in the early 2010s are coming to an end or entering a transition period. This has triggered a period of reflection within the synthetic biology community concerning what has been achieved so far and where to go next (e.g. RAE, 2019; SBLC, 2019).

5.4 Findings

This section presents the findings of the study. It is structured in three sections which correspond to the three interlocking dimensions of the analytical framework elaborated in Section 5.2.4 and Figure 5.1. The findings were derived from the analysis as described in Section 5.3.1 and summarised in Table D.2.

5.4.1 Diverse expectations for an emerging field

It is possible from the data collected in this study to delineate some of the key visions and rationales put forward to promote the field and how these differ between actors. Advocates for the field[50] justified policy support for synthetic biology by pitching it as an exciting platform technology that could be highly disruptive in a range of sectors. They described it as an area where the UK could harness its strong research base to create high-tech jobs and economic growth through the increased commercialisation of research outputs. This was sometimes accompanied by the warning that without action the UK risked falling behind as other countries capitalise on these scientific developments. Together, these visions presented a persuasive case to policy-makers for support and are evident in many of the key policy reports which such advocates have often played a key role in writing or steering (Table D.3).

Accompanying this economic vision was a broader one, focussed on how synthetic biology could provide solutions to grand challenges, particularly that of creating a more sustainable society. Indeed, many of the proposed application areas map to the SDGs (see Table 1.1 in Chapter 1). While this sustainability promise has been put forward to some extent from the start (e.g. Endy, 2005), it became more overt in recent years, as sustainability concerns, and particularly agendas around Net Zero and plastics, have grown in prominence.[51] References to sustainability benefits have often been broad and ambiguous although there was a noticeable focus on the environmental rather than social benefits of synthetic biology. Most prominent was the promise of

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[50] By “advocates for the field” I mean individuals who commit often considerable time, resources, and reputation to publicly support and articulate the benefits of the technology.

[51] A recent supplement in the New Statesman carries articles from many key advocates very clearly putting the sustainability argument ahead of the economic one (New Statesman, 2020).

weening society from its dependence on fossil fuels by providing alternative bio-based routes to chemicals, energy carriers, and materials, potentially making use of waste carbon sources.[52] Many advocates for the field saw the sustainability agenda as a means to communicate the benefits of this technology and provide a compelling story for why it should be supported. As a result, the adjective *sustainable* has often been used when describing synthetic biology, for example in delivering “sustainable solutions” or “sustainable materials”. In some cases, bio-based technologies were presented as intrinsically sustainable. The link had become black-boxed.

Not all visions of synthetic biology’s impact were quite so positive. Early-on, civil-society organisations tabled some stark warnings concerning where the field appeared to be heading (e.g. ETC Group, 2007). Three central issues were raised: a) that the field was overhyped and the claimed benefits for society lacked evidence; b) that the ethical, socioeconomic, and environmental risks were manifest and poorly understood; and c) that regulation was essential, self-regulation dangerous, and that wider society should play a key role in determining what is permitted. This debate was seen by some as a reigniting of the “GM debate”, something many advocates feared (Marris, 2015). Interestingly, these alternative visions were also largely sustainability-focussed, but often with a broader definition, a *vulnerable nature* worldview, and greater attention to socioeconomic issues (Asveld et al., 2014).

Meanwhile, social scientists, principally working in the fields of STS and innovation studies, also highlighted some of the risks and challenges posed by synthetic biology concerning biosafety and biosecurity, ethics, global justice, patenting and monopolies, and ethical dilemmas around the creation of artificial life (Balmer & Martin, 2008). Building on considerable engagement in the emergence of the nanotechnology paradigm, researchers continued to emphasise the uncertainties, unknowns, and unintended consequences that typify emerging technologies and the need for the ‘opening up’ of appraisal and governance to broader perspectives and values (Ribeiro et al., 2017; Stirling, 2008a). They proposed the use of more responsive, iterative, and participatory governance models such as RRI for emerging technologies like synthetic biology (Marris & Calvert, 2020; Stilgoe et al., 2013; Wiek, Guston, et al., 2012).

5.4.2 Choosing synthetic biology

With these diverse visions, promises, and expectations now elaborated, I will explore how synthetic biology came to be chosen for policy intervention. Policy change necessitates the alignment of a recognised problem with a recognised solution at a politically appropriate time (Kingdon, 1984). The 2010 UK general election resulted in a coalition government, led by the Conservative party, for which two notable policy priorities were evident - to stimulate and maintain economic growth in the aftermath of the financial crash, and to reduce the public sector

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[52] Health and Medicine also represents a key application area and has a clear link to the SDGs (Particularly goal 3: *Good Health and Well-Being*). Yet, claims of sustainability for the field have tended to focus on environmental aspects and the link between improving health outcomes and sustainable development was rarely articulated. For this reason, they are not the focus of the analysis presented here.

net deficit.[53] Therefore, there was a desire to play to the UK's strengths, one of which has long been considered the UK's research base. However, there has also been a perception that while the UK is good at research, it is bad at commercialising it.[54] In this new government, David Willetts (now The Lord Willetts) was made Minister of State for Universities and Science at the Department for Business, Innovation and Skills (BIS).[55] Willetts, together with the Liberal Democrat Business Secretary Vince Cable, supported an interventionist strategy of targeted support for high-tech innovations to stimulate economic growth.[56]

Meanwhile, synthetic biology by the early 2010s had received a steady flow of funding from the research councils, helping to establish the beginnings of a synthetic biology community in the UK (Figure 5.2; Shapira et al., 2017). The 2009 Royal Academic of Engineering (RAE) report highlighted synthetic biology as a field where the UK was already strong and presented opportunities for wealth and job generation alongside tackling global challenges (RAE, 2009). The report also emphasised the urgent need to develop a strategy for synthetic biology. Consequently, this emerging field found itself well-positioned to capitalise on the policy window which consisted of a policy problem in the need to drive economic growth while making efficient use of limited public funds, a promising solution offered by synthetic biology, and a political environment that supported interventionist innovation policies.

Around the same time, synthetic biology had begun to appear as a topic in Government horizon-scanning efforts, notably the Technology and Innovation Futures reports (see Government Office for Science, 2010, 2012).[57] A roundtable discussion at BIS hosted by David Willetts in the autumn of 2011 led to the establishment in November 2011 of a working group tasked with developing a roadmap for synthetic biology in the UK. The Roadmap was duly published, under a tight schedule, in July of 2012 (Marris & Calvert, 2020). As well as touting the considerable benefits of the technology, it set out a series of recommendations centred concerning how to support the development of synthetic biology in the UK (SBRCG, 2012). These recommendations were positively received and several policy initiatives were subsequently announced in alignment with

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[53] The coalition's *programme for government* stated: "We recognise that deficit reduction, and continuing to ensure economic recovery, is the most urgent issue facing Britain." (HM Government, 2010, p. 15)

[54] For example, an inquiry on this issue by the House of Commons Science and Technology Committee House was launched in 2011 with the statement: "A key recurring issue that has been raised in the Science and Technology Committee's previous inquiries is the difficulty of translating research into commercial application…". However, whether or not this widespread view is justified has been the subject of debate (e.g. see Mazzucato, 2013, pp. 52-3).

[55] This department is now called the department for Business Energy and Industrial Strategy (BEIS) after the merger in 2016 of BIS with the Department for Energy and Climate Change (DECC).

[56] This approach accompanied political discussions concerning the need for a dedicated Industrial Strategy, which did eventually become a reality under the May government (HM Government, 2017). Vince Cable set out in a 2012 letter to the then Prime Minister David Cameron and Deputy Prime Minister Nick Clegg his view that "Market forces are insufficient for creating the long-term industrial capacities we need" and that "…the Government can show more leadership in identifying and supporting key technologies. We have a fantastic scientific tradition in this country, and technology leadership must drive economic activity in the future." (Cable, 2012).

[57] These Foresight reports would inspire the *Eight Great Technologies*, of which Synthetic Biology was one (Willetts, 2013).

the roadmap recommendations (Willetts, 2012). Of course, public documents often mask the actions that occur ‘behind the scenes’ to enable the exploitation of a policy window in which there is a key role played by policy entrepreneurs. In this case, two key individuals can be identified. Willetts, as already discussed, was receptive to the case for policy intervention in support of emerging technologies like synthetic biology, and willing to make the case for it both within and outside government. Meanwhile, Lionel Clarke[58] led the development of the roadmap, playing a key role in articulating a compelling argument for support and aligning this with the priorities of the government of the day.

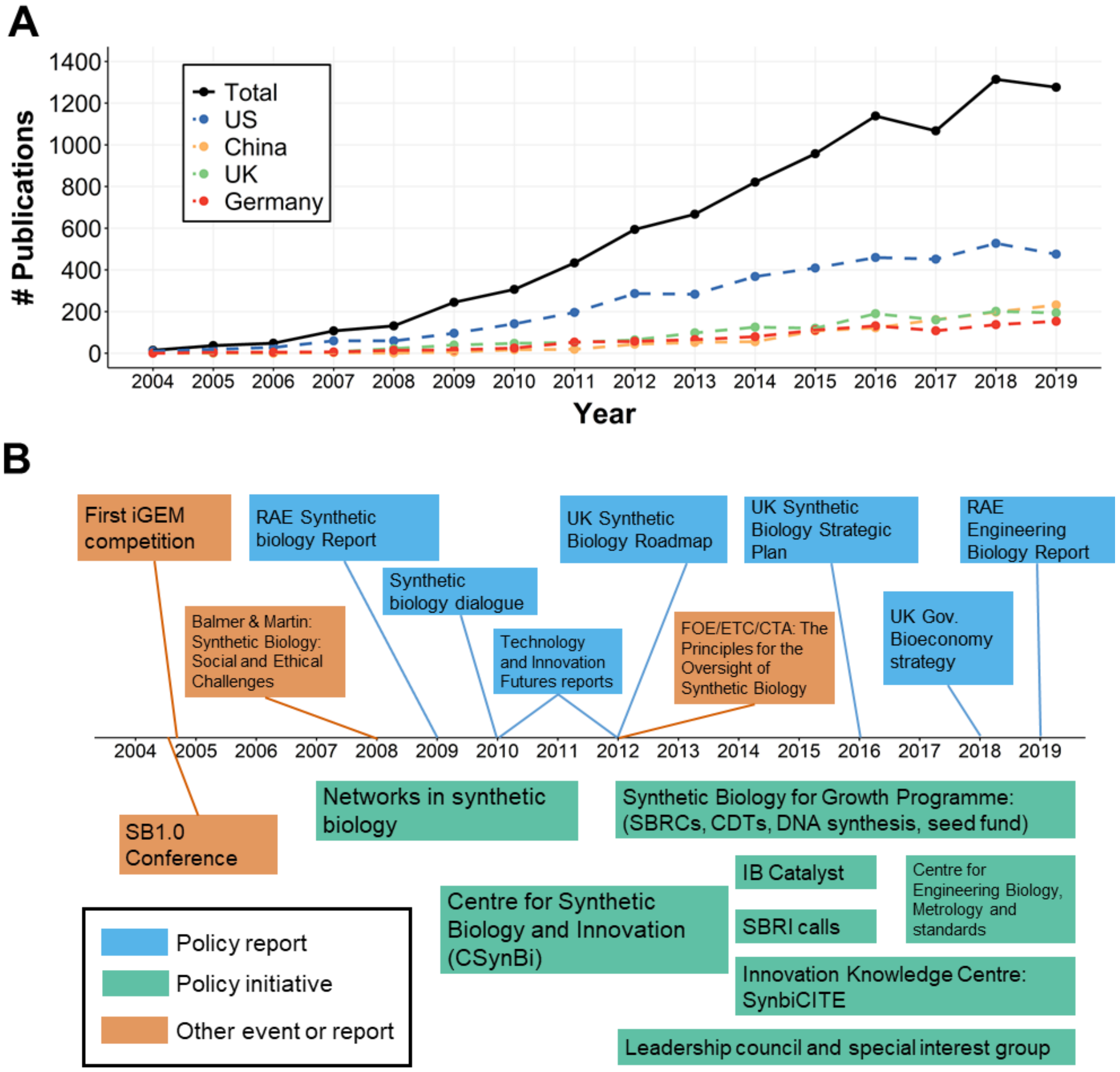

Figure 5.2: The emergence of the synthetic biology field. (A) Annual Web of Science indexed publications mentioning “synthetic biology” in their title, abstract, or keywords. (B) Overview timeline of key events, reports, and initiatives referred to in the text.

Synthetic biology attracted controversy and debate from almost the moment it emerged as a concept. Indeed, the complex ethical, legal, and social aspects (ELSA) of the technology were recognised by its advocates and one response was to actively engage social scientists as contributors to the policy development process (Calvert & Martin, 2009). A key example of this

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[58] At the time, Clarke was a Global Strategic Programme Manager for Shell Global Solutions.

was the act of inviting social scientists, often from STS traditions, to sit on the working group for key policy reports, notably the 2009 RAE report and the 2012 roadmap (RAE, 2009; SBRCG, 2012). STS research provides a wealth of insights that can inform the policy processes such as by outlining how hype, promises, and expectations can become self-fulfilling prophecies (Borup et al., 2006), and how present policy and governance approaches often fail to acknowledge the value judgements embedded in decision-making around STI and tend to lead to the closing down of debate (Smallman, 2019; Stirling, 2008a; Wilsdon & Willis, 2004). This often quite critical stance can create tensions. STS scholars have not always had a receptive response to their critiques and have sometimes found that their insights and text have been utilised in a manner distinct from what they intended (Marris & Calvert, 2020). The implications of this are discussed in subsequent sections.

The role of sustainability in this melting pot of visions and ideas can be difficult to track. The promise of tackling sustainability challenges seems to have helped to generate enthusiasm for synthetic biology alongside promises of economic growth and responsible innovation. In line with this, many of the influential policy reports, particularly those focussed on industrial biotechnology[59], referred to sustainability as a key reason to fund the field (Table D.3). Although the 2012 roadmap made only occasional mention of sustainability, on page seven it is highlighted as one of the key global needs which synthetic biology can address. Meanwhile, synthetic biology to “heal us, feed us, and fuel us” became a popular tagline for politicians around 2012. Indeed, it appears to be the way in which an opportunity to drive high-tech economic growth seemingly overlapped with delivering solutions to global sustainability and health challenges that made synthetic biology such a compelling investment case for the UK Government.[60]

5.4.3 Policy intervention in support of synthetic biology

The successful exploitation of the c.2012 policy window by synthetic biology’s advocates resulted in considerable policy support in the UK (Figure 5.2B; Table 5.1). This section will examine the resulting policy mix with respect to the four characteristics outlined by Rogge & Reichardt (2016): *consistency*, *coherence*, *comprehensiveness*, and *credibility*.

Considering first the overall policy strategy, this needs to be *consistent* in that the objectives of policy intervention should be complementary, drawing out synergies between them (Rogge & Reichardt, 2016). The UK policy strategy was largely outlined in two policy documents: the 2012 Synthetic Biology Roadmap and the 2016 strategic plan (SBLC, 2016; SBRCG, 2012). The roadmap set out a vision for a UK synthetic biology community which was: i) “economically vibrant, diverse and sustainable”, ii) “cutting edge”, and iii) “of clear public benefit… addressing global societal and environmental challenges” (SBRCG, 2012, p. 4). In terms of the first aspect, this was clearly into a policy objective in the subsequent strategic plan with the target of achieving “a £10bn UK synthetic biology market by 2030” (SBLC, 2016, p. 2). This would appear

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[59] Industrial biotechnology represents one of the major application areas for synthetic biology. Reports focussed on industrial biotechnology are included in this analysis due to their tight overlap with the synthetic biology ecosystem in the UK.

[60] In a 2012 speech, Willets stated: “Synthetic biology could provide solutions to many of humanity's most pressing issues and at the same time presents significant growth opportunities”.

to be synergistic with the second vision – of a “cutting edge” synthetic biology community in the UK as both imply policy interventions which seek to address market and system failures in order to support the development, scale-up, and commercialisation of synthetic biology applications. Correspondingly, the recommendation of the roadmap centred on supply-side support for research, innovation, and translation; training and skills development; networking and information brokerage services; and establishing a leadership council to give strategic direction and coordination. An instrument mix was subsequently put in place which was largely *consistent* with these recommendations, as will be discussed.

The third vision, relating to being of “clear public benefit”, was more ambiguous. The concept of RRI was introduced into the roadmap by social scientists involved in its authorship, and the corresponding section of the roadmap explicitly sought to address how synthetic biology can be “demonstrably directed towards new products, processes and services that can bring clear public benefits” as well as “solutions to compelling problems” (SBRCG, 2012, p. 19). Yet, besides one mention of RRI in the subsequent recommendations of the roadmap, there was comparatively limited attention to how “clear public benefit” was to be achieved. This *inconsistency* may reflect a lack of *coherence* in the policy processes that resulted in the critical 2012 roadmap. Social scientists on the steering group successfully introduced the concept of RRI into the roadmap, reframed the focus on public acceptability in terms of generating public benefit, and introduced phrases such as “diverse and sustainable” (Marris & Calvert, 2020). However, they were unable to question the dominant focus on economic imperatives which meant that the underlying messages of RRI were not reconciled within a *coherent* policy strategy (ibid.). This would have required the policy strategy and instrument mix to be designed in a way that took greater account of uncertainty concerning often assumed benefits such as sustainability by embedding mechanisms for anticipation, inclusion, reflexivity, and responsiveness (Stilgoe et al., 2013). Instead, positioned as subservient to the dominant economic growth agenda, “RRI was interpreted as a means to smooth this path” (Marris & Calvert, 2020, p. 18).

Nonetheless, the characteristics identified above in the policy processes and policy strategy fed through clearly into a relatively *comprehensive* instrument mix (Tables 5.1 and D.4), which put into practice the recommendations laid out in the 2012 roadmap and focussed on building the research base and promoting commercialisation. At the core of this was the BBSRC’s *Synthetic Biology for Growth Programme*[61] which represented over £100 million of direct support for research, infrastructure, training, and venture capital. By 2016, total public sector investment in synthetic biology was estimated at over £300 million[62] once all the various funding routes are taken into account (SBLC, 2016).

Consistent with the recommendations of the roadmap, there was a noticeable focus on economic instruments with the purpose of technology push (Table 5.1; Figure 5.3A). These policies

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[61] Prior to this programme, synthetic biology had already been receiving government funding to support R&D and networking (SBRCG, 2012). Seven networks in synthetic biology were funded by UK Research Councils in 2007 and the first dedicated research centre for synthetic biology (CSynBi at Imperial College London) was established in 2009.

[62] The total of policies listed in Table 5.1 comes to £245 million but this is just direct funding from the UK government and excludes funds from EU and Scottish Government sources.

primarily addressed the market failure rationale for STI policy intervention[63], investing in areas that the market tends to underinvest in due to knowledge spill-overs and positive externalities (Weber & Rohracher, 2012). A large proportion of the allocated funding (~£70 million) was channelled into the establishment of six dedicated synthetic biology research centres (SBRCs) in 2013 and 2014. £18 million was also invested over two rounds in growing the UK's DNA synthesis capacity and a centre for doctoral training in synthetic biology was established in 2014. Meanwhile, acknowledging that seed funding for high-tech start-ups can be difficult to come by, the BBSRC allocated £10 million in 2013 to a seed fund targeting synthetic biology start-ups which could allocate up to £1 million to each company. There have also been several rounds of industry-focussed R&D funding[64] while the industrial biotechnology catalyst allocated £75 million between 2014 and 2016 before it was discontinued.[65]

Signalling the *comprehensive* nature of the instrument mix, there was also a range of initiatives that sought to address systemic issues such as institutional, infrastructural, and network failures (Weber & Rohracher, 2012). The Knowledge Transfer Network (KTN) sought to coordinate and network the field, maintaining a Synthetic Biology Special Interest Group which was founded in 2012 and brought together over one thousand members. The KTN has also provided the secretariat for the Synthetic Biology Leadership Council (SBLC)[66] which, co-chaired by a government minister and an industrialist, has sought to provide strategic oversight over activities in the UK. SynbiCITE, an Innovation Knowledge Centre, was established to invest in and generate co-funding for commercialisation projects, provide facilities and expert support for start-ups, host events and other networking opportunities, and deliver business and entrepreneurship training. Meanwhile, in the closely related area of industrial biotechnology, the BBSRC-funded networks in industrial biotechnology and bioenergy (NIBBs) were established to provide networking combined with proof of concept funding to "build capacity and capability in the UK supporting research and translation in sustainable, biologically based manufacturing" (BBSRC, 2019). The recently established Future Biomanufacturing Research Hub (FBRH) represents a further attempt to promote commercially relevant R&D and support the commercialisation of biomanufacturing.

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[63] In addition to this targeted policy support, UK research councils provide "responsive mode" funding which researchers can apply for at any time. The UK also has a range of more generalised, cross-cutting policies aimed at supporting research-intensive businesses. For example, R&D tax credits allow companies to claim tax relief in proportionate to their investment in R&D while from 2013 a Patent Box scheme was introduced with a lower corporation rate on profits from patented inventions.

[64] There were synthetic biology-specific calls from Technology Strategy Board (later Innovate UK) in 2012 (up to £6.5 million for feasibility studies), and 2013 (up to £3.8 million focussed on tools and services). The small business research initiative (SBRI) also had Synthetic Biology specific calls, notably two in 2014 and 2016 from DSTL focussing on defence applications.

[65] The Industrial Biotechnology Catalyst supported both researchers and businesses to work on translational projects with the intention of bridging the "valley of death" and accelerating commercialisation.

[66] Note that the SBLC was recently renamed the Engineering Biology Leadership Council.

Policy initiative	Date	Value	Type	Purpose
Synthetic biology research centres (SBRCs)	2013 - present	£70M	• Economic instruments	• Technology push
DNA synthesis infrastructure	2014 - 2016	£18M	• Economic instruments	• Technology push • Systemic
Centres for doctoral training	2014 - present	£12M	• Information	• Technology push
Innovation knowledge centre (SynbiCITE)	2014 - present	£6M	• Information • Economic instruments	• Technology push • Systemic
Future Biomanufacturing Research Hub (FBRH)	2019-present	£10 million	• Economic instruments	• Technology push • Systemic
Rainbow/UKI2S seed fund	2013 - present	£10M	• Economic instruments	• Technology push
Industrial biotechnology catalyst	2014-2016	£75M	• Economic instruments	• Technology push • Systemic
Networks in industrial biotechnology and bioenergy (NIBBs)	2014-present	£29M	• Economic instruments • Information	• Technology push • Systemic
Small Business Research Initiative	2014 and 2016	£8M	• Economic instruments	• Technology push • Systemic
Synthetic biology special interest group	2012-2019	Unknown	• Information	• Systemic
Synthetic biology leadership council	2012 - present	Unknown	• Information	• Systemic
BSI standards in synthetic biology	2015	Unknown	• Regulation	• Demand pull
Centre for Engineering Biology, Metrology and Standards	2017 - present	£7M	• Regulation	• Demand pull

Table 5.1: A summary of key policy initiatives used to promote synthetic biology in the UK. Type and purpose classifications according to Rogge & Reichardt (2016). For an expanded version of this table see Table D.4.

Where the instrument mix has not been so *comprehensive* is in its relative consideration of the demand-side (Figure 5.3A). While some bias towards the supply-side might be expected given the early stage of development of the field, there has been a lack of policy measures that seek to stimulate demand in the potential application sectors for synthetic biology. There has, however, been some investment in developing standards[67] as well as some support for demand articulation through the promotion of collaborative R&D[68]. The Small Business Research Initiative (SBRI) and the Industrial Biotechnology Catalyst also represent policies with some demand-side orientation[69] in that they support translation focussed on specific sectors. However, temporal *consistency* has been reported as a problem here, with intermittency in the funding of translational research, notably through the catalyst which was scrapped in 2016.

The relative importance and necessary balance of policy instruments within a given mix evolves over time (Cunningham et al., 2016; Flanagan et al., 2011). Therefore, the initial prioritisation of policies focussed on R&D, skills development, and establishing infrastructure may be justifiable providing that subsequent refinement of the mix introduces a greater focus on generating and articulating demand in application sectors.[70] The 2018 Bioeconomy Strategy promised to address this within the wider UK Industrial Strategy (HM Government, 2018). It integrated synthetic biology within a broader mission to expand the bioeconomy and sought to promote coordination across several sector-specific councils[71] as well as government departments and agencies. However, this is where *credibility* has been a potential issue as it was reported in interviews that this strategy appeared to lack high-level government buy-in, and therefore the corresponding coordinated policy intervention, has not been forthcoming. Relatedly, while David Willetts and subsequently George Freeman as Life Sciences minister represented important advocates for the field, since the latter politician left government in 2017[72] there has been less visible high-level backing for synthetic biology. More broadly, the Industrial Strategy under which the Bioeconomy Strategy was developed was scrapped in its present form in 2021.

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[67] Increased standardisation has been a central narrative in efforts to make biology into an engineering discipline, and in 2015 the British Standard Institute published standards for synthetic biology funded by Innovate UK. More recently in 2017, a £7 million Centre for Engineering Biology, Metrology and Standards was established as part of a partnership between the National Physical Laboratory and SynbiCITE.

[68] However, such policies involving collaborative R&D have still been largely focussed on technology push.

[69] There is some debate over whether these initiatives should be classified as supply- or demand-side (Edquist & Zabala-Iturriagagoitia, 2015). In this analysis, following the Rogge & Reichardt (2016) typology, they are annotated as “systemic” in Tables 5.1 and D.4 based on their promotion of collaborative R&D.

[70] Policy options here include regulatory incentives and public procurement (Edler & Georghiou, 2007).

[71] Namely, the Industrial Biotechnology Leadership Forum, the Food and Drink Sector Council, the Chemistry Council, and the Medicines Manufacturing Industry Partnership.

[72] George Freeman ceased to be Minister for Life Sciences in July 2016 but remained as chair of the Prime Minister's Policy Board until November 2017.

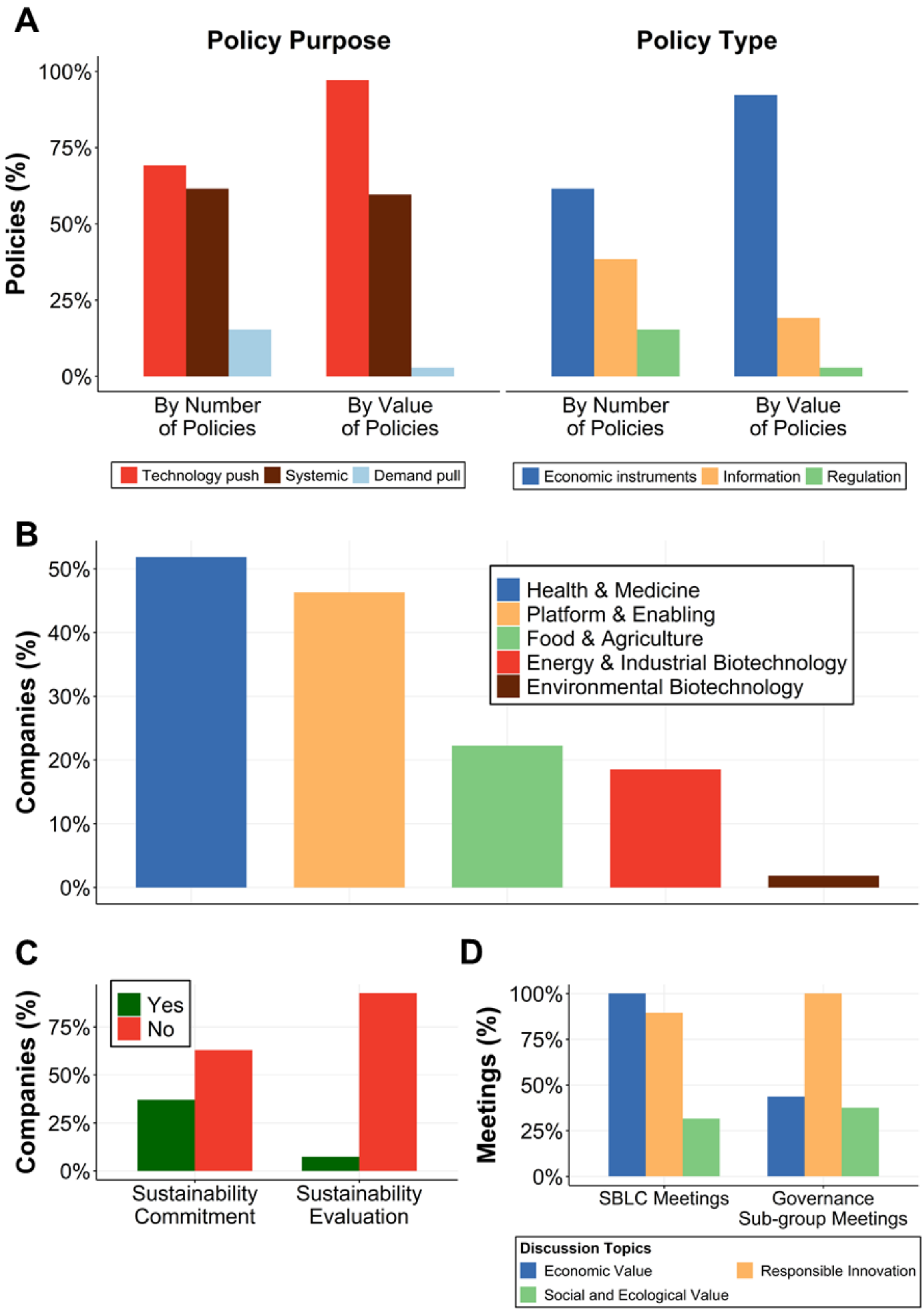

Figure 5.3: A summary of results from analyses of the policy mix, company websites, and SBLC meeting minutes. (A) The characteristics of the policy mix according to purpose and type as a percentage of total policies (13) and total value of investment (£245M) (Tables 5.1 & D.4); (C, D) the percentage of UK synthetic biology companies (n=54) (B) according to application domain and (C) demonstrating a commitment to sustainability and evidence of sustainability assessment or critical evaluation (Table D.5); and (D) the percentage of SBLC meetings and of its Governance Sub-group where economic value, responsible innovation or social and ecological value have been discussed (Table D.7). Note that for graphs A, B, and D the annotations are non-exclusive and so the figures will not add up to 100%.

5.4.4 Transformational failures in the UK synthetic biology programme

The previous section focussed on analysing the policy mix characteristics and how it was designed to address market and systemic failures in order to support the development and commercialisation of synthetic biology applications. This section will build on the issues identified there, with particular focus on how the policies have been applied in practice, to explain how the corresponding programme appears to have failed in addressing several transformational failures - namely in terms of *policy coordination*, *reflexivity*, and *directionality* (Weber & Rohracher, 2012).

In many senses, the UK synthetic biology programme has been a success. The UK remains a leading player in synthetic biology research, second only to the US in terms of publications[73] (Figure 5.2A; Shapira & Kwon, 2018). In terms of commercialisation, around 150 start-ups have reportedly been founded[74] and by one estimate over £1.8bn in private investment raised (SBLC, 2019). The BBSRC-funded seed fund has played a role in this by directly supporting synthetic biology start-ups and leveraging considerable co-investment from private investors (SQW, 2020). These start-ups are concentrated on platform and enabling technologies, which largely service other synthetic biology researchers and companies, as well as health and medicine (Figure 5.3B; Table D.6). Health and medicine represents a domain where the UK economy has long-standing strengths, a strong market-pull, and there is a well-established commercialisation route for start-ups involving gaining IP protection followed by acquisition by large pharmaceutical companies (a so-called “exit”) (Clarke & Kitney, 2020).

However, as discussed in the previous section, while a policy mix to promote the development and scale-up of synthetic biology applications has been established, there has been a lack of *policy coordination* in terms of the broader sectoral and cross-cutting policies necessary for transformation (Weber & Rohracher, 2012). Correspondingly, there has been less success in several key application domains such as industrial biotechnology[75] (Figure 5.3B) and relatively few start-ups have so far progressed to scale-up[76]. The previously discussed gap in the broader policy mix in terms of regulations, incentives, and public procurement initiatives that might stimulate demand for new bio-based technological solutions in application sectors may at least partially explain some of the scaling challenges faced in these application sectors. Significantly, it is also in these application sectors where the promised sustainability benefits of synthetic biology will or will not be realised.

Transformative change also calls for institutionalised *reflexivity* in order to anticipate, monitor, and be responsive in the face of uncertainty about the outcomes of innovation (Weber & Rohracher,

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[73] Albeit, Figure 5.2A suggests that the UK might have dropped below China in terms of publications in 2019.

[74] This was using a relatively broad definition and is a proprietary dataset. This study identified 54 UK-based companies currently operating (as of December 2020) working largely or exclusively in the domain of synthetic biology (see Appendix D.2).

[75] For example, Green Biologics, a flagship UK company in the renewable chemicals space that raised £60 million of investment in 2015, closed its doors in 2019 after it struggled to compete with petrochemical-based incumbents.

[76] See: https://medium.com/@spchambers007/uk-synthetic-biology-survey-2019-48981e3695f0

2012). In line with the 2012 roadmap, the RRI agenda has sought to embed reflexive capacity within the field, enabling distributed monitoring and governance. Some in the field have also considered these ongoing RRI activities to be the place where matters of sustainability should be considered. However, the subservient relationship of RRI to the dominant economic agenda and the often taken-for-granted nature of the sustainability benefits of synthetic biology, as described in the previous sections, seems to have shaped the way these policies were applied in practice.

The most notable example of RRI integration has been in the six SBRCs where ongoing evaluation required the integration of social science researchers and active consideration of ELSA[77] within the projects. A flexible approach was taken by funders concerning the kind of ELSA-work required and what kinds of social scientists should be involved. The position and power of RRI researchers within projects has also been ambiguous with their work tending to be separated from the core research and commercialisation efforts. Consequently, each of the centres has taken quite distinct approaches, from sociologists conducting ethnographic laboratory studies to attending science festivals and other science communication activities, to hosting an artist in residence (Table D.6). Notably, while social scientists from a range of backgrounds have been involved, they did not tend to have backgrounds in sustainability. Furthermore, available assessment methodologies for monitoring the largely environmental sustainability promises made are mostly the domain of the natural sciences rather than social sciences. Consequently, the gathering of evidence concerning the sustainability implications of synthetic biology has been relatively limited within the research centres (Table D.6).

A similar absence of monitoring was found in an analysis of UK synthetic biology company websites (Figure 5.3C; Table D.5). This might be explained by the early stage of many of the companies – available monitoring approaches such as sustainability assessments are challenging to undertake responsibly at the early stages of technological development, and require considerable time, resources, and interdisciplinary expertise (Chapter 2; Matthews, Stamford, et al., 2019). Another reason might have been the assumed and somewhat black-boxed link between “bio-based” and “sustainable”. That said, a subset of actors were seen to be acknowledging and grappling with sustainability trade-offs and some have commissioned or are undertaking sustainability assessments predominantly in the form of environment-focussed life-cycle assessment (LCA) (Figure 5.3C; Table D.5). Such validation of sustainability claims was typically undertaken voluntarily, perhaps to avoid future accusations of greenwashing. Indeed, this study found no evidence of public-sector funders, investors, or regulators asking for or requiring evidence to support claims of improved sustainability.

It is also notable the level at which this monitoring and anticipation has taken place, often within individual research initiatives or companies where there is relatively limited capacity to change the direction of travel, rather than being undertaken by those that set the overall strategic direction such as the SBLC and research funders.[78] An analysis of meeting minutes of the

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[77] ELSA can be considered a major precursor to the RRI framework (see Zwart et al., 2014).

[78] Indeed, no one with expertise in this area (e.g. sustainability assessment) seems to have been a member of the leadership council or have been involved in steering any of the major policy reports.

leadership council (the SBLC) and its governance sub-group revealed a focus on commercialisation and economic value creation, primarily at the main SBLC meetings (Figure 5.3D; Table D.7). At the council's Governance sub-group, there was considerable discussion of proactive approaches to regulation and dealing with biosecurity issues, but an equivalent focus on social and environmental value *creation* was not evident.[79] This might be explained by two factors. Firstly, there were many other seemingly more pressing matters to discuss such as efforts to avoid the declaration of a moratorium on synthetic biology research and/or applications through the convention on biological diversity (CBD). Secondly, and more fundamentally, none of the long-term members of the SBLC or the sub-committee had particular expertise in sustainability.[80] Thus, matters of sustainability, particularly environmental aspects, seemed to fall through a gap in the middle of the two largely incongruent parallel streams. That is, the pursuit of economic value through the commercialisation of synthetic biology on the one side (primarily discussed at the main SBLC meetings), and on the other, attempts to deal with risks and potential controversy through proportionate regulation and RRI (primarily discussed at the governance sub-group).

Taken together, while there have been considerable efforts to embed distributed *reflexivity* at lower levels within the field, and some proactive attempts by researchers and companies to anticipate and monitor sustainability implications, this has not been integrated within the governance mechanisms that set the strategic direction. This greatly limits the capacity for responsiveness. Therefore, while individual actors may have gained the capacity to act reflexively, the wider innovation system has not. Furthermore, while some companies and researchers have sought to evaluate and evidence sustainability implications (with an environmental focus), these have been voluntarily and disparately undertaken, implying that considerable knowledge gaps are likely to exist regarding the sustainability potential of the field.

A final consideration is that of *directionality*. The UK synthetic biology programme has focussed on developing an effective innovation ecosystem around this emerging technology to accelerate the development and commercialisation of the applications it promises. While a comprehensive policy mix has sought to achieve this through overcoming market and system failures, there has been limited attention to the *directionality* of change. This is demonstrated on the one hand through the lack of *coordinated policy intervention* in wider application sectors which would be used to generate demand, particularly for innovations that could tackle unsustainable practices in these sectors. On the other hand, the policies which were implemented failed to promote institutionalised *reflexivity* in the innovation system with respect to the sustainability potential of these technologies. Furthermore, in an area like synthetic biology where there promised future benefits are contested, as was described in Section 5.4.1, the need to establish collective, shared

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[79] This is not to say that sustainability was not occasionally discussed or mentioned but that there appeared little strategic consideration of how to actively draw out the sustainability benefits, ensure that they are evidenced, or grapple with inevitable trade-offs.

[80] Two one-off exceptions to this were found: one meeting of the SBLC was attended by a member of the Government Office for Science Environment team and a Professor of Environmental Psychology attended one meeting of the Governance Sub-group. Civil servants in attendance from the Department for Environment, Food and Rural Affairs were generally focussed on GMO regulation as opposed to broader environmental sustainability aspects.

visions for that future becomes even more important. The 2012 roadmap, informed by the 2009 Synthetic Biology Dialogue, did attempt to put forward such a vision. However, as was described in Section 5.4.3 and by Marris & Calvert (2020), this lacked coherence when it came to considering broader social and environmental value creation (within the framework of RRI) alongside economic value creation. As a result, the policies that have been implemented have had many features that are directed at multiple levels towards actively creating technologies that are commercially viable[81], while the creation of technologies that are viable from a social and environmental point of view has not received equivalent attention.

Without explicit attention to *directionality* in the policy mix, the ‘application space’ currently being explored by the field risks failing to deliver on sustainability promises (see Figure 5.4). It is certainly likely that many synthetic biology applications, if commercially viable, will generate sustainability benefits compared to using fossil fuels[82] (top right of Figure 5.4). However, there are also likely to be trade-offs which without active monitoring and mitigation could undermine promised sustainability benefits (as indicated in Chapter 3). It also remains the case that despite the introduction of some carbon pricing through emissions trading schemes, most environmental and social value represent externalities from a financial point of view and so there would be little to stop the scale-up of technologies that inadvertently create new social and environmental problems[83] (top left of Figure 5.4). Furthermore, the necessity of financial value creation (excluding externalities) in present economic systems also leaves an area of unexplored promise (bottom right of Figure 5.4) where there are environmental and social benefits to be found but a lack of adequate financial return to justify commercial exploitation.[84]

5.5 Discussion and conclusion

This study has sought to trace the role that sustainability has played in the promotion of synthetic biology in the UK, guided by the analytical framework (Figure 5.1). Sustainability has formed a significant part of the promise of synthetic biology and has played an important discursive role in establishing joint expectations and thereby legitimising policy intervention in support of this emerging technological paradigm. Yet, this study also identified how this commitment to the creation of broader social and environmental value was not reconciled in policy processes or the policy strategy with the dominant rationale of economic growth through commercialisation. Correspondingly, relatively little attention to sustainability was found in the subsequent policy mix,

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[81] Examples of this include policy features that encourage researchers to engage with businesses, actively seek to tackle industry-led challenges, and commercialise their research.

[82] Indeed, a considerable proportion of the commercial and research activity has been specifically directed at the creation of social and environmental value as well as economic value (Figure 5.3C; Tables D.5 and D.6).

[83] Admittedly, reputational damage and environmental regulation can both disincentivise the commercialisation of such applications. However, environmental regulations remain relatively lax and the well-documented and continuing problem of greenwashing can prevent this reputational damage from occurring (Delmas & Burbano, 2012).

[84] Note that this does not necessarily mean the application is not “commercially viable” in the long-term, but rather that the promised financial returns are not significant enough to justify the potentially risky and long-term investment. This lack of present attractiveness may also be driven by many of the benefits being externalities.

neither in terms of design and implementation nor in ongoing strategic leadership efforts. This is likely to be resulting in transformational failures in terms of *policy coordination*, *reflexivity*, and *directionality* (Weber & Rohracher, 2012). In this final section, I will draw out the key points from the findings, identify some potential explanations, and suggest some avenues to address them.

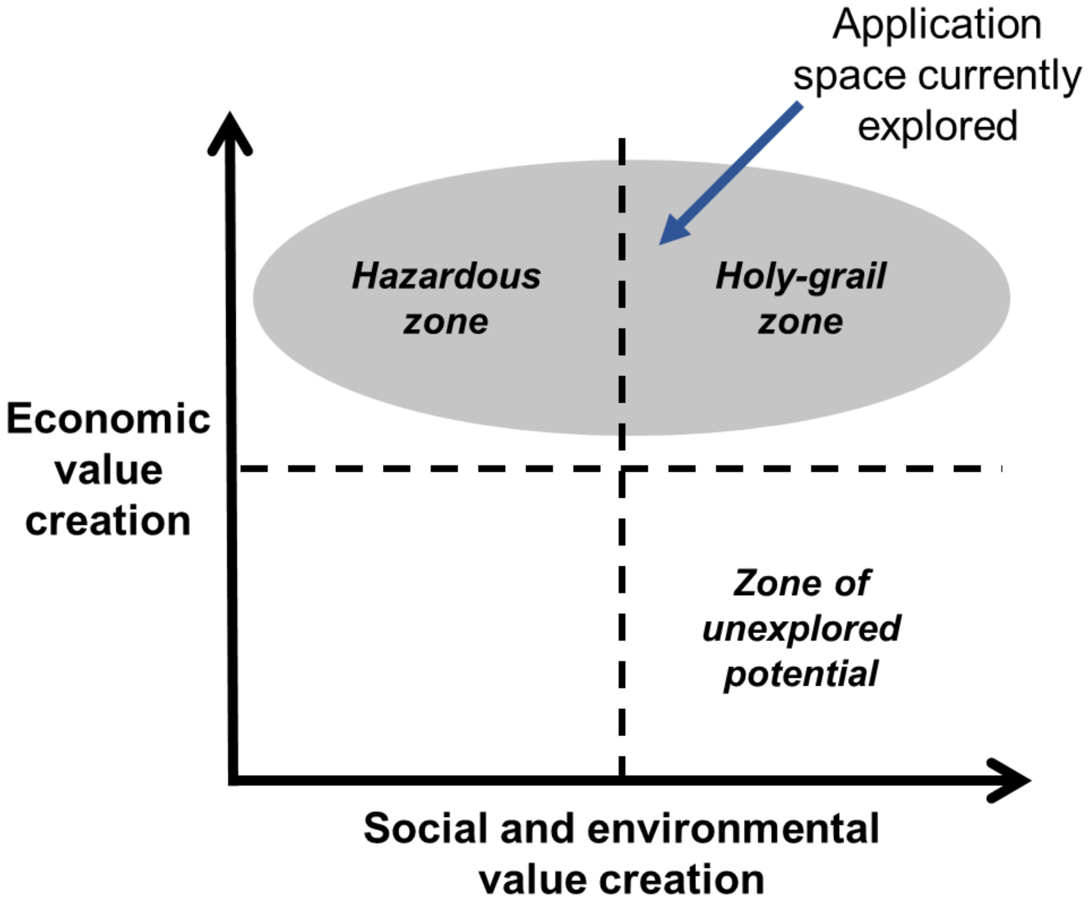

Figure 5.4: The 'application space' currently being explored by the UK synthetic biology field (Source: author's elaboration drawing on Dyck & Silvestre 2018).

I will start by highlighting three key points that may explain why the policy processes and resulting instrument mix developed in this way. Firstly, it is notable how social scientists and the critical insights they bring have been integrated at an early stage into policy discussions, with their most prominent contribution being to introduce and embed RRI within the strategy (Marris & Calvert, 2020). An inability to reach a collective and coherent vision within the policy strategy which reconciled the imperatives of RRI with broader economic goals considerably limited the impact that it could have on the resulting instrument mix and its implementation. This may explain the lack of institutionalised reflexivity which has resulted. It is also important to note that while related, RRI is not synonymous with sustainability and that most researchers brought in to work on RRI would not describe themselves as sustainability researchers. This is despite an assumption that sustainability considerations could be dealt with through RRI activities. The relative absence of other disciplines such as ecologists, environmental scientists, and chemical engineers in both policy discussions and policy implementation suggests that this focus on RRI and the prominent role given primarily to social scientists from STS traditions may have inadvertently crowded out the integration of these other disciplines. This was seen particularly in discussions at the SBLC which tended to focus on commercialisation and RRI, but not sustainability.

A second but related issue centres on the unquestioned link between synthetic biology applications and sustainability, an assumption that was present both explicitly and implicitly in policy discussions. This fed through into the resulting policy strategy and instrument mix which was targeted at promoting the development and commercialisation of synthetic biology in general with limited attention to whether it delivered sustainable outcomes in the application sectors targeted. Such assumptions about sustainability and a tendency not to problematise it are deep-rooted, and also present in the sustainability transitions literature (see Susur & Karakaya, 2021). However, it is also well-established in the case of bio-based technologies that this assumption of sustainability is flawed (Escobar & Laibach, 2021; French, 2019; Matthews, Cizauskas, et al., 2019; Ögmundarson et al., 2020). More generally, transitioning to a more transformational framing of innovation policy and redressing the deeply embedded unsustainable directionality of present socio-technical change is likely to need more fundamental embedding of these new ambitions within policy strategies, objectives, plans, and instruments (Schot & Kanger, 2018; Schot & Steinmueller, 2018). This study has demonstrated how it is important not to take the sustainability promises of emerging technological paradigms at face value and instead subject them to structured evaluation as is enabled by the analytical framework employed here.

Thirdly, the way in which evolving rationales interacted with a path-dependent instrument mix seems to have played an important role in this case.[85] When the instrument mix was predominantly determined during the c.2012 policy window neither the Paris Agreement nor the SDGs existed while the need for economic growth in the aftermath of the great recession and austerity was particularly urgent.[86] Meanwhile, the focus on the *Eight Great Technologies* at the time may explain the relative absence of consideration in the policy mix for generating and articulating demand in potential application sectors (Willetts, 2013). As time went on, the focus on sustainability was seen to grow in prominence in policy documents while a return to a more holistic industrial strategy in the broader policy environment provided a potential opening to coordinate synthetic biology policy with intervention in potential application sectors. Given the success the programme seemed to have had in establishing a vibrant and cutting-edge synthetic biology community and a broad range of start-ups pursuing commercialisation, this would have arguably represented an opportune time to integrate more demand-side and explicitly directional policy, as has as have been more extensively used in energy policy (Edler, 2016). However, the 2018 Bioeconomy Strategy does not appear to have so far had the high-level backing to realise this critical evolution of the policy mix.

These issues and challenges aside, the synthetic biology field remains early in development and thereby its impacts remain to a significant extent undetermined. Of course, this also means that the analysis presented here is inherently anticipatory, and therefore the argument made to some degree conceptually as well as empirically grounded. To what extent synthetic biology on its

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[85] The importance of these temporal considerations has been previously emphasised in the literature (Edmondson et al., 2018; Flanagan et al., 2011).

[86] The UK narrowly avoided a “double-dip” recession in 2012.

current trajectory helps or hinders sustainable development will only truly become apparent with time. Nonetheless, technological trajectories are path-dependent and so early decisions matter (Collingridge, 1980). Therefore, despite its limitations, it is an appropriate time to undertake and present this analysis as the field is mature enough to start revealing its trajectory, but before the technologies it underpins have become so embedded in society that modulation and redirection become infeasible.

For the UK synthetic biology community, the policies originally put in place around 2012 are now largely coming to an end while a rebranding exercise is currently underway towards a more application-focussed *engineering biology*.[87] In the context of the COVID-19 pandemic, the widely regarded success of the industrial strategy in the context of the Oxford/Astrazeneca vaccine (Balawejder et al., 2021), and a renewed focus on sustainable technologies to assist with the "build back better" agenda (HM Government, 2020), there is the possibility of a new policy window opening which could be used to evolve the policy mix to include more demand-side policies focussed on application sectors.

Based on the findings presented here, I put forward several tentative recommendations for this potential evolution of the policy mix. The first would be to institute more coordinated policy intervention that actively supports the articulation and generation of demand in application sectors such as chemicals, materials, and agriculture. Targeted policies might include public procurement[88] as well as regulations and incentives[89]. Such policies would likely interact favourably with the new UK-specific Emissions Trading Scheme[90] in incentivising transitions to lower-emitting bio-based technologies enabled by synthetic biology. Second, existing and new policies need to include stringent minimum sustainability standards rather than simply providing a blanket incentive for bio-based production. To support greater reflexive consideration of sustainability implications, funders and investors could also require elaboration and evidence of sustainability claims in grant applications and evaluations[91], and be willing to withdraw support if necessary. Third, efforts towards improved directionality need a collective and shared vision to guide it (Weber & Rohracher, 2012). An opportunity here is provided by the growing interest in the use of citizen assemblies to elaborate on the preferences of citizens (the users) for sustainable technologies.[92] Synthetic biology research agendas could be (re)directed to try and address the priorities and preferences that emerge from these dialogues. Additionally, foresight activities can help to support improved policy coordination and enable the elaboration of shared

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[87] For example, the SBLC was recently renamed the Engineering Biology Leadership Council.

[88] This could potentially be modelled on the US BioPreferred scheme (USDA, n.d.). In this vein, the UK Government recently announced that a "social value model" will now be integrated into procurement decisions (Cabinet Office, 2020) while the new Industrial Decarbonisation Strategy includes the use of public procurement to promote decarbonisation (HM Government, 2021).

[89] For example, initiatives like the Renewable Transport Fuel Obligation (RTFO) could be expanded to other sectors such as chemicals and plastics.

[90] See: https://www.gov.uk/government/publications/participating-in-the-uk-ets

[91] The UKRI environmental sustainability strategy now commits the UK's principal research funder to implement this (UKRI, 2020).

[92] For example, the UK Climate Assembly recently reported its findings (Climate Assembly UK, 2020).

visions for sustainable synthetic biology applications, linking up the supply- and demand-sides (Georghiou & Cassingena Harper, 2011).

This chapter has provided empirical insights from a case study beyond the much-studied domain of energy transitions (Hansmeier et al., 2021; Kern et al., 2019). As transitions are sought in more complex and contested contexts such as those which synthetic biology promises to contribute towards, avoiding taking the sustainability of emerging technologies at face value will become increasingly important (Susur & Karakaya, 2021). Furthermore, policy mixes focussed on indiscriminate support for a given technology are likely to become increasingly ineffective. In line with Flanagan et al. (2011), this study also emphasises the significance of interpretive flexibility in determining the effectiveness of policy instruments in addressing sustainability concerns. There is therefore a need to continue complementing high-level policy mix studies with the in-depth investigation of individual (technological) innovation systems as reported here. In combination, such studies can provide important insights concerning how policy intervention can be used to mobilise STI for sustainable development.

Chapter 6: Conclusion

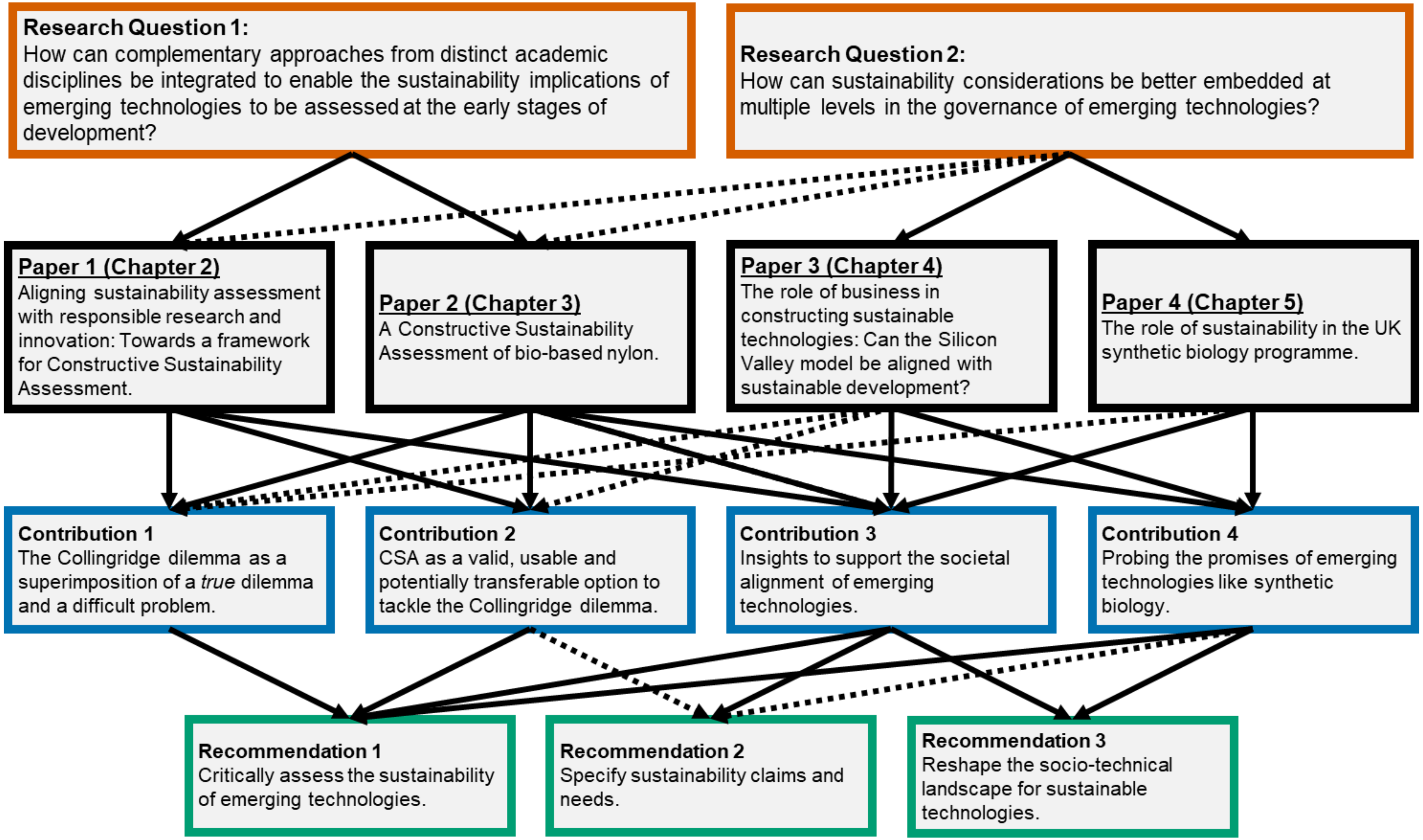
In the introduction to this thesis, I posed two overarching research questions:

- Research Question 1: How can complementary approaches from distinct academic disciplines be integrated to enable the sustainability implications of emerging technologies to be assessed at the early stages of development?
- Research Question 2: How can sustainability considerations be better embedded at multiple levels in the governance of emerging technologies?

Tackling these questions through a mixed-methods, action research, and interdisciplinary approach, the thesis has sought to explore how we can better control our technology through improvements in both assessment and governance. This concluding chapter revisits some of the ideas, gaps, and questions posed in the introduction. It begins with an articulation of the key contributions of the thesis. I then reflect on the limitations and opportunities for further research before drawing out recommendations for research, policy, and business. Figure 6.1 provides a summary of the logical flow that connects the research questions, the empirical chapters, the four contributions, and the recommendations.

6.1 Contributions

The thesis offers four contributions to theory and practice. Firstly, the Constructive Sustainability Assessment (CSA) framework represents an integrated response to the Collingridge dilemma with implications for the very nature of the dilemma. Secondly, the CSA framework has been conceptually grounded, empirically testing, and open-source tools developed to support its application. Therefore, the thesis demonstrates it to be a usable, valid, and potentially transferable approach. Thirdly, the findings can be integrated to put forward a model for how the dilemma of control and the dilemma of societal alignment (Ribeiro et al., 2018) can be tackled in tandem. Finally, the thesis highlights the critical importance of not taking the sustainability potential of emerging technologies for granted. These contributions will now be further discussed and elaborated in turn.



Research Question 1:
How can complementary approaches from distinct academic disciplines be integrated to enable the sustainability implications of emerging technologies to be assessed at the early stages of development?

Research Question 2:
How can sustainability considerations be better embedded at multiple levels in the governance of emerging technologies?

Paper 1 (Chapter 2)
Aligning sustainability assessment with responsible research and innovation: Towards a framework for Constructive Sustainability Assessment.

Paper 2 (Chapter 3)
A Constructive Sustainability Assessment of bio-based nylon.

Paper 3 (Chapter 4)
The role of business in constructing sustainable technologies: Can the Silicon Valley model be aligned with sustainable development?

Paper 4 (Chapter 5)
The role of sustainability in the UK synthetic biology programme.

Contribution 1
The Collingridge dilemma as a superimposition of a *true* dilemma and a difficult problem.

Contribution 2
CSA as a valid, usable and potentially transferable option to tackle the Collingridge dilemma.

Contribution 3
Insights to support the societal alignment of emerging technologies.

Contribution 4
Probing the promises of emerging technologies like synthetic biology.

Recommendation 1
Critically assess the sustainability of emerging technologies.

Recommendation 2
Specify sustainability claims and needs.

Recommendation 3
Reshape the socio-technical landscape for sustainable technologies.

Figure 6.1: A graphical representation of the thesis logic and argument. This figure shows how the research questions relate to the four papers, then to the four main contributions, and finally to the three groups of recommendations. Solid arrows indicate a direct link while dotted lines indicate a more oblique contribution.

6.1.1 Constructive Sustainability Assessment and its implications for the Collingridge dilemma

The thesis started by introducing Collingridge's dilemma of control, which he described as follows:

> *"…attempting to control a technology is difficult, and not rarely impossible, because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequences are apparent, control has become costly and slow" (Collingridge, 1980, p. 19).*

The dilemma consists of two conflicting problems, described by Collingridge as the two 'horns' of the dilemma. The first horn refers to the lack of information or knowledge of impacts early in technological development. The second horn refers to the high cost and difficulty of control later on in development.

Collingridge's work continues to have considerable influence in the present-day technology assessment and Responsible Research and Innovation (RRI) communities (Genus & Stirling, 2018). Recently, a dilemma of societal alignment was proposed to complement the dilemma of control (Ribeiro et al., 2018). Ribeiro et al. (2018) defined this additional dilemma as the challenge "of engaging multiple and often diverse publics, framing societal needs and aligning the objectives and configurations of science, technology and innovation for meeting those needs." (p. 9). This proposition provoked scholarly debate not just on the validity and necessity of the new dilemma but also on the very nature of the original dilemma of control (Ribeiro et al., 2020). It was clear from this dialogue that there are several different readings of Collingridge concerning the extent to which what he proposed is (a) a *true* dilemma that "we take it at our own peril for a problem to be managed or solved" (Nordmann, 2018, p. 333), (b) "a complex issue of balancing and choosing between competing and potentially contradictory demands" (Ribeiro et al., 2020, p. 4) or (c) a true dilemma but with fuzzy boundaries where the two horns can be considered "boundary conditions that must be battled against, even if the logical pincers don't always bite hard or definitively" (Guston, 2018, p. 348). The contributions of the thesis with respect to the dilemma of societal alignment will be discussed in Section 6.1.3. This section will position the CSA framework as a constructive response and expansion of these contemporary discussions of Collingridge's work, focussing on the nature of the dilemma and to what extent it can be tackled or even solved.

CSA can be seen as an integrated response to the Collingridge dilemma, implying that neither 'horn' of the dilemma is fundamentally limiting. To demonstrate this argument, we can consider each horn in turn. Starting with the second – controllability – Collingridge (1980) argues that due to the dubious validity of methods to forecast the impacts of technology, "the only hope seems to be in tackling the other [second] horn of the dilemma of control" (p. 19). He goes on to propose a "theory of decision-making under ignorance" which prioritises decisions that are "reversible, corrigible, and flexible" (ibid., p. 12). In line with this, the CSA approach elaborated in Chapter 2 draws on frameworks such as RRI and Constructive Technology Assessment (CTA) to propose iterative cycles of CSA which can support an open, inclusive and incremental approach to the governance of emerging technologies (Schot & Rip, 1996; Stilgoe et al., 2013).

Therefore, there seems to be some consensus around the view that controllability can be partially addressed through governance and policy intervention to enable greater reflexivity and responsiveness on the part of technological decision-makers[93]. However, while some aspects of the second horn are driven by issues that can be tackled, such as actors not being in a position to respond quickly and effectively to new information, processes such as lock-in are necessary for development and deployment to proceed and thus represent intractable features of the second horn. The implications of this are shown graphically in Figure 6.2. While in a baseline scenario, controllability might drop off quickly during technology development (green dashed line), by implementing approaches that preserve flexibility and responsiveness the curve can be raised to an extent (dotted lines) and so controllability can be preserved later into development when more knowledge of impacts is likely to be available.

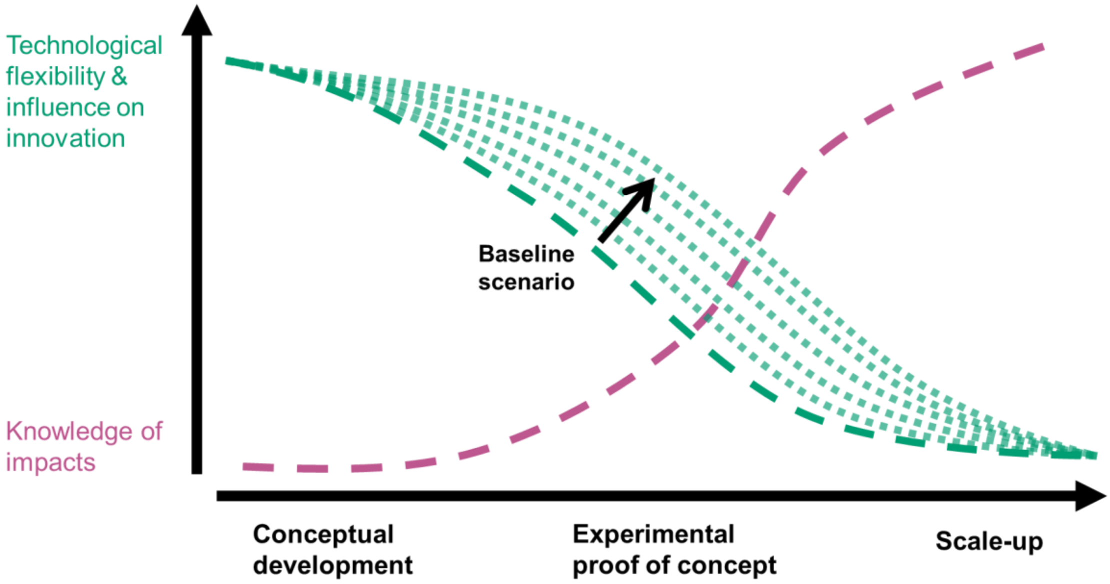


Figure 6.2: Conceptual demonstration of the malleability of the second horn of the Collingridge dilemma – controllability. The dashed green line shows the baseline scenario described in the text while the dotted lines indicate how the curve can be raised through interventions to improve flexibility and responsiveness (Source: Author's elaboration based on Collingridge, 1980).

On the first horn – knowledge of impacts – Collingridge perceived improved forecasting to be a futile endeavour. Conversely, the research contained in this thesis suggests that the first horn can be actively tackled, alongside the second, through the anticipatory use of sustainability assessment. Accordingly, the fourth design principle of CSA – *anticipation of futures* – draws on the work of several others (e.g. Wender, Foley, Hottle, et al., 2014) to argue that analytical approaches such as LCA, while not appropriate for deterministic prediction at such early stages of development, can be used productively to explore and rationalise uncertainty. Such an

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[93] Technological decision-makers can be considered a broad range of actors from policy-makers who make decisions about funding and regulation to businesses and researchers who actively take design decisions.

approach is again in line with frameworks such as RRI, CTA, and anticipatory governance in focussing on the anticipation of plausible and possible future eventualities and impacts as opposed to the deterministic prediction of technological futures, something that Collingridge rightly critiques (Collingridge, 1980, p. 19).

The implications of this for the first horn are demonstrated graphically in Figure 6.3. In the baseline scenario (purple dashed line), decision-makers wait for the technology to become embedded in society when potential “unwelcome consequences” become readily apparent. Alternatively, frameworks such as CSA can be used to implement sustainability assessment at the early stages of development. Therefore, much like with controllability, the curve in Figure 6.3 can be raised (dotted lines) by making information regarding potential sustainability impacts available to decision-makers earlier in development. This was demonstrated empirically in Chapter 3, where through the early application of CSA, knowledge of possible and plausible impacts was increased for a given stage of technological development.

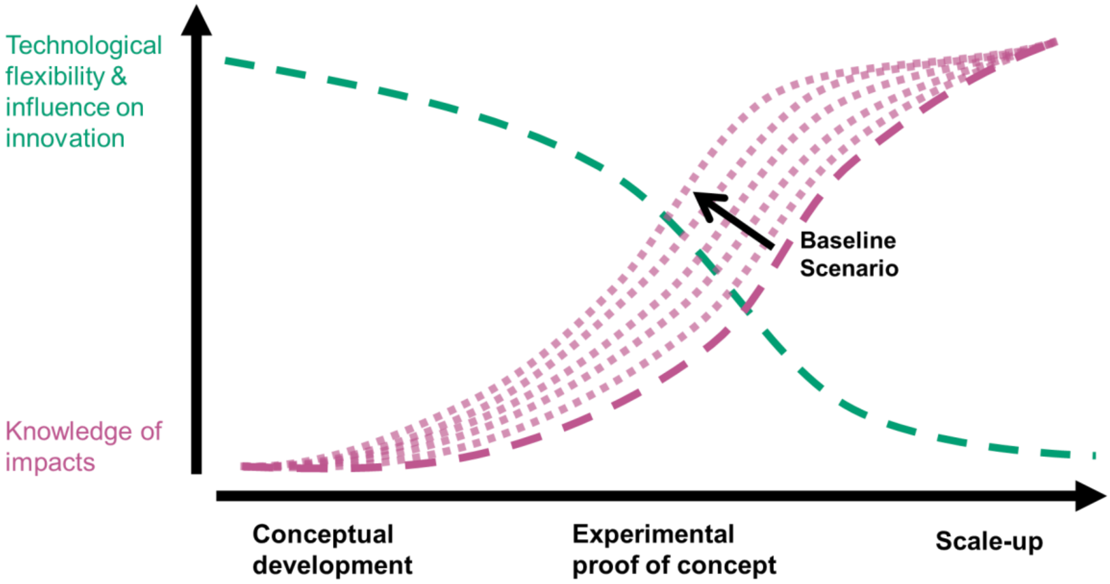

Figure 6.3: Conceptual demonstration of the malleability of the first horn of the Collingridge dilemma - knowledge of impacts. The dashed purple line shows the baseline scenario described in the text while the dotted lines indicate how the curve can be raised through the early application of sustainability assessments (Source: Author’s elaboration based on Collingridge, 1980).

However, there are many distinct aspects and types of knowledge that contribute to the first horn of the dilemma. Some aspects are, as Collingridge suggests, unknowable at the early stages of technological development – so-called unknown unknowns and black swans (see Taleb, 2007). Other aspects, such as societal preferences for a given future socio-technical arrangement, are likely to be moving targets and will co-evolve with the technology. Finally, some aspects are simply difficult to measure and anticipate (i.e. known unknowns), such as the potential greenhouse gas (GHG) emissions from the technology. Thus, while the second horn can be tackled, knowledge of impacts will always be somewhat limited at the early stages of technological development.

These findings suggest that both the first horn regarding knowledge of impacts and the second horn regarding controllability are challenges that can be partially, but not completely, alleviated. Therefore, with respect to the debate over the nature of the dilemma introduced at the start of this section, I conclude that Collingridge's dilemma of control is neither exclusively a *true* dilemma nor a difficult problem. Rather, it is a superimposition of multiple aspects, some with the characteristics of a dilemma, others of a difficult problem.

Looking at this in another way, if each horn of the dilemma could plausibly be exacerbated by slow and ineffective responses (such as those discussed in Chapter 5), and if we also accept that even if theoretically solvable, we will only ever be able to find partial solutions to the *difficult problem* aspects of the dilemma, then by deduction we will always find ourselves in what Guston describes as: "the fuzzy politics between the horns of the dilemma" (Guston, 2018, p. 348). It thus makes sense, especially for those looking to exert some rational control on technology and avoid its 'unwelcome consequences', to focus on the difficult problems to which some partial solutions can be found while remaining acutely aware of the fundamental constraints that the *true* dilemma aspects convey. I propose that structured yet flexible approaches such as CSA, which embed the state-of-the-art in analytical assessment within a broader, deliberative and iterative framework, represent a promising avenue to support decision-makers and other societal actors to more productively explore that fuzzy space in-between.

6.1.2 Usability, validity, and transferability of Constructive Sustainability Assessment

Now that CSA has been positioned with respect to historic and contemporary discussions concerning the Collingridge dilemma, it is worthwhile to consider the usability, validity, and transferability of the approach.

Starting with usability, undertaking the assessment and deliberation activities prescribed in the CSA framework requires access to the necessary tools and resources, interdisciplinary knowledge and expertise, and time. To assist usability, the methodology described in Chapter 2 seeks to provide a relatively simple and flexible methodological approach to structure assessment and deliberation activities. Meanwhile, the SustAssessR codebase has been made publicly available such that it can be used and adapted for other bio-based technologies (Matthews, 2019). Finally, Chapters 3 and 4 proposed internal company stakeholders as an early intelligence source to assist this process. Further streamlining and simplification of approaches such as CSA could be explored but must be done cautiously. Considering sustainability proactively in the design of emerging technologies will always be necessarily difficult, costly, and time-consuming because complex questions inherently have complex answers (Stirling, 2010). Therefore, ensuring the necessary incentives are in place to justify the integration of approaches like CSA is a key factor in determining their usability. The matter of incentives was discussed in Chapters 3, 4, and 5 and is further unpacked later in this concluding chapter.

Another important factor in determining the usability of CSA is the accessibility of evaluation methodologies such as LCA and associated sustainability data. As well as the more bespoke

SustAssessR codebase developed and used in the research presented here, versatile open-source software has also been developed by others such as OpenLCA (Ciroth, 2007) and Brightway2 (Mutel, 2017). However, even where the software is freely available, payment is still frequently required to access life-cycle inventory data which is essential for undertaking LCA analysis, although this situation is slowly improving with efforts to improve accessibility and interoperability.[94] Scaling-up the gathering of sustainability data (especially social sustainability data) concerning products, processes, and policies and making this freely available would seem to be a major opportunity and prerequisite for any attempts to address sustainability challenges and tackle the Collingridge dilemma.

Considering validity, there are three angles from which CSA is vulnerable to critique: the emphasis on analytical methods, lack of attention to stakeholder participation and social aspects, and a technology-centric viewpoint. Starting with the first critique, the anticipatory use of analytical methods such as LCA represents a key tenet of the CSA approach. CSA expands on A-LCA in taking account of the assumptions that underpin such methods and their failure to capture many types of uncertainty by situating the analytical methods within a broader iterative and deliberative approach (Wender, Foley, Hottle, et al., 2014). This helps to avoid the premature closing down of commitments and keeps options open (Stirling, 2008a). However, such an approach still exposes CSA to the well-trodden and very valid critiques of the use of expert-based scientific modelling to make sense of the future, particularly in relation to elements that cannot be represented within probability distributions (Knight, 1921; Stirling, 2008b; Taleb, 2007). This critique sits within a broader one concerning the substantial limitations to the objectivity of scientific knowledge, as many decades of scholarship in the field of STS has demonstrated (e.g. Kuhn, 1962; Latour & Woolgar, 1979).

Chapter 2 considered these limitations in detail and the four design principles and three-step iterative approach which underpin CSA were specifically developed to alleviate and actively manage these issues. The attempt to find a practical middle-ground is central to the CSA approach. As argued in Chapter 2, there are many aspects of sustainability that can be quantified (e.g. GHG emissions). Doing so can be extremely helpful in putting numbers on otherwise intractable sustainability issues, provoking helpful discussion and deliberation as reported in Chapters 3 and 4. Yet, there are many other aspects of sustainability, not least regarding the relative prioritisation of sustainability issues and desirability of transition pathways, which cannot be reasonably or responsibly quantified. We should avoid extending the use of analytical models beyond their reasonable useful capacity into these areas. More broadly, it is important to minimise the elite technocratic decision-making that can sometimes result from reliance on science-based approaches (see Smallman, 2019). Accordingly, CSA seeks to utilise analytical modelling approaches in a way that informs and supports the achievement of sustainability goals but with decision-making driven by stakeholders. This re-oriented role for science and expertise

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[94] UNEP's Global LCA Data (GLAD) network specifically seeks to address this issue and open-source datasets are being made available through initiatives such as the US LCA Commons and the EC Product Environmental Footprints. For a list of free LCA and social-LCA databases, see https://nexus.openlca.org/databases.

aligns with the arguments of Collins & Evans (2017; 2002) with respect to their proposed *third wave* of science studies, one that seeks to place scientific expertise in the service of democratic societies. The expanded use of citizens assemblies could play a crucial role in supporting this (Section 6.1.3).

Another angle of critique might be that CSA pays too little attention to social sustainability and stakeholder participation. As discussed in Chapter 2, there is a tendency in sustainability assessment more broadly to neglect the social pillar of sustainability relative to environmental and economic aspects which may be explained by its more subjective and contested nature (Boström, 2012; Palmeros Parada et al., 2017). Indeed, social aspects such as well-being, quality of life, and equity are much more likely to fall within the class of impacts for which analytical methods are unavailable and/or inappropriate. Therefore, by focussing on aspects that can be "responsibly measured" (see Chapter 2), CSA could be criticised as proliferating the neglect of the less easily quantifiable social sustainability dimension.[95] On the other hand, if one considers a starting point where carrying out an LCA is often the extent to which sustainability assessment currently extends (as seen in Chapter 5), CSA represents a pragmatic expansion of existing assessment practices to include social aspects where they would otherwise be excluded.[96]

A more comprehensive approach to take account of the social dimension might be to pursue broad stakeholder engagement, as is widely recommended or even prescribed in frameworks for responsible innovation (da Silva, Bitencourt, Faccin, & Iakovleva, 2019; Stilgoe, Owen, & Macnaghten, 2013). Undertaking engagement, particularly of impacted stakeholders and of citizens more widely, during the scale-up of emerging technologies might help to diversify the values and worldviews considered, gather knowledge on social impacts and implications, and more generally help align innovation with desirable and workable socio-technical outcomes (Boström, 2012; Ribeiro et al., 2018; Wilsdon & Willis, 2004). However, while undoubtedly valuable and important (e.g. see next section), both practical and conceptual issues need to be considered, as was discussed in Chapters 2 and 4 (also see Delgado, Kjølberg, & Wickson, 2011).

The approach to stakeholder participation recommended in the CSA framework has both conceptual and practical foundations. Firstly, it is recommended that broader engagement should be employed when it is necessary for the issue at hand rather than as an automatic feature of all stages of technological development. This reflects a substantive and outcome-focussed rather than normative and procedure-focussed rationale for engagement (see Stirling, 2008a). On the practical side, we must also recognise that broad participation can be time-consuming and risky for innovators[97], creating particular tensions in business contexts (T. Brand & Blok, 2019;

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[95] That said, the need to be transparent regarding "unmeasurables" was clearly emphasised in Chapter 2.

[96] This aligns with the experiences reported by van de Poel et al. (2020) in trying to operationalise responsible innovation in industry. They recommend working with existing assessment approaches employed within companies but "broadening the values and issues addressed" (ibid., p. 4).

[97] "Innovators" as used here can be taken here to refer to individuals and organisations (i.e. actors) who promote, develop and deploy emerging technologies.

Noorman et al., 2017). Thus, conceptual arguments aside, pragmatic decisions and compromises based on specific contexts are likely to be needed as to when to employ broad engagement, as argued in Chapters 2 and 4.

In developing CSA, I have at times prioritised practical applicability over conceptual purity and therefore one's view on its utility will inevitably depend on one's own outlook. In particular, its cautious and pragmatic integration of social aspects and stakeholder engagement reflects a focus on producing a framework that is broader than what currently exists but could also work within existing frameworks and market economies. This, in turn, reflects a view that change involves 'muddling through' and is therefore necessarily incremental (Lindblom, 1959).

This outlook also underpins the response to the last and more fundamental critique of CSA – that it is too technology-centric. This a valid critique. The CSA approach starts with a technology and then considers its societal implications rather than starting with an environmental issue or societal demand and identifying solutions, technological or otherwise (cf. Zijp et al., 2016). Consequently, this work is inevitably somewhat complicit in propping up the status-quo while arguably neglecting more fundamental questions about whether emerging technologies are necessary for sustainable development and whether more fundamental shifts in our thinking (and societal structures) are needed (see Dyck & Silvestre, 2018; Nierling, Ehlers, Kerschner, & Petra, 2018; Raworth, 2017; Saille & Medvecky, 2016). Nonetheless, by starting with the sustainability promises of emerging technologies and subjecting them to structured and holistic evaluation, CSA offers an approach that complements rather than undermines more radical perspectives. Indeed, the possible integration of technology- and society-centric perspectives is discussed in Section 6.1.3.

Related to the above discussion is the question of CSA's transferability to other emerging technologies and to other geographical and cultural contexts. In terms of the latter, as the sustainability aspects and relative prioritisation are not prescribed, CSA supports the use of different sustainability conceptualisations and differing norms around knowledge sources and engagement practices (Postal et al., 2020). However, this flexibility would need to be tested in practice and represents an opportunity for further research. The framework has thus-far been tested purely in the domain of synthetic biology so it would be premature to assume that it would necessarily generalise to other emerging technologies. However, CSA was described in Chapter 2 in a relatively technology-agnostic manner, drawing from frameworks that were developed primarily in application to distinct emerging technologies to synthetic biology.[98] CSA was specifically designed to be open and flexible, particularly in not being prescriptive as to which methods should be applied in the evaluation stage. Therefore, testing the approach on other emerging technologies might be another fruitful avenue for further research. When doing so, particular attention would be needed in determining appropriate and informative evaluation approaches during the formulation stage of CSA cycles.

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[98] For example, A-LCA was developed in the context of nanotechnologies (Wender, Foley, Prado-Lopez, et al., 2014).

6.1.3 Enabling the societal alignment of emerging technologies

The characteristics and tested capabilities of the CSA approach presented in this thesis have so far been positioned with respect to the Collingridge dilemma, focussing on how CSA can effectively tackle some of the challenges of controlling technology. In Section 6.1.1, the recently proposed complementary dilemma of societal alignment was introduced (Ribeiro et al., 2018). This poses an additional challenge of how to identify societal ‘wants’ and ‘needs’ and how to align emerging technologies accordingly.

Sustainable development represents a potential set of principles or goals towards which innovation could be directed to realise such societal alignment. However, as discussed in the introduction and throughout this thesis, a key feature of the sustainability agenda is the lack of a clear and specific definition. Its malleability is thought necessary when trying to coordinate the efforts of many actors, nations, and interests towards a common goal (Kates et al., 2005). Yet, the research presented here has demonstrated some of the problems and challenges that this lack of definition brings. While Chapter 3 demonstrated how it is possible to clarify and evaluate sustainability promises using CSA, the broad nature of the impacts can easily lead to decision paralysis. The implications of this issue were explored in Chapter 4 where we saw that ambiguity can drive cognitive challenges for innovators and preclude radical action. Without agreement at a higher level regarding what is to be sustained, what is to be developed, and how to prioritise potentially conflicting goals, developers of emerging technologies can find themselves with no clear target when it comes to the sustainability priorities of wider society. Similarly, in Chapter 5 we saw how high-level sustainability promises do not always translate into practical action at a policy level. These issues might partially explain why progress on sustainable development in its current guise remains slow, with many key indicators going in the wrong direction (UN, 2020).

In order to respond to these issues, I will integrate findings and conceptual propositions from across Chapters 2, 3, 4, and 5 of the thesis. I suggest that, in order to tackle both the dilemma of control and the dilemma of societal alignment collectively, CSA may have to be positioned within another, broader governance framework (Figure 6.4). In contrast to the CSA framework, which has been conceptually elaborated and empirically demonstrated in the thesis, this new framework is offered tentatively and provisionally, building on the findings of the thesis and some of the key challenges identified. Elaboration, testing, and refinement of the framework represents a key opportunity for further research.

At the core of this proposed framework is the idea that those pursuing technological innovation need to more clearly specify the claimed sustainability benefits of their technologies while mechanisms are also needed for citizens to more clearly specify the sustainability priorities and ‘needs’ of society (Figure 6.4, green arrows). On the left-hand side of Figure 6.4, approaches like CSA provide a mechanism through which innovators can specify (and transparently communicate) promised sustainability benefits during the formulation stage, critically evaluate them, reflect on the results and integrate them into decision-making. These processes are primarily focussed on grappling with the dilemma of control. Funders, investors, consumers, and governing authorities all have a role to play in asking the difficult questions and scrutinising innovators' sustainability claims to incentivise substantive commitments to sustainability and avoid greenwashing (Delmas & Burbano, 2012).

On the right-hand side of Figure 6.4, mechanisms could be established which enable citizens to more clearly specify their sustainability priorities so that those developing emerging technologies have something to aim at, as was suggested in Chapters 4 and 5. If this is done at too high a level then the clear specification is likely to be inhibited by needing to accommodate many different interests and worldviews, resulting in broad goals such as the Sustainable Development Goals (SDGs). Instead, I suggest that there is an important role for deliberation at the meso-level, low enough to have a reasonable chance of reaching localised consensus concerning sustainability priorities while high-enough to have legitimacy and foster collective responsibility. This could enable greater public engagement with innovation and sustainability in a manner that is both practical and useful and represents a potential means to grapple with the dilemma of societal alignment.

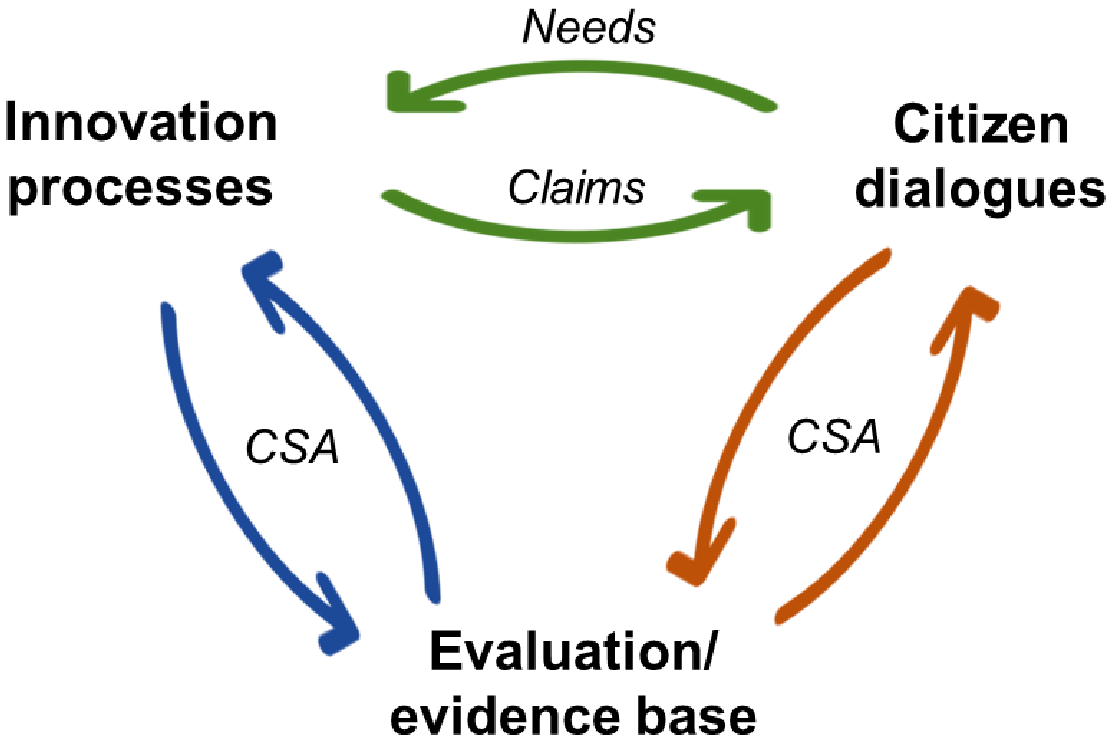

Figure 6.4: A tentative conceptual framework for an integrated response to both the dilemma of control and the dilemma of societal alignment.

Citizens assemblies, where representative groups of citizens come together in structured fora to discuss and elaborate sustainability priorities (see Climate Assembly UK, 2020), signify a promising opportunity to this effect. These could be undertaken at a national, regional, and sectoral level. The Institute for Government has suggested that the recent UK Climate Assembly could "be developed into a standing group of citizen advisers on climate change, convened by the CCC [Committee on Climate Change], which government and parliament could draw on for advice" (Sasse et al., 2020, p. 10). This model of citizen dialogue can make extensive use of the available evidence base and relevant expertise to inform but not drive the process in a manner that could be considered a form of CSA (Figure 6.3, orange arrows). This assembly model could also be used to provide guidance concerning sustainability priorities to innovators developing emerging technologies such as companies and research groups, a form of citizen-led demand-articulation (Boon & Edler, 2018).

The relative emphasis on different aspects of this model will depend on the level of consensus and clarity concerning the societal desirability of the particular sustainability impacts in question. Using the meta-responsibility approach proposed by Sonck et al. (2020) we can distinguish between two situations. Where the desired impact of innovation is clear (e.g. reducing GHG emissions), the emphasis can reasonably be on the left of Figure 6.4 - innovating with *care* to address agreed targets, as illustrated in Chapter 3. On the other hand, where there is less certainty regarding desirability, *responsiveness* should be prioritised and therefore ongoing citizen dialogues on the right of Figure 6.4 become more pertinent.

Regardless of the relative emphasis, the connection between innovation processes and citizens, represented by the green arrows in Figure 6.4, remains imperative. Greater stakeholder engagement in innovation processes is one means to provide that connection directly which could be operationalised by engaging citizens in the formulation and interpretation stages of CSA. However, respective specification of claims and needs does not always need to be undertaken directly and, as discussed in Chapters 2 and 4, such direct engagement is not always feasible. Alternatively, innovators can direct their efforts towards the findings of citizen dialogues without direct engagement. A lean start-up-inspired approach has also been proposed as means for innovation to be pursued in a manner that is responsive to the needs of citizens (see Noorman et al., 2017). This could be complemented by the mobilisation of internal stakeholders like company employees to help broaden perspectives (see Chapter 3).

More fundamentally, the governance approaches suggested here are time and resource-intensive to realise and therefore require a proactive approach from public authorities. Their potential role here is two-fold. On the one hand, they can support the establishment of citizen dialogues and assemblies and provide resources for sustainability assessment activities such as CSA. On the other hand, guided by the outputs from these dialogues and assessments, they can mediate the interaction between citizens and innovation processes by providing incentives and *tilting the landscape* in favour of more sustainable technologies (Mazzucato & Perez, 2015). Specific recommendations for how policy, business, and research might go about operationalising this are provided in section 6.3.3.

6.1.4 Probing the promises of emerging technologies

Emerging technologies such as synthetic biology are often accompanied by significant promises concerning their future potential to deliver sustainability benefits. A considerable volume of previous research has explored how such promises shape expectations and thereby the evolution of science and technology itself (Borup et al., 2006; Pollock & Williams, 2010). This thesis has drawn extensively on this work and has sought to critically evaluate the promissory rhetoric that accompanies the field of synthetic biology (Schyfter & Calvert, 2015).

One of the key messages put across in all three empirical chapters of this thesis (Chapters 3, 4, and 5) is the need for a nuanced view concerning the sustainability of emerging technologies such as synthetic biology. In particular, Chapter 3 reported the first comprehensive sustainability assessment of bio-based nylons 410 and 510 (Matthews, Cizauskas, et al., 2019).[99] In line with the growing literature on this subject (Escobar & Laibach, 2021; Ögmundarson, Herrgård, Forster, Hauschild, & Fantke, 2020), it demonstrated how synthetic biology-enabled bio-based production can provide potentially considerable savings in terms of GHG emissions but showed clear burden-shifting to many other environmental and social aspects. This has important implications for Net Zero targets which risk directing attention almost exclusively on GHG emissions.

No technology or family of technologies can be considered inherently sustainable. Rather, it is the specific way in which technologies emerge, interact with, and become embedded within society that determines their sustainability (Grunwald, 2007). Furthermore, as Chapters 4 and 5 demonstrate, it is doubtful that sustainability benefits can be relied on to emerge serendipitously. Instead, I have argued that such an approach is likely to lead to the exploration of only a narrow range of the ‘application space’ where socio-ecological performance and economic competitiveness go hand-in-hand while neglecting opportunities where there is no obvious business case (see Figure 5.4). Meanwhile, there is a risk of exploring opportunities that have economic potential but have adverse social and/or environmental consequences. This line of argument, grounded in the findings of the thesis, suggests that emerging technologies will require active governance and an appropriately supportive socio-technical landscape in order to provide the greatest chance of delivering on their sustainability promises.

Proactively constructing sustainable technologies is no easy task. However, I contend that if equivalent effort and resources to that which are presently put into creating *economically* viable technologies were also put into actively constructing *sustainable* technologies, then we would surely be able to make much greater strides towards achieving sustainable development. Practical recommendations on how to go about this are offered in the recommendations (Section 6.3).

6.2 Limitations and opportunities for further research

All research has its limitations and all knowledge claims are necessarily provisional. The limitations of this particular research have been discussed and reflected upon at various points throughout the thesis. Here, I restate and elaborate on them for clarity and outline some opportunities for further research.

In Chapter 2, the CSA framework was developed by building on the state-of-the-art across numerous domains. While I believe, as argued in Sections 6.1.2, that it represents a helpful and valid development from previous frameworks, I also acknowledge that it enters a somewhat

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[99] A recent review in *Nature Sustainability* (Ögmundarson et al., 2020) searched for articles on the subject between 2003 and 2018 and found no previous LCA studies for the key precursor 1,5-pentanediamine (referred to as cadaverine in Chapter 3). The chemicals company Evonik Industries has carried out LCAs for biobased polyamide 1010 and partially bio-based polyamide 510: https://www.vestamid.com/en/products-services/VESTAMID-terra/ecologic-benefits.

crowded intellectual landscape. There is therefore a danger of perennial reinventing of wheels, reflecting an academic system and wider society which tends to reward elaborate new ideas above the tenacious application of existing knowledge. That said, it is our role as academic researchers to continuously refresh, expand, and push the boundaries of knowledge and I aimed to do the same in developing the CSA framework. CSA contributes to a broad and growing toolkit of approaches that can help to support the responsible and proactive governance of emerging technologies towards tackling grand challenges and meeting societal wants and needs (Groves, 2017).

CSA remains in its early stages of development and would benefit from further elaboration by others bringing in new perspectives. It builds on frameworks and approaches almost uniquely developed and applied in European and North American contexts. Therefore, its transferability to other national and cultural settings cannot be assured (Postal et al., 2020). Exploring its applicability in Global South contexts represents an exciting but challenging opportunity for future research. Additionally, using systems thinking methods such as system mapping within the CSA framework could support the more integrated consideration of industrial processes, corporate actions, and societal responses (de Faria et al., 2021; A. Williams et al., 2017).

Chapter 3 reported on the first comprehensive application of the CSA approach. Many lessons were learnt during this process. I faced tensions between the need to demonstrate my capacities for independent research in pursuant of my PhD while also applying an approach that is resource-intensive and requires, by design, a transdisciplinary team. The early stage of development of SLCA methodologies, as discussed in Chapter 2, limited coverage of social aspects. While new guidelines from UNEP have recently been published (see UNEP, 2020), there remain important questions about whether social aspects can be robustly accounted for through life-cycle methods or whether a more fundamentally distinct approach should be pursued. In future, it would also be pertinent to more explicitly link CSA outputs to KPIs and pursue multiple cycles of CSA within a diversity of organisational contexts.

Co-publishing the article that underpins Chapter 3 with industry collaborators enabled a somewhat novel and insightful perspective to be offered. However, it also limited the capacity to offer an external or ‘outsider’ viewpoint. This was instead provided in Chapter 4. As an action research case study, there was a necessary prioritisation of depth over breadth in the empirical data collected. The chapter focussed particularly on the perceptions of company employees and is forthright about this, although we must of course be mindful of the subjectivity of their perspectives and their own agendas in engaging with the research (Berry, 2002). Although the views of senior managers were gathered both through interviews and other data sources (such as public interviews), access and time constraints meant that there was a potential bias towards more junior employees. An ethical and contractual responsibility to protect commercially sensitive information from the case company also limited some of the empirical data such as quotes that could be directly presented.

Chapter 5 complemented the company-specific insights reported in Chapters 3 and 4 with a more high-level policy study. It should be noted that the geographical location of the case company was the US while Chapter 5 focussed on the UK context. The synthetic biology field extends beyond national boundaries and both the UK and US are notable for their technologically advanced liberal-market economies and high levels of activity in the field (Shapira et al., 2017; Soskice & Hall, 2001). Even so, this does bring limitations for generalisability.

The chapter made considerable use of documentary evidence such as policy reports, published meeting minutes, websites, and news articles. Such data sources can provide rich insight but can also give a selective and glossy account of what happened (Bowen, 2009). To mitigate against this, triangulation was pursued through the use of multiple data sources including semi-structured interviews. However, the data collection for Chapter 5 was mostly carried out during a global pandemic. Thus, while a good number of targeted interviews were undertaken, there were additional individuals with whom I would have liked to engage with as well as events, conferences, and workshops where I would have liked to test ideas and seek constructive challenge. Finally, Chapter 5 aimed to evaluate the impact of the synthetic biology field before many of the impacts become apparent. This is defended in Chapter 5 as an important means to gain early insight, a kind of high-level midstream modulation (Fisher et al., 2006). Nonetheless, there is a strong case for ongoing analysis as the field evolves.

More broadly, the kind of research presented in this thesis, reliant on in-depth single case studies, raises questions for generalisability (Firestone, 1993; Polit & Tatano, 2010). While it may not meet the gold-standard for statistical generalisation of a randomised control trial, so-called “analytic generalisation” (Yin, 2018) has been possible by grounding and discussing the findings with reference to existing theoretical understandings. Nonetheless, caution should be practiced by any actor, whether from policy, research or practice, looking to draw generalised conclusions solely from the work in this thesis. Generalisability can be enhanced by considering the findings within the broader knowledge base which it builds upon and contributes. Accordingly, systematic reviews offer the possibility of future analytic and statistical generalisation through the integration of the findings presented here with the broader research base (Polit & Tatano, 2010). Other researchers might also draw on the insights reported in the thesis and relate them to their own work and experiences through naturalistic generalisation (Melrose, 2012). It is through the combination of these different mechanisms for generalisation where I believe that this thesis provides a substantial contribution to knowledge.

Lastly, it is worth briefly reflecting on the matter of researcher subjectivity and positionality. It is unavoidable that my values and background will have had some influence on the process and outcomes of the research. While it is not possible to completely exclude such issues, it is possible to acknowledge them and to mitigate them where possible and appropriate. This is particularly important given the normative and political nature of the sustainable development agenda (Meadowcroft, 2011). However, the underlying research problem tackled here is not sustainable development *per se*, but the desire to exert societal control over technology in order for it to better contribute to desirable ends. Thus, the main normative prescription that underlies this thesis is that it is a worthwhile endeavour to exert greater control over technology. It is rather agnostic concerning what the *ends* should be. Indeed, the ambiguous yet contested nature of sustainability has been a key focus of the analysis. Where necessary, internationally agreed agendas such as the SDGs have been used as *normative anchor points* (see von Schomberg, 2013) rather than my own personal viewpoint. This approach has helped to minimise the influence of my biases on the findings.

6.3 Recommendations

While a good number of practical and policy implications have been drawn out in the preceding chapters and the previous sections of this concluding chapter, this final section will summarise some key recommendations for researchers, policy-makers, and practitioners interested in *constructing sustainable technologies*.

6.3.1 Critically assess the sustainability of emerging technologies

The empirical chapters of the thesis demonstrated how the sustainability of emerging technologies like synthetic biology cannot be taken for granted and this was reiterated in Section 6.1.4. Therefore, to productively tackle the Collingridge dilemma, as much knowledge as possible concerning their sustainability implications needs to be gathered as early as possible to best support the emergence of sustainable technologies. As argued in Chapter 2 and demonstrated in Chapter 3, the integration of insights and methodologies from across both the natural and social sciences provides a potentially fruitful avenue to support such early-stage evidence gathering. Doing this at scale will require considerable allocation of resources but it also represents a clear public good. Therefore, there is a strong case for intervention and support from governments at multiple levels as well as supranational organisations. Meanwhile, for actors in business, research, and policy seeking to integrate sustainability considerations into what they do, there is a growing patchwork of overlapping approaches and tools to help, of which CSA is one. This provides many opportunities but also risks confusion concerning how best to proceed. Therefore, I propose the following recommendations:

1. National governments and supranational organisations should invest in continuously and responsively building the evidence base concerning the sustainability of emerging technologies. This could include greater public funding of data collection and curation efforts as well as the development of more open-source software for sustainability assessment, minimising barriers to undertaking sustainability assessments.
2. Governments should continue to invest in building key skills and competencies which are needed for understanding these complex sustainability issues. This should particularly include systems thinking given the systemic nature of many of the challenges described in this thesis (Wiek et al., 2011).
3. Researchers should continue to develop methodologies and approaches for sustainability assessment at the early stages of development by integrating insights and methods from both the natural and social sciences. Increased focus on making available accessible and open-source tools to practitioners and providing greater guidance on method selection (e.g. Chebaeva et al., 2021) should be a priority.
4. Emerging technology promoters and developers in industry and research should engage proactively in sustainability assessments. This could be achieved through expanding

existing RRI programmes to more comprehensively take sustainability into account. Even where there might not be the resources or expertise for more intensive and comprehensive assessment, considerable benefit could be gained through reflecting on potential sustainability issues at an early stage and reviewing available evidence to identify potential issues and opportunities.

6.3.2 Specify sustainability claims and needs

Through this research, it has become apparent how the vague nature of the sustainability concept poses challenges to many actors. In Chapter 4, we saw how this lack of clarity and specificity can create potential decision paralysis. In Chapter 5, we saw how ambiguity and assumed (or black-boxed) sustainability claims led to a lack of attention to it in policy implementation. Accordingly, in Section 6.1.3 I presented a framework for enabling greater specification both in terms of the sustainability claims made by promoters and developers of emerging technologies and more broadly from citizens themselves concerning what kind of sustainable society they want to live in. However, this should not be construed as placing the responsibility purely on individuals. There is a need to create the systems, spaces, and incentives that enable such specification to occur. I propose the following recommendations to achieve this:

1. Promoters of emerging technologies such as synthetic biology should specify more clearly and precisely what they expect the sustainability implications of their technologies and products to be. The formulation stage of CSA provides a potential mechanism to achieve this.
2. Influential actors within innovation systems, particularly funders and investors, should make the demonstrable potential for sustainability benefits a key factor in the evaluation of funding and investment bids. They should also encourage and support researchers and companies to pivot away from technologies that are later discovered to have less promising sustainability profiles.
3. National, regional, and local governments should convene standing groups of citizen advisors to enable greater specification of sustainability needs and relative priorities to guide and inform technological trajectories.

6.3.3 Reshape the socio-technical landscape for sustainable technologies

The need for a systems approach to understand and tackle the complex dynamics that underpin sustainability challenges is long-established (e.g. Meadows et al., 1972). Yet, in present-day attempts to address sustainability challenges, more holistic approaches are still frequently neglected in favour of the kind of technology-centric pathways discussed in Chapters 4 and 5. Such approaches fail to address more fundamental issues regarding the underlying goals, power structures, and institutions of socio-technical systems - issues that were acutely apparent in the empirical chapters of this thesis. Conversely, if appropriate changes in the socio-technical landscape could be brought about, technology-centric approaches such as the Silicon Valley model discussed in Chapter 4 could potentially be put at the service of sustainable development. Drawing on the work of many others, I recommend the following:

1. Policy-makers should recognise that the construction of sustainable technologies cannot take place in isolation and must instead be undertaken in concert with systemic interventions that tilt the socio-technical landscape in favour of the characteristics they wish to promote (Mazzucato & Perez, 2015). Activities like citizen assemblies can help to guide the direction of this ‘tilting’. There is no one-size-fits-all approach to achieve this, but some options in the context of UK synthetic biology were outlined in Chapter 5. There appears to be broad agreement in the need for both supply- and demand-side intervention to create the conditions for more sustainable technologies to thrive (Kanger et al., 2020; Mazzucato, 2016; MOIIS, 2019).
2. While researchers in the area of sustainability transitions must avoid being overly prescriptive concerning the political aspects of sustainable development (Meadowcroft, 2011), they can and should continue to offer insight and critique where the present and proposed approaches taken by policy-makers and other actors such as businesses are inconsistent with their stated aims. An example of such a critique was provided in Chapter 5.
3. All individuals can play a role in supporting, facilitating and driving system change whether in their roles as consumers, policy-makers, researchers, business leaders and employees, or citizens in democratic societies. We can do so by focussing on where we have influence through our connections to other actors and by concentrating on “leverage points” (see Meadows, 1999).

6.3.4 New needs and prospects for change

Exploring the empirical case of synthetic biology, this research has sought to understand how we might better control our technology in support of sustainable development. In response, the CSA framework has been put forward as a means to proactively grapple with the sustainability implications of emerging technologies. Furthermore, the findings have highlighted the need for significant changes in policy and governance if new technologies are to be aligned with sustainability. When I commenced this thesis in 2017, such developments seemed highly unlikely to emerge. Yet, the COVID-19 pandemic has clearly shown that societies are capable of undertaking and weathering rapid change while also demonstrating the lack of sustainability and resilience in existing globalised supply chains (Gölgeci et al., 2020; Miroudot, 2020). This raises the possibility of a post-COVID world with greater public support for radical sustainability transitions (see Climate Assembly UK, 2020) and national governments that are prepared to implement more interventionist industrial strategies to rebuild their economies sustainably (e.g. HM Government, 2020). Consequently, while far from inevitable, there is a potential opening for an accelerated transition to more sustainable production and consumption systems (Boons et al., 2020). The next few years represent a critical opportunity to truly embed sustainability considerations in the governance of emerging technologies. Never before has *constructing sustainable technologies* been so important.

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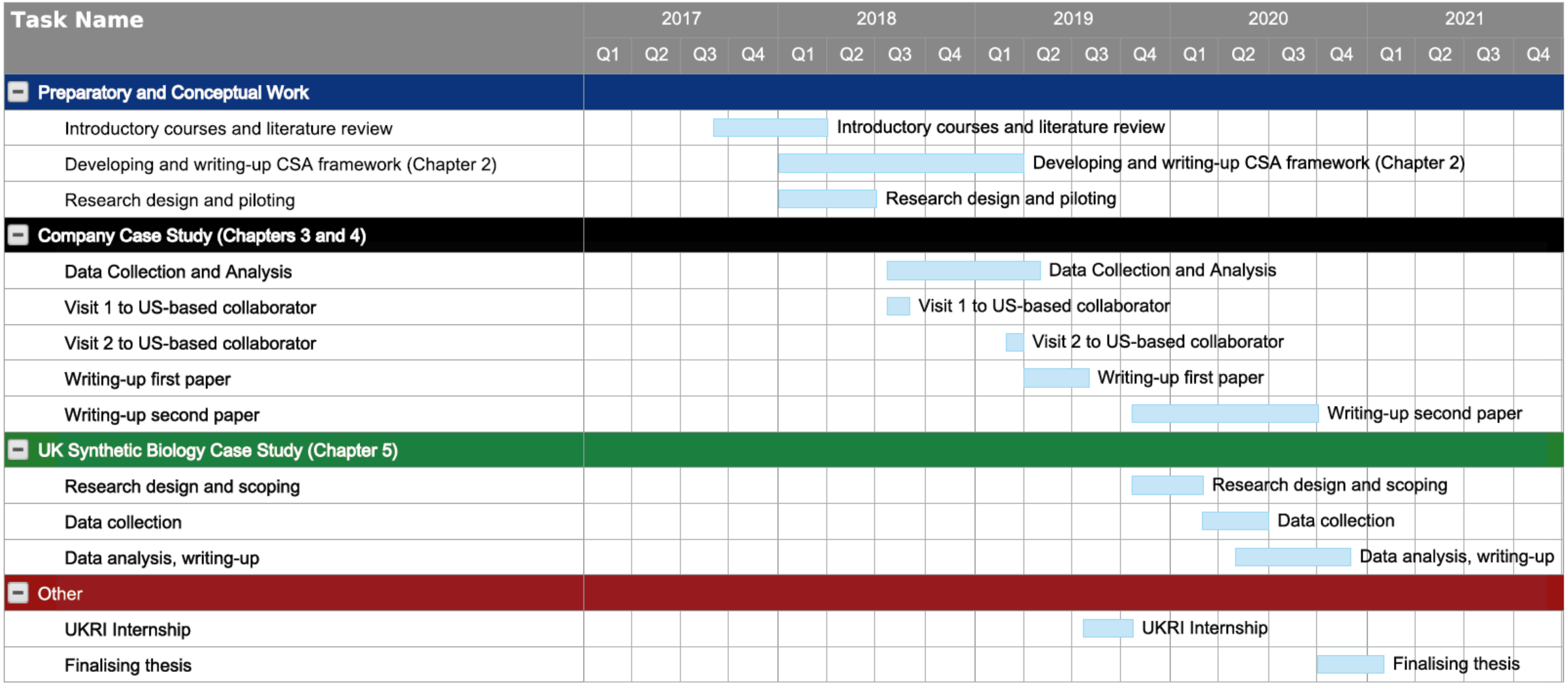
Appendix A: Additional information for Chapter 1

Appendix A.1: A Gantt Chart summarising the research process



Appendix A.2: Table of engagement and data collection activities.

This table does not include the collection of documentary evidence or the use of analytical methods such as LCA.

Date	Activity	Description	Participants/role	No. of Participants	Approx. Duration	Associated Study	Data collected
Nov-17	Poster	Presentation of CSA approach at the Manchester Institute of Innovation Research 50th Anniversary	Business school researchers	N/A	N/A	CSA framework	Verbal feedback
Feb-18	Progression review	1st year mid-year review	Supervisory team	2	1 hour	Overall thesis approach	Verbal feedback
Apr-18	Poster	Presentation of CSA approach at the SynBioChem symposium	SynBioChem symposium attendees	N/A	N/A	CSA framework	Verbal feedback
Jun-18	Poster	Presentation of CSA approach at the University of Manchester Postgraduate Summer Research Showcase	University of Manchester Researchers	N/A	N/A	CSA framework	Verbal feedback
Jul-18	Progression review	1st year annual review	Supervisory team and independent reviewer	3	1 hour	Overall thesis approach	Verbal feedback
Aug-18	Presentation	Invited seminar presenting the proposed CSA approach at the Joint Bioenergy Institute, Emeryville, CA	Joint Bioenergy Institute researchers	~7	1 hour	CSA framework	Verbal feedback
Aug-18	Survey	Survey of case company employees to inform formulation stage of CSA	Case company employees	153	NA	Company case	Survey Results
Aug-18	Workshop	CSA formulation workshop with case company development team	Case company development team	4	1 hour	Company Case	Notes, wordcloud
Aug-18	Workshop	CSA formulation workshop with case company legal team	Case company legal team	4	1 hour	Company Case	Notes, wordcloud
Aug-18	Workshop	CSA formulation workshop with case company business development team	Case company business development team	8	1 hour	Company Case	Notes, wordcloud
Aug-18	Workshop	CSA formulation workshop with case company manufacturing team	Case company manufacturing team	4	1 hour	Company Case	Notes, wordcloud
Oct-18	Presentation	Presentation of CSA approach at the International Sustainable Production and Consumption Conference	Sustainability researchers	~20	1 hour	CSA framework	Verbal feedback
Jan-19	Progression review	2nd year mid-year review	Supervisory team	2	1 hour	Overall thesis approach	Verbal feedback
Mar-19	Interview	Interview about company case study and CSA approach	Head of modelling, case company	1	30 minutes	Company Case	Notes

Appendix A.2 (cont.): Table of engagement and data collection activities.

Date	Activity	Description	Participants/role	No. of Participants	Approx. Duration	Associated Study	Data collected
Mar-19	Interview	Interview about company case study and CSA approach	Projects team lead, case company	1	30 minutes	Company Case	Notes
Mar-19	Interview	Interview about company case study and CSA approach	Member of the senior leadership team, case company	1	30 minutes	Company Case	Notes
Mar-19	Interview	Interview about company case study and CSA approach	Materials development, case company	1	30 minutes	Company Case	Notes
Mar-19	Interview	Interview about company case study and CSA approach	Manager of projects, case company	1	30 minutes	Company Case	Notes
Mar-19	Interview	Interview about company case study and CSA approach	Business development, case company	1	30 minutes	Company Case	Notes
Mar-19	Interview	Interview about company case study and CSA approach	Materials and chemical development, case company	1	30 minutes	Company Case	Notes
Mar-19	Poster	Presentation of CSA approach at the SynBioChem symposium	SynBioChem symposium attendees	N/A	N/A	CSA framework	Verbal feedback
Mar-19	Presentation	Presentation of results from company case (constructive sustainability assessment of bio-based nylon)	Case company employees	~40	1 hour	Company case	Verbal feedback
Mar-19	Survey	Survey of case company employees to inform interpretation stage of CSA and provide feedback on CSA approach and applicability	Case company employees	54	NA	Company case	Survey Results
Mar-19	Workshop	CSA interpretation workshop with case company development team	Case company development team	5	1 hour	Company Case	Notes
Mar-19	Workshop	CSA interpretation workshop with case company legal team	Case company legal team	6	1 hour	Company Case	Notes
Mar-19	Workshop	CSA interpretation workshop with case company business development team	Case company business development team	5	1 hour	Company Case	Notes
Mar-19	Workshop	CSA interpretation workshop with case company modelling team	Case company modelling team	6	1 hour	Company Case	Notes
Mar-19	Workshop	CSA interpretation workshop with case company products team	Case company products team	5	1 hour	Company Case	Notes
Mar-19	Workshop	CSA interpretation workshop with case company manufacturing team	Case company manufacturing team	5	1 hour	Company Case	Notes

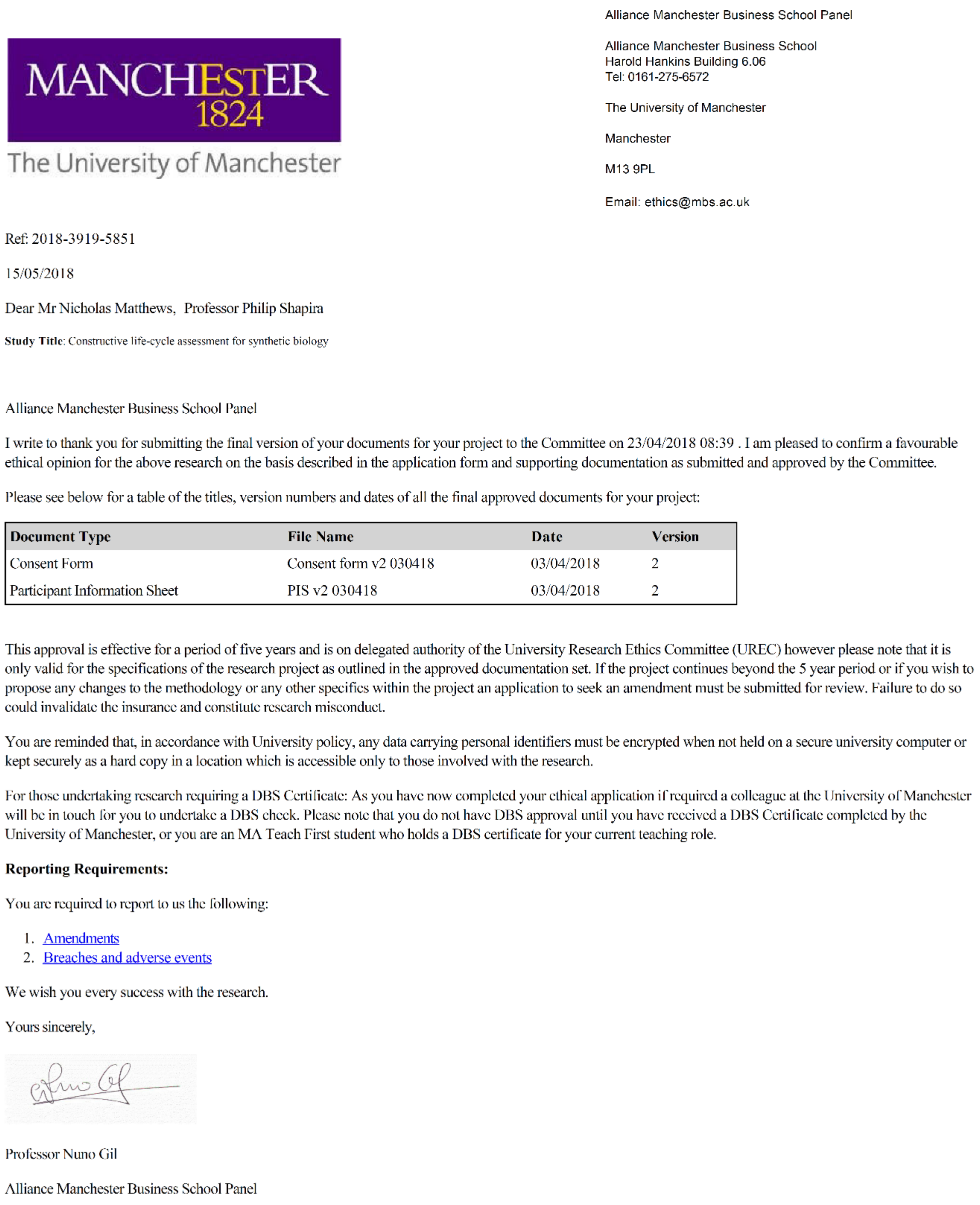
Appendix A.2 (cont.): Table of engagement and data collection activities.

Date	Activity	Description	Participants/role	No. of Participants	Approx. Duration	Associated Study	Data collected
Apr-19	Presentation	Presentation of final company case results to Sustainable Industrial Systems group meeting	UoM SIS group members - LCA experts	9	1.5 hours	Company Case	Verbal feedback
May-19	Presentation	Alliance Manchester Business School Doctoral conference	Business school researchers	~15	15 minutes	CSA framework	Verbal feedback
Jul-19	Progression review	2nd year annual review	Supervisory team and independent reviewer	4	1 hour	Overall thesis approach	Verbal feedback
Sep-19	Presentation	ASSIST-UK Conference 2019	Science Technology and Innovation Studies researchers	~10	20 minutes	CSA framework	Verbal feedback
Dec-19	Presentation	Presentation of initial company case results to Sustainable Industrial Systems group meeting	UoM SIS group members - LCA experts	~9	1.5 hours	Company Case	Verbal feedback
Jan-20	Progression review	3rd year mid-year review	Supervisory team	2	1 hour	Overall thesis approach	Verbal feedback
Feb-20	Presentation	Presentation of company case results and CSA approach at the AAAS 2020 general meeting	AAAS 2020 general meeting attendees	~30	20 minutes	Company case and CSA approach	Verbal feedback
Apr-20	Interview	Interview about the role of sustainability in UK synthetic biology	Employee of a national research funder	1	1 hour	UK Synthetic Biology case	Notes
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Leading synthetic biology academic	1	1 hour	UK Synthetic Biology case	Notes, transcript
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Member of Synthetic Biology Leadership Council Governance sub-group	1	1 hour	UK Synthetic Biology case	Notes, transcript
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Senior manager at a Synthetic Biology company	1	1 hour	UK Synthetic Biology case	Notes, transcript
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Managing director of a pharmaceutical company	1	30 minutes	UK Synthetic Biology case	Notes, transcript
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Member of 2012 Synthetic Biology Roadmap Steering Group	1	1 hour	UK Synthetic Biology case	Notes, transcript
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Employee of a knowledge transfer organisation with responsibility for synthetic biology	1	1 hour	UK Synthetic Biology case	Notes

Appendix A.2 (cont.): Table of engagement and data collection activities.

Date	Activity	Description	Participants/role	No. of Participants	Approx. Duration	Associated Study	Data collected
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Employee of a knowledge transfer organisation with responsibility for synthetic biology	1	1 hour	UK Synthetic Biology case	Notes
May-20	Interview	Interview about the role of sustainability in UK synthetic biology	Employee of a relevant industry association	1	1 hour	UK Synthetic Biology case	Notes, transcript
Jun-20	Interview	Interview about the role of sustainability in UK synthetic biology	Investment director with responsibility for synthetic biology	1	1 hour	UK Synthetic Biology case	Notes, transcript
Jun-20	Progression review	3rd year annual review	Supervisory team and independent reviewer	3	1 hour	Overall thesis approach	Verbal feedback
Oct-20	Poster	Presentation of initial UK Synthetic Biology case results at SynbiTECH 2020 Conference	SynbiTECH 2020 attendees	N/A	N/A	UK Synthetic Biology case	Verbal feedback

Appendix A.3: Pre-GDPR ethical approval confirmation



Alliance Manchester Business School Panel

Alliance Manchester Business School
Harold Hankins Building 6.06
Tel: 0161-275-6572

The University of Manchester

Manchester

M13 9PL

Email: ethics@mbs.ac.uk

Ref: 2018-3919-5851

15/05/2018

Dear Mr Nicholas Matthews, Professor Philip Shapira

Study Title: Constructive life-cycle assessment for synthetic biology

Alliance Manchester Business School Panel

I write to thank you for submitting the final version of your documents for your project to the Committee on 23/04/2018 08:39 . I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation as submitted and approved by the Committee.

Please see below for a table of the titles, version numbers and dates of all the final approved documents for your project:

Document Type	File Name	Date	Version
Consent Form	Consent form v2 030418	03/04/2018	2
Participant Information Sheet	PIS v2 030418	03/04/2018	2

This approval is effective for a period of five years and is on delegated authority of the University Research Ethics Committee (UREC) however please note that it is only valid for the specifications of the research project as outlined in the approved documentation set. If the project continues beyond the 5 year period or if you wish to propose any changes to the methodology or any other specifics within the project an application to seek an amendment must be submitted for review. Failure to do so could invalidate the insurance and constitute research misconduct.

You are reminded that, in accordance with University policy, any data carrying personal identifiers must be encrypted when not held on a secure university computer or kept securely as a hard copy in a location which is accessible only to those involved with the research.

For those undertaking research requiring a DBS Certificate: As you have now completed your ethical application if required a colleague at the University of Manchester will be in touch for you to undertake a DBS check. Please note that you do not have DBS approval until you have received a DBS Certificate completed by the University of Manchester, or you are an MA Teach First student who holds a DBS certificate for your current teaching role.

Reporting Requirements:

You are required to report to us the following:

1. Amendments
2. Breaches and adverse events

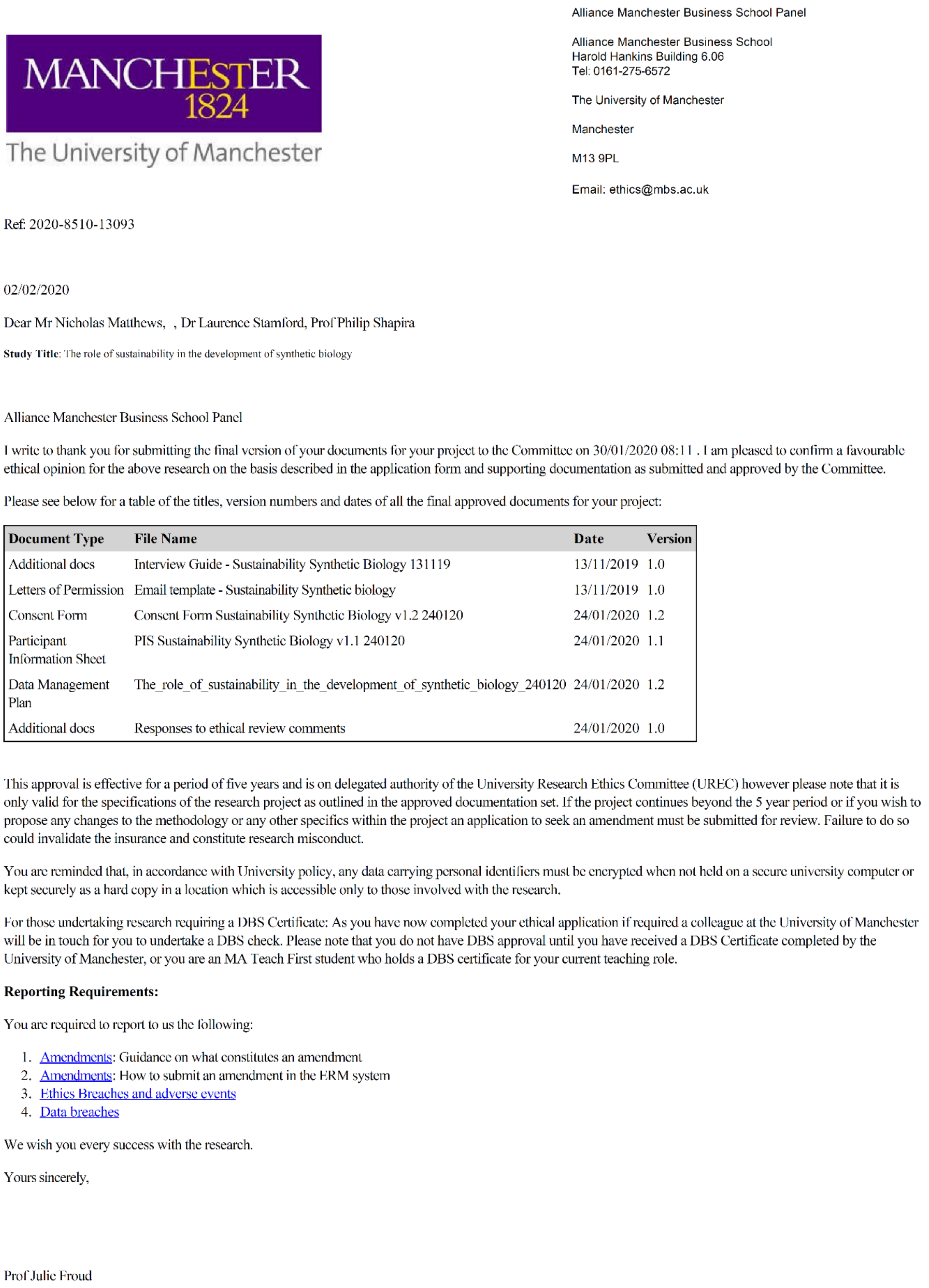
We wish you every success with the research.

Yours sincerely,

Professor Nuno Gil

Alliance Manchester Business School Panel

Appendix A.4: Post-GDPR ethical approval confirmation



Alliance Manchester Business School Panel

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The University of Manchester

Manchester

M13 9PL

Email: ethics@mbs.ac.uk

Ref: 2020-8510-13093

02/02/2020

Dear Mr Nicholas Matthews, , Dr Laurence Stamford, Prof Philip Shapira

Study Title: The role of sustainability in the development of synthetic biology

Alliance Manchester Business School Panel

I write to thank you for submitting the final version of your documents for your project to the Committee on 30/01/2020 08:11 . I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form and supporting documentation as submitted and approved by the Committee.

Please see below for a table of the titles, version numbers and dates of all the final approved documents for your project:

Document Type	File Name	Date	Version
Additional docs	Interview Guide - Sustainability Synthetic Biology 131119	13/11/2019	1.0
Letters of Permission	Email template - Sustainability Synthetic biology	13/11/2019	1.0
Consent Form	Consent Form Sustainability Synthetic Biology v1.2 240120	24/01/2020	1.2
Participant Information Sheet	PIS Sustainability Synthetic Biology v1.1 240120	24/01/2020	1.1
Data Management Plan	The_role_of_sustainability_in_the_development_of_synthetic_biology_240120	24/01/2020	1.2
Additional docs	Responses to ethical review comments	24/01/2020	1.0

This approval is effective for a period of five years and is on delegated authority of the University Research Ethics Committee (UREC) however please note that it is only valid for the specifications of the research project as outlined in the approved documentation set. If the project continues beyond the 5 year period or if you wish to propose any changes to the methodology or any other specifics within the project an application to seek an amendment must be submitted for review. Failure to do so could invalidate the insurance and constitute research misconduct.

You are reminded that, in accordance with University policy, any data carrying personal identifiers must be encrypted when not held on a secure university computer or kept securely as a hard copy in a location which is accessible only to those involved with the research.

For those undertaking research requiring a DBS Certificate: As you have now completed your ethical application if required a colleague at the University of Manchester will be in touch for you to undertake a DBS check. Please note that you do not have DBS approval until you have received a DBS Certificate completed by the University of Manchester, or you are an MA Teach First student who holds a DBS certificate for your current teaching role.

Reporting Requirements:

You are required to report to us the following:

1. Amendments: Guidance on what constitutes an amendment
2. Amendments: How to submit an amendment in the ERM system
3. Ethics Breaches and adverse events
4. Data breaches

We wish you every success with the research.

Yours sincerely,

Prof Julie Froud

Appendix B: Additional information for Chapter 3

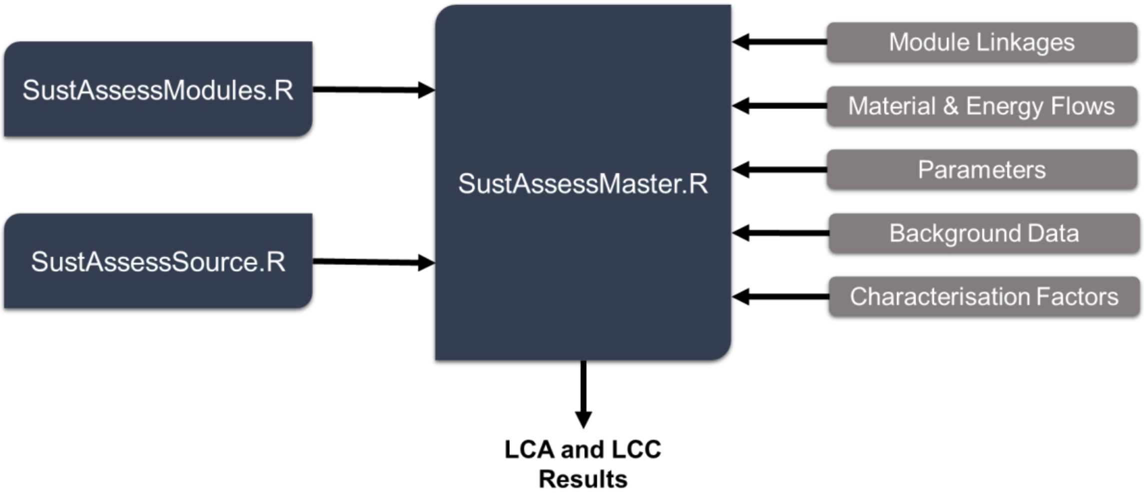

Figure B.1: Program structure for SustAssessR (Matthews, 2019).

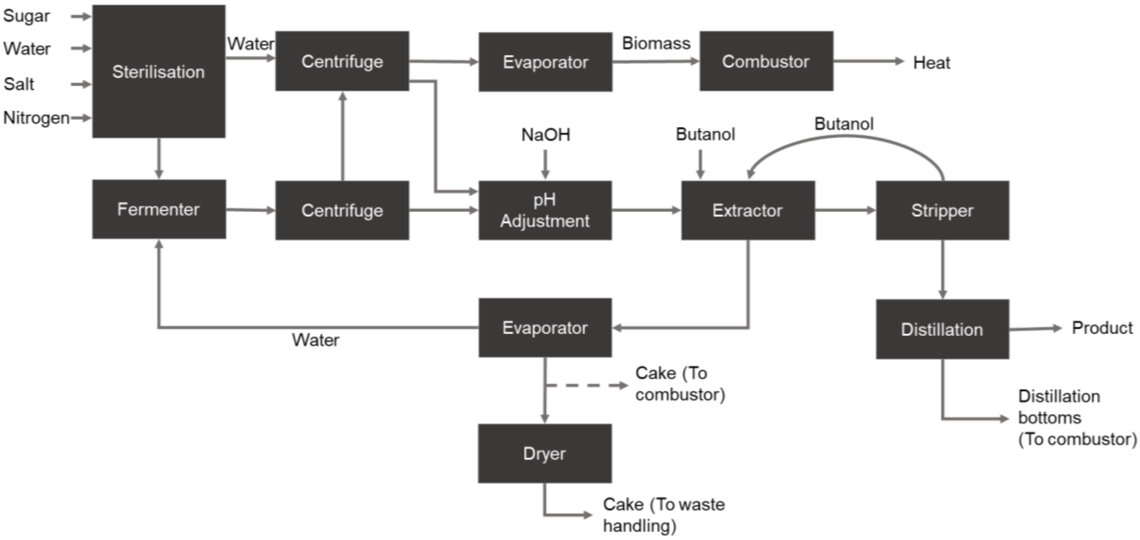

Figure B.2: Process model for cadaverine and putrescine production (adapted from Kind and Wittman, 2011).

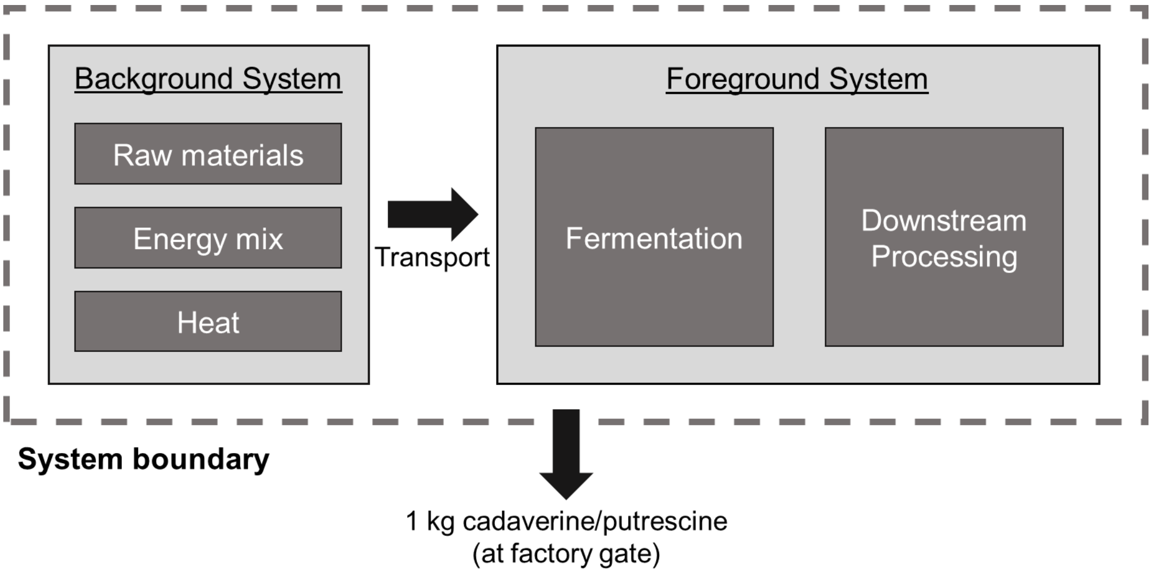

Figure B.3: System boundary for monomer production.

Total capital investment (TCI) = biorefinery cost * ((# of fermenters/10) ^ scaling exponent (capital))

Raw materials = process model flows * prices

Utilities = process model flows * prices

Waste = process model flows * prices

Total labour = labour cost * ((# of fermenters/10) ^ scaling exponent (labour))

Maintenance = TCI * maintenance rate

Tax = TCI * tax rate

R&D and marketing costs = (total labour + tax + maintenance) * R&D and marketing rate

Overheads = total labour* overheads rate

Other fixed operating costs = maintenance + tax + R&D and marketing + overheads

Figure B.4: A summary of the methodology for calculating total biorefinery costs.

Table B.1: Deliberative engagement activities undertaken.

Date	Activity	CSA Stage	Participants	Number of Participants	Duration	Data collected
August 2018	Workshop	Formulation	Development team	4	1 hour	Notes, wordcloud responses
August 2018	Workshop	Formulation	Legal team	4	1 hour	Notes, wordcloud responses
August 2018	Workshop	Formulation	Business development team	8	1 hour	Notes, wordcloud responses
August 2018	Workshop	Formulation	Manufacturing team	4	1 hour	Notes, wordcloud responses
August 2018	Survey	Formulation	Company employees	137	N/A	Survey responses
March 2019	Workshop	Interpretation	Development team	5	1 hour	Notes
March 2019	Workshop	Interpretation	Legal team	6	1 hour	Notes
March 2019	Workshop	Interpretation	Business development team	5	1 hour	Notes
March 2019	Workshop	Interpretation	Modelling team	6	1 hour	Notes
March 2019	Workshop	Interpretation	Products team	5	1 hour	Notes
March 2019	Workshop	Interpretation	Manufacturing team	5	1 hour	Notes
August 2018	Survey	Interpretation	Company employees	54	N/A	Survey responses

Table B.2: Parameterisations used to generate the process model. Further details and full citations are provided in the Methods (Chapter 3).

Parameter	Value	Min	Max	Distribution	Units	Source	Uncertainty Source
Energy Sterilisation	0.1	0.1	0.1	Triangular	kg/kg	Patel et al. 2006	Patel et al. 2006
Energy Agitation Aeration	3	1	5	Triangular	kwh/m3	Patel et al. 2006	Patel et al. 2006
Energy Centrifugation	7	3.5	16	Triangular	kwh/m3	Patel et al. 2006	Patel et al. 2006
Drying Steam	1.5	0.95	1.67	Triangular	kg/kg	Patel et al. 2006	Patel et al. 2006
Evaporation Triple Effect (Steam)	0.4	0.3	0.5	Triangular	kg/kg	Patel et al. 2006	Patel et al. 2006
Water Content Biomass	1.5	1.5	1.5	None	kg/kg	Davis et al. 2013	N/A
Water Content Waste	0.3	0.3	0.3	None	kg/kg	Ecoinvent v3.3	N/A
Biomass to Heat	14.32	7.16	14.32	Triangular	MJ/kg	Ecoinvent v3.3	Default
Annual operating time	7900	7900	7900	None	hours	Industry standard	N/A
Down time	12	6	24	Triangular	hours	Assumed	Default
Solvent required	0.1	0.05	0.2	Triangular	kg/kg	Krzyzaniak et al. 2013	Default
Solvent loss rate	1	0.5	2	Triangular	% per cycle	Assumed	Default
Distillation efficiency	23.8	11.9	47.6	Triangular	%	Cavaletto 2013	Default
Polymerisation electricity	2.7	2.7	5.4	Triangular	MJ/kg	Plastics Europe 2014	Default
Polymerisation heat	6.6	6.6	13.2	Triangular	MJ/kg	Plastics Europe 2014	Default
Polymerisation transport	0.2	0.1	0.4	Triangular	tkm/kg	Assumed	Default

Table B.3: Background data sources used in the environmental assessment.

Background Data	Data source	Dataset name	Geographic specificity	Used in
Electricity - grid	Ecoinvent v3.3	Market for electricity, medium voltage	BR/FR/US	General
Electricity - biomass	Ecoinvent v3.3	Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 014	BR/FR/US	General
Heat - grid	Ecoinvent v3.3	Steam production in chemical industry	RoW	General
Heat - biomass	Ecoinvent v3.3	Heat and power co-generation, wood chips, 6667 kW, state-of-the-art 014	BR/FR/US	General
Waste treatment	Ecoinvent v3.3	Treatment of municipal solid waste, incineration	RoW	General
Combustion	Ecoinvent v3.3	Heat production, softwood chips from forest, at furnace 5000kW, state-of-the-art 2014	CH (with GLO background data)	General
Water	Ecoinvent v3.3	Market for water, decarbonised, at user	GLO	General
Sodium Hydroxide	Ecoinvent v3.3	Market for sodium hydroxide, without water, in 50% solution state	GLO	pH adjustment, corn stover processing
Sodium Chloride	Ecoinvent v3.3	Market for sodium chloride, powder	GLO	Fermenter
Ammonium Sulfate	Ecoinvent v3.3	Market for ammonium sulfate, a N	GLO	Fermenter, corn stover processing
Butanol	Ecoinvent v3.3	Market for 1-butanol	GLO	Extraction
Corn Steep Liquor	USLCI	Corn steep liqour	RNA	Corn stover processing
SO2	Ecoinvent v3.3	Market for sulfur dioxide	RoW	Corn stover processing
Soybean Oil	Ecoinvent v3.3	Market for soybean oil, refined	GLO	Corn stover processing
Ammonia	Ecoinvent v3.3	Market for ammonia, liquid	RoW	Corn stover processing
Lime	Ecoinvent v3.3	Market for lime	GLO	Corn stover processing
Sulfuric Acid	Ecoinvent v3.3	Market for sulfuric acid	GLO	Corn stover processing
Fermentation plant	Ecoinvent v3.3	Market for ethanol fermentation plant	GLO	General
Transport	Ecoinvent v3.3	Market for transport, freight, lorry, unspecified	GLO	Polymerisation

Table B.4: Feedstock scenarios and their corresponding LCI data sources for agricultural production and processing to sugar.

Feedstock Scenario	Location	Raw Feedstock	Sugar	Agricultural data	Processing data
BR Sugarcane	Brazil	Sugarcane	Sucrose	Ecoinvent v3.3	Ecoinvent v3.3
FR Sugar Beet	France	Sugar beets	Sucrose	Ecoinvent v3.3	Ecoinvent v3.3
US Corn	United States	Corn starch	Glucose	US LCI/NREL	Renouf et al. 2008
US Ligno	United States	Corn stover	Glucose and Xylose	US LCI/NREL	NREL

Table B.5: LCI table of inputs for 1kg sugar production from harvested corn. Figures derived from Renouf et al. (2008).

Input	Amount	Unit	Data Source (Ecoinvent v3.3)
Corn	1.50E+00	kg	RNA: Corn, production, average, US, 2022
Electricity	9.34E-01	MJ	US: market group for electricity, medium voltage
Natural Gas	1.66E-01	m3	US: market for natural gas, high pressure
Chlorine	1.20E-05	kg	GLO: market for chlorine, liquid
Cyclohexane	5.50E-05	kg	GLO: market for cyclohexane
Lime	3.00E-04	kg	GLO: market for lime
Sodium chloride	6.50E-05	kg	GLO: market for sodium chloride, powder
Sodium hydroxide	2.82E-04	kg	GLO: market for sodium hydroxide, without water, in 50% solution state
Sulfur dioxide	3.06E-03	kg	RoW: market for sulfur dioxide, liquid
Sulfuric acid	4.50E-04	kg	GLO: market for sulfuric acid
Urea	2.08E-04	kg	GLO: market for urea, as N

Table B.6: LCI for processing of corn stover to sugar (glucose and xylose). Figures derived from two different NREL studies using a consistent base model. Background data sources are outlined in Table B.2.

Inputs	Amount	Units	Source
Corn Stover	1.04E+05	kg	NREL 2017 Biochemical Sugar Model
Sulfuric Acid	2.24E+03	kg	NREL 2017 Biochemical Sugar Model
NaOH	1.42E+03	kg	NREL 2017 Biochemical Sugar Model
Ammonia	6.82E+02	kg	NREL 2017 Biochemical Sugar Model
Glucose	1.21E+03	kg	NREL 2017 Biochemical Sugar Model
Corn Steep Liqour	8.20E+01	kg	NREL 2017 Biochemical Sugar Model
Corn Oil (Modelled as soybean oil)	7.00E+00	kg	NREL 2017 Biochemical Sugar Model
Water	1.99E+05	kg	NREL 2017 Biochemical Sugar Model
Lime	1.51E+02	kg	NREL 2017 Biochemical Sugar Model
SO2	8.00E+00	kg	NREL 2017 Biochemical Sugar Model
Host Nutrients (Ammonium Sulfate)	3.40E+01	kg	NREL 2017 Biochemical Sugar Model
Outputs			
Glucose	3.03E+04	kg	Davis et al. 2015
Xylose	1.67E+04	kg	Davis et al. 2015
Ash	4.46E+03	kg	NREL 2017 Biochemical Sugar Model
Electricity	1.41E+04	kWh	NREL 2017 Biochemical Sugar Model
Emissions			
Carbon Dioxide	7.47E+04	kg	Davis et al. 2015
Methane	1.60E+00	kg	Davis et al. 2015
Nitrogen dioxide	5.30E+01	kg	Davis et al. 2015
Carbon monoxide	5.30E+01	kg	Davis et al. 2015
Sulfur dioxide	1.10E+01	kg	Davis et al. 2015

Table B.7: Nylon types considered in analysis and their corresponding data sources.

Nylon Type	Diamine		Dicarboxylic Acid	
	Name	LCI Data Source	Name	LCI Data Source
Nylon 6,6	HMDA	Dros et al. 2015	Adipic acid	Ecoinvent v3.3
Nylon 4,6	Putrescine	This study	Adipic acid	Ecoinvent v3.3
Nylon 4,10	Putrescine	This study	Sebacic acid	thinkstep
Nylon 5,10	Cadaverine	This study	Sebacic acid	thinkstep

Table B.8: Life-cycle inventory for 1kg HMDA production. Associated Ecoinvent v3.3 dataset used for background data is indicated. Data marked with a * denotes cut-off flows which were not modelled. Figures derived from Dros et al. (2015).

Input	Amount	Units	Data source (Ecoinvent v3.3)
HCN	5.43E-01	kg/kg	GLO: market for hydrogen cyanide
Butadiene	5.45E-01	kg/kg	GLO: market for butadiene
NH3	1.75E-03	kg/kg	RoW: market for ammonia, liquid
Steam	8.46E+00	kg/kg	GLO: market for steam, in chemical industry
Electricity	4.60E-01	kwh/kg	GLO: market group for electricity, medium voltage
Fe-catalyst*	6.00E+00	g/kg	N/A
Hydrogen	6.70E-02	kg/kg	RoW: market for hydrogen, liquid
Sodium bisulfite*	1.09E-01	kg/kg	N/A
Sodium sulfite	6.70E-02	kg/kg	GLO: market for sodium sulfite
Process water	1.23E+00	kg/kg	GLO: market for water, decarbonised, at user
Inert gas*	1.00E-02	L/kg	N/A
Cooling water*	2.72E-01	m3/kg	N/A

Table B.9: Modelling parameters and assumptions used for the costings model. Further details and full citations are provided in the Methods of Chapter 3.

Name	Distribution	Units	Mode	Min	Max	Source
Tax Rate	Uniform	%	N/A	0.7	3.0	Davis et al. 2015 (Min) Gargalo et al. 2016 (Max)
Maintenance Rate	Uniform	%	N/A	3.0	6.0	Davis et al. 2015 (Min) Gargalo et al. 2016 (Max)
R&D and Marketing Costs	Triangular	%	6.0%	3.0	12.0	Patel et al. 2006 (Mode) Default uncertainty
Overheads Rate	Uniform	%	N/A	60.0	90.0	Gargalo et al. 2016 (Min) Davis et al. 2015 (Max)
Interest Rate	Triangular	%	8.0	4.0	16.0	Davis et al. 2015 (Mode) Default uncertainty
Income Tax Rate	none	%	35.0	N/A	N/A	Davis et al. 2015
Labour Scaling Factor	none	exponent	0.25	N/A	N/A	Patel et al. 2006
Capital Scaling Factor	none	exponent	0.836	N/A	N/A	Gallagher et al. 2006
Discount Rate	Uniform	%	N/A	10.0	24.0	Davis et al. 2015 (Min) Gargalo et al. 2016 (Max)
Project Timespan	Uniform	years	N/A	10	30	Davis et al. 2015 (Max) Sensitivity case (Min)
Loan Repayment Period	none	years	10	N/A	N/A	Davis et al. 2015

Table B.10: Decision hierarchy for determining distributions for prices and costs.

Grade	Modal Value	Uncertainty range
1st (Best)	Average from historic price trend or literature figure	Historic price trend (specific) or literature figure
2nd	Estimate from literature/industry	Historic price trend (generic, US Government)
3rd	Estimate from literature/industry	Historic price trend (generic, Index Mundi)
4th (Worst)	Estimate from literature	Generic estimate (double and half)

Table B.11: A summary of price parameterisations used for the costings model.

Parameter	Distribution	Value	Min	Max	Units	Figure Source	Uncertainty Source	Grade
Sugar	Triangular	0.37	0.20	0.65	$/kg	Sugar #11[1]	Sugar #11[1]	1st
Lignocellulosic Sugar	Triangular	0.41	0.20	0.81	$/kg	NREL[2]	Default	4th
Butanol	Triangular	1.56	0.97	2.20	$/kg	Gargalo et al. 2016	Gargalo et al. 2016	1st
Salt	Triangular	0.06	0.04	0.09	$/kg	USGS[3]	IndexMundi[4]	3rd
Ammonium Sulfate	Triangular	0.59	0.42	0.66	$/kg	USDA[5]	USDA[5]	1st
Ammonium Nitrate	Triangular	0.62	0.44	0.69	$/kg	USDA[5]	USDA[5]	1st
Corn Steep Liqour	Triangular	0.08	0.05	0.08	$/kg	Davis et al. 2015	USDA[5]	2nd
Sodium Hydroxide	Triangular	0.20	0.14	0.22	$/kg	Davis et al. 2015	IndexMundi[4]	3rd
Electricity	Triangular	0.07	0.06	0.07	$/kWh	EIA[7]	EIA[7]	1st
Steam	Triangular	0.44	0.15	0.64	¢/kg	Gargalo et al. 2016	IndexMundi[8]	3rd
Water	Triangular	0.05	0.03	0.07	¢/kg	Gargalo et al. 2016	IndexMundi[4]	3rd
Wastewater treatment	Triangular	0.05	0.03	0.11	¢/kg	Gargalo et al. 2016	Default	4th
Waste management	Triangular	0.04	0.02	0.07	$/kg	Gargalo et al. 2016	Default	4th
Capital Cost of Plant	Triangular	370.28	185.14	740.56	m$	Tsagkari et al. 2016	Default	4th
Labour Cost	Triangular	3.66	1.83	7.32	m$/yr	Davis et al. 2015	Default	4th

[1] *https://www.indexmundi.com/commodities/?commodity=sugar&months=120*
[2] *https://www.nrel.gov/extranet/biorefinery/aspen-models/downloads/bc1707a/sugar-model-readme.pdf*
[3] *https://minerals.usgs.gov/minerals/pubs/commodity/salt/mcs-2015-salt.pdf*
[4] *https://www.indexmundi.com/commodities/?commodity=industrial-inputs-price-index&months=120*
[5] *https://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx*
[7] *https://www.eia.gov/electricity/data.php*
[8] *https://www.indexmundi.com/commodities/?commodity=energy-price-index&months=180*

Table B.12: Company employee views on the relative influence of different information sources. Table shows a summary of answers given to the question: “How might the following sources of information influence your perspective of the sustainability of a product?” (n=137)

Influence	Modelling data	Real-world data	Experts	Impacted stakeholders	Civil society organisations	Government resources
Not influential at all	2.19%	0.00%	1.46%	12.41%	7.30%	5.11%
Slightly influential	40.15%	6.57%	10.95%	38.69%	40.88%	37.96%
Quite influential	46.72%	31.39%	59.85%	27.01%	44.53%	43.80%
Very influential	10.95%	62.04%	27.74%	21.90%	7.30%	13.14%

Table B.13: Relative prioritisation of sustainability aspects by company employees. A summary of different sustainability aspects and their associated average score given in survey responses to the question: “In your opinion please score the following aspects of sustainability as to how significant they are for the biotechnology sector” (n=153). The relevant SDGs for each aspect are also listed.

Sustainability Aspect	Average Score (1-5)	Relevant SDGs
Tackling climate change	4.17	15
Improving the health of global ecosystems	4.16	13, 14
Promoting equality, peace, and justice	2.99	4, 5, 10, 16
Eliminating poverty, hunger, and poor-health	3.90	1, 2, 3, 6, 7
Sustaining employment and economic growth	3.79	8, 9, 11

Table B.14: The CSS used to identify potential social hotspots for each of the four production scenarios analysed in the study.

Production Scenario	CSS Feedstock	CSS Biorefinery
BR Sugarcane	Sugar cane, sugar beet	Chemical, rubber, plastic products
FR Sugar Beet	Sugar cane, sugar beet	Chemical, rubber, plastic products
US Corn	Cereal grains nec	Chemical, rubber, plastic products
US Ligno	Cereal grains nec	Chemical, rubber, plastic products

Table B.15: Selected individual indicator results for social category “Health & Safety”. Figures derived from the SHDB.

Social Theme	Indicator	Brazil chemicals	Brazil sugarcane	France chemicals	France sugar beet	US chemicals	US cereals
Occupation injuries and deaths	Fatal injury rate by country	High	High	Medium	Medium	Medium	Medium
	Fatal injury rate by sector	Very High	Very High	Medium	High	Medium	Very High
	Non-fatal injury rate by country	Very High	Very High	Very High	Very High	Low	Low
	Non-fatal injury rate by sector	Very High	High	Very High	Very High	Medium	Medium
Occupational toxins & hazards	Overall risk of loss of life years by exposure to carcinogens in occupation	Medium	Medium	High	High	Medium	Medium
	Overall risk of workplace noise exposure, both genders	Medium	Medium	Low	Low	Low	Low
	Risk of loss of life years by airborne particulates in occupation	High	High	Medium	Medium	Low	Low

Table B.16: Selected individual indicator results for social category “Labour Rights & Decent Work”. Figures derived from the SHDB.

Social Theme	Indicator	Brazil Chemicals	Brazil Sugarcane	France Chemicals	France Sugar Beet	US Chemicals	US Cereals
Child labour	Risk of child labour in sector, Total (Qual)	Medium	Medium	No evidence	No evidence	Low	Medium
	Risk of child labour in sector, Total (Quant)	Medium	Very High	No data	No data	No data	No data
Forced Labour	Risk of forced labour by sector	High	Very High	Low	Low	Medium	Medium
Collective bargaining	Risk that country lacks or does not enforce Collective Bargaining rights	Medium	Medium	Medium	Medium	Very High	Very High
	Risk that country lacks or does not enforce Freedom of Association rights	High	High	Medium	Medium	High	High
	Risk that country lacks or does not enforce the right to strike	Medium	Medium	Medium	Medium	High	High
Labour laws	Risk that country does not provide adequate labour laws by sector	Medium	Low	Low	Low	Low	Low
	Risk that country does not ratify ILO conventions by sector	Low	High	Low	Medium	Medium	Medium
	Risk that minimum wage has not been updated	Low	Low	Low	Low	Medium	Medium
Migrant Workers	Risk that migrant workers are treated unfairly (qualitative)	Medium	Medium	Low	Low	Medium	Medium
	Risk that women are not accepted into the country as immigrants	Medium	Medium	Low	Low	Medium	Medium
	Risk that country does not pay immigrants enough for remittances	Medium	Medium	Medium	Medium	High	High
Poverty	Risk of wages being under $2 per day	Medium	Medium	Low	Low	Low	Low
Unemployment	Risk of unemployment in Country	Medium	Medium	High	High	High	High
Wage assessment	Risk of sector average wage being lower than the country's minimum wage	Low	Very High	Low	Low	Low	High
	Risk of sector average wage being lower than the country's non-poverty guideline	Low	Very High	Low	Very High	Low	Medium
Working time	Risk of excessive working time by sector	Low	Low	Medium	Medium	Medium	Medium

Appendix C: Additional information for Chapter 4

Appendix C.1: Workshop protocols

Note: These workshop protocols were previously reported in the methods section of Chapter 3 and in Matthews, Cizauskas, et al., (2019).

The formulation workshops explored the following topics:

- What does it mean for a product to be sustainable? What aspects matter?
- In terms of sustainability, what sources and types of information are useful and influential?
- What kinds of data and presentation formats are preferred?

The interpretation workshop explored the results of the sustainability assessment and how they could be integrated into decision-making and inform future work. After a short presentation of the results of the sustainability assessment, the following topics were discussed:

- Discussion of results: What do you think of the results? Are they as expected? Were there any unexpected results?
- Making decisions: How could the results be used? Do they change how you might make decisions?
- Future work: Where do we need more information and clarity? What are the priorities for further analysis and data collection?

Appendix C.2: Copy of the interview protocol

This interview schedule gives an overview of the questions that will be covered during the interview as outlined in the participation information sheet. The questions aim to explore how your view sustainability in the context of synthetic biology and your views on the constructive sustainability assessment framework. Some follow-up questions may be asked during the interview.

If you have any inquiries or concerns, do not hesitate to contact the researcher. The researcher will be happy to clarify any questions during the interview.

Sustainability and synthetic biology

- What do you think about the role of synthetic biology/biotechnology in sustainable development?
- What are the possible sustainability benefits of synthetic biology?
- What are the possible risks or detrimental sustainability impacts of synthetic biology?

Constructive sustainability assessment

- Can you tell me what, if anything, you know about the framework for constructive sustainability assessment that I have been working on in collaboration with [The Company]?

Depending on the answer to the above question the researcher will give more details on the constructive sustainability assessment process and ask some appropriate follow-up questions such as:

- What do you think of the process? What impact has the process had?
- Can you tell me anything that has changed, or you think will change as a result of the process?
- More generally, what role does/could sustainability assessment play at [The Company]?
- Could a process like constructive sustainability assessment have an impact on decision-making in the future?
- Can you see this type of process being applied more widely and permanently?
- What are any barriers to doing so?

Competing considerations

- How do sustainability considerations fit with other aspects in choosing and promoting synthetic biology applications?
- How does this fit with scientific and technical considerations?
- How does this fit with considerations of profitability and business competitiveness?

Appendix C.3: Supplementary tables

Table C.1: Survey 1 (August 2018) responses and results

Question 1: What department(s) at [The Company] are you a member of?

Answer	Count	Percentage
Development	41	26.80%
Technology	37	24.18%
HR/Recruitment	5	3.27%
Products	6	3.92%
Finance/Procurement	5	3.27%
Facilities Management	8	5.23%
Manufacturing	46	30.07%
Legal	4	2.61%
Other	1	0.65%

Question 2: What roles do you consider yourself to perform at [The Company]?

Answer	Count	Percentage
Lab based science	81	52.94%
Desk based science (incl. modelling, data and software)	70	45.75%
Strategy	16	10.46%
Management	44	28.76%
Administration	12	7.84%
Business Development	11	7.19%
Communication and marketing	4	2.61%
Legal	5	3.27%
Environmental Health & Safety	8	5.23%
Other	17	11.11%

Question 3: In your opinion, please score the following aspects of sustainability as to how significant they are for the biotechnology sector? (1 = low significance, 5 = high significance)

Answer	Average score
Tackling Climate Change	4.17
Improving the health of global ecosystems	4.16
Promoting equality, peace, and justice	2.99
Eliminating poverty, hunger, and poor-health	3.90
Sustaining employment and economic growth	3.80

Question 4: Do you believe there are relevant sustainability aspects not included in the above list? If so please detail below.

Answer	Count	Percentage
Responses	32	20.92%
Blanks	121	79.08%

Question 5: Do you have any comments on your answers to the above questions?

Answer	Count	Percentage
Responses	35	22.88%
Blanks	118	77.12%

Question 6: There are often trade-offs involved when considering sustainability. In your opinion can benefits in one area of sustainability off-set detrimental effects in other areas?

Answer	**Count**	**Percentage**
Yes	117	76.47%
No	21	13.73%
Blank	15	9.80%

Question 7: How might the following sources of information influence your perspective of the sustainability of a product?

Modelling data	**Count**	**Percentage**
Not influential at all	3	2.19%
Slightly influential	55	40.15%
Quite influential	64	46.72%
Very influential	15	10.95%
Real-world data	**Count**	**Percentage**
Not influential at all	0	0.00%
Slightly influential	9	6.57%
Quite influential	43	31.39%
Very influential	85	62.04%
Experts	**Count**	**Percentage**
Not influential at all	2	1.46%
Slightly influential	15	10.95%
Quite influential	82	59.85%
Very influential	38	27.74%
Impacted stakeholders	**Count**	**Percentage**
Not influential at all	17	12.41%
Slightly influential	53	38.69%
Quite influential	37	27.01%
Very influential	30	21.90%
Civil society organisations	**Count**	**Percentage**
Not influential at all	10	7.30%
Slightly influential	56	40.88%
Quite influential	61	44.53%
Very influential	10	7.30%
Government resources	**Count**	**Percentage**
Not influential at all	7	5.11%
Slightly influential	52	37.96%
Quite influential	60	43.80%
Very influential	18	13.14%

Question 8: Are there any sources of information not listed above which might influence your perspective?

Answer	**Count**	**Percentage**
Responses	14	9.15%
Blanks	139	90.85%

Question 9: Do you have any comments to make concerning your answers to the above questions?

Answer	Count	Percentage
Responses	17	11.11%
Blanks	136	88.89%

Question 10: How relevant is sustainability in the way that you make decisions in everyday life?

Answer	Count	Percentage
It is of no relevance	2	1.31%
It is of background relevance	26	16.99%
It is an important consideration among others	103	67.32%
It is my primary consideration	6	3.92%
Blanks	16	10.46%

Question 11: Products with an improved sustainability profile often cost more, how much more would you be willing to pay for an everyday product (e.g. a bottle of water or a t-shirt) if it was considered more sustainable?

Answer	Count	Percentage
Less	1	0.65%
The same price	9	5.88%
A small amount (10%) extra	62	40.52%
Up to 50% extra	53	34.64%
Up to 100% extra	10	6.54%
More than 100% extra	2	1.31%
Blanks	16	10.46%

Question 12: Do you have any comments concerning your answers to the above questions?

Answer	Count	Percentage
Responses	34	22.22%
Blanks	119	77.78%

Table C.2: Survey 2 (March 2019) responses and results

Question 1: What department(s) at [The Company] are you a member of?

Answer	Count	Percentage
Development	20	37.04%
Technology	12	22.22%
Manufacturing	8	14.81%
HR/Recruitment	3	5.56%
Business Development	5	9.26%
Products	7	12.96%
Facilities Management	1	1.85%
Legal	1	1.85%
Finance/Procurement	2	3.70%

Question 2: What role(s) do you consider yourself to perform at [The Company]?

Answer	Count	Percentage
Lab based science	23	42.59%
Desk based science (incl. modeling, data and software)	16	29.63%
Automation	5	9.26%
Strategy	15	27.78%
Management	16	29.63%
Administration	6	11.11%
Business Development	6	11.11%
Communication and marketing	9	16.67%
Legal	1	1.85%
Environmental Health & Safety	0	0.00%
Other	7	12.96%

Question 3: In your opinion, what are the potential sustainability benefits and/or risks of bio-based production of chemicals or materials?

Answer	Count	Percentage
Responses	39	72.22%
Blanks	15	27.78%

Question 4: Please rank how important you think it is that the bio-based production of chemicals or materials results in the following? (1 = most important, 7 = least important)

Answer	Average score (low=more important)
Combats climate change	2.53
Preserves global resources, ecosystems, and biodiversity	2.17
Delivers a profit	3.15
Makes available novel materials/compounds	2.57
Distributes costs and benefits evenly among stakeholders	4.68
Tackles poverty, hunger and poor health	3.43
Replaces incumbent production approaches	3.06

Question 5: Do you have any comments concerning your answer to question 4?

Answer	Count	Percentage
Responses	22	40.74%
Blanks	32	59.26%

Question 6: To what extent is sustainability relevant for commercial decision-making at [The company]?

Answer	Count	Percentage
Background relevance	14	25.93%
An important consideration among others	35	64.81%
The primary consideration	3	5.56%
Blanks	2	3.70%

Question 7: Please explain your answer to question 6. Why is this so? Can you think of any barriers to it being more relevant?

Answer	Count	Percentage
Responses	43	79.63%
Blanks	11	20.37%

Question 8: Do you have any further comments to add?

Answer	Count	Percentage
Responses	10	18.52%
Blanks	44	81.48%

Question 9: What did you think of the results of the [sustainability] assessment? Were they as you expected? Was anything unexpected? Why was this so?

Answer	Count	Percentage
Responses	23	42.59%
Blanks	31	57.41%

Question 10: To what extent has engaging in the constructive sustainability assessment process had an impact on the way you think about the sustainability of bio-based production processes?

Answer	Count	Percentage
No impact	9	16.67%
Small impact	14	25.93%
Significant impact	8	14.81%
Moderate impact	8	14.81%
Blanks	15	27.78%

Question 11: If applicable, please specify what impact the process has had and why.

Answer	Count	Percentage
Responses	20	37.04%
Blanks	34	62.96%

Question 12: Do you have any thoughts on the application of (constructive) sustainability assessments at biotechnology companies like [The Company]? Should they be applied now? Could they be applied in the future? Where could they be applied and at what stage of development?

Answer	**Count**	**Percentage**
Responses	21	38.89%
Blanks	33	61.11%

Question 13: Do you have any feedback or suggestions for how elements of the constructive sustainability framework could work better?

Answer	**Count**	**Percentage**
Responses	11	20.37%
Blanks	43	79.63%

Question 14: Do you have any further comments to add?

Answer	**Count**	**Percentage**
Responses	8	14.81%
Blanks	46	85.19%

Table C.3: A summary of identified themes.

Broad theme	Narrow theme	Data sources	Brief description	Example quotes
Vision, strategy and business model	Sustainability a key mission	• Survey responses • Workshops • Interviews • Documentation	Delivering sustainability benefits through the use of their platform was a key part of the company's overarching mission and an important motivator for many employees.	*"Sustainability is important to company values and creating a positive company culture."* (Survey response, lab-based scientist)
	Sustainability not a critical factor in decision-making	• Survey responses • Workshops • Interviews	Sustainability was not a critical or primary consideration when it came to decision-making and business strategy.	*"I think the profit motive of companies is the primary concern and sustainability from an environmental point of view is secondary."* (Survey response, company employee involved in strategy) *"we are ultimately a for-profit company. i've been part of multiple business scoping efforts, and in my experience, this is background relevance for projects we pursue"* (Survey response, desk-based Scientist)
	Novelty as vehicles for sustainability	• Survey responses • Workshops • Interviews • Documentation	Generating novel compounds and materials with advantageous characteristics was the primary value proposition within the company's business model. It was hoped that this would in turn enable sustainability.	*"[The company] is developing a technology platform that can be used to provide sustainable solutions. To fund this development, projects can be undertaken that are not necessarily focused on sustainability, yet sustainability is still a long-term goal."* (Survey response, desk-based scientist)

Table C.3 (cont.): A summary of identified themes.

Broad theme	Narrow theme	Data sources	Brief description	Example quotes
Cognitive factors	Deep engagement with sustainability	• Survey responses • Workshops • Interviews	Company employees engaged actively with the CSA process and demonstrated a deep understanding and appreciation of sustainability issues.	*"I think some of the risk that exist in petroleum based industries will continue to exist in the biology based industry. Not all biologically created materials are sustainable or non toxic"* (Survey response, employee involved in strategy) *"Industrial processes are incredibly complicated, and no single solution addresses every impact."* (Survey response, employee involved in automation)
	Sustainability of products assumed	• Survey responses • Workshops • Interviews	There was sometimes a view that sustainability potential of bio-based technologies didn't need to be critically evaluated of evidenced because they are inherently sustainable.	"*I believe that bio-based production has sustainability benefits inherently associated with it because of the source materials*." (Survey response, lab-based scientist)
	Conflicting views on influential data sources	• Survey responses • Workshops • Interviews	There was a wide variety of views on what constituted the most important and influential data sources for informing sustainability evaluation.	*"I am skeptical of the agenda of impacted stakeholders and non-profits when making any statements on sustainability. Models and viewpoints from academics are both valuable to me, but an important caveat would be in understanding how a model is built and where the funding from the academics research is coming from."* (Survey response, lab-based scientist)
	Difficulty in interpreting sustainability assessment results	• Workshops • Survey responses • Interviews	The results across a wide variety of impact categories with high levels of uncertainty were challenging to interpret and translate into meaningful actions.	"*The only barriers I can see are that doing this work is inherently speculative, and seems to create more questions than answers. Nothing definitively enough to take to investors or to the market.*" (Survey response, desk-based scientist)

Table C.3 (cont.): A summary of identified themes.

Broad theme	Narrow theme	Data sources	Brief description	Example quotes
Systemic context	Dependence on clients	• Survey responses • Workshops • Interviews • Documentation	Operating "B2B", as is common in high-tech and emerging technology sectors, made the company dependent on the sustainability priorities of clients.	*"We are limited by client or potential customer interest as a business. Very often, especially with client programs, costs are the main driver."* (Interview response, development scientist and manager)
	Lack of societal incentives	• Survey responses • Workshops • Interviews	There was a perception that there is no "green premium" – consumers are not generally willing to pay extra for more sustainable products.	*"It's so difficult to convince consumers to pay"* (Interview response, member of the company's senior leadership ream)
	Lack of regulation or tax incentives.	• Survey responses • Workshops • Interviews	The potential sustainability benefits brought by the company's technology were externalities and could not be fully integrated until supportive regulation or tax incentives were implemented.	*"This [sustainability not being the primary consideration] could change if governments were willing to subsidize this technology or if the public were willing to pay significant markups for sustainable products."* (Survey response, company employee involved in strategy)
	Locked-in incumbents	• Workshops • Interviews • Survey responses	Many incumbent industries have fully depreciated assets and can be difficult to compete with on price.	*"Largest risk is the inability to articulate the value of sustainable products. In the current environment, sustainable products must match cost and performance of other materials. The whole life cycle cost of the incumbent products is not reflected in their selling price"* (Survey response, company employee in the products team)
	Need to make a return for investors	• Workshops • Interviews • Survey responses	The company, funded by venture capital, needed to generate a financial return for their investors.	*"I doubt investors are primarily concerned about sustainability. It's an added benefit to them. Investors guide the decision making of the company because they are in control of the finances."* (Survey response, development scientist)

Appendix D: Additional information for Chapter 5

Appendix D.1: Copy of the interview protocol

The role of sustainability in the development of synthetic biology

Interview Guide

This interview schedule gives an overview of the questions that will be covered during the interview as outlined in the participant information sheet. The questions aim to explore the participant's role in the development of the field of synthetic biology in the UK, and their perceptions concerning the role that sustainability has and continues to play in that development. Some follow-up questions may be asked during the interview.

Visions of sustainability

First of all, I'm just going to ask you some general questions to get us both warmed up and for me to learn a little be more about you and your view of synthetic biology and the role of sustainability.

1. What does synthetic biology mean to you?
2. What does sustainability mean to you?
3. From your perspective, to what extent has sustainability been the rationale for the promotion of synthetic biology in the UK?
    a. Has sustainability been a stated aim for funders of synthetic biology? Or an underlying implicit aim?
    b. How about for others engaging with it - researchers, companies, non-profits - to what extent has sustainability been a rationale for them?

Policy implementation

Thank you. Now I'd like to ask you a few questions about how policies have been used to promote synthetic biology in the UK.

4. In terms of the policies used to promote synthetic biology, I can identify the funding of underlying research, particularly through the SBRCs, building underlying skills through the CDTs and SynbiCITE, the promotion of commercialisation (SynbiCITE and SynBio seed-fund) and the building of networks through the KTN and NIBBs.
    a. Are there any others I should be aware of?
5. To what extent has a contribution to sustainable development been incentivised in these initiatives?
    a. Are there specific elements that aim to incentivise more sustainable outcomes? Are initiatives evaluated based on sustainability impacts?
    b. What attention has there been to evidencing sustainability, such as the use of sustainability assessments?

   c. Can you tell me of an area where sustainability considerations have specifically influenced decision-making in the field of synthetic biology? This might be by yourself, or others.

6. RRI has been much talked about with respect to synthetic biology, with perhaps unprecedented involvement from social scientists, what do you think has been the impact of this?
   a. What is the relationship between RRI and sustainability?
7. How do the policy initiatives with relation to synthetic biology fit and interact with broader policy initiatives in the UK and globally?
   a. For example, how do policies relating to synthetic biology relate to broader bioeconomy or industrial biotechnology policy.
   b. Are these interactions synergistic? Are they in any way antagonistic?
   c. Do you think that synthetic biology policies have encouraged transformation and/or disruption of existing systems?

Outputs and evaluation

- What are the metrics for success of synthetic biology? What would “good” look like?
- What would sustainable synthetic biology look like?
  - What are the possible sustainability benefits of synthetic biology?
  - What are the possible risks or detrimental sustainability impacts of synthetic biology?
  - Are all synthetic biology applications likely to be sustainable?
- Do you think synthetic biology in the UK in its present form is contributing to a sustainable future? And if so how?

Wrap-up

Thank you. That’s pretty much everything I’d like to ask, I just have some final wrap-up questions.

- Is there anything you would like to see done differently?
- Are there any people I should talk to, or initiatives/documentation that I should look at?
- Do you have any questions for me?

Appendix D.2: Coding manual for supplementary tables

This section of the appendix outlines the coding rules used to generate tables D.3-D.7. Under each heading, the method used to source entries is briefly described as well as the protocol used to determine the value under each field (i.e. column heading).

Table 5.1

Policies were identified by their inclusion in the "Synthetic Biology for Growth Programme", through mentions in interviews and other documentary evidence (e.g. news articles or policy reports) or based on the author's three years of engagement with the synthetic biology community. Only UK government policies initiated between 2012 and 2019 were considered (not EU or Scottish Government policies). A more detailed version of this table is founding Table D.4.

- **Policy name:** Policy name as stated in documentation or as commonly known.
- **Date:** Time period over which the policy was active.
- **Approximate Value:** Approximate value of public investment associated with the policy as reported in documentary sources.
- **Type:** Economic instrument, regulation, or information (see Rogge & Reichardt, 2016, Table 2).
- **Purpose:** Technology push, demand-pull, or systemic (see Rogge & Reichardt, 2016, Table 2).

Table D.3

Key reports were identified according to their prominence in interviews and other documentary evidence and based on the author's three years of engagement with the UK synthetic biology community.

- **Report title:** Title as stated.
- **Author:** The organisation or group credited with authoring the report.
- **Date:** Date published as stated in the report.
- **Headline message:** A summary of the report's main message based on the author's reading of the report.
- **Recommendations:** A summary of the report's main recommendations based on the author's reading of the report.

Table D.4

This is a more detailed version of Table 5.1.

- **Policy name:** Policy name as stated in documentation or as commonly known.
- **Goal:** "the intended effect of instruments that contribute to achieving overarching policy objectives" (Rogge & Reichardt, 2016, p. 1623)
- **Date:** Time period over which the policy was active.

- **Approximate Value:** Approximate value of public investment associated with the policy as reported in documentary sources.
- **Funder:** Principle source of the funding as reported in documentary sources. EPSRC = Engineering and Physical Science Research Council, BBSRC = Biotechnology and Biological Sciences Research Council, DSTL = Defence Science and Technology Laboratory, BEIS = Department for Business, Energy and Industrial Strategy. BBSRC, EPSRC and Innovate UK are now all part of UK Research & Innovation (UKRI), founded in 2018.
- **Type:** Economic instrument, regulation, or information (see Rogge & Reichardt, 2016, Table 2).
- **Purpose:** Technology push, demand pull, or systemic (see Rogge & Reichardt, 2016, Table 2).
- **Design features:** Brief description of how the policy was designed and implemented.

Table D.5

Synthetic biology companies were identified from the following sources:

- SynbiCITE's list of industrial partners (source: http://www.synbicite.com/collaboration/Partners/type/industrial/).
- Members of the 2017 BioStart synthetic biology accelerator (source: http://www.synbicite.com/news-events/2017/feb/20/bio-start-selects-first-cohort/).
- Companies that have received funding from the UKI2S seed-fund (source: personal communication).
- Spin-outs or collaborators of UK Synthetic Biology Research Centre (source: centre websites).
- SynbiCITE's 2017 Synthetic Biology Start-up Survey (Source: SynBICITE, 2017). Note that the full list for this survey is not publicly available.

In total, 104 candidate companies were identified and screened for inclusion. The following exclusion criteria were used to filter the candidates:

- No detailed information could be found online (e.g. Morph Bioinformatics).
- Company no longer exists (was sold or went bust) as of December 2020 (e.g. Green Biologics).
- Company not based in the UK (e.g. LanzaTech).
- Large company for which specifics on synthetic biology-related operations couldn't be easily identified (e.g. Shell UK).
- No evidence of directly using synthetic biology (e.g. London Haskspace, Microsoft).

The remaining 55 companies were then coded according to the following fields:

- **Company name**: As stated.
- **Source:** From which of the above sources the company was initially identified.

- **Application domain:** Classified according to the following options based on the EBRC (2019) classification with "platform & enabling" added to and "Energy" merged with "industrial Biotechnology". The options were as follows:
    - Platform & Enabling
    - Health & Medicine
    - Food & Agriculture
    - Energy & Industrial Biotechnology
    - Environmental Biotechnology
- **Sustainability or social/environmental value claims:** Whether the company website or other public documentation (e.g. quotes in news articles) made specific claims of improved sustainability or social/environmental value creation from their products or processes. Where the answer is "Yes" a quote is provided. Note that purely working in the domain of Health & Medicine was not in itself considered to constitute a social and environmental value claim.
- **Sustainability monitoring and anticipation**: Whether there is evidence on the company website or in other public documentation of specific monitoring or anticipation of claims made. The author looked for activities that sought to reflect on, anticipate and monitor sustainability implications. Examples might include published sustainability assessments or specific collaborations on the topic.

Table D.6

The websites and other publicly available documentation for each of the six research centres funded as part of the synthetic biology for growth programme were reviewed and summarised/coded according to the following fields:

- **SBRC:** The name of the Synthetic Biology Research Centre.
- **Start date:** The date when the grant started.
- **Proposal – economic value:** Whether the grant proposal mentions potential economic value creation.
- **Proposal – social or environment value:** Whether the grant proposal mentions broader social or environmental value creation.
- **Stated impact:** Impact of the centre as stated on the website.
- **RRI/ELSA activities:** How the centre meets its requirement to undertake RRI/ELSA activities and research.
- **Sustainability monitoring and anticipation:** Whether sustainability monitoring and anticipation activities are mentioned on the website or other publicly available information (e.g. publications). The author looked for activities that sought to reflect on, anticipate and monitor sustainability implications. Examples might include specific workshops on the topic or published sustainability assessments.

Table D.7

All publicly available minutes (as of the 7th May 2020) of the synthetic biology leadership council (SBLC) were reviewed and each meeting summarised/coded according to the following fields:

- **Meeting date:** Date as reported in the minutes.
- **Meeting type:** Whether the meeting was of the main SBLC or its Governance Sub-Group.
- **Meeting number:** The meeting number as reported in the minutes. The main council and its sub-group have separate numbering.
- **Economic value creation:** Whether there was discussion of creating economic value through synthetic biology. For example, discussion of accelerated commercialisation or IP protection.
- **Responsible Research and Innovation:** Whether explicit RRI-related issues were discussed. For example, discussion of public dialogues/engagement.
- **Social or environmental value creation:** Whether there was discussion of creating broader social or environmental value through synthetic biology. For example, discussion of actively directing synthetic biology towards societal grand challenges or the need to evidence sustainability claims. Discussion of engagement with the Convention on Biological Diversity was generally not in itself considered to be a discussion of social or environmental value creation as it was mostly focussed avoiding a moratorium on synthetic biology research and/or applications.
- **Key topics:** The main topics discussed at the meeting.

Appendix D.3: Supplementary tables

Table D.1: Interviews carried out as part of this study.

Date	Activity	Participant	Approximate Duration	Data collected
Apr-20	Interview	Employee of a national research funder	1 hour	Notes
May-20	Interview	Leading synthetic biology academic	1 hour	Notes, transcript
May-20	Interview	Member of Synthetic Biology Leadership Council governance sub-group	1 hour	Notes, transcript
May-20	Interview	Senior manager at a synthetic biology company	1 hour	Notes, transcript
May-20	Interview	Industrialist involved in several influential policy reports	30 minutes	Notes, transcript
May-20	Interview	Member of 2012 Synthetic Biology Roadmap Steering Group	1 hour	Notes, transcript
May-20	Interview	Employee of a knowledge transfer organisation with responsibility for synthetic biology	1 hour	Notes
May-20	Interview	Employee of a relevant industry association	1 hour	Notes, transcript
Jun-20	Interview	Investment director with responsibility for synthetic biology	1 hour	Notes, transcript

Table D.2: A summary of identified themes. Data sources and thematic codes are summarised along with example quotes across the three dimensions of the analytical framework.

Dimension	Research sub-questions	Main data sources	Themes	Example quotes
Policy processes	• What have been the rationales for promotion of synthetic biology in the UK? • What were the visions and expectations for the future?	• Policy reports • Stakeholder interviews • Grant proposals	Synthetic biology for economic growth	"It has the potential to deliver important new applications and improve existing industrial processes – resulting in economic growth and job creation" (2012 Synthetic Biology Roadmap)
			Synthetic biology for a more sustainable society	"…it can help generate more sustainable materials, chemicals and energy" (SBLC, 2016 in *Biodesign for the Bioeconomy*)
			Unquestioned link between bio-based technologies and sustainability	"It's a kind of an agenda that's unspoken and many of them because they're using sustainable manufacturing methods by using biology…" (interviewee) "By improving the productivity of biomanufacturing processes it [Synthetic Biology] can help generate more sustainable materials, chemicals and energy." (SBLC, 2016 in *Biodesign for the Bioeconomy*)
			Concerns over hype, lack of society engagement, and under-regulation	"…this new technological frontier poses significant health, safety and environmental hazards, as well as profound social, economic and ethical challenges." (ETC Group, FOE & CTA, 2012)
			Conditional support from the public	"Findings from the dialogue showed there was conditional support for synthetic biology" (Synthetic Biology Dialogue Report, 2010)
	• How did synthetic biology come to be the subject of policy intervention in the UK?	• Policy reports • News articles • Letters • Meeting minutes • Stakeholder interviews	2010 coalition prioritises economic growth	"We recognise that deficit reduction, and continuing to ensure economic recovery, is the most urgent issue facing Britain." (HM Government, 2010)
			Interventionist approach to STI policy	"We have a fantastic scientific tradition in this country, and technology leadership must drive economic activity in the future." (Vince Cable, 2012)
			Synthetic biology seen as providing economic benefits alongside sustainability message	"Synthetic biology could provide solutions to many of humanity's most pressing issues and at the same time presents significant growth opportunities" (Willets, 2012)
			Social scientists actively engaged in the process and introduce RRI discussion	"The roadmap can be seen a significant marker in the emergence of a discourse around the concept of RRI in the UK" (Marris & Calvert, 2019) "…it [the introduction of RRI] was more of a like trying to stop it being public acceptance and trying to get something else in there which was more STS-amenable I suppose" (Interviewee)

Table D.2 (cont.): A summary of identified themes.

Dimension	Research sub-questions	Main data sources	Themes	Example quotes
Policy intervention	• What policy approach has been used to promote synthetic biology?	• Policy reports • Stakeholder interviews • Meeting minutes • Grant proposals	Feeding the innovation pipeline	"…the investment that led to like the establishment of SynBioChem and all the other research centres as well as SynbiCITE" (Interviewee) "And there's a lot of financial incentives that the government has in place to help like R&D tax credits which are really important." (Interviewee)
			Commercialisation a priority	"Talking about a pipeline from research to translation to company scaling it up. That's the model for impact in synthetic biology at the moment." (Interviewee)
			Limited demand-side policy	"No and there needs to be and I think that's the big issue [The lack of demand-side policy]. There's a big gap there. We need to do that." (Interviewee)
			Potential inconsistency between economic and broader sustainability goals in the strategy	"The putting together of sustainability and economic growth can also be somewhat problematic as it assumes the two are compatible and that you can have it all." (Interviewee)
			Lack of high-level support for the bioeconomy strategy	"I mean the potential there [of the bioeconomy strategy] was really big but it has really run into the sand… the strategy itself, I didn't feel like it had real government buy-in" (Interviewee)
Socio-technical change	• What have been the outcomes of the synthetic biology programme? • To what extent is synthetic biology promoting transformational change?	• Policy reports • Outcome reports • Stakeholder interviews • Meeting minutes • Websites	Field of synthetic biology established	"The 200 or 300 million pounds has been spent pretty much …what we've got out of it is essentially the establishment of the field in the United Kingdom." (Interviewee)
			Active commercialisation, yet mixed results	"The government has done a good job in providing slightly larger grants and there's more money going to the sector so that Valley of Death used to be at quite an early stage in the TRL levels, it's moved up a little bit, but it's still a significant gap…" (Interviewee) "…support and focus on translation and commercialisation has been widely recognised as being underpowered and intermittent." (RAE 2019)
			Significant support for RRI activities	"I think there's been an exceptional commitment to fund that work and also to see that work as being very important, equally important in some extent to the actual Science and Technology development." (Interviewee)
			Sustainability neglected and difficult to consider	"…the way the responsible research and Innovation is kind of framed and the EPSRC-level anyways, doesn't really talk about sustainability at all." (Interviewee) "…to do that kind of circular economy economic analysis but it's actually quite difficult and quite specialised" (Interviewee) "It's just people talk about it [Sustainability], but it's not a thing" (Interviewee)

Table D.3: A summary of key policy reports relevant to synthetic biology.

Report Title	Author	Date	Headline message	Recommendations
Synthetic Biology: scope, applications and implications	Royal Academy of Engineering	2009	"Synthetic biology has the potential to create another raft of major new industries, the development of which is likely to have profound implications for the future of the UK, European and world economies."	Develop a strategic plan for UK synthetic biology which includes broad stakeholder engagement, establish training and research infrastructure, collaborate with social scientists and philosophers to consider societal and ethical implications.
IB 2025: Maximising UK Opportunities from Industrial Biotechnology in a Low Carbon Economy	Industrial Biotechnology Innovation and Growth Team	2009	"Currently, IB is being impeded from delivering this prize in the UK – primarily because of low awareness of the potential of the technology, a lack of the necessary facilities to demonstrate its commercial feasibility, and insufficient connectivity between the key players. These are inhibiting the UK's establishment of an IB foundation for the lowcarbon, knowledge-based economy so urgently needed – using bio-based resources to make products and provide services that are not only less damaging to the planet and its people, but are also able to offer new additional features and benefits."	"Improve the connectivity of UK IB activities", "De-risk access to new products and technologies", "Accelerate the innovation and knowledge transfer process", "Retain and develop the necessary interdisciplinary talent in science and management", "Create a 'public' and 'business' environment that is supportive of IB"
A synthetic biology roadmap for the UK	Synthetic Biology Roadmap Coordination Group	2012	A vision for UK synthetic biology which is "economically vibrant, diverse and sustainable", "cutting edge" and "of clear public benefit… addressing global societal and environmental challenges"	Key recommendations are the establishing of multidisciplinary research centres, building the skills base, accelerate commercialisation, and pursuing networking and coordination nationally and internationally.
Biodesign for the bioeconomy: UK Synthetic Biology Strategic Plan 2016	Synthetic Biology Leadership Council	2016	"Synthetic biology is capable of delivering new solutions to key challenges across the bioeconomy... The successful commercialisation of such opportunities within the UK will contribute direct benefits to health, security and the economy."	"accelerating industrialisation and commercialisation; maximising the capability of the innovation pipeline; building an expert workforce; developing a supportive business environment, and building value from national and international partnerships."

Table D.3 (cont.): A summary of key policy reports relevant to synthetic biology.

Report Title	Author	Date	Headline message	Recommendations
Enabling Technologies for a Sustainable Circular Bioeconomy: A National Industrial Biotechnology Strategy to 2030	Industrial Biotechnology Leadership Forum	2018	"Industrial Biotechnology (IB) offers huge potential for the UK, providing jobs and economic growth across a wide range of market and industry sectors. IB can mitigate climate change through the development of greener, cleaner manufacturing processes, as well as offering opportunities for waste utilisation and new products that benefit society which cannot be made any other way."	Focussed on building the base of infrastructure and skills and delivering a supportive regulatory and finance environment for commercialisation. There is a commitment to RRI which is focussed on outreach, communication and building public awareness.
Improving lives and strengthening our economy: A national bioeconomy strategy to 2030	HM Government	2018	"Growing our bioeconomy will ensure that the UK becomes an inviting and vibrant place to invest and do business, supporting innovation and stimulating economic growth. We will become a global leader in developing, manufacturing, using and exporting bio-based solutions, strengthening the UK economy and moving us towards a low carbon future."	Promote industry-University collaboration, translation and commercialisation; build the skills and infrastructure base; nurture a supportive business environment; build local capacity; establish a governance group which will develop: "...bioeconomy metrics, including economic, environmental and societal impact".
Engineering biology: A priority for growth	Royal Academy of Engineering	2019	"Engineering biology presents a suite of opportunities to solve the problems people and the planet face, now and tomorrow. As well as bringing cheaper, greener and custom-designed products to market, engineering biology can dramatically transform the processes that underpin existing industries, such as helping to lessen the impacts fossil fuels have while they are still an embedded component of our lives."	Increase support for translation and communication, promote business-university collaboration, improve accessibility and communication, and support the research base.

Table D.4: The primary instruments of the UK synthetic biology policy mix. Based on the conceptualisation from Rogge & Reichardt (2016).

Policy name	Goal	Time period	Approximate Value	Funder	Type	Purpose	Design Features
Synthetic biology research centres (SBRCs)	"to boost national synthetic biology research capacity and ensure that there is diverse expertise to stimulate innovation in this area"	2013/14 - present	£70 million across 6 centres	BBSRC & EPSRC	Economic instruments	Technology push	• 6 centres funded, 3 each in 2013 and 2014. Initial five-year funding commitments later extended. • Multidisciplinary research to advance synthetic biology capabilities. • Strong focus on generating IP and commercialising outputs. • Dedicated social science research programmes, centres must consider broader impacts of the research.
DNA synthesis infrastructure	"to bring academic expertise to bear on bottlenecks in DNA synthesis, build bridges between academia and synthetic biology companies"	2014-2016	£18 million across two phases	BBSRC	Economic instruments	Technology push; Systemic	• First phase - funding for five foundries spread across the country and focussed on a range of DNA synthesis needs. • Second phase - four more targeted initiatives focussed on advancing synthesis capabilities.
Centres for doctoral training	To train PhD students with the relevant multi-disciplinary skills for synthetic biology.	2014-present (Synthetic Biology CDT) 2019-present (Biodesign CDT)	£5 million (Synthetic Biology CDT) £7 million (Biodesign CDT)	BBSRC & EPSRC	Information	Technology push	• Synthetic Biology CDT spread across Bristol, Warwick and Oxford. Focussed on skills development. ELSA and public engagement integrated into training programme. • Biodesign CDT spread across Imperial, Manchester and UCL. Focussed on developing Biodesign Engineers. Combines training in underlying biological and engineering skills with industrial experience and entrepreneurial training.

Table D.4 (cont.): The primary instruments of the UK synthetic biology policy mix.

Policy name	Goal	Time period	Approximate Value	Funder	Type	Purpose	Design Features
Innovation Knowledge Centre (SynbiCITE)	To bridge the "valley of death" from research outputs at TRLs 1 and 2 to TRL 5 where industry can take over	2014-present	£6 million across two phases	EPSRC	Information; economic instruments	Technology push; Systemic	Based at Imperial College London with the following activities: • Invest in and generate co-funding for start-ups and spinouts. • Facilities and expertise to support early-stage commercialisation. • Networking opportunities for the synthetic biology community Business and entrepreneurship training (BioStart and 4-day MBA initiatives).
Future Biomanufacturing Research Hub (FBRH)	A "biomanufacturing accelerator" to support the development of commercially-relevant bio-based manufacturing routes.	2019-present	£10 million	BBSRC & EPSRC	Economic instruments	Technology push; Systemic	• Based at the Manchester Institute of Biotechnology with six "spokes" across the UK. • Provides facilities and expertise to address industrial scale-up and integration challenges. • There is a major focus on collaborative R&D with industry.
Rainbow/UKI2S seed fund	Help provide very early-stage funding for synthetic biology start-ups when other sources of funding are not normally available	2013-present	£10 million	BBSRC	Economic instruments	Technology push	• £10 million evergreen funding. Funds at the very earliest stages - pre-seed and seed. • Ultra-patient capital to meet the needs of "deep technology" companies. Fund takes active role in the company, providing advice and support. • Typically funds as part of a syndicate, cannot invest more than £1million in a synthetic biology company.

Table D.4 (cont.): The primary instruments of the UK synthetic biology policy mix.

Policy name	Goal	Time period	Approximate Value	Funder	Type	Purpose	Design Features
Industrial Biotechnology Catalyst	Fund businesses and researchers to work on translational projects and therefore accelerate commercialisation.	2014-2016	£75 million	Innovate UK	Economic instruments	Technology push; Systemic	• Supported R&D into "the processing and production of materials, chemicals and bioenergy through the sustainable exploitation of biological resources". • Funds available for academics and industry at various stages: translation, technical feasibility studies, industrial research, and experimental development.
Networks in industrial biotechnology and bioenergy (NIBBs)	Support research and translation, "foster collaboration between academic researchers and businesses at all levels"	2014-present	£29 million (two phases)	BBSRC & EPSRC	Economic instruments; Information	Technology push; systemic	• Provide funding for proof-of-concept project and "business interaction vouchers". • Host networking events such as conferences and workshops.
Small Business Research Initiative	Connect government organisations with innovative businesses.	Calls in 2014 and 2016	£8 million	DSTL	Economic instruments	Technology push; systemic	• Two Synthetic biology-specific grants from DSTL have been provided through SBRI. • First call covered synthetic biology application in defence, the second synthetic biology for novel materials.
Synthetic Biology special interest group	Join-up and network the UK synthetic biology community and act as an information brokerage service.	2012-2019	Unknown	Innovate UK	Information	Systemic	• Established online in 2012. Membership of over 1,000 after two years. • Delivered events to support networking and collaboration. Provided information brokerage services, publicising funding calls and other opportunities. • Maintained an online landscape map of the synthetic biology ecosystem.

Table D.4 (cont.): The primary instruments of the UK synthetic biology policy mix.

Policy name	Goal	Time period	Approximate Value	Funder	Type	Purpose	Design Features
Synthetic biology leadership council	"strategically oversee the development of a successful synthetic biology industry sector in the UK"	2012-present	Unknown	Innovate UK	Information	Systemic	• Established in 2012, co-chaired by an industrialist and a government minister. Oversight of strategy, tasked with delivering the vision of synthetic biology put forward in the roadmap. • Meets three times a year, including one open-meeting. • A governance sub-group covers "governance, policy and regulation, citizen and stakeholder engagement, and communication, as they relate to science and innovation in SB".
BSI Standards in synthetic biology	Gives "guidance on using standards for digital biological information in the design and fabrication of a synthetic biological system"	2015	Unknown	Innovate UK	Regulation	Demand pull	• British Standards Institute provided with funding from Innovate UK in 2015 to produce guidance on standards for synthetic biology.
Centre for Engineering Biology, Metrology and standards	To facilitate the development of standards for synthetic biology, thus accelerating their industrialisation.	2017-present	£7 million	BEIS	Regulation	Demand pull	• Collaboration between the National Physical Laboratory and SynbiCITE in partnership with the LGC group and the National Institute for Biological Standards and Control. • Virtual lab to develop "industry-led measurements and standards", Focussed mostly on therapeutics.

Table D.5: The sustainability commitments of UK synthetic biology companies. 54 UK synthetic biology companies' websites coded according to whether they make claims of sustainability and whether there was any evidence or reports of them monitoring or anticipating these claims. Note that purely working in the domain of Health & Medicine was not in itself considered to constitute a social and environmental value claim.

Company name	Source	Application domain	Specific Sustainability claims	Sustainability evaluation
4D Pharma research	Synthetic Biology Start-up Survey	Health & Medicine	No	No
Agilent Technologies UK Ltd	SynbiCITE Industrial partner	Platform & Enabling	No	No
Algenuity	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Food & Agriculture	Yes - "Sustainable plant-based, protein-rich ingredients."	Yes - future partnership with Unilever will include a full life cycle assessment
Antiverse	UK S&I Seed Fund	Health & Medicine	No	No
Autolus	Synthetic Biology Start-up Survey	Health & Medicine	No	No
Bento Bioworks	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Platform & Enabling	No	No
Better Origin	BioStart Accelerator members	Food & Agriculture	Yes - "accelerating the transition to sustainable methods of farming"	No
Biocatalysts	Synthetic Biology Start-up Survey	Platform & Enabling	No	No
Biome Bioplastics	Synthetic Biology Start-up Survey	Energy & Industrial Biotechnology	Yes - "A more sustainable product"	No
Biotangents	BioStart Accelerator members; Synthetic Biology Start-up Survey	Health & Medicine; Food & Agriculture	Yes – improve the sustainability of agriculture	No
C3 Biotech	SBRC spinout/collaborator	Energy & Industrial Biotechnology	Yes - "Energising a low carbon world"	Yes - advertising for a PhD which will include looking at sustainability implications
Celbius	Synthetic Biology Start-up Survey	Platform & Enabling; Energy & Industrial Biotechnology; Health & Medicine	Yes - "committed to driving innovation in its key operational space of sustainable green processing"	No
Chain biotechnology	UK S&I Seed Fund; SynbiCITE Industrial partner; SBRC spinout/collaborator; Synthetic Biology Start-up Survey	Health & Medicine	Yes - "The aim is to deliver a robust fermentation bioprocess that supports a sustainable and cost-effective route to manufacture"	No

Table D.5 (cont.): The sustainability commitments of UK synthetic biology companies.

Company name	Source	Application domain	Specific Sustainability claims	Sustainability evaluation
Colorifix	BioStart Accelerator members	Energy & Industrial Biotechnology	Yes - "Sustainability is at the very core of what we do and we believe that for a technology to be truly sustainable, it needs to be sustainable environmentally, financially and socially."	No
Cytoseek	UK S&I Seed Fund	Health & Medicine	No	No
Deep branch biotechnology	SBRC spinout/collaborator	Food & Agriculture	Yes - "What if we could solve both carbon reduction & sustainable food production in one step"	Yes - collaboration with EU JRC and University of Leiden to assess sustainability of the platform.
Demuris	Synthetic Biology Start-up Survey	Health & Medicine	No	No
Destina Genomics	Synthetic Biology Start-up Survey	Platform & Enabling	No	No
EnzBond	BioStart Accelerator members	Platform & Enabling; Health & Medicine	No	No
Evonetix	Synthetic Biology Start-up Survey	Platform & Enabling	No	No
Fujifilm Diosynth Biotechnologies	SynbiCITE Industrial partner	Health & Medicine	No	No
Glialign	UK S&I Seed Fund	Health & Medicine	No	No
Gyreox	UK S&I Seed Fund	Health & Medicine; Enabling & Platform	No	No
Helixworks Technologies	BioStart Accelerator members	Platform & Enabling	No	No
Horizon Discovery	Synthetic Biology Start-up Survey	Platform & Enabling	No	No
Hypha Discovery	Synthetic Biology Start-up Survey	Platform & Enabling; Health & Medicine; Food & Agriculture	No	No
Iceni Diagnostics	SBRC spinout/collaborator; Synthetic Biology Start-up Survey	Health & Medicine	No	No
Ikarovec	UK S&I Seed Fund	Health & Medicine	No	No

Table D.5 (cont.): The sustainability commitments of UK synthetic biology companies.

Company name	Source	Application domain	Specific Sustainability claims	Sustainability evaluation
Ingenza	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Energy & Industrial Biotechnology	Yes - "development of sustainable and cost-competitive biotechnology"	Yes - offer LCA as a service
Isogenica	Synthetic Biology Start-up Survey	Platform & Enabling; Health & Medicine	No	No
Isomerase Therapeutics	Synthetic Biology Start-up Survey	Platform & Enabling; Health & Medicine; Energy & Industrial Biotechnology	No	No
LabGenius	SynbiCITE Industrial partner; BioStart Accelerator members; Synthetic Biology Start-up Survey	Health & Medicine; Enabling & Platform	No	No
Leaf expression systems	SBRC spinout/collaborator	Platform & Enabling; Health & Medicine; Food & Agriculture	Yes - "an excellent way of producing sustainably highly valuable molecules"	No
Linear Diagnostics	UK S&I Seed Fund; BioStart Accelerator members	Health & Medicine	No	No
MyoDopa	UK S&I Seed Fund	Health & Medicine	No	No
Nanotether Discovery Sciences	Synthetic Biology Start-up Survey	Platform & Enabling; Health & Medicine	No	No
Nemesis Bioscience	UK S&I Seed Fund; Synthetic Biology Start-up Survey	Health & Medicine	No	No
Nuclera Nucleics	BioStart Accelerator members	Platform & Enabling	No	No
Oxford Biotrans	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Energy & Industrial Biotechnology	Yes - "We intend to realise scalable, 'green', biocatalytic processes for these products."	No
Oxford Genetics	Synthetic Biology Start-up Survey	Platform & Enabling; Health & Medicine	No	No
Oxitec	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Health & Medicine; Food & Agriculture	Yes - "We offer an [sic] environmentally sustainable solutions…"	No
Persephone Bio	SBRC spinout/collaborator	Energy & Industrial Biotechnology; Food & Agriculture	No	No

Table D.5 (cont.): The sustainability commitments of UK synthetic biology companies.

Company name	Source	Application domain	Specific Sustainability claims	Sustainability evaluation
Phase Biolabs	SBRC spinout/collaborator	Energy & Industrial Biotechnology; Food & Agriculture	Yes - "harnessing biology for a greener tomorrow"	No
Phenotypeca	SBRC spinout/collaborator	Platform & Enabling	Yes - "our long-term aim is to improve access to life-saving medicines and promote sustainable manufacturing globally"	No
Phytoform Labs	BioStart Accelerator members	Food & Agriculture; Platform & Enabling	Yes - "Making Agriculture Sustainable"	No
Procarta	UK S&I Seed Fund	Health & Medicine	No	No
Prokarium	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Health & Medicine	No	No
Prozomix	Synthetic Biology Start-up Survey	Platform & Enabling; Health & Medicine; Food & Agriculture; Energy & Industrial Biotechnology	No	No
Puraffinity	SynbiCITE Industrial partner/BioStart Accelerator members	Environmental Biotechnology	Yes - "We are a green technology company incorporated in 2015 focussed on designing smart materials for environmental applications."	No
Sphere Fluidics Limited	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Platform & Enabling	No	No
Synthace Ltd	SynbiCITE Industrial partner; UK S&I Seed Fund; Synthetic Biology Start-up Survey	Platform & Enabling	Yes - "it’s about enabling scientists to do experiments that they have never been able to before, leading to better biological insights, and in turn, more sustainable products and process"	No
Touchlight Genetics Ltd.	SynbiCITE Industrial partner; Synthetic Biology Start-up Survey	Platform & Enabling	No	No
Tropic Biosciences	UK S&I Seed Fund	Food & Agriculture	Yes - "improve sustainable environmental practices, using cutting edge genetic editing technologies"	No
Zentraxa	UK S&I Seed Fund; BioStart Accelerator members; spinouts	Platform & Enabling	Yes - "environmentally-sustainable solutions like ours."	No

Table D.6: A summary of the six Synthetic Biology Research Centres according to their stated goals, attention to sustainability, and RRI activities.

SBRC	Start date	Proposal - economic value	Proposal – social and environmental value	Stated impact	RRI/ELSA activities	Sustainability monitoring and anticipation
SynBioChem	Nov-14	Yes, lots of mention of translation and benefits to UK economy.	Yes, in terms of green chemistry and sustainable manufacturing.	Developing underlying capabilities and tools to support biomanufacturing. 10 patents and 455 publications.	Dedicated RRI group (including sociologists and innovation studies/policy scholars) within the centre who "provide expertise, guidance and training in responsible governance of SynBio innovation, and foster public engagement and training for the research community".	Researchers in the centre have undertaken and published sustainability assessments.
BrisSynBio	Jul-14	Some mention of quick and cheap production, paragraph specifically on IP and spin-outs.	Some mention of health benefits, grand challenges and reducing dependence on fossil fuels.	Research has focussed on a range of enabling areas such as the development of cell factories, genome editing of higher organisms and modelling. Reports industrially-relevant projects in novel chemistry, peptide design, agri-tech, therapeutic platforms.	RRI activities led by a Sociologist/STS expert and Philosopher - "A resident philosopher will work alongside synthetic biology researchers at BrisSynBio". Has an artist in residence. Have also undertaken public engagement activities.	None evident.
Nottingham SBRC	Jul-14	Yes, generally through linking sustainability and economics.	Yes, front and centre. "We are passionate about sustainability and we believe we can share this vision to the rest of the UKs scientific community and the general public who use our products."	Primary focus on aerobic gas fermentation, engineering *Cupriavidus necator* to make various bio-based products. 7 patents and 61 publications. Two start-up companies building from research at the centre.	Has an Interdisciplinary Responsible Research and Innovation Group. Mostly STS researchers. Various outreach and engagement activities.	Project on "Circling sustainability and responsibility" seeking to explore the link "between the circular economy and novel biotechnology applications".

Table D.6 (cont.): A summary of the six Synthetic Biology Research Centres according to their stated goals, attention to sustainability, and RRI activities.

SBRC	Start date	Proposal - economic value	Proposal – social and environmental value	Stated impact	RRI/ELSA activities	Sustainability monitoring and anticipation
OpenPlant	Jul-14	Mostly in terms of IP and the need for better IP models to enable innovation.	Yes, they advocate for dialogue on sustainable agriculture and land use, and highlight that the technology is "inherently low cost, renewable and has obvious applications for new sustainable technologies".	Enabling research for plant synthetic biology and more open data sharing. Various spin-outs and collaborations.	RRI promoted through a dedicated fund for research and exchange as a well as outreach activities, training, tools and workshops.	Directly seek to address access and benefit sharing issues through an open-source approach and addressing barriers to adoption in Africa.
WISB	Nov-14	Partnerships with companies and maximising industrial impact through industry engagement and tech transfer.	Mentioned with regards to applied research areas, but not really elsewhere.	Underpinning research in engineering metabolic pathways, microbial communities and plants.	ELSA activities led by researchers interested in science studies, sociology and cognitive science. Held a workshop on "societal issues in synthetic biology".	None evident.
Edinburgh SBRC	Nov-14	Specifically talks about IP generation, innovation and industrial partnership.	Briefly talks about medical applications.	Developing tools for engineering biology, engineering biological systems to improve understanding, and generating "insights for medicine".	Developed framework for Proportionate and adaptive governance of innovative technologies. "Synthetic Aesthetics" project exploring the intersection of synthetic biology and design.	None evident.

Table D.7: A summary of published meeting minutes from the Synthetic Biology Leadership Council (SBLC) and its Governance Sub-group. Each meeting is coded as to whether there was discussion of 1) Economic value creation, 2) RRI/public engagement and 3) Social and environmental value creation. Bullet points summarising the key topics discussed are also provided.

Meeting date	Meeting Type	Meeting Number	Financial value creation	RRI	Social or environmental value creation	Key Discussion Topics
13-Dec-12	SBLC	1	✓	✓	✗	• Discussed recent funding announcements. • Discussed key issues from council members: IP/regulatory, public perceptions and engagement, progressing science, commercialisation, training. • Discussed establishing regulatory sub-group.
14-Mar-13	SBLC	2	✓	✓	✗	• Discussion of public dialogue, called for impartial external body like ScienceWise to deliver public engagement paper. • Discussion of commercialisation and links to other initiatives like IBLF.
17-Jul-13	SBLC	3	✓	✓	✗	• Key challenges from SynBio special interest group - funding, connections, processes for commercialisation. • International discussions linked to SB6.0 • Discussion of IP and patenting.
16-Oct-13	SBLC	4	✓	✓	✗	• First open meeting. • Proposal for LEAP programme in the UK • Ongoing discussions around international, commercialisation, risk and regulation. • Extensive discussion of governance/public engagement. Critique of bias towards commercialisation.
19-Mar-14	SBLC	5	✓	✓	✗	• Invited guest speaker discussed US initiatives and biosecurity. Biosecurity a major topic of discussion. • Standards and IP discussions.
03-Jul-14	SBLC	6	✓	✓	✓	• Meetings amongst SBLC, Agri-tech leadership council and IBLC taking place. • Discussion of targeting synbio towards a grand challenge. • Biosecurity, governance sub-group, national coordination. • Synthetic biology capital funding.
27-Nov-14	SBLC	7	✓	✓	✗	• Second Open meeting. Lots of questions on public, RRI and NGOs. • Commercialisation challenges highlighted. Lack of venture capital. • The responsible minister talked extensively about economic imperatives. • It was highlighted that the synthetic biology community wants to tackle environmental issues, but no further discussion evident..

Table D.7 (cont.): A summary of published meeting minutes from the Synthetic Biology Leadership Council (SBLC) and its Governance Sub-group.

Meeting date	Meeting Type	Meeting Number	Financial value creation	RRI	Social or environmental value creation	Key Discussion Topics
18-Mar-15	SBLC	8	✓	✗	✗	• Delegation from Canada present. • New strategic plan discussed, agreed to have an emphasis on market pull. • Presentation from investors. • Discussion of convention on biological diversity and Nagoya protocol • Mention of synbio for a "sustainable future" but no further elaboration or discussion evident.
02-Jul-15	SBLC	9				Discussed strategic plan, minutes not published
16-Jul-15	SBLC	10	✓	✓	✓	• Open meeting • Discussed a series of themes for the roadmap, including grand challenges, commercialisation, regulation & governance, skills & training, community.
11-Sep-15	SBLC	11				Discussed strategic plan, minutes not published
10-Mar-16	SBLC	13	✓	✓	✗	• Successful publication of strategic plan. • Discussion of the fact that the Governance sub-group has no dedicated resource to implement the plan. • Need for consideration of how to undertake public engagement.
14-Jul-16	SBLC	14	✓	✓	✗	• Need for greater representation from industry and expertise in commercialisation and investment. • Discussed regulatory systems and standards for synthetic biology. • Also discussed biosecurity strategy and a potential bioeconomy strategy.
24-Nov-16	SBLC	15	✓	✓	✗	• Open meeting • Lots of discussion of regulatory environment. • Discussed some of the challenges of operationalising RRI. Dedicated RRI breakout session.
29-Mar-17	SBLC	16	✓	✗	✓	• Highlighting some of the challenges that synthetic biology could tackle. • Discussion of regulation and commercialisation.
12-Jul-17	SBLC	17	✓	✓	✗	• CBD and Nagoya protocol discussions and regulation • Presentation of proportional and adaptive governance for innovative technologies work. • Various commercialisation related discussions: new industry members, growing the bioeconomy, VC investment and entrepreneurship.

Table D.7 (cont.): A summary of published meeting minutes from the Synthetic Biology Leadership Council (SBLC) and its Governance Sub-group.

Meeting date	Meeting Type	Meeting Number	Financial value creation	RRI	Social or environmental value creation	Key Discussion Topics
08-Nov-17	SBLC	18	✓	✓	✗	• Open Meeting. • Update on work on the Bioeconomy strategy. • Lots of commercialisation discussion. Synthetic biology start-up survey presented. • Regulation and biosecurity. • Breakout session considered fundamental bioscience, investment & trade, teaching and business.
21-Mar-18	SBLC	19	✓	✓	✓	• Discussion of decarbonisation, clean growth, link to plastics and the 25-year environment plan, sustainable aviation fuel. • "Need to identify what is missing in the landscape to enable progress and commercialisation".
19-Jul-18	SBLC	20	✓	✓	✗	• Civil servant from the Environment team in the Government Office for Science joined the meeting. • Discussion of tension between doing social science research and "acting as a constructive challenge" to synthetic biologists. • Workshop hosted in July 18th 2018 to discuss next 5-10 years of synthetic biology, feeding into "Roadmap 2020".
21-Nov-18	SBLC	21	✓	✓	✓	• Open meeting. • Suggestion to create a commercialisation sub-group. • Breakout sessions on UK strengths, skills and systems for translation and industrial challenges. • Upcoming SynbiTECH conference focussed on how to create a sustainable bioeconomy.
19-Mar-19	SBLC	22	✓	✓	✓	• Bioeconomy strategy launched in December 18. • Discussion of sustainability and climate change issues as providing market pull. • Discussion of efforts towards a responsible innovation standard.
17-Jan-14	Governance Sub-group	1	✗	✓	✗	• Regulation of genetically modified organisms. • RRI - general discussion.
06-Jun-14	Governance Sub-group	2	✗	✓	✓	• Discussion of public dialogues and a standard for responsible research and innovation. • Discussion of UN CBD included discussion of "How can we inject rigour into claims being made for economic, social and environmental benefits and risks, to balance the rigour of the scientific research."

Table D.7 (cont.): A summary of published meeting minutes from the Synthetic Biology Leadership Council (SBLC) and its Governance Sub-group.

Meeting date	Meeting Type	Meeting Number	Financial value creation	RRI	Social or environmental value creation	Key Discussion Topics
17-Nov-14	Governance Sub-group	3	✘	✓	✓	• Discussion of Ecover/Solazyme controversies and work by Forum for the Future (FFF) asking "is there a role for this technology in a sustainable world?". • Discussion of CBD work and the risk of a moratorium on synbio.
10-Mar-15	Governance Sub-group	4	✓	✓	✓	• Use of synbio for healthcare discussed. Further discussion of regulation. • CBD/Nagoya discussion. Desire to avoid further regulation or a moratorium. • Analysis of arguments used by NGOs against SynBio presented.
18-Jun-15	Governance Sub-group	5	✘	✓	✓	• Further discussion of CBD and Nagoya protocol • Discussion of refresh of the roadmap. • Discussion of Ecover/Solazyme controversy, including sustainability and environmental impact.
01-Oct-15	Governance Sub-group	6	✘	✓	✘	• More CBD discussion. Including costs and benefits. • RRI element of the roadmap refresh. • Extensive discussion of public engagement - what to aim for and how to realise it.
02-Mar-16	Governance Sub-group	7	✘	✓	✓	• Further CBD discussion. • Discussion on public/stakeholder engagement and responsible innovation. Included discussion of the need for evidence of benefits and impacts, and broadening the definition of benefits beyond economics. • Suggested developing a strategy for RRI governance to try and anticipate issues.
07-Jun-16	Governance Sub-group	8	✘	✓	✘	• CDB discussions. • Discussion of Proportionate and Adaptive Governance of Innovative Technologies project. • Discussion included the avoidance of environmental harm but not value creation.
01-Nov-16	Governance Sub-group	9	✓	✓	✘	• CBD and Nagoya protocol discussions. • Discussion of Brexit implications for synthetic biology governance and regulation. • Stakeholder understandings of gene editing, CRISPR and gene drives discussed.
12-Apr-17	Governance Sub-group	10	✓	✓	✘	• CBD discussions. • Potential impact of Brexit on synthetic biology governance and the possibility of a bioeconomy sector deal. • Responsible innovation and stakeholder dialogue.
28-Jun-17	Governance Sub-group	11	✘	✓	✘	• Wellcome Trust perspective on gene editing presented. • CBD update. • Responsible innovation and stakeholder dialogue.

Table D.7 (cont.): A summary of published meeting minutes from the Synthetic Biology Leadership Council (SBLC) and its Governance Sub-group.

Meeting date	Meeting Type	Meeting Number	Financial value creation	RRI	Social or environmental value creation	Key Discussion Topics
19-Oct-17	Governance Sub-group	12	✓	✓	✓	• Discussion of synthetic biology communication and the science media centre. • Biosecurity discussion. • Various regulation-related matters incl. EU process and HSE approach. • Discussed the arsenic biosensor project with potential to improve detection of arsenic in drinking water.
26-Feb-18	Governance Sub-group	13	✓	✓	✘	• Need for more large businesses at future SBLC open meetings. • Mechanisms for making RRI more relevant to companies - PAGIT. • CBD update.
19-Jun-18	Governance Sub-group	14	✘	✓	✘	• Stakeholder engagement discussions. • Update on regulatory developments. • Role of the sub-group and relationship to the SBLC discussed.
18-Oct-18	Governance Sub-group	15	✓	✓	✘	• Revision of terms of reference. • Oxitec and Rothampsted regulation experiences discussed.
26-Feb-19	Governance Sub-group	16	✓	✓	✘	• Discussion of Bioeconomy strategy and potential sector deal. • BSI standard for responsible innovation discussed. • CBD update and discussion of human genome editing case in China.
		Totals	**26**	**33**	**12**	