



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Sustainability and Anticipatory Governance in Synthetic Biology

Citation for published version:

Wiek, A, Guston, D, Frow, E & Calvert, J 2012, 'Sustainability and Anticipatory Governance in Synthetic Biology' *International Journal of Social Ecology and Sustainable Development*, vol 3, no. 2, pp. 25-38., 10.4018/jsesd.2012040103

Digital Object Identifier (DOI):

[10.4018/jsesd.2012040103](https://doi.org/10.4018/jsesd.2012040103)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Author final version (often known as postprint)

Published In:

International Journal of Social Ecology and Sustainable Development

Publisher Rights Statement:

© IGI Global and Wiek, A., Guston, D., Frow, E., & Calvert, J. (2012). Sustainability and Anticipatory Governance in Synthetic Biology. *International Journal of Social Ecology and Sustainable Development*

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



Sustainability and Anticipatory Governance in Synthetic Biology

Arnim Wiek,^{1,2} David Guston,² Emma Frow³ and Jane Calvert⁴

¹ School of Sustainability, Arizona State University, PO Box 875502, Tempe, AZ 85287-5502, USA

² Center for Nanotechnology in Society and the Consortium for Science, Policy & Outcomes, Arizona State University, PO Box 875603, Tempe, AZ 85287-5603

³ Department of Science, Technology and Innovation Studies, The University of Edinburgh, Old Surgeon's Hall, High School Yards, Edinburgh EH1 1LZ, UK

⁴ ESRC Innogen Centre, The University of Edinburgh, Old Surgeon's Hall, High School Yards, Edinburgh EH1 1LZ, UK

Published as: Wiek, A., Guston, D., Frow, E., & Calvert, J. (2012). Sustainability and Anticipatory Governance in Synthetic Biology. *International Journal of Social Ecology and Sustainable Development*, 3(2), 25-38doi: 10.4018/jsesd.2012040103

Abstract

A prominent imaginary of synthetic biology is the sustainability of bio-based technologies. We discuss various reports, papers and activities in synthetic biology in relation to a core set of principles of sustainability, paying particular attention to the concept of “prudent vigilance” as introduced by the report by the US Presidential Commission for the Study of Bioethical Issues. We then introduce two additional concepts – anticipatory governance and transformational sustainability science – and outline an approach for systematically incorporating sustainability considerations into the development of synthetic biology that addresses the challenges and opportunities presented by the field in a more robust way than prudent vigilance. We conclude that there is an opportunity to shape synthetic biology toward sustainable outcomes, and we make recommendations for how research funders might seize this opportunity.

Keywords: synthetic biology; prudent vigilance; bioethical issues; anticipatory governance; transformational sustainability science; research funding

I. Introduction

The front cover of the program for the recent ‘Synthetic Biology 5.0’ conference states: “Our mission is to ensure that the engineering of biology is conducted in an open and ethical manner to benefit all people and the planet.”¹ As with many of the prominent imaginaries or visions of what is to become of synthetic biology in the future, this mission statement aligns quite clearly with goals of sustainability. But despite the prominence and prevalence of such sustainability-oriented visions, there is currently remarkably little robust discussion of how synthetic biology might pursue sustainability or precisely what kind of outcomes it could contribute to.

In this paper, we examine some of these imaginaries through an overview of how various reports, papers and activities in synthetic biology address sustainability. We discuss these in relation to a core set of principles of sustainability that can be derived from the literature. Our review of the connections proposed between synthetic biology and sustainability pays particular attention to the recent report by the US Presidential Commission for the Study of Bioethical Issues, which offers an extensive discussion of a concept introduced as “prudent vigilance” that in fact has a great deal in common with sustainability (as spelled out in the core principles). We then introduce two additional concepts – anticipatory governance and transformational sustainability science – and through these, outline an approach for systematically incorporating sustainability considerations into the development of synthetic biology that addresses the challenges and opportunities presented by the field in a more robust way than prudent vigilance. Finally, we argue that since synthetic biology is still in its early stages, there is an opportunity to shape its development towards sustainable outcomes, and we make recommendations for how research funders might seize this opportunity.

II. Synthetic biology imaginaries

In the introduction to a collection of essays on the “technoscientific imaginary”, George E. Marcus (1995:4) describes the imaginary as looking “to the future and future possibility through technoscientific innovation but [being] equally constrained by the very present conditions of scientific work.” As synthetic biology is an emerging field of technoscience with so much more to be planned and performed, the imaginaries associated with it play a particularly important role. Many synthetic biology imaginaries draw on notions of sustainability, and we find these imaginaries to be as diverse as scholars’ and practitioners’ understandings of synthetic biology and sustainability themselves.

Among the more curious and ambitious of these imaginaries is the idea that synthetic biology might act in the service of sustainability by replacing lost biodiversity, and could even to take us beyond what is found in nature to develop new biodiversity. For example, some synthetic biologists argue that nature’s canvas is limited by the contingencies and path-dependencies of evolution, and that with their technical powers and imagination they could eventually restore damaged portions of the canvas (for example, by restoring to life extinct species like mammoths) or even enlarge the canvas (by devising species new to nature, see Deamer 2008; Bedau and Parke 2009). Similarly, Poste (2007) talks about how synthetic biology will enable us to explore ‘biospace,’ the immense realm of mathematical possibilities for biological diversity that has been neglected by evolution.

A range of more speculative synthetic biology futures (perhaps closer to science fiction) have also been voiced and tie into discourses of sustainability. For example, there are discussions of how synthetic biology might enable us to grow houses rather than build

¹ See <http://sb5.biobricks.org/files/sb5-program-book-v3.pdf>. According to its website, “the SBx.0 international conference series is the preeminent meeting in the field of Synthetic Biology” (<http://sb5.biobricks.org/about/>).

them,² and of how living cells could be used to construct more sustainable buildings (Armstrong and Spiller 2010). Speculative designers Ginsberg and Pohflepp have imagined the possibility that synthetic biology might result in a future where goods are transported in the form of seeds that grow into desired commodities, in this way greatly reducing freight costs.³ In line with a common science fiction trope, NASA is exploring the possibility of giving Mars its ecosystem back through synthetic biology (or introducing a new ecosystem if it turns out Martian genomes cannot be reconstructed),⁴ and some envision efficient interstellar travel by sending the genetic instructions for recreating Earth-like environments and their inhabitants – even people – to planets orbiting distant stars.

Of course, critiques of these imaginaries also exist. The vision of biodiversity presented above focuses squarely on genes rather than broader habitats and ecosystems. Resurrecting a mammoth might be seen as a trivial achievement without, for example, resurrecting a larger population or community of mammoths, along with their associated grasslands, foodstuff, predators, parasites, etc. Critics also maintain that since synthetic biology would produce lifeforms that have no evolutionary or ecological history – and thus would not fit into the appropriate evolutionary and ecological niches – they cannot be considered substitutes for naturally evolved species and thus cannot contribute to biodiversity as properly conceived (Preston 2008; Norton 2010). And the ethics of terra-forming other worlds, while much anticipated in fiction, rehearses disputes among those who favour preservation, conservation, or use here on Earth. Our purpose is neither to evaluate how the imaginaries of synthetic biology relate properly to biodiversity (as one aspect of sustainability), nor to assess their likelihood of merging at some time in the future with the reality of synthetic biology research. Rather, it is simply to suggest that a number of imaginaries exist for synthetic biology that speak to important aspects of sustainability, and that provoke thought — and potentially conflict — over their pursuit. Before a more in-depth review of the proposed intersections between synthetic biology and sustainability (Section IV), we summarize a core set of sustainability principles that can help to differentiate across the spectrum of positions and proposals encountered.

III. Principles of Sustainability

When it comes to principles, criteria or guidelines of sustainability and of sustainable governance, there is some ambiguity about what these principles actually are, how they are justified, how they might be applied, and how individual principles are conceptually linked (Wiek et al. under review). Most importantly, the term ‘principle’ is used, often without clear indication, to denote either an *objective* (e.g. maintain a sufficient level of biodiversity in a given ecosystem), or an *instruction* (e.g. involve all legitimate stakeholders into a given decision-making process). Principles of sustainability as objectives spell out what governance needs to accomplish if it ought to qualify for the distinction ‘*sustainable governance*,’ whereas principles-as- instructions pertain to activities governance must carry out if it seeks to accomplish the objectives set forth. We focus in this section on sustainability principles as objectives. We return later to the principles of sustainable governance as instructions, when proposing how the concepts of anticipatory governance and transformational sustainability science can inform and support the responsible development of synthetic biology (Section V).

² See the ‘FAB TREE HAB’ designed by a team at the Massachusetts Institute of Technology; <http://www.archinode.com/bienal.html>

³ See <http://www.daisyginsberg.com/projects/growthassembly.html>

⁴ Synthetic Biology SB5.0 NASA Satellite Meeting, NASA Ames Research Center, California, USA (15 June 2011).

The concept of sustainability can be defined as a society's capacity to simultaneously secure viability and integrity of ecosystems (Principle 1), human and social well-being (Principle 2), and equitable opportunity for livelihood and economic activities (Principle 3) — within one given community (Principle 4), across inter-dependent communities (Principle 5), and over time (Principle 6) (Turner 1993; Gibson 2006; Wiek and Larson, in press). These principles can be structured conceptually along two axes: one concerned with ecological, social, and economic issues, and the second concerned with intra- and inter-generational equity.

Principle 1 – *Viability and Integrity of Ecosystems* means that sufficient levels of resource quantity, quality, and diversity are maintained in ecosystems not only for their bare viability but for their integrity and full functionality – because ecosystems are a valuable good in themselves, and they are indispensable for services ranging from climate regulation, detoxification, and geological stability to resource extraction, recreation, and tourism.

Principle 2 – *Human and Social Well-being* means that equitable access to sufficient quantity and quality of indispensable resources and services, including food, shelter, health services, educational opportunities, and so on, is ensured for all people, not only for survival but for well-being – because human and social well-being is considered a basic human right and the backbone of viable societies.

Principle 3 – *Equitable Opportunity for Livelihood and Economic Activities* means that equitable access to sufficient quantity and quality of resources and services is ensured for all people pursuing livelihood and economic activities – because those activities are a means to human and social well-being.

Principles 4-6 – *Justice Within One Community, Across Inter-dependent Communities, and Over Time* means that the content of the first three principles is ensured for all people living within one community, for all people living in inter-dependent communities (interconnectedness: upstream-downstream linkages, global markets, North-South dependencies, etc.), and for future generations over the long term. These principles are based on the concept of distributional justice (equitable access to resources and services), ethical stances (human rights), and other considerations (e.g. mitigation of conflicts).

Balancing all six principles (and their underlying claims) requires, at times, collective rejection of some or all claims in an equitable manner. Such 'trade-offs,' however, should be made without critically compromising any of the six principles (Gibson 2006). That is, conditions might require favouring some principles over others, but not in a durable fashion that would prevent a temporarily unfavoured principle from equal consideration in the future.

IV. Sustainability as articulated in synthetic biology reports

The core principles of sustainability can help us to articulate how the visions of sustainability described above are in fact cast narrowly. In promoting goals of restoring or enhancing ecosystems' biodiversity and reducing environmental impact through the use of renewable materials, they focus primarily on Principle 1 — the viability and integrity of ecosystems. Interestingly, the critiques (for example, regarding non-evolutionary life forms) refer to the same principle.

The principles can also help us identify and characterize the imaginaries in the broader public discussion around synthetic biology. Ironically, apart from these speculative visions, what is perhaps most notable about the discussion of sustainability in synthetic biology today is its absence. We have reviewed 40 reports on synthetic biology published between 2004 and 2011 and found mentions of the term 'sustainability' in 21

of these (see Appendix).⁵ Most of the reports that mention sustainability offer no explanation of what precisely is meant (which is why we outline the core principles above), giving the distinct impression that the authors of these reports believe that, somehow, synthetic biology will contribute to sustainability, but through what means they do not know.

Several of the reports make general claims about synthetic biology and sustainability. For example, oral and written evidence provided during the UK House of Commons 2009/2010 inquiry into Bioengineering make arguments that the challenges of “a productive economy, a healthy society and a sustainable planet” (p.79) are best served by science, and that synthetic biology is an important tool in this armoury. Similarly, a report jointly published by the OECD and the Royal Society in 2010 maintains that “[s]ynthetic biology can help address key challenges facing the planet and its population, such as food security, sustainable energy and health” (p.8). A number of reports also highlight economic dimensions of sustainability, such as efficiency gains, wealth creation, and international trade (e.g. Woodrow Wilson Center 2009; House of Commons 2011; Zhang et al 2011). Although economic considerations are critical for sustainability (Principle 3), it is important to recognize that sustainability requires the fulfilment of all principles *simultaneously*. Thus, the idea of a separable “economic dimension of sustainability” is at odds with the integrated idea of sustainability and the notion of bounding the impact of trade-offs. This position is articulated in a 2010 report by the nongovernmental organization GeneWatch that challenges the assumption that “investments in the biosciences and biotechnology will inevitably deliver health, wealth and sustainability” (p.115) and argues that the narrowly defined economic benefits that many reports advocate conflict with the integrated objective of sustainability. This report also questions the research priorities that are often assumed to foster sustainability, arguing that sustainability is not solely an issue of technological development. We return to this position in Section V when outlining the concepts of anticipatory governance and transformational sustainability science that encourage the allegedly paradoxical exploration of alternative solutions (including non-technological ones) in the development of emerging technologies.

Somewhat more specific examples of how synthetic biology might contribute to sustainability emerge in statements such as synthetic biology “could make the chemicals industry more environmentally friendly and sustainable” (NEST 200, p.8); in a similar vein, several reports suggest that synthetic biology will lead to the production of sustainable chemicals, fuels, and materials (e.g. European Academies Science Advisory Council 2010; International Risk Governance Council 2011). The construction of an artificial metabolic pathway in *E. coli* and yeast to produce the anti-malarial drug artemisinin is often cited in this context (Martin et al. 2003; Ro et al. 2006), and it has been suggested that synthetic biology approaches could be used to produce a variety of useful therapeutics, flavours, and scents (Ajikumar et al. 2008).

Discussions of artemisinin bring other aspects of sustainability to the fore, namely, the principle of human and social well-being (Principle 2) and issues of justice and equality (Principles 4-6). The latter have been used to point to possible negative impacts caused by the production of artemisinin. The ETC Group, a Canadian NGO, is a prominent critical voice in the field, and its 2007 report on synthetic biology argues that the production of artemisinin using synthetic biology is not as sustainable as facilitating its local production by farmers in East Africa (the chemical precursor to artemisinin is currently extracted from the sweet wormwood plant *Artemisia annua*). A 2008 report commissioned by the UK’s Biotechnological and Biological Sciences Research Council

⁵ The list of reports surveyed is published on p.35-36 of Zhang et al (2011).

(BBSRC) also maintains that it is important to ask whether synthetic biology will create new inequalities or potentially exacerbate existing ones (Principles 4-6). Both of these reports link synthetic biology and sustainable development to broader issues of global justice.

Another topic of debate relating to the principle of ecosystem viability and integrity (Principle 1) is the idea that synthetic biology (among other technologies) will facilitate a transition away from a petroleum-based economy towards a bio-based one (European Commission 2005).⁶ (This can be seen, for example through DARPA's recent 'Living Foundries' funding stream.)⁷ Arguments are being made for the importance of moving to a sustainable biological manufacturing platform centred around biorefineries (as opposed to petrochemical refineries). The implicit future is one where the behaviour of consumers does not have to change, but rather that existing industrial infrastructure will simply be replaced with infrastructure that processes biological material. For example, a 2007 report by NEST identifies a role for synthetic biology as a technology to "convert sustainable feedstocks to fuels" (p.14). Mentions of sustainability frequently come up in the context of synthetic biology for biofuel production, with recurring suggestions along the lines that synthetic biology can "make the biofuel process more energy efficient, and therefore more economical and environmentally sustainable" (Woodrow Wilson Center 2009, p.19). The scientific literature on synthetic biology and biofuels also regularly mentions sustainability (e.g. Sheridan 2009; Dellomonaco et al 2010). However, the inherent sustainability of a 'post-petroleum economy' and the shift towards more biologically-based manufacturing is challenged in general terms in several articles (e.g. Naylor et al. 2007; Frow et al 2009), and more specifically in relation to synthetic biology by the ETC Group, which argues that it rests on the assumption that there will be unlimited supplies of cellulosic biomass. Their 2008 report asks "can massive quantities of biomass be harvested sustainably without eroding/degrading soils, destroying biodiversity, increasing food insecurity and displacing marginalized peoples?" (ETC Group 2008, p.4). This critique refers back to issues of justice (Principles 4-6).

Another category of references to sustainability that surfaces in reports on synthetic biology is the sustainability of synthetic biology itself as a field of R&D (TESSY 2008). Such concerns are sometimes linked to the sustainability of intellectual property regimes (engaging primarily with Principle 5). The International Risk Governance Council argues, for example, that synthetic biology requires intellectual property frameworks that will stimulate innovation in a sustainable manner (IRGC 2011), and a 2009 report by the European Group on Ethics (EGE) asks whether the open-source model being promoted for synthetic biology is sustainable in the context of life science R&D. Models of open-source or distributed innovation in synthetic biology are sometimes discussed in the context of mitigating the dominance of multinational corporations, and also in terms of extending the boundaries of synthetic biology to include non-expert groups (Zhang et al 2011). The aspiration we see to turn biological engineering into a low-cost, easy-access, open-source technology can again be related to questions of sustainability and the distribution of power and responsibility.

⁶ See also Brian Pflieger's work:

http://www.engr.wisc.edu/che/newsletter/2008_springsummer/article05_brian_pflieger.html

⁷

https://www.fbo.gov/index?s=opportunity&mode=form&id=010c6a305013fb972061e3d76fcea2dd&tab=core&_cview=0

Prudent Vigilance and the Presidential Bioethics Commission report

To the modest extent that these 40 reports address sustainability, they seem to fall into a general pattern, emphasizing either the potential contributions of synthetic biology to discrete aspects of sustainability, particularly the environmental and economic aspects, or emphasizing the equity concerns of sustainability as well as its integrative character (these issues are addressed primarily in reports written by NGOs).

The 2010 report on synthetic biology published by the US Presidential Commission for the Study of Bioethical Issues is a significant recent contribution to the discussion of the field. We pay particular attention to it here because in its relatively balanced and integrative treatment, this report stands in some contrast to its predecessors. Yet it nevertheless falls short in precisely those dimensions that lead us on to our discussion of anticipatory governance.

One of the ways that the Commission report has imagined grappling with the prospective importance of synthetic biology is through a process of what it calls “prudent vigilance”. In addressing synthetic biology, the Commission believes it has the opportunity “to be forward looking instead of reacting. We are ahead of the emerging science,” it declares (p. 3). Looking for a “middle way” between “a moratorium on synthetic biology until all risks are identified and mitigated” (which is how the Commission characterizes the demands of precaution) and “unfettered freedom for scientific exploration” (p. 8; which the Commission characterizes as “proaction”), the Commission outlines an approach that:

does not demand extreme aversion to all risks. Not all safety and security questions can be definitively answered before projects begin, but prudent vigilance does call for ongoing evaluation of risks along with benefits. The iterative nature of this review...recognizes that future developments demand that decisions be revisited and amended as warranted by additional information about risks and potential benefits. The duty to be responsible stewards of nature, the earth’s bounty, and the world’s safety rests on concern not only for human health and well-being today but also, and importantly, for future generations and the environment looking forward (p. 27).

The Commission identifies:

five ethical principles relevant to considering the social implications of emerging technologies [including synthetic biology]: (1) public beneficence, (2) responsible stewardship, (3) intellectual freedom and responsibility, (4) democratic deliberation, and (5) justice and fairness (p. 4).

These principles, and their subsidiary ones, align closely with the sustainability principles outlined above. For example, the principle of responsible stewardship is defined as a:

shared obligation among members of the domestic and global communities to act in ways that demonstrate concern for those who are not in a position to represent themselves (e.g., children and future generations) and for the environment in which future generations will flourish or suffer (p. 4).

This corresponds to Sustainability Principles 4-6 and “can be interpreted in an operational way to pose the question, ‘What can and should we, as a society, do...to be responsible stewards of nature, the earth’s bounty, human health and well-being, and the world’s safety, now and into the future?’” (p. 123). Because of the vast uncertainties over both risks and benefits involved in emerging technologies, the Commission believes that responsible stewardship:

calls for prudent vigilance, establishing processes for assessing likely benefits along with assessing safety and security risks both before and after projects are undertaken. A responsible process will continue to assess safety and security as technologies develop and diffuse into public and private sectors. It will also include mechanisms for limiting their use when necessary (p. 4).

The Commission seeks to promote responsible stewardship of synthetic biology by recommending (in summary) various coordinating actions at the cross-agency level by the US Executive Office of the President and early and repeated risk assessments, including gap analysis for field releases of synthetic organisms and products (recommendations 4-7). The Commission also recommends “ethics education similar or superior to the training required today in the medical and clinical research communities...for all researchers and student-investigators outside the medical setting” (recommendation 9, p. 11) and “ongoing evaluation” of moral objections that have and may in the future be raised about synthetic biology (recommendation 10, p. 12).

The Commission makes other recommendations specifically associated with other principles yet convergent with responsible stewardship, including “scientific, religious, and civic engagement” (recommendation 14, p. 15) and the fair distribution of “risks in research” and “risks and benefits in commercial production and distribution” (recommendations 17 and 18, pp. 16-17).

The Commission’s perspective shares a great deal with the sustainability perspective previously outlined in that it attempts to incorporate, accommodate, and balance concerns derived from economic, environmental, and societal perspectives across spatial and temporal scales. However, it is less successful in comparison to the three capacities sought by anticipatory governance: foresight, engagement, and integration, as well as the procedures proposed in transformational sustainability science. We turn now to these concepts.

V. Anticipatory governance and transformational sustainability science approaches

We outline here how the sustainability principles introduced above, and other critical principles as *instructions*, can be endorsed in the development of synthetic biology. To this end, we recommend a novel approach that combines anticipatory governance and transformational sustainability science. The approach has been applied to emerging nanotechnologies, and more specifically, in the context of nanotechnological applications in cities and the built environment (Wiek et al. under review). We are aware of distinct differences between nanotechnology and synthetic biology (Torgersen 2009). However, we believe the approach is sufficiently generic to be adapted to the case of synthetic biology in a way that reflects the particularities of the field.

Anticipatory governance provides a set of procedural principles about how to collectively imagine, deliberate, design, and influence the development of emerging technologies (Guston and Sarewitz 2002; Macnaghten et al. 2005; Barben et al. 2008; Guston 2008). It envisions the societal capacity for engaging in the development of

emerging technologies like synthetic biology before interests and innovations are too reified for reflection, revision, and refinement. Transformational sustainability science provides a normative framework and a procedural template for applying those principles in a structured and goal-oriented way. It combines the analysis of current socio-technical systems with future-oriented and normative inquiries in order to craft governance strategies to transition towards sustainable dynamics (Loorbach 2010; Sarewitz et al. 2010; Wiek et al. 2012). Both approaches share key principles while complementing each other in their epistemological, methodological, and institutional frameworks.

The combined approach focuses on the actual “doing of/with synthetic biology”. The main argument is that a governance perspective needs to be “closest” to the actions and activities it intends to govern, namely here, the envisioning, making, use, and disposal of novel biological systems. We adopt a procedural framework proposed by Robinson (2009) that is inspired by life-cycle thinking and conceptualizes synthetic biology innovation as a sequence of overlapping phases from idea inception to waste disposal (Fig. 1).

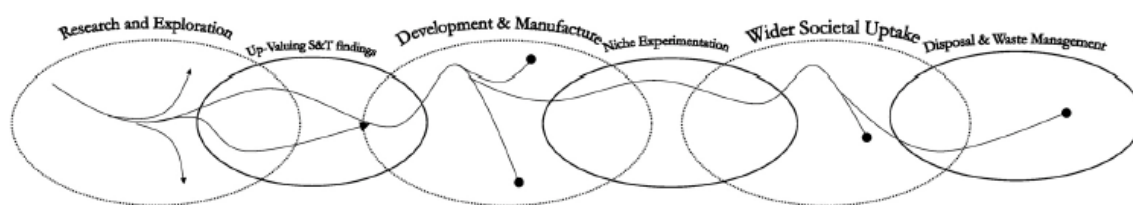


Figure 1. A dynamic model of synthetic biology innovation (adapted from: Robinson, 2009)

Through those phases, the combined approach of anticipatory governance and transformational sustainability science supports synthetic biology innovation through five interconnected research activities:

1. *Systemic Analysis of Synthetic Biology Innovation.* This module reviews the spectrum of potential synthetic biology applications, what their specific functions are, how they are being developed, who is involved in the innovation process at what stage, what are the power constellations and institutional settings among different actor groups etc. from a systems perspective. Drivers, interactions, dynamics, feedback-loops, and other systems features of the innovation process are systematically described and analysed to gain a comprehensive overview of the current situation.
2. *Foresight.* Most of the synthetic biology applications are still in the making. We do not know how they might play out in the future. While there is still potential for new directions, adjustment, and change, governance regimes need to be created that anticipate and account for future developments (Rutz 2007; Selin 2007; Wiek et al. 2009). The second module, therefore, builds upon the system analysis and combines two activities:

First, visions of synthetic biological systems are reviewed and evaluated against the following guiding questions: What is the contribution of such novel biological systems to the enhancement or maintenance of the viability and integrity of ecosystems, human and social well-being, and equitable opportunity for livelihood and economic activities across spatial and temporal scales? (This casts sustainability principles as objectives.) What sustainability problems are such

novel biological systems capable of mitigating or solving? Are these challenges the most pressing and salient ones from a sustainability perspective?

Second, these visions are further scrutinized and assessed with respect to a set of complementary guiding questions that reflect potential costs and downsides of synthetic biology innovation: What will be the **costs** (in a comprehensive sense) of such novel biological systems? What could be the unintended consequences or negative side effects? Who will benefit from these novel biological systems and who will bear the costs? Do the promised benefits justify the associated costs and potential side effects? Are there alternative solutions (including non-technological ones) that could yield results more quickly, more effectively, more efficiently, and with fewer (harmful) side effects?

3. *Backcasting Governance Strategies.* On the basis of the previous two modules, strategies for anticipatory governance of synthetic biology are created, crafted, and tested. The purpose is to deliberate on and construct governance arrangements that seem to be conducive for avoiding undesirable synthetic biology futures and enabling the desired ones. This exploration goes into the networks, tactics, roles, and responsibilities of different stakeholder groups affected by or involved in the synthetic biology innovation process. It identifies critical constellations, such as missing key stakeholders, non-fulfilment of required governance functions, non-availability of required knowledge systems, and deviations between self- and cross-perception (Wiek et al. 2007).
4. *Engagement.* Throughout the three modules described above, engagement with a variety of lay publics and stakeholder groups, as well as knowledge integration across academic disciplines, needs to be facilitated. Anticipatory governance seeks to build and sustain substantive and deliberative public engagement. Preferences, expectations, potential benefits, and concerns related to synthetic biology are often contested and vary greatly among different stakeholder groups (Kahan et al. 2009; Pauwels 2009). The principle of engagement is realized through provision of continuous opportunities to deliberate on the opportunities and risks of synthetic biology within and across different communities of knowledge and practice. This has been identified as a critical challenge for synthetic biology innovation (Chopra and Kamma 2006). The lack of deliberation leaves divergences largely unrevealed, which might undermine collaborative and coordinative efforts to explore the potential of synthetic biology for sustainability. Such engagements are best pursued in “real-world” contexts where the novel biological systems are embedded in everyday life experience, activities, and decisions (Wiek et al. under review). A clear link between discourse and experience is prone to a greater willingness to engage (people care about their society and environment), more meaningful engagement processes (people understand the functionality and implications), and tangible outcomes. Finally, because an important goal of the combined approach of anticipatory governance and transformational sustainability science is to explore and articulate new governance strategies for synthetic biology, engagement needs to go beyond passive statements of positions, perspectives, and preferences—in short, beyond extractive social science.
5. *Integration.* Anticipatory governance also entails the integration of the natural sciences and engineering, on one hand, with the social sciences and humanities on the other. The novel approach enables this type of integration throughout the three modules based on the concept of “socio-technical integration research” (e.g. Fisher 2007). The basic idea is to embed anticipatory governance researchers and sustainability scientists in organizations alongside the innovation process —

that is, in academic or private laboratories and development facilities, public sector agencies, and non-governmental organizations. Through this embedding, researchers are able to spark and engage in dialogues about responsible technological innovation *in situ* and across different disciplinary fields, as well as across different communities of knowledge and practice. For several years now, the field of synthetic biology has been experimenting with models for including social science and humanities researchers in its networks and research activities (see Calvert and Martin 2009), but to date sustainability scientists have not been well represented in these endeavours.

In summary, the adoption of a novel approach that combines anticipatory governance and transformational sustainability science for guiding and supporting synthetic biology innovation ventures into an engaged process to: 1) better understand the current situation of synthetic biology innovation and governance; 2) explore the potential contributions of synthetic biology to sustainability and to evaluate potential costs and negative side-effects; and 3) develop governance strategies to provide guidance towards realizing such desirable and sustainable visions as well as actively avoiding undesirable and unsustainable ones.

VI. Implications for research councils and funding agencies

Although concrete discussions of sustainability are strikingly absent from current discussions of synthetic biology, at this stage in the development of the field there is clear scope to begin integrating sustainability concerns into research design and practice — of findings ways to use sustainability principles-as-objectives in developing concrete instructions for practice. We would like to see best practices of anticipatory governance and transformative sustainability science extended across all research programmes in synthetic biology. To this end, we make the following recommendations for funders investing in synthetic biology research. First, there should be support for social science and sustainability science research to be done in close connection with synthetic biology research; this could and should include funding social science components as part of individual research projects as well as larger-scale programmes for synthetic biology. Such close links are important to ensure that analyses of synthetic biology are closely grounded in current research practices, and that findings from foresight, backcasting and engagement efforts can be fed back into research design processes at the laboratory level. Second, funders should encourage projects that develop specific tools, techniques, and capacities in foresight and backcasting for synthetic biology, and for experimenting with approaches to engagement and integration. The five stages outlined in Section V should be seen as elements of an iterative and ongoing process, and developing programmes, research teams and capacities not just to carry out this research in ways attentive to the specific context of synthetic biology, but also to find ways of integrating across these stages, should be treated as a funding priority. Encouraging interactions between researchers studying synthetic biology as well as other emerging technologies (such as nanotechnology and geoengineering) may help to extract principles of best practice from anticipatory governance and transformative sustainability science in guiding the development of new technologies. Finally, finding ways to translate findings from transformational sustainability science into concrete priority-setting and other policymaking processes for synthetic biology is a challenge that should also receive funding and support, particularly if wanting to ensure that synthetic biology research and applications do indeed make positive contributions to longer-term sustainability goals.

References

- Ajikumar, PK, Tyo ,K, Carlsen, S, Mucha, O, Phon, TH and Stephanopoulos, G (2008) 'Terpenoids: Opportunities for Biosynthesis of Natural Product Drugs Using Engineered Microorganisms' *Molecular Pharmaceutics*, 5 (2), 167-190
- Armstrong, R and Spiller, N (2010) 'Synthetic biology: living quarters' *Nature*, 467 (7318): 916-918.
- Barben D, Fisher E, Selin C, Guston D H, 2008, "Anticipatory governance of nanotechnology: foresight, engagement, and integration", in *The Handbook of Science and Technology Studies* 3rd edition, Eds E J Hackett, O Amsterdamska, M Lynch, J Wajcman (MIT Press, Cambridge, London) pp 979 - 1000
- Bedau, M.A. and Parke, E.C. (2009) 'Introduction to the ethics of protocells' in Bedau, M.A. and Parke, E.C. (eds) *The Ethics of Protocells: moral and social implications of creating life in the laboratory* Cambridge, MA: MIT Press.
- Biotechnology and Biological Sciences Research Council (2008) *Synthetic Biology: Social and Ethical Challenges*. Online at:
<http://www.bbsrc.ac.uk/organisation/policies/reviews/scientific-areas/0806-synthetic-biology.aspx>
- Calvert, J and Martin, P (2009) 'The role of social scientists in synthetic biology' *EMBO reports*, 10(3): 201-204
- Chopra, P. and Kamma, A. (2006). Engineering Life through Synthetic Biology, *In Silico Biology* 6, 401-410.
- Deamer, D (2008) 'First life, and next life: the origins and synthesis of living cells' 9th EMBL/EMBO joint conference, Heidelberg, Germany, 7th November 2008.
- Dellomonaco, C, Fava, F and Gonzalez, R (2010) 'The path to next generation biofuels: successes and challenges in the era of synthetic biology' *Microbial Cell Factories*, 9:3
- Dunbar, SJ (2010) 'Synthetic biology opportunities in agriculture' Second RoSBNet Synthetic Biology Workshop, Oxford, 12th-14th July 2010, online at:
http://sysos.eng.ox.ac.uk/control/RoSBNet/images/c/c1/Rosbnet_SDunbar.pdf
- ETC Group (2007) *Extreme Genetic Engineering: An Introduction to synthetic Biology*. Online at:
<http://www.etcgroup.org/upload/publication/602/01/synbioreportweb.pdf>
- ETC Group (2008) *Commodifying Nature's Last Straw? Extreme Genetic Engineering and the Post-Petroleum Sugar Economy*. Online at:
<http://www.etcgroup.org/upload/publication/703/02/sugareconomyweboct10-2008.pdf>
- European Academies Science Advisory Council (2010) *Realising European Potential in Synthetic Biology: Scientific Opportunities and Good Governance*. Online at:
http://www.easac.eu/fileadmin/PDF_s/reports_statements/Synthetic%20Biology%20report.pdf
- European Commission (2005) *New Perspectives on the Knowledge-Based Bio-Economy*. Online at:
http://ec.europa.eu/research/conferences/2005/kbb/pdf/kbbe_conferencereport.pdf
- European Group on Ethics in Science and New Technologies to the European Commission (2009) *Ethical Aspects of Synthetic Biology*. Online at:
http://ec.europa.eu/bepa/european-group-ethics/docs/publications/round_table_ethical_aspects_of_synthetic_biology.pdf
- Fisher E (2007) *Ethnographic invention: probing the capacity of laboratory decisions*. *NanoEthics* 1 155-165.
- Frow, E., Ingram, D., Powell, W., Steer, D., Vogel, J. & Yearley, S. (2009) *The politics of plants*. *Food Security* 1(1): 17-23.
- Gibson, R.B. (2006). *Sustainability assessment: basic components of a practical approach*. *Impact Assessment and Project Appraisal* 24, 170-182.

- Guston D H (2008) Innovation policy: not just a jumbo shrimp *Nature* 454: 940-941
- Guston D H, Sarewitz D, 2002, "Real-time technology assessment" *Technology in Society* 24(1-2): 93-109
- House of Commons (2010) *Bioengineering Seventh Report of Session 2009-10: Report, Together with Formal Minutes, Oral and Written Evidence*. Online at: <http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsstech/220/220.pdf>
- International Risk Governance Council (2011) *Guidelines for the Appropriate Risk Governance of Synthetic Biology*. Online at: http://www.irgc.org/IMG/pdf/irgc_SB_final_07jan_web.pdf.
- Kahan D M, Braman D, Slovic P, Gastil J, Cohen G (2009) "Cultural cognition of the risks and benefits of nanotechnology." *Nature Nanotechnology* 4(2): 87-90
- Khalil, AS and Collins, JJ (2010) 'Synthetic biology: applications come of age' *Nature Reviews Genetics* 11, 367-379
- Loorbach D, 2010, "Transition management for sustainable development: a prescriptive, complexity-based governance framework" *Governance* 23(1): 161-183
- Macnaghten P, Kearnes M B, Wynne B (2005) "Nanotechnology, governance, and public deliberation: what role for the social sciences?" *Science Communication* 27(2): 268-291
- Marcus, GE (1995) *Technoscientific Imaginaries: Conversations, Profiles, and Memoirs*. Chicago: University of Chicago Press.
- Naylor R, Liska AJ, Burke MB, Falcon WP, Gaskell JC, Rozelle SD, et al. (2007) The ripple effect: biofuels, food security and the environment. *Environment* 49, 30-43.
- New and Emerging Science and Technology (NEST) (2005) *Synthetic Biology: Applying Engineering to Biology*. Online at: ftp://ftp.cordis.europa.eu/pub/nest/docs/syntheticbiology_b5_eur21796_en.pdf
- NEST (2007) *Synthetic Biology: A NEST Pathfinder Initiative*. Online at: <ftp://ftp.cordis.europa.eu/pub/nest/docs/5-nest-synthetic-080507.pdf>.
- Norton (2010) 'Synthetic Biology: Some Concerns of a Biodiversity Advocate' Remarks on Synthetic Biology to the Presidential Commission on Bioethics, online at: <http://www.bioethics.gov/cms/sites/default/files/Synthetic-Biology.pdf>
- OECD and the Royal Society (2010) *Symposium on Opportunities and Challenges in the Emerging Field of Synthetic Biology: Synthesis Report*. Online at: <http://www.oecd.org/dataoecd/23/49/45144066.pdf>.
- Pauwels, E., 2009. Review of quantitative and qualitative studies on U.S. public perceptions of synthetic biology. *Systems and Synthetic Biology* 3, 37-46
- Poste, G (2007) 'Synthetic biology and sustainability' Presentation at 1st Interdisciplinary Symposium: Global Sustainability – A Nobel Cause, Potsdam, FDR 10 October 2007
- Preston, CJ (2008) 'Synthetic Biology: Drawing a Line in Darwin's Sand' *Environmental Values* 17: 23-39.
- Presidential Commission for the Study of Bioethical Issues (2010) *New Directions: The Ethics of Synthetic Biology and Emerging Technologies*. Online at: <http://www.bioethics.gov/documents/synthetic-biology/PCSBI-Synthetic-Biology-Report-12.16.10.pdf>
- Robinson, D.K.R. (2009). Co-evolutionary scenarios: An application to prospecting futures of the responsible development of nanotechnology. *Technological Forecasting & Social Change* 76, 1222-1239
- Rutz B (2007) Synthetic biology through the prism of scenarios. *Biotechnology Journal* 2, 1072-1075
- Selin C, 2007, "Expectations and the emergence of nanotechnology" *Science, Technology, & Human Values* 32(2) 196 – 220

- Sarewitz, D., Kriebel, D., Clapp, R. Crumbley, C., Hoppin, P., et al., 2010. The Sustainable Solutions Agenda. Consortium for Science, Policy and Outcomes and Lowell Center for Sustainable Production, Arizona State University and University of Massachusetts, Lowell.
- Sheridan (2009) 'Making green' *Nature Biotechnology*, 27: 1074-1076.
- Towards a European Strategy for Synthetic Biology (2008) *TESSY Achievements and Future Perspectives in Synthetic Biology*. Online at: http://www.tessy-europe.eu/public_docs/TESSY-Final-Report_D5-3.pdf.
- Torgersen, H. 2009. Synthetic biology in society: learning from past experience? *Systems and Synthetic Biology* 3, 9-17
- Turner, R.K., 1993. Sustainability: principles and practice. In: Turner, R.K. (Ed.), *Sustainable Environmental Economics and Management: Principles and Practice*. Belhaven Press, London, pp. 3-36.
- Wiek A, Zemp S, Siegrist M, Walter A I, 2007, Sustainable governance of emerging technologies--critical constellations in the agent network of nanotechnology. *Technology in Society* 29(4), 388 - 406
- Wiek, A., Gasser, L., Siegrist, M., 2009, Systemic scenarios of nanotechnology - Sustainable governance of emerging technologies. *Futures* 41, 284-300.
- Wiek, A., Ness, B., Brand, F.S., Schweizer-Ries, P., Farioli, F., 2012. From complex systems analysis to transformational change: A comparative appraisal of sustainability science projects. *Sustainability Science* 7 (Supplement 1), 5-24.
- Wiek, A., Larson, K.L., in press. Water governance, people, and sustainability - A systems approach for analyzing and assessing water governance regimes. *Water Resources Management*.
- Wiek, A., Guston, D., van der Leeuw, S., Selin, C., Shapira, P., under review. The nano-enhanced city, sustainability challenges, and anticipatory governance.
- Woodrow Wilson Center (2009) *New Life, Old Bottles: Regulating First-Generation Products of Synthetic Biology*. Online at: http://www.synbioproject.org/process/assets/files/6319/nano_synbio2_electronic_final.pdf.