SYNTHETIC BIOLOGY, SUSTAINABILITY, AND THE CIRCULAR BIOECONOMY – SEEING THE BIGGER PICTURE IN THE TRANSITION TO A SUSTAINABLE CHEMICAL INDUSTRY

1 INTRODUCTION

The production of chemicals and materials will be an increasingly important driver in the growth of fossil oil and gas consumption[1]. Of course, this growth in petrochemical production has implications for the climate and should be considered in strategies to address climate change.

The global chemical industry in aware of the issue and many companies have begun the transition from petrochemical to biobased chemical processes[2,3,4].

The adoption of industrial biotechnology to produce chemicals from renewable feedstocks using cell factories is expected to be key enabling technology in this transition.

Rapid advances in synthetic biology (or engineering biology) present the increasing ability to quickly engineer cell factories to produce chemicals efficiently and sustainably. Recognising this opportunity, significant sums of research funding has been directed to the development and application of synthetic biology and roadmaps[5,6] providing direction for the development of communities and facilities have been produced.

SHIKIFACTORY100 is one project providing a collaborative effort to boost European synthetic biology competitiveness. This 8 million Euros project aims to produce more than 100 high-value compounds from the shikimate pathway, a hub in cell metabolism, through the development of an optimized chassis and the proposal and implementation of novel biosynthetic routes for the production of known and new to nature molecules[7].

However, research and technology development are just one component of innovation[8]. An innovation system is built from components which provide the structure for the system[9]. Research applies to technological component of the system which define and constrain the system such as costs, safety, and reliability. Beyond technology innovation relies on systems actors, e.g., the organisations contributing to a technology, as a developer or adopter, or indirectly as a regulator or financier. A third component are the institutions, which lie at the core of the ecosystem providing the rules and boundaries in which the system operates. These include formal institutions such as governmental laws and policy and informal institutions reflecting societal morals values and ethics.

Innovation relies on the effective interaction of all systems actors. Without this interaction, knowledge development and transfer will be limited; legal and regulatory frameworks could be misguided or inappropriate; entrepreneurs will be poorly informed on business opportunities and risks, and industry, academia and Government will struggle to find a consensus around the legitimate direction of technology development.

The legitimacy of a biobased economy has been widely questioned by both NGOs and the academic community[10,11,12,13,14], although criticisms have been largely targeted at biofuel production, these concerns do apply to biobased products. Questions over biodiversity impacts, social concerns around

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food security and even questions on the potential for greenhouse gas emission reductions, serve to reduce the acceptance of biobased products as a positive change for good.

This position has resulted in the discrepancy seen between positive policy statements, recognising the need to reduce fossil inputs in material production[15], and the inertia in the actual practical implementation of policy[16,17]. This issue is widely recognised in the UK and across the EU, although the biobased economy is attractive in many ways; for too many stakeholders, it's complicated and fraught with risk, resulting in a wait and see, or a let's focus on simpler issues mind set.

Therefore, unlocking the full potential of the biobased economy rests on achieving a consensus between stakeholders on what a transition could look like and how it should be managed.

At the heart of societies environmental crisis lies the issue of overconsumption[18,19]. This isn't just a fossil fuel problem but an issue which cuts across the extraction of all natural resources whether it be water for food production, sand for concrete manufacture or precious metals for mobile phones. 'Earth overshoot day' [20] creeps earlier each year and it is argued that without intervention, by 2030 we will need 2 planets to meet both our resource needs and absorb societies wastes.

1. Reduce consumption

So, the first step in the journey to a sustainable biobased economy is to embrace the need to reduce consumption[21]. Reducing consumption reduces the volume of raw material extracted from the natural environment and therefore degradation of landscapes and the subsequent loss in biodiversity.

Reducing consumption means changing consumer attitudes and societal norms[22], and a shift in business activities from the sale of goods to the sale of services[23]. For materials this means designing products for durability and longevity of use[24,25], it means rethinking the idea of fashion and the commercial push for constant change[26,27]. For agriculture and the food chain it means reducing avoidable waste at all points in the value chain[28]. The growing population only heightens the need to rethink consumption and although an era of population decrease is on the distant horizon, this will come far too late to stop the significant environmental damage resulting from unmitigated climate change.

2. Reduce virgin raw material demand

Consumption cannot be eliminated but we can optimise the use of the materials we extract from the natural environment, ultimately decoupling extraction from economic output.

The circular economy aims to design out the negative impacts of economic activity by keeping materials in use and targeting the effective use of waste (even eliminating the concept of waste[29]). Design is the key element of the circular economy. Designing products to be reusable and if not, ensuring they can be efficiently and economically recycled. The circular economy functions as an expanding set of circles where inner circles, including product reuse and closed loop mechanical recycling[30], represent low energy and resource efficient cycling of materials. While less efficient, outer circles such as chemical recycling[31] and recovering carbon dioxide from energy from waste plants[32] keep valuable carbon resource in the economy and reduce the leakage of toxic emissions back into the environment.

3. REDUCE COMPETING BIOMASS DEMAND

There is a myriad of competing demands for biomass, from the traditional applications of construction, paper and oleochemicals, to new policy driven demand for biomass as a feedstock for electricity generation, and the production of heat and liquid fuels[33].

At the heart of bioenergy policies is the aim to reduce greenhouse gas emissions and particularly a reduction in carbon dioxide emissions[34]. By the nature of the carbon cycle, biofuels can reduce the net carbon dioxide emissions relative to fossil fuels[35], but they are still a source of carbon dioxide emissions. It is recognised that ideally energy needs should be supplied by technologies with no combustion emissions, i.e., decarbonised[36]. As such wind, solar and a raft of renewable technologies are the preferred source of electricity, and furthermore this electricity can be used to power road transport. Other sectors are harder to decarbonise, but it is possible, green hydrogen is a future fuel for the aviation sector[37,38] and the conversion of green hydrogen to ammonia provides a fuel for maritime shipping[39].

Decarbonisation of energy supply allows precious biomass resource to be directed towards applications requiring carbon as a physical input i.e., organic chemicals and derived materials. These materials which include plastics cannot be decarbonised, only defossilised[40].

4. REDUCE LAND DEMAND

The production of biomass is inextricably linked to the use of land resource. Biomass for biobased product production is either cultivated as a primary raw material (cereals, vegetable oils, timber etc), or produced, either as a residue from primary production (straw, forest thinnings etc) or from material processing (cereal husks, sawdust etc). Outside of the forest industry, biobased products are predominantly produced from cereal, sugar or oil crops. Given the current low volume of production, biobased product demand has little impact on global land use or the cultivation economics of food or feed crops[41]. The use of these arable crops offers the most competitive economics for biobased product production and with their mature supply chains are necessarily the base from which the industry must grow. However, the potential for the industry to adopt widely available lignocellulosic biomass (biomass residues or dedicated biomass crops such as miscanthus) which can be processed by various means (thermal, chemical, or using biotechnology) provides a means of avoiding competition with other land demand (food, feed, or cultural uses[42,43]).

Atmospheric carbon dioxide is another non-fossil feedstock for chemical and material production. Developing direct air capture (DAC) technology[44] provides the means to utilise renewable carbon and in conjunction with green hydrogen, holds significant long-term promise. Together the use of biomass residues and atmospheric carbon can significantly mitigate issues with future land use requirements.

5. MAKE EFFECTIVE AND EFFICIENT USE OF BIOMASS

If land and biomass are precious finite resources, then it is our duty to make the most effective and efficient use of them. This means ensuring that land is put to best use and using sustainable practices which maintain (or restore) soil health and productivity, while protecting the wider environment.

The understanding and assessment of ecosystem services and natural capital must be at the heart of climate-smart forestry[45] and agriculture[46,] where increasing carbon storage in forests, on farms and in biobased products works in conjunction with the need to provide other ecosystem services. Climate-

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smart biomass sourcing seeks to enhance ecosystem (farm and forest) health and resilience through climate change adaptive management.

The continued development of biorefineries is required to ensure that all parts of the biomass feedstock are optimally used. Too often the development of biorefineries is seen as a new endeavour rather than one that builds on the existing knowledge and infrastructure of the forest and agri-food sectors. Building out from traditional biomass using sectors gives the best opportunity to efficiently use biomass for new applications without disturbing existing and important markets such as food and construction.

2 THE TRANSITION

The transition away from fossil fuels will take several decades and will continue beyond 2050. The transition will require careful management, to avoid technology lock-in and to ensure that the 'perfect' technologies or applications of the future don't become the enemies of the presents 'good'[47].

Existing bioenergy industries provide infrastructure, knowledge, and the platform to develop the technology, processes, and the products of the future. Markets, industry, and technologies inevitably evolve to adapt to new demands. Additionally, we must not lose sight of the important role that bioenergy currently plays in decarbonising transport and in the treatment of waste.

For example, anaerobic digestion (AD) is the UKs preferred technology for the treatment of food and biogenic farm wastes. Through AD (whether wet, dry or in combination with composting), organic waste with high moisture content such as food waste, is diverted from landfill, thus avoiding damaging GHG emissions. Instead, it is used to produce valuable energy, in the form of biomethane, and soil improving digestate or compost[48]. The need to collect and effectively treat unavoidable food waste is increasingly recognised and provides the basis for current AD investment. Importantly, AD it is not a lock-in technology, remaining fully flexible in terms of both inputs and outputs. The biomethane output can be used to produce chemicals such as methanol[49] or hydrogen,[50] and with research the chemical transformations taking place within the anaerobic digestion process can be modified and manipulated to produce new products[51,52]. Building the current AD infrastructure and allowing the optimisation of process technologies will underwrite an eventual transition from AD as a generator of power, heat, and biomethane fuel, to a producer of chemicals and materials.

Similar transitions can be envisaged for the biofuel fermentation industry and in the use of waste vegetable oils to produce naphtha as a chemical feedstock[53] rather than for the manufacture of aviation fuel.

3 CARBON CAPTURE

Alongside making the efficient use and recycling of biogenic carbon there is also the need to capture and store any unusable carbon emissions[54]. There is the potential to capture and store carbon dioxide, after the energy contained in biogenic residues and in end-of-life products is recovered through AD or in energy-from-waste plants. This provides an opportunity to reduce net greenhouse gas emissions from agriculture and the potential for negative emissions from the use of biobased products.

4 CONCLUSION

The carbon-based chemical and materials sectors cannot be decarbonised. To do so means their replacement with materials such as cement, glass, and metal, all of which have their own environmental issues. However, it is possible to defossilise them through the move to the use of renewable carbon.

This transition has been inhibited due to a paralysis of political action resulting primarily from concerns over biomass availability and land use impacts. It is our contention that this paralysis can be overcome, but more attention needs to be focussed on understanding the position and scale of the biobased economy within the larger and broader transition to a more sustainable economy.

A broader vision is required in the debate around biomass availability, land use and feedstock demand. Changes in consumption patterns, the move away from fast fashion or towards vegetarian diets, alongside the push to increase the circularity of the economy with increasing recycling rates, can dramatically change the perspective on biomass demand and therefore supply. In turn, this creates a vision of the future and gives a new context for the potential and realisation of biobased economy opportunities.

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ABOUT THE SHIKIFACTORY100 PROJECT

The SHIKIFACTORY100 project aims towards the production of a universe of more than 100 high-added value compounds from the shikimate pathway, a hub in cell metabolism, through the development of an optimized shikimate chassis (based in 3 sub-hubs: Phe, Trp and Tyr) and the proposal and implementation of novel biosynthetic routes exploring enzyme promiscuity to introduce new pathways for the production of known and newly designed compounds. Further information about the project and the partners involved are available under www.shikifactory100.eu.

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