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REALISING THE CIRCULAR BIOECONOMY

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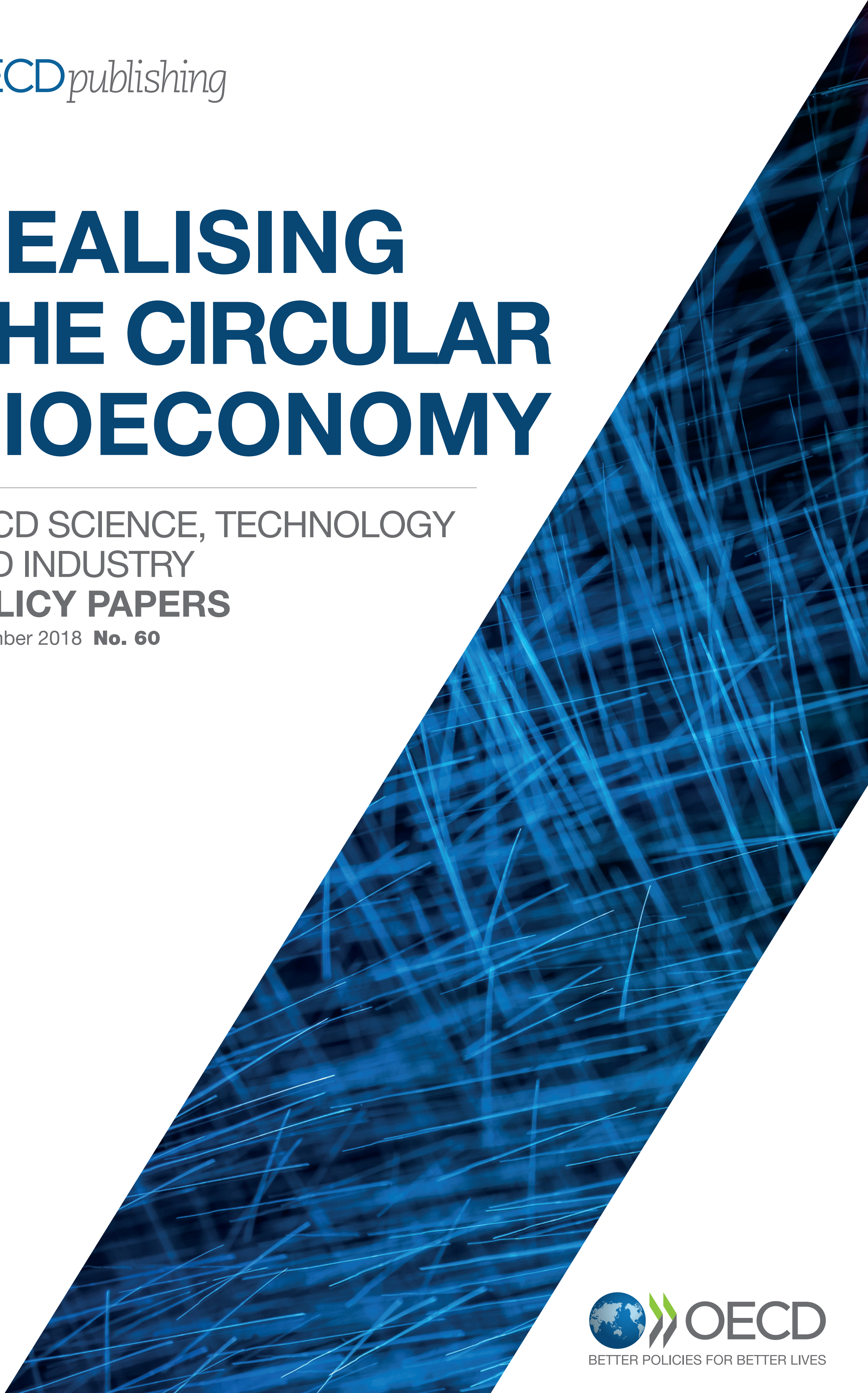

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BETTER POLICIES FOR BETTER LIVES

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Foreword

The circular economy concept is coming into practice in many OECD countries. In this concept, materials are kept within use for as long as possible through actions such as recycling and remanufacture. Bio-based manufacturing fits the concept when it comes to using residues and waste materials as feedstocks for biorefining. In particular there are benefits consistent with the recent emergence of resource efficiency within production.

The bioeconomy predates the first industrial revolution. In the absence of fossil resources, the human population lived, more or less, off the land. However, at that time (the mid-1700s) the world population was around 700 million, and the industrial revolution enabled a rapid increase. By 1800, there were 1 billion humans alive. At the dawn of the fourth industrial revolution, returning to a bioeconomy is made hugely more complicated by a population more than seven times the 1800 number. While there is no tangible shortage of oil and gas to the public, that population growth has started a spiral of resource depletion that needs to be addressed. The only feasible replacement source of carbon is renewable. That is where much of bioeconomy policy is directed – the transition to manufacturing and services based on biomass.

Equally, efforts at waste minimisation and recycling are decades old, but have often failed to impact on the strain on natural resources. The circular economy foresees an end to ‘take, make, dispose’ in a linear fashion to keep resources in circulation for as long as possible through reuse, recycling, remanufacture and waste minimisation.

At the crossroads lies the circular bioeconomy. Biology is not wasteful and is often demonstrably circular – circular metabolic pathways, cycles of nitrogen, carbon, phosphorus, even life and death ‘cycles’ are perpetual. However, combining engineering with biotechnology to make biological materials such as fuels, chemicals, plastics and textiles may be circular – but not necessarily so. This paper attempts to show how this combination of the bioeconomy and circular economy concepts can be made to create this more sustainable future. There are many policy issues along the way, policies that both promote change and remove barriers to change.

On 26 October, 2018, Dirk Carrez, the executive director of the Bio-Based Industries Consortium (BIC) in Europe, was published saying that: “*In 2050, we will live in a circular bio-society*”[1]. When asked why this new vision is necessary, he replied:

“…*the circular economy concept has been introduced and is gaining momentum, we need to make sure the Paris Agreement on Climate Change is implemented, and discussions for possible partnerships under Horizon Europe – the next EU research and innovation program – are underway. It will not be business as usual*”.

This paper partially fulfils the requirements of a broader OECD Central Priorities Fund project on “Resource productivity and the transition to a circular economy” led by the Environment Directorate.

This report has been review by the Working Party on Biotechnology, Nanotechnology, and Converging Technologies, and declassified by the Committee for Scientific and Technological Policy (CSTP). This report was written by Jim Philp and edited by David Winickoff from OECD STI. Peter Borkey from the OECD Environment deserves thanks for his engagement with this project.

1. Introduction

First the bioeconomy and then circular economy have gained political traction during the second decade of this century. While there are commonalities to the concepts, their far-reaching and long-term societal implications mean that there is also potential for policy contradictions which can be expensive and time-consuming to rectify.

The OECD in 2009 described the bioeconomy as "the set of economic activities in which biotechnology contributes centrally to primary production and industry, especially where the advanced life sciences are applied to the conversion of biomass into materials, chemicals and fuels". As the concept has grown, other interpretations have been described. A most notable divergence has been in the United States, where the 2012 Bioeconomy Blueprint (White House, 2012) included human health, for example "personalized medical treatments based on a patient's own genomic information".

To be effective the bioeconomy it must mobilise large quantities of biomass from a range of resources, including materials that may currently be considered as wastes (e.g. agricultural and forestry residues, and the organic fraction of domestic waste). A major objective is the gradual replacement of fossil-based production with bio-based, and as such it is necessary to be sure that the economic, environmental and social benefits are real and guarantee a future based on sustainable production.

In the circular economy concept, the linear production model ("take, make and dispose") is replaced by a circular model in which the waste products that would be disposed in the linear model are kept within the system - waste materials are drastically reduced, and wastes are recycled and remanufactured.

Therefore there is a clear intersection of the two concepts – by using waste materials in bio-based production on a global scale, waste materials could be drastically reduced (e.g. Hetemäki et al., 2017). This is a central theme of the circular bioeconomy (CBE). It will be evident that the implications strike at the core of the economy. Supply and value chains, instead of originating at the sources of fossil feedstocks with subsequent transportation across oceans, have the opportunity to be developed more locally. This would create jobs much closer to the feedstocks: in particular here is a chance for addressing the policy goal of rural regeneration. But this would create the need for a new generation of both R&D and production companies that is almost entirely missing at present. New skills, training and education will be required on a large scale, and the higher education sector would need to be adjusted to provide this. In the Netherlands alone, a demand for 10 000 bio-based experts is expected in the next eight years (Langeveld et al., 2016).

Key stakeholders and publics will need to be involved in such transitions, indicating a need for continued engagement. As bio-based production is often still more expensive than fossil-based, it is necessary for governments to unambiguously engage the public on how CBE can best be implemented to advance key sustainability goals. This is especially important given that the policy goals are meant to be addressing some of the most pressing grand challenges being faced by humanity e.g. climate change, food and energy security. These grand challenges are complicated by the fact that they interact with each other in ways that may not be obvious, which will create policy synergies and contradictions. They can be viewed as a grand challenges ecosystem, whereby potential solutions to one challenge may lead to good or bad effects in others.

Whenever humans intervene in a system, from the level of genetics to whole community, all the way to globally, there are interactions with other components of the system, and new consequences. The ‘behaviour’ of these grand challenges is assuming characteristics of an ecosystem: an intervention in one location results in changes there but also elsewhere. Ultimately the goal is interacting solutions to interacting grand challenges. This calls for multi-disciplinary research and systems innovation. There is no simplistic technological fix. Table 1 below gives examples of some potential policy synergies and contradictions.

Table 1. Potential bioeconomy and circular economy policy synergies and conflicts.

Location	Key Bioeconomy Policy	Key Circular Economy Policy	Synergies and Conflict
European Union	Renewable Energy Directive (Current: European Commission, 2009; Post 2020 Recast: European Commission, 2017c) Bioeconomy Strategy (European Commission, 2012)	EU action plan for the Circular Economy (European Commission, 2015a)	The action plan for circular economy and bioeconomy strategy are consistent in promoting the cascading use of biomass, which prioritises material uses of biomass over energy uses. However, neither the current nor the recast Renewable Energy Directives put a systematic restriction on the direct use of biomass for energy purposes, besides sustainability and traceability criteria.
Denmark	National Bioeconomy Panel (2014)	Waste Prevention Strategy (The Danish Government, 2015)	As a pioneer in circular economy and industrial symbiosis since 1972 (Kalundborg), Denmark set an objective to recycle 50% household waste by 2022.The bioeconomy panel recognises that current waste legislation may hamper novel utilisations of waste for energy (e.g. sludge, MSW).
Finland	National Bioeconomy Strategy (Bioeconomy, 2014)	Strategic Programme (European Commission, 2017b)	Finland aims to strongly push for the joint deployment of strategies for bioeconomy and circular economy (through cascading use of wood for material and energy uses) in an optimal way.
Sweden	Swedish Research and Innovation Strategy for a Bio-based Economy (2012)	Strategy for sustainable consumption (Government Offices of Sweden, 2016)	Considerable efforts are undertaken to decarbonise the Swedish economy through biomass (e.g. biofuels). This gets coherently integrated in a higher level strategy for reduced resource consumption through reuse and recycling.
Italy	Bioeconomy strategy (BIT, 2016)	Circular economy model currently in consultation	The bioeconomy strategy includes the aim to shift from fossil to renewable resources, but also mentions "biowaste valorisation' and circularity. The circular economy model document insists on the need to dedicate waste resources to produce advanced biofuels.
Scotland	Biorefinery Roadmap for Scotland (Scottish Enterprise, 2015)	Strategy for the circular economy (Natural Scotland, 2016)	Scotland has developed an integrated approach in which the use of biological resources is maximised through biorefineries. Materials and chemicals derived from biomass are prioritised over energy recovery.
People's Republic of China (hereafter "China")	2012 Plan for Development of Bioindustry (German Bioeconomy Council, 2015)13th Five Year Plan (2016-2020)	2009 Circular Economy Promotion Law (World Economic Forum, 2014)	China has an ambitious strategy to cope with the challenges of waste management and resource optimisation. The decarbonisation of the economy is also part of the FYP, building upon biomass resources to replace fossil material and energy sources.
Brazil	2005 Innovation Law	2010 Solid Waste National Policy	Brazil has a long history in bioeconomy with its pioneering Proalcool program in the 1970s. No federal policy currently defines a strategy for the circular economy, but numerous regional and private initiatives looking at resource optimisation and reverse logistics.
Spain	Spanish strategy on Bioeconomy (2016)	España Circular 2030, draft	Bioeconomy has been considered as a tool for the Circular Economy in Spain, especially for biological wastes and residues use purposes. Bioeconomy yearly action plan is a proposed measure in the Circular Economy Strategy.

This paper attempts to summarise the intersection of these two major economy concepts to show how they can work with each other to present a united approach to developing sustainability into a working policy field. Both bioeconomy and circular economy policy communities need to be in close communication with each other to create coherent policy design that maximises efficiencies and minimises contradictions and lock-ins. What distinguishes bioproduction from some activities of the circular economy is the focus on value added[2]. Compare, say, making a high-value specialty chemical from wastes with simple recycling.

This report features a number of key findings and conclusions. The use of biomass as a resource is a key intersection point between the bioeconomy and circular economy. Given concerns about the use of food sources, there has been a global push towards non-food sources of biomass, which constitute many 'waste', 'co-product', 'by-product', 'residue' sources, such as agricultural or forestry residues and municipal solid waste (MSW). This resonates with the circular economy concept in several ways:

- It keeps materials in the economy for longer
- It closes material loops
- It increases resource productivity.

Some of the effects that are consistent with the circular economy are reduced reliance on virgin materials and new products and substitution of secondary raw materials in production. At the same time, reductions in greenhouse gas (GHG) emissions are sought through bioeconomy production (by using renewable feedstocks rather than fossil).

However, some tensions are foreseeable in the CBE, including:

- In some countries the qualification of a material as a 'waste' rather than a 'secondary raw material' disqualifies it from being used as a biorefinery feedstock
- There is a well-described tension between biomass as a feedstock for bio-based chemicals and materials and its use in bioenergy applications. This in a broader sense describes a policy conflict between industrial and environmental policy
- Waste markets can be disrupted as some waste materials that currently go to recycling, landfill or incineration could in the future be bound for biorefineries. This could have profound effects on the waste management market and public infrastructure (as much public money had been invested in waste management facilities).

The concept that zeroes in to the very heart of the issue is the cascading use of biomass, which in some countries, such as Germany, has a close strategic link with the goals of the circular economy (Fehrenbach et al., 2017).

The synergies between the bioeconomy and the circular economy concepts are there to be exploited. This will need a combination of initiatives by the public and private sectors. However, there are many policy challenges and goals for the public sector to act upon first, as much of what has been described is too highly risk-laden for the private sector to contemplate alone.

It cannot be stressed enough that this represents another historic transition, differentiated from the earlier transitions such as wood-to-coal and coal-to-oil in that there is a need to act boldly in order that the most serious repercussions of climate change, food, energy, water security and resource depletion can be avoided. These transitions call for transition management, which needs very extensive public policy inputs over long periods, but with the close cooperation of the private sector and other stakeholders that needs to be encouraged by the permanency of the policies being embedded.

In the grand scheme of bioeconomy policy, the roles of innovation and biotechnology are often overlooked. There are many goals at many levels, from the laboratory to full-scale implementation, including pilot and demonstration in the middle. Ongoing work at BNCT is focussing on research and innovation (R&I) policy issues.

2. Waste as a resource in the CBE

2.1. Introduction

Waste is a core issue for CBE policy. While the circular economy envisages waste minimisation in the long-term, in the bioeconomy organic wastes are used as feedstocks for bio-based production (now and into the long-term). Not only does this help solve a waste issue, it creates value-added of varying levels (high for small volume, high value products such as specialty chemicals, lower for high volume liquid transport fuels). This should be a defining feature of the CBE – environmental and economic issues tackled together. Moreover, social issues are addressed through job creation in the engine of the CBE – the biorefinery or bioproduction plant.

A central manifestation of the bioeconomy is the biorefinery, be it a stand-alone facility making a single product (such as first generation ethanol mills) or more complex facilities making more products at a single complex (typical of the integrated biorefinery concept). These come in a variety of models, and more models are being added with the passage of time.

The biorefinery also fits the circular economy concept, particularly 'bio-waste' biorefineries that use wastes or residues as the feedstocks. The nature of this fit may be subtle however. Using such materials is clearly not classical recycling, reuse or remanufacturing as biorefining is making value-added 'virgin' materials from waste sources. This value creation distinguishes waste biorefining from standard waste management practices, and thus placing it within the waste management hierarchy is difficult. It highlights a need for re-defining such materials as, perhaps, 'secondary raw materials' to avoid a clash with waste management regulation.

With the theme of value-added in mind, this chapter concentrates on biorefining to bio-based chemicals and materials. The pros and cons of producing biofuels versus bio-based chemicals and materials have been explored several times in the OECD in past (e.g. OECD, 2011a; 2014a). There are many examples in the academic literature of the production of higher value-added bio-based chemicals and materials, so therefore there must be important reasons why the valorisation of waste in biorefineries is not more widespread.

Resource efficiency is central to the bioeconomy. The food *versus* fuel controversy that arose during the first decade of this century (e.g. see Tomei and Helliwell, 2016) spurred the move towards cellulosic biorefinery R&D, and the concomitant use of the waste materials outlined above. Reduction in GHG emissions has now entered the thinking on resource efficiency. It also speaks to the much wider issues about biomass sustainability (e.g. OECD, 2014c), which relates to the amount of biomass that can be used without decreasing the sustainability of it as a resource. Therefore the primary drivers for the bioeconomy are directly related to resource efficiency.

2.2. First versus second generation biorefining

The vast majority of the world's existing biorefineries are first generation ethanol mills that use food crops as feedstocks. These have been dealt with elsewhere and are not the focus of the current OECD work on the CBE (see OECD, 2018). Rather, biorefining in the current context should be concentrated on second-generation biorefining, where feedstocks consist of non-food resources (renewable or non-renewable). Very often these will be waste materials. Along with agricultural and forestry residues, in theory this is a large stock of potential feedstocks.

However, the specific exclusion of first-generation biorefineries here does not imply that they cannot be sustainable or circular. Recently Dammer et al. (2017) demonstrated that, in fact, food crop biorefining can indeed pass many criteria for sustainability. In particular, the high land efficiency of some food crops such as sugar beet, when GHG emissions reductions are demonstrably high and proven, means that their exclusion in national policy is not always warranted. The main drivers for use in a national strategy should be the adherence to sustainability criteria and that using food crops in this way does not compromise food security.

One very good reason for this is that it gives farmers another outlet for their products. In face of poor and/or variable prices for food crops, first generation biorefining can give farmers certainty year-on-year that there is an alternative route to market for their produce that helps de-risk future farm investments.

2.3. The landfill dilemma

In many countries there has been a movement to reduce landfilling of waste through policy interventions such as a landfill tax, making landfilling a less popular option for waste management. It is becoming more difficult to find suitable sites for properly engineered landfilling in most countries. Even in a country like Australia, with a large land mass and low population, there are good reasons to consider the available supply of landfill to be a scarce resource that should be used conservatively (Pickin, 2009). A country with quite the opposite conditions is Japan, where there is limited space and high population density. In Japan, it is becoming increasingly difficult to obtain public acceptance to install waste disposal facilities, such as landfill sites, due to a rising pressure on land use and growing public concern over environmental and health protection (Ishizaka and Tanaka, 2003). The UK is experiencing landfill shortage at the national level, but also residual waste is being transported greater distances to sites with spare landfill capacity (Suez Recycling and Recovery UK, 2017). Meanwhile, serious consideration is being given to 'enhanced' mining of old landfill sites, of which there are around half a million in Europe alone, for resource recovery (Jacobs, 2018).

Since the 1980s more than three-quarters of all landfills in the US have closed (*Biomass Magazine*, 2011), while waste quantities have ballooned. The waste output of Chicago is now more than 300% what it was in the early 1980s, with remaining landfills getting further from the city. Across the US it has gone up about 65%, with over half of it still being landfilled (USEPA, 2014). Figures for 2013 show an Illinois-wide landfill life expectancy of 21 years (Illinois Environmental Protection Agency, 2014). For Chicago itself, it could be less than ten years. Since 1997, four of the boroughs of New York City have sent MSW by road or rail to landfills as far away as Ohio, Pennsylvania, South Carolina, and Virginia. Meanwhile, New York State has imported MSW from New England and Canada to its up-state landfill sites.

In the EU the waste management and recycling sector has a high growth rate, is labour-intensive and provides between 1.2 and 1.5 million jobs (Fava et al., 2015). Waste volumes, however, continue to grow. Variation is large: some countries landfill 100%, others nil. On the whole, European data show that preferences for treating waste have shifted in the past decade, with more waste being pushed up the classical waste hierarchy (Figure 6a) to be recovered for energy or recycled. Landfill remains the major disposal method in half of the OECD countries (OECD 2015).

Meanwhile, new landfill construction might be the single-least popular kind of construction a municipality might have to undertake. Among the complex regulatory issues inherent to the process of landfilling are: siting restrictions in floodplains, wetlands and faults; endangered species protection; surface water protection; groundwater protection; disease and vector (rodents, birds, insects) control; open burning prohibitions; explosive methane gas control; fire prevention through the use of cover materials; prevention of bird hazards to aircraft; and closure and post-closure requirements. So from several directions, there is continuous pressure to reduce the amount of material being landfilled. Some of MSW, if it can be sorted, can be directed towards biorefining.

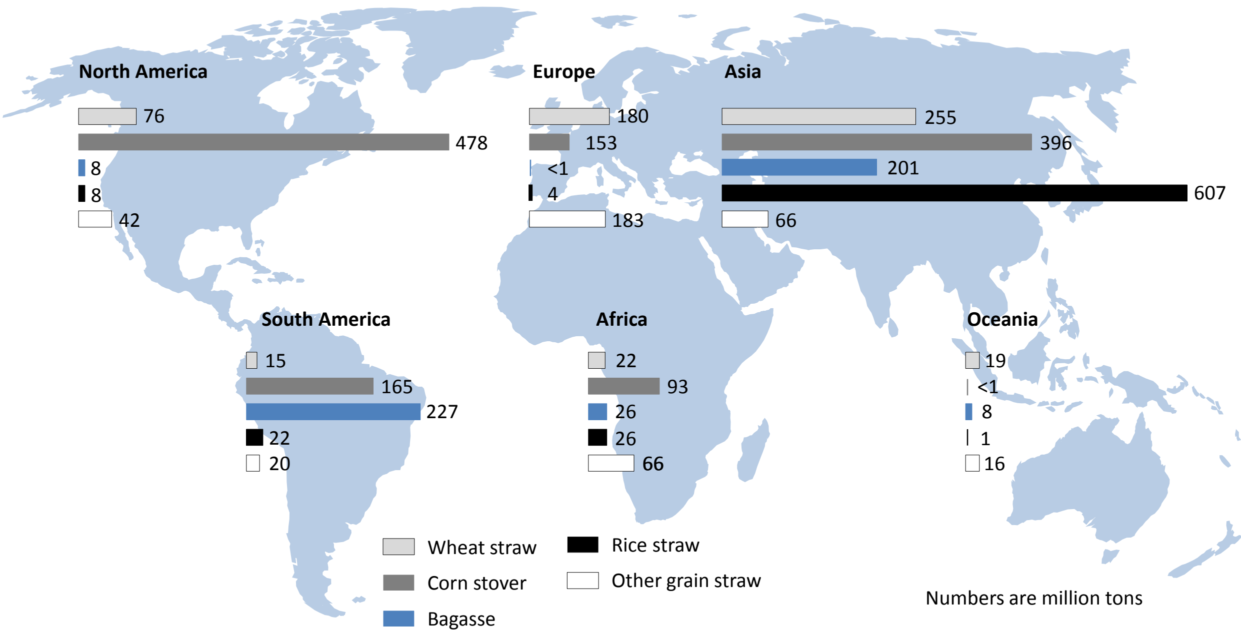
Furthermore, there are powerful policy motivators. For example, in the EU the so-called ‘landfill directive’, Directive 99/31/EC, limits the quantities of biodegradable wastes (kitchen and similar wastes, including paper) that can be landfilled. Sending organic material to landfill can then be discouraged via taxes on landfill tipping (Scharff, 2014). Several US states, including Connecticut, Vermont, California and Massachusetts are passing legislation to drive organic waste diversion, thus (slowly) creating regulatory pressure to adopt other conversion technologies. Over the last decade, Japan has shifted from a waste management policy to an integrated waste and material management approach that promotes dematerialisation and resource efficiency. Landfill shortage and dependency on natural resources imports have been key drivers of these changes (OECD, 2010).

3. Waste materials available for bio-based production

3.1. Lignocellulosic wastes

Theoretically, a vast treasure trove of solid, liquid and gaseous wastes is available (Figure 1), but this is limited in practice for various reasons. Collecting straw or forestry residues, for example, may not be worthwhile for farmers or forest owners, and therefore might need to be incentivised. Municipal solid waste contains a lot of fermentable materials, but they are mixed up with non-fermentable materials. Industrial waste gases exist in profusion and are often in a relatively pure form, but microbial processes for their fermentation are immature, and there may be little incentive for companies to capture waste gases.

Figure 1. Estimates of lignocellulosic waste materials available globally for bioproduction.



Note: Numbers are million tons.
Source: KTN (2016).

There is no doubt that there is a large amount of waste that can be used as feedstock, but there has to be the political will to incentivise its collection. In the case of rice straw, for example, well over half a billion tonnes is available in Asia, and this material is routinely burned. Biorefining rice straw would reduce GHG and other emissions by avoiding burning.

Bioproduction bottlenecks in the US have occurred as a result of multiple factors such as high costs of biomass resources, the recalcitrant nature of lignocellulosic feedstocks, the high cost of enzymes or chemical to de-construct biomass, and the need for optimised bioprocesses for a wider array of varying feedstocks. The USDA has been addressing the needs for new feedstocks (Box 1) while at the same time helping to maintain and develop the first generation ethanol and biodiesel industry.

Box 1. The need for new feedstocks in the US: initiatives of the USDA

To address bioproduction bottleneck factors, the US Department of Agriculture (USDA) introduced five Regional Biomass Research Centres. One advantage of this USDA programme was that it provided incentives for field researchers, those optimising crops as feedstocks for biofuels, to work closely with researchers developing biorefinery technologies. As the industry evolved, focus has gone from creating corn and grain-derived ethanol to creating cellulosic ethanol, and now toward development of integrated processes that produce drop-in replacements for petroleum products. Technologies to produce advanced biofuels such as *n*-butanol, pyrolysis bio-oil, hydroxymethylfurfural, liquefied biogas, and even (bio)hydrogen have been developed and are arguably commercially viable.

It should be noted, though, that the corn ethanol industry is a multi-billion dollar enterprise that merits research towards making it as efficient as possible. The industry added USD 44 billion to the US GDP in 2015 and paid USD 10 billion in taxes (RFA, 2016). One strategy to ultimately reach the Renewable Fuels Standard (RFS) targets is to make stepwise improvements in the existing biorefinery concepts. These stepwise improvements must include a regional strategy that builds in enough flexibility to use the "cheapest sources of renewable carbon" within a given region. Such flexibility implies, for example, using grain sorghum, switchgrass, or miscanthus in the US Midwest, sweet sorghum or cane sugar in the US South, guayule bagasse in the US Southwest, almond hull sugars in California and even citrus peel waste in Florida. Another key element is the ability to integrate existing ethanol plants with other operations, specifically utilising thermochemical conversion of all biomass sources or utilising integrated digester to produce biogas and biogas-derived products. Biorefinery strategies are best optimised when field feedstock research on yield, crop quality and biomass cost is coordinated with biorefinery strategies (Orts and McMahan, 2016).

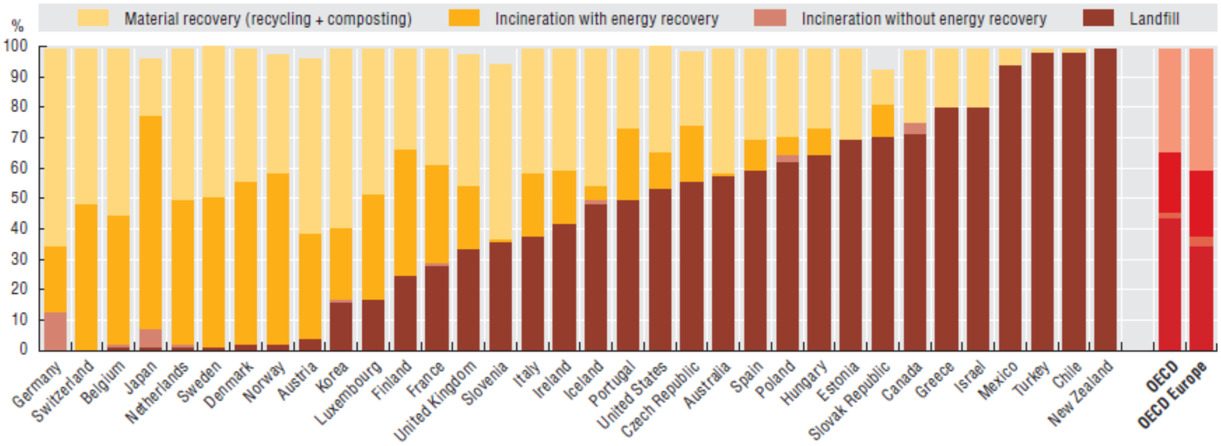
Source: Courtesy of Harry Baumes, USDA (retired)

3.2. Municipal solid waste (MSW) and food wastes

Municipal solid waste is the household-generated waste that has traditionally been disposed of to landfill. It contains significant quantities of food waste. Over 50% of MSW is biodegradable, which permits its usage as potential feedstock for production of biofuels, bioenergy, commodity chemicals. A person living in the OECD area generates on average 520 kg of waste per year; this is 20 kg more than in 1990, but 30 kg less than in 2000 (OECD, 2015).

MSW is therefore available in large tonnages, and its biorefining would make more sense in some OECD countries than in others, especially those with large quantities being landfilled (Figure 2). With separated waste collection mandatory in Europe by 2023, the model for other countries could be established.

Figure 2. OECD member states municipal waste disposal and recovery shares, 2013 or latest



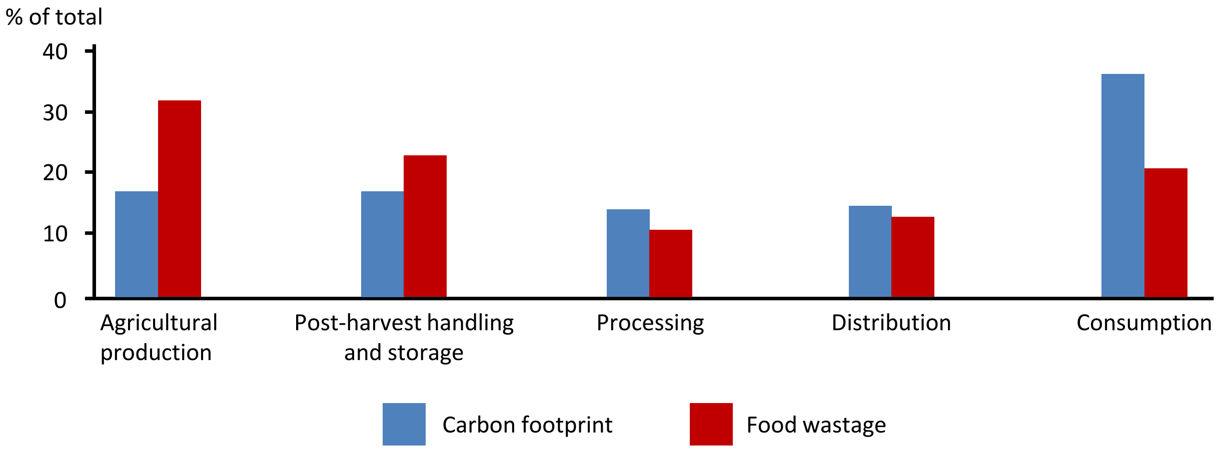
Source: OECD (2015)

Food wastes, by their very nature, are biodegradable and many are amenable to conversion in biorefineries (e.g. Dahiya et al., 2018). To date, hardly any food waste is utilised in this fashion, despite an estimated annual global deposition of about 1.3 billion tonnes of food waste in landfills (Hao et al., 2015). This suggests that one-third of the total global food production is wasted each year, costing the global economy over USD 900 billion[3]. The fate of food waste in landfill is ultimately its bioconversion to biogas, a combustible mixture of methane and CO_2 and small amounts of hydrogen. In modern engineered landfill sites this biogas can be captured and used for district heating or electricity generation. On a global scale, however, it simply adds to GHG emissions as methane is a much more potent GHG than CO_2 (USEPA, 2017). Global food loss and waste generate annually 4.4 Gt equivalent of CO_2, or about 8% of total anthropogenic GHG emissions[4], making the contribution only slightly less than that of global road transportation (Sims et al., 2014).

The focus of the last few years has been very much on cellulosic wastes. By comparison, data on food waste biorefining are difficult to find and are not yet robust. A monolithic approach of gathering data simply on ‘food waste’ is not particularly helpful. However, the limited data suggest that food losses are much higher at the immediate post-harvest stages in developing countries. For affluent economies, post-consumer food waste accounts for the greatest overall losses (Parfitt et al., 2010), with influences from factors such as aesthetics and arbitrary sell-by dates. It has been estimated that the amount of food wasted per year in UK households is 25% (by weight) of that purchased, which is only the food wasted in the home. Of this in the UK, bread is the largest contributor to food waste; 32% of all bread purchased is dumped[5].

Therefore an examination of food wastes at different points in the food supply chain (Figure 3) is instructive for governments because the stage at which a food product is wasted greatly influences the carbon footprint associated with the wastage. The further along the supply chain from the point of harvest at which a food product is wasted, the greater the carbon intensity of the wastage since the harvesting, transportation and processing accumulates additional GHGs along the supply chain.

Figure 3. Contribution of each phase of the food supply chain to carbon footprint and food wastage



Source: UN Food and Agriculture Organisation (UNFAO), http://www.fao.org/3/a-bb144e.pdf

3.3. Fish waste

Wild fisheries and aquaculture fish represent emissions-efficient food for humans compared to ruminant production (D'Hondt et al., 2015). However, about 40% of the fish is discarded as waste and over 20 million tons of fish wastes including liver, heads, intestine, backbones and skin are discarded into the environment around the world, resulting in pollution or a difficult waste disposal problem, and the loss of valuable nutrients (Enascuta et al., 2018).

One of the challenges facing the expansion of aquaculture is the provision of high quality fish feed. One scenario to ameliorate the challenge of feed supply is utilising more fish processing waste in the production of fishmeal and fish oil (World Bank, 2013). Already, for example, 90% of the ingredients used in fishmeal produced in Japan come from fish waste.

3.4. Industrial gases as fermentation feedstocks

For an OECD workshop, Adani (2015) attempted to quantify how much of different categories of waste are available and to put those numbers into the context of industrial production. Fermentable gases are produced in large quantities from different sectors. However, their collection from some of these sectors is not feasible. Two of those which are feasible for collection are also major contributors to emissions: energy supply and industry.

In the sectors where collection is feasible, CO_2 is by far the most important gas. Four critical figures given by Adani regarding the potential of gas utilisation in waste biorefining are:

1. Consumption of renewable raw material for chemical industry and others: 857 million tonnes per year
2. Total mass used producing chemicals: 271 million tonnes per year
3. Total mass from CO_2 industry and energy production: 7 596 million tonnes per year

4. Total mass from bio-waste and food loss: ~ 354 million tonnes per year.

The figures would indicate, at least at a superficial level, that the amount of CO_2 available is far in excess of what is required. Totals, however, can mask many feasibility issues e.g. the efficiency of the use of gases in biorefinery operations, other technical aspects relating to e.g. purity of gases, ease and cost of collection. Some preliminary estimates from LanzaTech, a leading company in gas fermentations, suggest that more than 30 billion gallons per year of high value products can be produced from steel mill waste gases alone; this is a considerable contribution to the worldwide energy and chemical pool[6].

3.5. Plastic waste as a CBE issue

"*We need to reduce waste and come up with new, biodegradable alternatives to plastic. But one of the easiest steps is changing the way we use and discard the more ephemeral plastic products*."

The Guardian, March 22/2018[7]

This article is one of many appearing in media and literature. The issue of the accumulation of plastic waste in ocean gyres is not new (see OECD, 2013). However, this article highlights the discovery of a Pacific Ocean garbage patch that is twice the size of France and 16 times larger than previously estimated. Worryingly, microplastics can be taken up by living cells (von Moos et al., 2012), and have been shown to interfere with reproduction, and offspring performance in oysters (Sussarellu et al., 2016).

By 2050 it is estimated that an extra 33 billion tonnes of plastic will be added to the planet (Galloway, 2016). Their lack of biodegradability means that plastic waste is an ever-increasing problem unless solutions can be found. One circular solution is the burning of plastic waste and energy recovery, which is widely practiced, but it does not stop the accumulation of plastics in the oceans.

Bioplastics can be either biodegradable or durable, and market projections are for an increasing share of durable plastics (Philp et al., 2013). Biodegradable plastics are still considered niche products. Despite decades of R&D, market penetration by biodegradable bioplastics is still small. These niche markets are nonetheless, important ones, including: compostable bio-waste bags, fruit and vegetable bags, lightweight carrier bags; coffee capsules and tea bags; thin film applications for fruit and vegetable packaging (European Bioplastics, 2017).

Biodegradable plastics can add value in the circular economy. They can be processed in industrial composting facilities or contribute to biogas generation in anaerobic digestion facilities. Certified industrially compostable plastics contribute to efficient waste management and the circular use of resources in various ways, including (European Bioplastics, 2017):

- They divert bio-waste from landfill into organic recycling
- They divert bio-waste from incineration, which is complicated by the high moisture content of bio-waste
- They divert bio-waste from mechanical plastic recycling
- They provide additional second-generation bio-based feedstocks for industrial purposes.

4. Some selected waste biorefining initiatives

It is beyond the scope of this paper to be exhaustive in examining the scope of waste biorefining. Instead some pertinent examples are given using different categories of waste and the wider potential is highlighted. In each case the link to the circular economy is made.

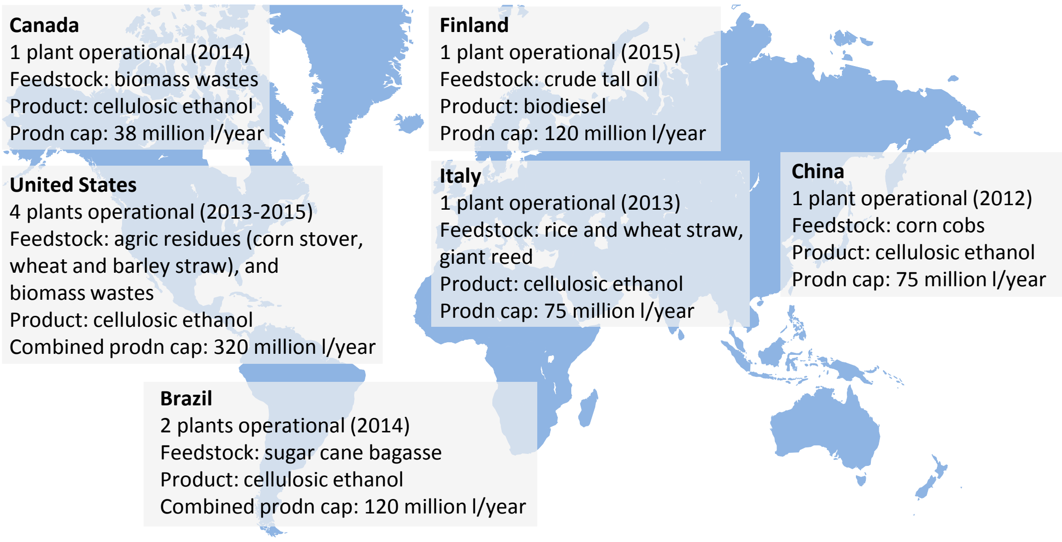
4.1. Cellulosic wastes: biorefining and composting

4.1.1. Cellulosic biorefineries

Lignocellulose is composed of carbohydrate polymers (cellulose, hemicellulose), and an aromatic polymer (lignin). It is the most abundant raw material for biorefining as it contains large amounts of fermentable sugars. However, the sugars needed for fermentation are tightly bonded within the lignocellulose. This becomes a barrier to using lignocellulose from biomass in biorefining. Much of the technical effort to unleash the vast bounty for biorefining is related to overcoming this recalcitrance of the feedstock (Wernick et al., 2016); the "conversion" has been the bottleneck. About 40-60% of the total operating cost of a typical biorefinery is related to the feedstocks chosen (Parajuli et al., 2015). However, the most significant cost for second-generation cellulosic biofuels may be conversion of woody biomass into fermentable sugars.

The integrated biorefineries, exploiting the overall lignocellulosic waste components to generate fuels, chemicals and energy, have recently been described as "*the pillar of the circular economy*" (Liguori and Faraco, 2016). However, a crisis of sorts has arrived in cellulosic biorefining. Technical problems surrounding conversion have proven so intractable that only a handful of these biorefineries have become commercially viable (Figure 4), and at the time of writing most of these are still troubled facilities. Abengoa Bioenergy Biomass of Kansas sold its Hugoton, Kansas cellulosic ethanol plant to Synata Bio due to bankruptcy[8]: The cellulosic biorefinery at Crescentino, Italy, closed down in 2017[9].

Figure 4. Global capacity in cellulosic biorefining



4.1.2. Industrial-scale composting

An alternative and circular solution is the conversion of cellulosic wastes to composts and soil amendments. Unlike cellulosic biorefining, composting has a centuries-long history in maintaining soil fertility, the literature on composting is vast, and the microbiology known in broad terms, although the detail remains elusive. Industrial-scale composting is a lot newer, and is not optimised, requiring the convergence with other technologies to improve efficiency and process control (Onwosi et al., 2017). The utility of the processes in a CBE can be demonstrated by the number and types of waste materials amenable to industrial-scale composting. Suitable wastes and residues include (Kutzner, 2001): grass clippings, leaves, hedge cuttings, food remains, fruit and vegetables waste from the food industry, residues from the fermentation industry, solid and liquid manure from animal houses, forestry residues, paper industries wastes, rumen contents from slaughtered cattle, and sewage sludge from wastewater treatment plants.

At first view the products are unexciting and lack value-added. However, consideration has to be given to the state of arable land generally and the underestimated importance of soils to human and planet health. The state of soils is worthy of serious attention from policy makers. A good example of awareness raising was the International Year of Soils initiative (2015) of the United Nations Food and Agriculture Organisation[10].

It is worth summarising these issues for policy makers to understand the imperative for a circular economy:

- More than 95% of all food is derived from cropland (Gore, 2013)
- Soil accounts for some 20% of the capture of human CO_2 emissions (European Commission, 2007)
- Its slow rate of formation means that soil should be treated as a non-renewable resource - it takes 1 000 years to generate three centimetres of top soil
- It is being destroyed at unprecedented rates - if current rates of degradation continue all of the world's top soil could be gone within 60 years (Arsenault, 2015)

- In economic terms, soil should be viewed as natural capital. It has been estimated that 17% of New Zealand's GDP depends on the top 150 mm of its soil (Kirkham and Clothier, 2007).

While artificial fertilizers have enormously improved agricultural yields, they have created problems that cut across industry, agriculture, energy and environment (Gauvreau et al., 2018). The environmental issues around mineral fertilizers are well-described and have been known for decades (e.g. Byrnes, 1990; OECD, 2015). The Haber-Bosch process for making fertilizers is very energy-intensive. It consumes 3 to 5% of the world's natural gas production and releases large quantities of CO_2 into the atmosphere (Licht et al., 2014).

An excellent example of what is possible is efforts at Caviro, an Italian wine cooperative (Figure 5).

Figure 5. Industrial-scale composting at Caviro, Italy.

Note: Marc (80 000 tonnes per year) and wine dregs (30 000 tonnes per year) are thus converted from waste to resource (background).
Source: Courtesy of Caviro company.

The Caviro Group's value chain includes 13 000 wine growers from seven regions of Italy, producing some 11% of all Italian grapes It has about 14% of market share by volume to large retail chains in Italy.

Caviro Distillerie is the distillery division of Caviro. The circular economy activities at Caviro Distillerie have the mission to add value to the by-products of the Italian food and farming industries, whilst pursuing environmental protection. The products include alcohol, oneocyanin, grape seeds, tartaric acid. The most familiar CBE processes are: agro-industrial wastewater purification, renewable energy and compost production.

A crucial by-product for these activities is grape marc (or pomace) which is the solid remains of grape pressings for juice. It contains the skins, pulp, seeds, and stems of the fruit. Grape marc has traditionally been used to produce a brandy such as grappa. Additionally it can be used for lower value-added products such as fodder and fertilizer, and/or for higher value-added products such as polyphenols for medical/food purposes. As marc is a form of biomass, then here is another example of cascading use.

4.2. MSW biorefining: the case of Edmonton, Canada

Enerkem Alberta Biofuels is a subsidiary of Enerkem, headquartered in Montreal, Canada. The Enerkem Alberta Biofuels biorefinery facility in Edmonton is the first of its kind to convert non-recyclable, non-compostable municipal solid waste into liquid biofuels and chemicals. This commercial-scale facility has the capacity to process 100 000 metric tons of solid waste annually, which includes items like textiles, non-recyclable plastics, or soiled food containers, to produce over 40 million litres of fuel-grade, cellulosic ethanol. The facility has received approval from the United States Environmental Protection Agency (EPA) to sell cellulosic ethanol produced under the US Renewable Fuels Standard (RFS).

It contributes to the City of Edmonton's goal to divert up to 90% of household waste from landfill. In January 2018, Enerkem and Sinobioway Group paved the way for a joint venture that will lead to the construction of over 100 Enerkem facilities in China by 2035[11].

4.3. Food and beverage wastes

"*Compared to production of a single component for food waste valorisation, integrated processing of food waste via a combination of different novel technologies to produce multiple products based on a biorefinery concept has significant advantages, including full utilisation of feedstocks, minimisation of waste generation during processing, synergy effects of different technologies, and diversification of the revenues by covering multiple markets*".

Jin et al. (2018)

There are many processes either in research, development, demonstration or commercialisation phase. This section aims only to highlight the potential and to draw attention to the fit to the policy goals of a CBE. Conversion of food waste into high-value products has been reviewed in greater detail (Ravindran and Jaiswal, 2016).

4.3.1. Cheese waste – plentiful, costly to treat and environmentally damaging

Whey is a highly polluting by-product of cheese and casein powder manufacture with worldwide production of whey estimated at around 190 million tons per year (Ryan and Walsh, 2016). It is a very 'strong' waste that cannot be discharged directly into water bodies. There are various valorising and non-valorising processes for dealing with whey, reviewed by Prazeres et al. (2012). Valorisation through biotechnology would be a classic bioeconomy approach which is also circular in the regard that resources are kept within the economy for longer by making 'virgin' materials from a polluting waste stream.

The AgriChemWhey flagship project[12] of the Bio-based Industries Joint Undertaking (BBI JU) proposes to build an integrated biorefinery in Ireland to convert dairy side-streams into the value-added products L-lactic acid, polylactic acid (an emerging bioplastic), minerals for human nutrition and bio-based fertiliser. As such the project addresses several CBE policy goals:

- Rural job creation and regional development
- Relieves pressure on land
- GHG emissions savings
- Pollution prevention

- Waste valorisation
- Creation of new circular value chains and innovation ecosystems
- Increases the sustainability of milk production.

4.3.2. Bread waste to succinic acid

Bread accounts for around a quarter of domestic food waste in the Netherlands, with the average citizen throwing out 9.2 kg per year. Due to a growing rat population, some councils have funded bread collection schemes to remove a major source of their food. A company BroodNodig has set up collection bins to collect waste bread. At the time of writing there were around 50 collection points in Rotterdam. The collected bread can be made into fertilizer, but there are plans to create large-scale anaerobic digestion plant to make biogas from waste bread.

However, baking the bread in the first place is likely to take more energy than can be recovered in biogas. An alternative approach may be the preferred CBE approach of generating greater value-added through a bioproduction process. For example, in a research demonstration Leung et al. (2012) fermented bread hydrolysate as the sole feedstock for the production of succinic acid, with an overall yield of 0.55 g succinic acid per g bread. This was the highest succinic acid yield compared with other food waste-derived media reported at the time. Succinic acid is considered one of the future platform chemicals of a sustainable chemical industry. It is a precursor for many chemicals, with a production capacity of about 30 000 tonnes per year. The projected market value for succinic acid by 2022 is thought to be USD 1.1 billion[13].

4.3.3. Fish waste to fish feed and cascading use

To further prevent fish waste becoming a waste disposal problem, there are applications beyond fishmeal and fish oil as high quality feed for farmed fish. Enascuta et al. (2018) pre-treated fish oil and through transesterification created saturated and unsaturated fractions of fatty acid ethyl esters (FAEE). The saturated content can be used as biofuel, while the unsaturated FAEE can be further transesterified with glycerol (already a by-product of biodiesel production) in order to obtain oil rich in polyunsaturated fatty acids (PUFAs). PUFAs are high-value products; therefore this is an example of cascading use of fish waste. Similarly, Fadhil et al. (2017) cascaded fish waste to liquid fuels and activated carbon.

4.3.4. Whisky waste to biofuels

Production residues of the malt whisky industry in Scotland currently include 750 000 tonnes of dregs and 2 billion litres of pot ale, again strong waste streams that can be very environmentally damaging. Pot ale has high biological oxygen demand (BOD) and contains yeast, inorganic salts and a wide variety of organic compounds including unfermented sugars. Past treatment efforts have involved anaerobic digestion to produce biogas (e.g. Goodwin and Stuart, 1994) which can be used for heating or generating electricity.

Research at Celtic Renewables Ltd has demonstrated the technology required to convert whisky wastes into butanol, an advanced biofuel, via a microbiological route. The company is starting to build a demonstrator plant at Grangemouth, Scotland, home of a large petrochemicals complex. It is intended as a commercial demonstrator plant that will produce over half a million litres of biofuel each year.

The CBE policy goals addressed include:

- Regional development
- Relieves pressure on land
- GHG emissions savings
- Pollution prevention
- Waste valorisation
- Creation of new circular value chains and innovation ecosystems
- Increases the sustainability of whisky production
- Improves the sustainability of transportation.

4.4. Gas fermentation

Gas-fermenting microorganisms are able to fix CO_2 and CO, and often utilise H_2 as well. They have been manipulated such that they are capable of converting gaseous carbon to fuels and chemicals. The technology can utilise a range of solid feedstocks if those feedstocks can be readily gasified. These include: MSW; biomass in many forms, such as agricultural residues; and significantly industrial waste gases. This latter category is important in volumes from certain industries, such as steel making, and also extends the range of feedstocks for bio-based processes.

4.4.1. Steel mill gases to ethanol

Over the years, gas fermentation has progressed to the point of large demonstration at a Chinese steel mill (see Pavanan et al., 2013), and now there are plans to build a larger plant in Ghent, Belgium. This project, a collaboration of LanzaTech, ArcelorMittal and Primetals Technologies, will generate 47 000 tons of ethanol per year from waste gases originating from steel making.

A distinction is made between ‘green carbon’ and ‘black carbon’. This is because, legally, only syngas from solid biomass can be considered as ‘green carbon’. If fossil sources, or products made from fossil sources, are used to generate syngas, it has to be considered as ‘black carbon’ (Bengelsdorf and Dürre, 2017).

However, the technology is complex, not yet standardised, and to date is not competitive for ethanol production. Added value can be generated by suitable integration of thermochemical, biochemical, and chemical processes (Dahmen et al., 2017). Clearly the technology can be applied to more valuable intermediate chemicals than ethanol (Liew et al., 2016). This strategy would support the concepts of the integrated biorefinery and cascading use (whether of black carbon or green).

Gas fermentations have similar policy goals to those highlighted already. It is worth emphasising that this use of ‘black carbon’, which is available in very large quantities, has a large advantage in land saving. The policy issues surrounding land use change are essentially eliminated by using waste industrial gases instead of food or non-food crops.

4.4.2. Gas to fish feed: feeding the fish that feed humans

Today, farmed seafood production exceeds that of wild fisheries and has significant potential for future growth (OECD, 2015c). The aquaculture industry needs to find new fish food sources, particularly to replace or supplement these high-quality inputs currently derived from fishmeal and oil, as this is increasingly seen as a limitation for future growth in aquaculture production (IUCN, 2017). At the same time, reducing the environmental footprint of aquaculture has become a high priority as part of the drive for greater sustainability.

Calysta, US, is scaling up production of FeedKind, a high-protein feed produced by bacterial digestion of methane. Set to begin production in 2019 at a facility in Memphis, the plant will have an initial capacity of 20 000 tonnes per year but could expand to as much as 200 000 tonnes per year in a second phase (*Chemical & Engineering News*, 2017).

4.5. Anaerobic digestion

Anaerobic digestion of sewage sludge to produce biogas has been used for over a century in the biological treatment of wastewater. Typically, it stabilises sewage sludge by removing pathogens. However, methane is typically used to generate electricity and this can often be enough to power an entire wastewater treatment plant, adding to the environmental and economic sustainability of such plants.

Anaerobic digestion is highly scaleable and has been perfected down to individual farm level, where a variety of waste materials can be converted to biogas e.g. sludge, grass, solid manure, chicken manure and straw. Moreover, the effluents after anaerobic digestion are better balanced to meet crop needs than raw manure slurries, thereby reducing the need for supplementary chemical N and P fertilizers (Massé et al., 2011) while reducing GHG emissions (Siegmeier et al., 2015). Despite standardised technology and these various advantages, in many OECD countries only about 5% of the organic fraction of municipal solid waste (OFMSW) is currently digested. For many of these countries, the preference is for disposal by incineration (Clarke, 2018).

Now, biogas production is being seen as part of the biorefinery concept (Kaparaju et al., 2009). Multiple biofuels production from, say, wheat straw (bioethanol, bio hydrogen and biogas) can increase the efficiency of biomass utilisation enshrined within the cascading use of biomass concept. The volatile fatty acids (VFAs) produced from anaerobic microbial activity, often considered a nuisance or environmentally damaging, have the potential as the precursors for the biotechnological production of polyhydroxyalkanoates (PHAs) as bio-based plastics (Martinez et al., 2016).

4.6. Wastewater biorefineries

It has been acknowledged that wastewater management will need to play a central role in achieving future water security in a world where water stress will increase (UN-Water, 2015). And yet in developing countries 90% of sewage and 70% of industrial wastes are discharged without treatment into surface water. With over a century of experience with biological treatment of wastewater, large problems could be addressed simply with greater implementation of current biological wastewater treatment technologies (El-Chichakli et al., 2016). However, wastewater biorefining would add value.

Consider the case of South Africa. Maintaining the integrity of the basic water treatment infrastructure and its optimal performance is already a struggle in South Africa with its burgeoning urban populations and limited financial and skill-based resources. Integrating the goals of water treatment with the goals of the bioeconomy is viewed as a way to transcend these challenges and create a new industry (Harrison et al., 2017). The wastewater biorefinery (WWBR) is seen as part of this integration. Many hurdles exist. A policy goal discussed in several OECD countries is also needed in South Africa – the reclassification of waste as a raw material.

4.6.1. Plastics from wastewater

Research is demonstrating how the organic carbon present in domestic wastewater can be converted by mixed microbial cultures into PHA bio-based plastics. A pilot-scale biorefinery process was operated over 22 months at the Brussels North Wastewater Treatment Plant (WWTP) in order to evaluate PHA production, integration with services of municipal wastewater and sludge management (Morgan-Sagastume et al., 2015). Full-scale demonstration of the complete value chain alongside continuous polymer production remains to be validated (Paillard, 2016).

4.6.2. Microbial electrolysis cells: electricity from wastewater

Microbial electrolysis cells (MECs) can theoretically convert any biodegradable waste into H_2, biofuels, and other value-added products. Since their invention in 2005 (Kadier et al., 2016), research has increased the H_2 production rate and yield by orders of magnitudes. However, there are still many challenges remaining, and they need to be overcome in order for MECs to be applied in large scale systems (Randolph and Studer, 2013).

It is theoretically possible to integrate MEC technology into lignocellulosic biorefining. These biorefineries produce large amounts of wastewater that contains biodegradable organics, which can be used in MECs for additional energy production (Zeng et al., 2015), thereby contributing to the sustainability of cellulosic biorefining and to cascading use of biomass.

5. Policy contradictions

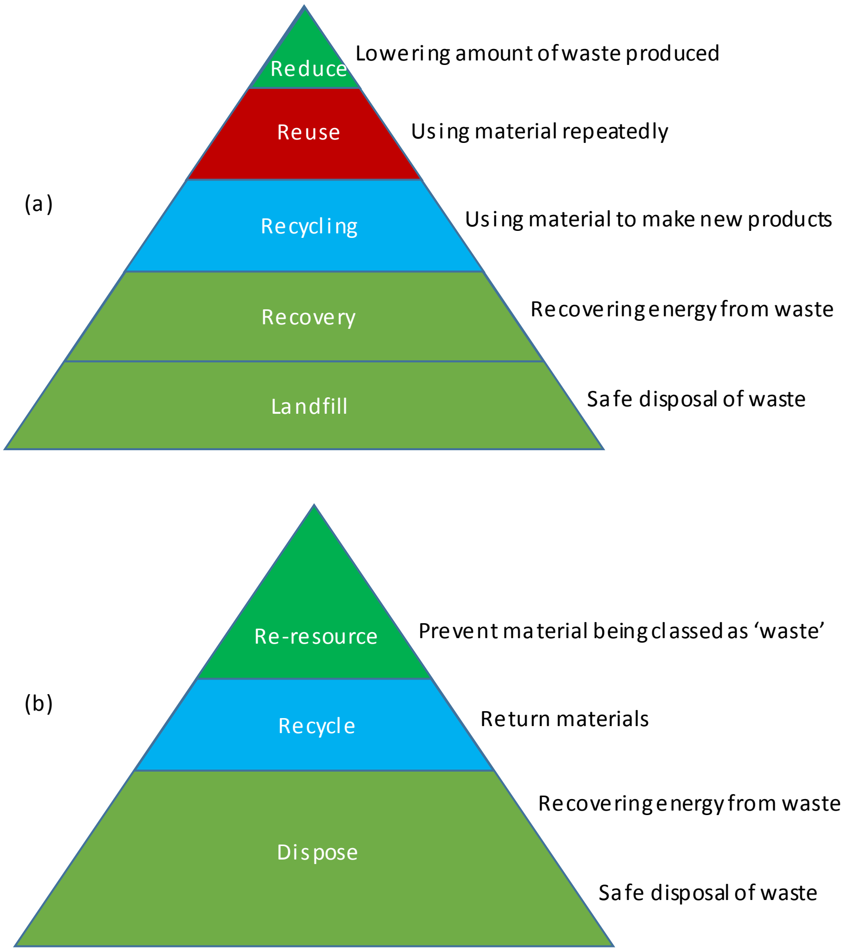
The use of what is currently termed waste can often be used as a feedstock in biorefining. There are many opportunities to valorise waste in a sustainable bioeconomy, but this may require re-defining suitable wastes to prevent a policy contradiction and blockage. Here some of the more obvious policy contradictions are highlighted. Review of policy contradictions should be an ongoing process within governments as a contradiction may arise in the future as the result of a new policy. Such a review before the launch of new policy could greatly simplify any future attempts at rectification as it would prevent expensive lock-ins before they have a chance to surface.

5.1. Where does biorefining fit within the waste hierarchy?

National policy that overwhelmingly favours second-generation biorefining using waste materials as feedstocks directly contradicts national policy that aims to minimise waste. This has to be a central point of policy design in a CBE.

The creation of 'virgin' value-added products from waste feedstocks makes second-generation biorefining difficult to categorise within the classical waste hierarchy (Figure 6a). A variant on the classical waste hierarchy (Figure 6b), or variations therein, would be more appropriate to a waste management regime that prevents wastes from being classed as wastes in the first place, and would make these 'secondary raw materials' available for biorefining with lower waste management regulatory barriers.

Figure 6. The classical waste hierarchy (a) and one more appropriate to reducing barriers to waste biorefining in a CBE (b).



The danger here is that the value-added nature is not taken into consideration and that waste biorefining is given a lower priority in the hierarchy than an activity that does not generate value-added. In other words, as a result of a policy contradiction, the feedstocks for waste biorefining may be diverted to a less profitable activity with lower job potential and leave biorefineries starved of feedstock.

5.2. Waste regulation: a need for greater flexibility

Waste regulation has become increasingly stringent in most OECD countries. In Europe, the legal qualification of some residues or by-products as 'waste' hinders a broad range of potential biorefinery initiatives. Local environmental and spatial permits for managing bio-wastes are limiting possibilities. An example is crude glycerol, a 'by-product' of biodiesel production. Crude glycerol is a production residue that the chemical industry uses in the manufacture of several products, such as in cosmetics and pharmaceuticals. However, some national authorities classify crude glycerol as 'waste' because it needs to be refined before being used for consumer applications. This classification imposes administrative and financial burdens that discourage investments in existing business practices aimed at keeping the value of materials in the economy for as long as possible.

The legal situation varies from country to country. For example, in Germany bio-waste is well integrated into the public disposal system and detailed data are available, while detailed information on industrial waste utilisation is still unclear (Brosowski et al., 2016).

5.2.1. Interference with waste markets

Using such bio-wastes in biorefineries is effectively depriving other waste management facilities of their feedstocks. The deployment of progressive landfill tax policy has given the impetus for the creation of, for example, waste incineration plants and industrial-scale composting. This has often been achieved through public-private partnerships at high cost in taxpayers' money, and therefore represents a risk of asset stranding of publicly financed waste management facilities.

At first glance this form of asset stranding can be avoided by demarcating bio-wastes for biorefining and other solid wastes for incineration. However, this would prevent, for example, the gasification of plastic wastes and the subsequent fermentation of the produced gases in a biorefinery. While waste incineration plants have often encountered public opposition, modern incinerators have improved environmental performance and combining heat recovery and/or electricity generation makes waste incineration attractive. Some countries have chosen to import wastes for this purpose, and biorefining can clearly interfere with these markets. This can create a complicated clash of private and public sector policy. For example, in Sweden private companies import and burn waste, while the energy generated goes into a national heating network to heat homes through the Swedish winter[14]. Similarly, Germany imports wastes from Ireland, Italy, Switzerland, the UK and other countries to feed its waste incineration plants[15].

5.2.2. Interference with other markets

Imposing an end-use on wood may generate mismatches between supply and demand. The end-use(s) of biomass depends on several factors, but the fate of roundwood, pulpwood, harvest residues, industrial residues, recycled wood, dedicated energy crops or other biomass resources, will in most cases be primarily driven by market prices (Conway et al., 2003). In other words, biomass producers will generally look for the highest profit. Patterns of forest landowners' behaviours regarding harvest and selling of wood are also driven by other social factors such as amenity value of trees or the desire to save forests for the next generation.

Thus mandating biomass end-uses on forest landowners and other biomass producers might therefore not be aligned with their best economic interest. The same actually holds true for a systematic use of biomass for energy. There should always remain some flexibility for economic operators to decide upon the best use of biomass, with regards to availability, context, supply and demand, provided that environmental criteria are fulfilled.

Aside from bioenergy targets for climate change policy, some countries encourage intensive use of wood for energy to increase energy security by favouring a local energy carrier instead of an imported one. In such countries, using wood for energy (without cascading) would not necessarily compete with other wood-using sectors. For example a more intensive exploitation of forests in Switzerland may be possible: AEE Suisse (2015) considers that less than half of the annual wood production of Swiss forests is exploited.

5.3. Cascading use of biomass and bioenergy policy: creating context

An overly strict implementation of biomass cascading policy might interfere with bioenergy targets, which have the same policy goal (of climate change mitigation). Beside the risks of regulatory deadlocks and economic consequences of leaving those contradictions unresolved, a clear risk exists to undermine climate mitigation strategy by depriving the bioenergy sector of important biomass resources.

Prohibiting the use of biomass for energy when no alternative material use is practically possible could be detrimental to some economic sectors. Understanding and anticipating the exact socio-economic impacts of different biomass use scenarios in such situations requires the attention of policy makers and regulatory bodies.

For policy makers an experimental approach is suggested, whereby the best use of biomass could be decided on a case-by-case basis by trying to answer the question: which biomass use derives more environmental and economic benefits? Policy makers could explore a decision process for biomass use based on the desired impacts and strategic priorities, namely:

- Climate change mitigation (including preserving important carbon sinks)
- Protection of the environment (especially forests) and the people
- Energy security
- Economic stability and job creations.

This framing would allow decision making on a factual and objective basis regarding what biomass should be used to ensure an optimal contribution of biomass to climate change mitigation and economic development in a circular economy context.

While bioenergy production and consumption imply an immediate combustion of biomass, the cascading use of biomass prioritises material uses of biomass, which may maintain biomass in circulation in supply chains for long periods (e.g. as furniture) before it becomes available for energy use. This may represent a fundamental contradiction between the concept of circular economy and bioenergy production and consumption.

5.3.1. Cascading use is hardly represented in policy at all

To ignore cascading use in favour of only bioenergy applications has policy consequences. In doing so a gap is made between a welfare-maximising outcome where environmental externalities are taken into account, and a market-based outcome, which is distorted by high levels of intervention (Keegan et al., 2013). Without more efficient allocation of biomass between bio-based chemicals, materials and energy use, then suboptimal policy outcomes are guaranteed. What is required is a 'level playing field' for the allocation of biomass that results in cascading use when cascading use is seen to be appropriate. This implies a consideration of wider policy goals. Bioenergy targets emissions reductions. Bio-based chemicals and materials should also target emissions reduction, but other societal benefits should be considered e.g. job creation, added value, advanced manufacturing, resource depletion.

To rectify the dearth of policy requires the clarification of both public and private biomass volumes available at the national or regional level. There may be few or no public statistics available on privately held stocks of biomass. This is a major roadblock to assessing the efficiency of using smart cascades in material flows.

A range of barriers to cascading use have been identified in the literature. For future policy making, some key action points for consideration are (Fehrenbach et al., 2017):

- Certification and product labelling is needed, as both consumer and producer perspectives are equally important
- Management of renewable resources for increased material use
- Interlinkage of value chains
- Promotion of multidisciplinary and cross-sectoral research
- Specific guidelines for the promotion of successful cascading use approaches
- Consistent implementation of circular economy principles e.g. the waste hierarchy.

On the other hand, policy should not create a legally constraining implementation of biomass cascading as this could create regulatory deadlocks and thus negatively impact the development of a bioeconomy.

5.3.2. Green carbon and black carbon in legal terms

It has been noted that there is a legal distinction between 'green carbon' and 'black carbon' for gasification projects. In many OECD countries at present, fuels made by microorganisms can be referred to as 'biofuels' only, when the feedstock is of biological origin. However, using industrial waste gases as feedstocks, currently classed as 'black carbon', in the fermentations could offer environmental and economic sustainability benefits. This acts as an impediment to companies trying to introduce gas fermentation for biofuels production as they may be excluded from taking advantage of biofuels policy.

5.4. Waste separation, collection and storage

For some OECD countries waste separation and collection are no longer issues. For example, in Sweden hardly any waste goes to landfill sites. Waste management facilities are as a rule no more than 300 metres from any residential area. Most Swedes separate all recyclable waste in their homes and deposit it in special containers at their residencies or at a recycling station[16]. By 2023, separate collection of bio-waste or recycling at source (e.g. by home composting) is set to be mandatory throughout Europe, as set out in the revised Waste Framework Directive[17]. Lagging countries have to start building capacity now.

The amount and composition of municipal waste vary widely among OECD countries, being related to levels and patterns of consumption, the rate of urbanisation, lifestyles, and national waste management practices. On average, Europeans generate around 130 kg less than people living in America but 80 kg more than people living in the OECD Asia-Oceania region (OECD, 2015).

Therefore countries will have to invest in separation and collection as circular economy policy is deployed. For waste biorefineries to become an embedded part of the circular economy, there would need to be separate collection of bio-waste that is amenable to biorefining. The obligation on councils in Northern Ireland to provide receptacles for the separate collection of food waste from households is an example of using statutory instruments: the private sector could then be licenced for the collection of separated waste for biorefining.

A long-term commitment is needed from governments to achieve high levels of waste separation. South Korea exemplifies the effort, where the direct landfill of food waste was banned in 2005 (Ju et al., 2016). Since then, a separate collection system and recycling of food waste have been strongly supported by government. Citizens have to buy a specified plastic bag for discharge of food waste and the number of food waste recycling facilities (composting or feed manufacturing) has dramatically increased. With active cooperation from Korean society, the rate of food waste recycling is over 90%. To control costs, waste reduction policies were introduced concurrently.

If biorefining requires a purer waste stream as a feedstock, then facilities need to be provided and the public has to be aware of them. An example is bread waste collection in the Netherlands.

5.4.1. Bio-waste storage and processing

Major difficulties are associated with bio-waste (compared to fossil fuel feedstocks). Lignocellulosic wastes have to be dried before processing, storage or transport and must be kept dry to prevent spoilage. There are large energy and storage costs associated with these processes.

Stored biomass can emit gases due to decomposition, and if stored as a fine, dry material it can be explosive. Some biomass, such as the organic fraction of MSW, is notorious for producing smells, which are very difficult to contain, and this represents a major hurdle, especially as the public is readily sensitised to odours, even at low concentrations.

5.5. Some selected policy contradictions

Table 2 provides some generic policy implications where interference with other policy goals could be possible. (It is not exhaustive, merely illustrative).

Table 2. Bio-based production policy and how it may interfere with other major policy areas.

Policy goal	Potential policy conflicts	Example	Opinion
Biofuels production	Energy	Fossil fuel consumption subsidies	Biofuels have to compete on price, but the fossil fuel market is highly distorted.
	Agriculture	Food versus fuel	Really about competition for land.
		Set-aside (and its suspension)	Increased cropping for biofuels is sometimes associated with set-aside suspension.
	International trade	WTO regulations	Discrimination rules, such as ‘like’ products, and between different types of biofuels.
	Transport	Mandated production	Ethanol blend wall shows a need for a balance of supply and demand policies.

Increased biomass use	Energy	Bioenergy and wood pellets	Feed-in tariffs for bioenergy applications.
	Environment	Waste regulations	Collecting waste may contravene waste licensing regulations.
		Climate change	Non-renewable energy consumption for collection.
	Agriculture	Food versus fuel	The debate is on-going.
		Set-aside	More land needed, perhaps conflicts with set-aside in applicable countries ?
		ILUC	Some say impossible to measure, but ILUC may be written into policy.
		Sugar regime	How may cellulosic sugar conflict with the sugar regime ?
Low volume chemicals	Climate change	Low production volume	Do low volumes create enough climate change benefit to justify policy support ?
	International trade	State Aid rules	How the production may effect or affect trade between states.
High volume chemicals	Biofuels	Biomass pricing	Level playing field for bio-based material use.
	Bioenergy	Biomass pricing	Level playing field for bio-based material use.
Bioplastics	Environment	Landfill use	Will biodegradable plastics degrade in an anaerobic landfill environment ?
		Climate change	Biodegradation increases GHG emissions.
		Composting	Compliance with standards.
		Incineration	Efficient end-of-life option may depend on energy recovery.
		Climate change	GHG emissions lowest through recycling of durable bioplastics ?
Aromatics	Chemicals regulation	Stockholm Convention	Phasing out of toxic chemicals.
Rural biorefineries	Environment	Brownfield policies	Building biorefineries may need greenfield sites.

		Infrastructure	Cooling water.
	Transport	Infrastructure	New rail/road links, pipelines.
	Energy	Infrastructure	New sub-stations, distribution.
	Employment	Relocation	From city to rural life.
	Trade	Competitiveness	Economies of scale with petro-refineries (large, integrated, often coastal).
Marine biorefineries	Environment	Waste	Available waste CO_2.
		Waste	CO_2 capture.

6. Resource efficiency in a CBE

> *"If global resource consumption levels per capita across all developing regions were to catch up with consumption levels observed in OECD countries, the world would require 180 billion tons of materials in 2050, almost tripling the amount of materials used compared to 2008 levels. Clearly, such a level of consumption cannot be sustained*".
>
> RobecoSAM (2012)

Resource efficiency as a goal is congruent with the bioeconomy, with the significant emphasis that bioeconomy policy puts on sustainability. Resource efficiency is much more widespread in industry. However, as many sectors are being driven by business action to investigate and improve the sustainability of their operations, products and services, this link will be constantly referenced – the link between resource efficiency and sustainability. Of the 17 Sustainable Development Goals (SDGs), 12 directly depend on the sustainable economy-wide management of a whole range of natural resources (UNEP, 2016). In Europe, resource efficiency has acquired policy pre-eminence through its inclusion as one of the key pillars of the Europe 2020 strategy.

An aspect of resource efficiency in the bioeconomy that differs from most industry-specific cases is the ability valorise wastes, rather than recycling end-of-life resources. Although similar, there are clearly many opportunities to turn large volumes of waste materials that would otherwise be discarded into feedstocks.

6.1. What is resource efficiency?

Like biomass sustainability (Bosch et al., 2015), resource efficiency is a term that lends itself to measurement, and yet that measurement is complicated. In the European Commission, it has been simply summarised: "*Resource efficiency means using the Earth's limited resources in a sustainable manner while minimising impacts on the environment*"[18]. Hardly surprising, then that a definition is elusive when Sachs (2014), a leading authority on sustainability says: "*Sustainable development is the greatest, most complicated challenge humanity has ever faced*". The situation is further complicated as the interactions between global natural resource use, resource efficiency, economic growth and GHG emissions are not well understood (Hatfield-Dodds et al., 2017). And yet resource efficiency is a priority area of the United Nations Environment Programme (UNEP, 2016) and a flagship initiative of the EU (García et al., 2013). According to the OECD, improving resource efficiency is among the top priorities in today's world[19].

In resource efficiency terms, efficiency can be viewed as the ratio between the intended effect (benefit) and the environmental impact (Huysman et al., 2015). Resource efficiency can thus be improved by either reducing the amount of resources used to produce the output or by reducing the environmental impact associated with the output (Bundgaard et al., 2017). Resource efficiency has become popular with both policy makers and the private sector as it is a promising approach to simultaneously reduce environmental impacts and increase economic performance (Zschieschang et al., 2014). In practical terms the benefits of such are apparent when it is considered that material and energy costs represent about 50% of the operating costs incurred by small and medium-sized enterprises (SMEs) (Dobes et al., 2017).

Given the finite nature of many natural resources, especially fossil resources, and a growing world population, resource efficiency implies creating greater value with fewer input resources. Therefore policy in this area should also consider resource depletion and relative resource depletion, which is driving up production costs (e.g. Massari and Ruberti, 2013). Energy can be included as great improvements have been made in the energy efficiency of, for example, many household appliances (Ellmer et al., 2017) and vehicles[20].

The OECD has undertaken a number of projects in order to inform governments and other stakeholders on how to improve resource efficiency[21]. An OECD view is that: "*Improving resource efficiency is among the top priorities in today's world, as governments, businesses and civil society are increasingly concerned about natural resource use, environmental impacts, material prices and supply security*".

To explore the scope of resource efficiency: it should be applied to every step of the product lifecycle; eco-innovation should be applied to product design, both production and consumption need to be smarter, and; recycling and waste reduction should be supported in policy to abolish waste altogether. Hence resource efficiency has to be a pillar of circular economy concepts and action. It is also at the forefront of developing a sustainable bioeconomy.

6.2. Resource efficiency in industry

With the goals in mind of increasing economic performance while reducing environmental impacts, it should be no surprise that the resource efficiency approach has become popular across industry sectors. Table 3 shows a selection of recent studies that span a range of important industries.

A message for policy makers emerging from this table is that resource efficiency is being taken seriously across a very wide range of industries, but many are struggling with a lack of a standardised methodology. If left unaddressed, this will lead to inconclusive findings within the same industry and across different ones. Readily identifiable effects would be:

- Many industry and academic groups are proposing new methods and metrics for measuring resource efficiency. The more that this happens, however, the further away will be the possibilities for standardisation
- True assessment of the drive towards resource efficiency will be clouded by uncertainties, making future policy actions more difficult to design and deploy
- Industries are likely to 'go it alone' when regulatory targets are to be met but standardised methods are lacking
- Targeted support to leading or lagging sectors will not be possible
- Greenwashing as a marketing strategy is a distinct possibility (Hoffman, 2009).

The situation in the automotive industry sums up the situation more generally across different industries. Automotive sustainability assessment criteria can be found in the literature; however, there has been *no clear consensus amongst automotive experts* and other stakeholders on *which criteria are critical* and *which framework should be used as a standard* (Jasiński et al., 2016; italics are author's emphasis).

Table 3. Recent studies in resource efficiency across different sectors

Sector	Reference	Themes
Metals	Blume et al. (2017)	Common KPIs , decision-support tools.
Multiple	Dobes et al. (2017)	Application of the EDIT Value Tool to SMEs in: base metals; pulp and paper; clothing and textiles; furniture; food and beverage; electrical; mechanical equipment; structural metal products; chemicals.
Chemicals	Zschieschang et al. (2014)	Chemical process design models integrated in material flow networks to obtain information on resource efficiency design parameters.
Industrial wastewater	García et al. (2013)	Calls for a paradigm change to view organic solvents in wastewaters as resources to be recovered rather than pollutants to be treated.
Petro-refining	Han et al. (2015)	Energy and emissions refinery modelling results from 60 large refineries from the US and EU.
Electrical and electronic equipment	Juntao and Mishima (2017)	Metrics for resource efficiency in smart phones in three stages; manufacturing, utilisation and end-of-life treatment.
Laser cutting	Kellens et al. (2014)	An overview of the environmental performance (energy and resource efficiency) of different types of laser cutting systems and derived performance improvement strategies.
Multiple	Rohn et al. (2014)	Assessment of resource efficiency of 250 technologies, strategies, and products, and future potential
Copper mining	Spuerk et al. (2017)	Proposes a new method and associated techniques for the evaluation and quantification of resource efficiency in mining operations.
Brewing	Beloborodko and Rosa (2015)	The cumulative energy and CO_2 intensity for two alternative brewer's spent grain reuse scenarios.
Automotive	Jasinski et al. (2016)	A comprehensive automotive sustainability assessment framework (not strictly resource efficiency).

6.3. Towards measurement of resource efficiency in a CBE

As will be evident from Table 3, methods of measuring resource efficiency have proliferated, whilst standardisation has so far escaped possibility. The following illustrates the point but is not meant to be exhaustive. Material and Energy Flow Analyses (MEFA) provides information associated with environmental impacts of products, processes or combined system levels as well as accounting aspects. An established method rooted in lean manufacturing is Value Stream Mapping (VSM) systematically analyses process chains to reveal time-, stock- and quality-related inefficiencies. Extended versions also incorporate further aspects such as energy demands of processes and supporting services (Energy VSM/EVSM).

A weakness is that all of these approaches represent stand-alone methods usually executed in an isolated manner for a specific purpose. Thus, each method uses different data and varying Key Performance Indicators (KPIs) which hampers the comparability of the respective results (Blume et al., 2017). Indeed, research in circular economy assessment and indicators is still lacking (Elia et al., 2017). Bio-based production requires a different approach again due to the very different nature of the feedstocks.

The CBE differs fundamentally from these established, often fossil resource-dependent industries. First of all, the very youth of bioproduction provides challenges but also an opportunity. Challenges lie in the many unknowns around biomass sustainability and untried and fragmented supply and value chains. Also bioproduction is not restricted to a single industry sector; it applies over many of the largest, most important industries such as automotive, chemicals, plastics, textiles and food. As demonstrated above, as these industries have failed to reach consensus on methodologies for measuring resource efficiency, then such may be the fate of bioproduction.

However, the over-riding opportunity lies in the chance to build a resource efficiency framework from these earliest days. In all the cases in Table 3, sustainability and resource efficiency have to be layered on top of a very well established 'way of working' or business model. Thereby resource efficiency has to be made to fit. In the CBE, there is a chance to custom-fit resource efficiency rather than retrofit.

However, previous OECD work (e.g. OECD, 2014c) has shown that already the same problems exist for bioproduction as for more established industries, especially concerning the all-important feedstock – biomass. Sustainability criteria and schemes have emerged for liquid biofuels but nobody would argue that the situation is currently ideal; in 2012 UNICA described sustainability criteria for bioenergy as "*a universe in constant expansion*"[22].

Criteria for solid biomass remain to be developed and agreed. The opening sentence of the Foreword of a document comparing national sustainability schemes for solid biomass in the EU (Richter, 2016) states: "*There are no harmonised sustainability criteria for bioenergy or the sourcing of biomass across the European Union (EU)*". That same document highlights a realisation by the European Commission that if Member States were to use the amount of biomass indicated in their renewable energy plans, by 2020 the amount of wood used *for energy alone* would be equivalent to today's total EU wood harvest (italics are author's emphasis). The four recommendations of this document are also enlightening. Recommendation number three is for the EU to adopt "*further measures to ensure biomass is used in the most efficient way*".

6.3.1. Metrics and indicators

Measuring circularity

Resource efficiency as applied to the CBE must reference the five main phases of the circular economy paradigm. These pertain to the closed loop logic of the circular economy:

1. Material input
2. Design
3. Production
4. Consumption, and, finally
5. End-of-life (EoL).

These phases contain the processes whose performances must be measured to evaluate how circular is the overall system in analysis. So it must be, then, for a CBE. Box 2 shows the actions in italics that have been proposed to measure circularity (see Elia et al., 2017). To these, bioeconomy-specific actions have been added (normal type).

Box 2. Actions required to quantify the performance of circular products and systems

1. *Circular product design and production: several actions can be included in this category starting from eco-design methods oriented to facilitate product re-use, refurbishment and recycling, the design of products and processes with less hazardous substances*.

The guiding principle of bioproduction is that they must have similar, identical or better performance characteristics than the fossil products they replace, but first and foremost must offer substantial emissions savings (by and large these levels are not standardised yet). Then there can be the matter of less toxicity and greater biodegradability. Alternatively, non-biodegradable, durable bioplastics sequester carbon for longer periods.

2. *Business models: this category mainly includes the diffusion of new models, such as product service systems rather than product ownership, or collaborative consumption tools based on a wider diffusion of consumer-to-consumer channels*.

This is more difficult to envisage in bioproduction as the model is more business-to-business, and less business-to-consumer. This is inherent in the chemicals industry also. A bio-based product will often be part of a product, not all of it e.g. a bioplastic component in a phone. There are other products, of course, where the situation is clearer e.g. an eco-friendly cleaning product.

3. *Cascade/reverse skills: interventions basically focus on supporting closed loop cycles, e.g. with innovative technologies for high-quality recycling, which allows avoiding down-cycling, or for cascading use of materials where high quality recycling is not feasible. A more efficient support to secondary raw materials market will be also essential.*

This should be a huge strength of the bioeconomy but as yet cascading use of biomass is not strongly supported in policy. The final sentence of this action is absolutely essential to a future CBE – the various forms of biomass have to be seen as secondary raw materials, not wastes.

4. *Cross cycle and cross sector collaboration: actions in this category focus on building collaboration across the new value chain, also through the involvement of new actors, preventing by-products to become waste through an effective industrial symbiosis*.

This is a critical component of value chains in the bioeconomy, which are new, untried and often fragmented. However, the concept of local production, collection and transport of biomass to bioproduction facilities, along with local consumption and reuse of products, identifies a circularity that is often impossible with fossil-based products where the raw materials, principally oil, are likely transported thousands of kilometres to the manufacturing plants. A large near-term challenge is building the companies and making the industrial ecosystems where fossil products are the incumbents and are very cost-competitive.

At the individual product level, the following at least have to be measured for a CBE product:

- Reducing input and use of (fossil-based, non-renewable) natural resources
- Reducing emissions levels, both direct (especially the emissions savings resulting from bio-based carbon capture and sequestration) and indirect (e.g. reduction in primary fossil energy used in production)
- Reducing material losses through closed-loop processes e.g. reduction in landfilling or incineration
- Increasing the share of bio-based (principally biomass and bioprocesses) and renewable resources (wind, hydroelectric or solar energy in the production process)
- Increasing the durability of products where appropriate.

6.3.2. How is bio-based resource efficiency different from other approaches?

This is an important question as two quite distinct elements that need to be considered. Huysveld et al. (2015) distinguished these as resource efficiency at the (1) crop level and (2) at the bio-based product level. In the past, where production has been based on fossil resources, 'crop level' would be the equivalent of 'fossil feedstock' level, and would not have been relevant.. For bio-based production, the feedstock need not necessarily be a crop. Nevertheless it often will be either a food or non-food crop.

At the 'bio-based product' level, resource efficiency measurement will look much more familiar as it bears similar hallmarks to resource efficiency in other industries e.g. production process factors. It is a mistake to automatically assume that bio-based production is more environmentally benign than fossil-based. Bioprocesses are notoriously inefficient in terms of titre, but may also be inefficient in yield and productivity (Philp, 2015). These inefficiencies may come at the expense of the additional use of other resources, like land, water and nutrients, and associated environmental impacts, such as eutrophication (De Meester et al., 2011).

Therefore, a useful resource efficiency indicator for optimisation of human-controlled processes needs to distinguish between inherent natural inefficiencies e.g. inherent to biology and biotechnology processes, and inefficiencies that could be tackled by human intervention.

6.3.3. What criteria to use for biomass sustainability assessment?

Solid biomass sustainability and potential are fundamental to the argument as they are essential to deriving land use efficiency. Central to generating criteria for solid biomass sustainability are the quality and quantity of indicators that are used in their derivation. The Global Reporting Initiative (GRI) cited 36 indicators that seem to be related to sustainability. A list of 24 sustainability indicators has been suggested by the Global Biomass Partnership (GBEP) (GBEP, 2011) For efforts in international harmonisation, however, a small number of critical indicators are necessary, or the task becomes unwieldy (Pavanan et al., 2013).

International harmonisation requires not only robust analysis, but consensus, and the latter is often more difficult to achieve. The experience of van Dam and Junginger (2011) is illustrative. Based on responses to a questionnaire sent to international stakeholders from 25 European and 9 non-European countries, the respondents rated the following three sustainability criteria with the highest scores in terms of relevance to include in a biomass and bioenergy certification system:

1. Minimisation of GHG emissions
2. Optimisation of energy balance
3. Protection of water quality and quantity.

Minimisation of GHG emissions was the only one where there was unanimous agreement. This lack of agreement is one of the major factors that causes the huge discrepancies in biomass potential estimates (OECD, 2014c). In the long term, monitoring the biomass potential would allow the resource to be evaluated with quality data. A database of this kind would be instrumental to decision-making as bioeconomy policy is elaborated over time (Brosowski et al., 2016).

6.3.4. Tools

The most common tool for such measurements is Life Cycle Analysis (LCA) (Pawelzik et al., 2013). LCA is not relevant to financial and social criteria, however, and is therefore suboptimal for measuring biomass sustainability. Moreover, several studies have criticised the variability in published results when LCA is used to assess biomass and bioeconomy value chains. Cristóbal et al. (2016) attributed this variability to methodological assumptions, specifically the allocation of system boundaries, functional unit, energy recover, carbon emissions and storage methods. Differences in terminology and different methods of presenting results compound the issues leading to variability.

Conversely, when other tools such as Living Planet Index (LPI), City Development Index (CDI), Human Development Index (HDI), and Environmental Performance Index (EPI) are applied, they often fail to meet other scientific requirements for index formation: normalisation, weighting, and aggregation (Böhringer and Jochem, 2007). So currently no one assessment tool fits the needs of biomass sustainability. Taken together, all these issues speak to the need for methodological harmonisation and coherence for measuring sustainability of biomass and bioeconomy value chains.

Aggregation of sustainability issues into a single measure requires complicated trade-offs between, say, kilogrammes of carbon dioxide emissions and labour conditions. Using price information is understood by policy-makers and the market (Box 3). But placing monetary values on social and ethical costs and benefits is contentious. For example, differences between developed and developing countries require careful handling (Bosch et al., 2015).

Box 3. The Total Factor Productivity (TFP) approach to biomass sustainability

This is an index approach for sustainable benchmarking of biomass production chains based on the concept of TFP which has been routinely used in agriculture (e.g. Glendining et al., 2009; Gaitán-Cremaschi et al., 2015). The general idea of TFP is that it reflects the rate of transformation of inputs (capital, labour, materials, energy and services) into outputs (biomass stock), where negative social and ecological externalities associated to different sustainability issues are included in terms of "bad" outputs.

For example, the outputs of a soy production system may include soy oil and soy meal and the inputs of the same soy system may consist of land, seed, labour, pesticides and fossil fuel. The use of fossil fuel emits GHGs to the atmosphere contributing to climate change (this last output is a "bad" output of soy production). The quantification of outputs and inputs needed for the index may partly be obtained from an LCA analysis. The TFP index takes the analysis one step further in that it incorporates the several sustainability issues into a single measure of sustainability. Hence, the index facilitates the integration and comparison of sustainability issues affecting human well-being at different temporal and spatial scales. Thus, a biomass chain with the best sustainability performance, i.e. the highest TFP score, is the one that produces the highest ratio of output to input where the "bads" are output penalties that lower the sustainability performance. Multiple chains with different sets of outputs and inputs can be compared using the TFP index.

In order to use the TFP index, the multiple input-output variables must be expressed using a common denominator. One solution is to use prices that reflect the relative importance of input and output variables towards sustainability.

6.4. A resource-efficient bioeconomy: the role of the cascading use of biomass concept

"In a circular economy, a cascading use of renewable resources, with several reuse and recycling cycles, should be encouraged where appropriate. Bio-based materials, such as for example wood, can be used in multiple ways, and reuse and recycling can take place several times. This goes together with the application of the waste hierarchy and, more generally, options that result in the best overall environmental outcome. ... The bio-based sector has also shown its potential for innovation in new materials, chemicals and processes, which can be an integral part of the circular economy. Realising this potential depends in particular on investment in integrated bio-refineries, capable of processing biomass and bio-waste for different end-uses".

(European Commission, 2015).

6.4.1. What is cascading use of biomass?

While lacking a formal internationally-agreed definition (Fehrenbach et al., 2017), in the cascading use of biomass concept, biomass is first exploited for higher added-value products before final use of remaining material as an energy source (Keegan et al., 2013). The value-added can mean financial, but it can also mean environmental and social. For example, making furniture from wood sequesters carbon for long periods, which may increase the environmental value-added of the wood. It is also more valuable economically than burning for electricity generation and furniture making is likely to employ more people in higher skilled jobs. In the cascading use concept, any residual biomass left after making the furniture is then used for bioenergy purposes, thus maximising the efficiency of use of the biomass. This is consistent with the resource efficiency component of the circular economy concept (Di Maio et al., 2017).

An added aspect of cascading use that is important for future policy is the interaction with different value chains. Take, for example, lignocellulose. It has material use (as fibreboard), which can be followed by chemical use in the pulp and paper industry; and finally, the fibres remaining can be burned for energy (Geldermann et al., 2016).

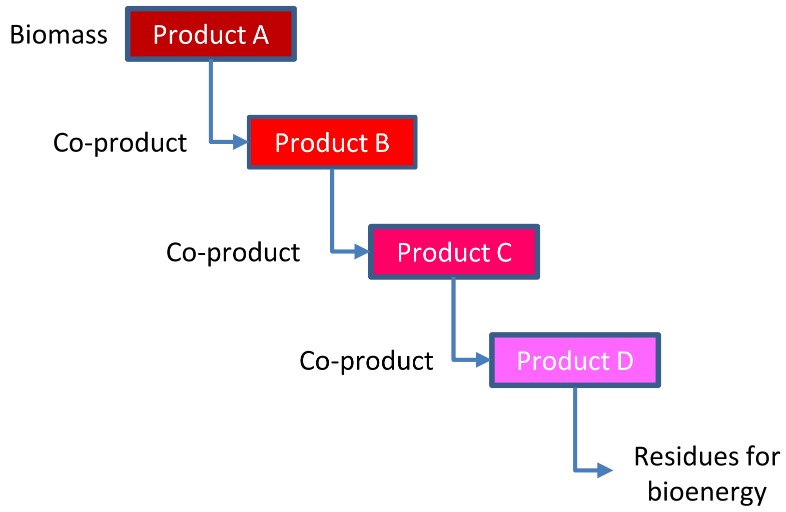
A large proportion of the global trade in wood pellets currently is for bioenergy i.e. burning pellets to generate electricity and/or heat. Using biomass in this way ignores the value-added that can be obtained from biomass as it goes straight to energy. Moreover, job creation for bioenergy applications is limited compared to bioproduction (Piotrowski et al., 2016). The major reason for using wood pellets in bioenergy applications is for countries to meet climate obligations (Röder et al., 2015). In Europe, bioenergy is being deployed on a large scale: by 2020 about 10% of the primary energy requirements of the EU may come from biomass (EEA, 2013). Yet there is much debate over the actual GHG emissions reductions obtained in this way. Haberl et al. (2012) captured the argument thus:

"*Frequently cited bioenergy goals would at least double the present global human use of plant material, the production of which already requires the dedication of roughly 75% of vegetated lands and more than 70% of water withdrawals. However, burning biomass for energy provision increases the amount of carbon in the air just like burning coal, oil or gas if harvesting the biomass decreases the amount of carbon stored in plants and soils, or reduces carbon sequestration… Failure to correct this accounting flaw will likely have substantial adverse consequences*".

In other words, the assumption that biomass combustion is carbon-neutral, regardless of the source of the biomass, may be flawed if the calculation omits CO_2 released by the burning of the biomass itself.

Cascading use can readily be understood diagrammatically (Figure 7).

Figure 7. Schematic representation of cascading use of biomass.



6.4.2. How is cascading use related to circular economy policy goals?

The Ellen MacArthur Foundation (2013) referred to cascading of components and materials within a circular economy as: "*putting materials and components into different uses after end-of-life across different value streams and extracting, over time, stored energy and material 'coherence'. Along the cascade, this material order declines (in other words, entropy increases)*". In this seminal publication on the circular economy, cascading is frequently referred to and can be understood as a central concept of circularity.

The value creation potential of cascading is rooted in the lower marginal costs of reusing the cascading material as a substitute for virgin material inflows and their embedded costs (labour, energy, material). Economically this is not axiomatic, however. In times of low oil prices, making virgin plastics, for example, can be less expensive than the recycling process, since cleaning and preparing used plastics require extra inputs of labour, energy and water[23]. In the absence of fossil fuel subsidy reform and an explicit price in carbon, these distorting factors can greatly influence the economic sense of cascading of some materials on a case-by-case basis.

A clearer case for cascading is textiles, whether from fossil- or bio-based origins. Textiles can be reused multiple times. Reuse of clothing in good condition offers low costs and big savings (Ellen MacArthur Foundation, 2013). Various models exist, from donations and clothes swaps to small- and large-scale commercial resale operations.

Cascading use of biomass in market terms operates quite differently however, as it refers frequently, but not exclusively, to the primary sector rather than secondary (manufacturing and industry) sector.

7. Policy considerations

The circular economy is clearly becoming more important politically as the grand challenges for the future are embedding in society. Involving reuse, repurposing, remanufacturing and recycling, the policy aspects of circularity cross many boundaries – trade, tax, environmental policy, industry, innovation policy to name some. Bioeconomy as a policy issue does the same, and includes other stakeholders such as farmers and foresters. Thus the circular bioeconomy makes for greater complication for the policy maker. This paper attempts to highlight the more obvious and important policy issues that will confront nations. There is considerable emphasis on wastes as feedstocks, and the idea of adding value is a high priority for bioeconomy aspirations.

Waste bioprocessing is a combination of the very traditional (e.g. anaerobic digestion and composting) with the very modern (cellulosic biorefining). This makes it unlikely to find a single policy regime that is suitable to cover the entire topic, although in more general, circular and sustainability terms are obviously common themes. For example, there is less need for upstream R&D for composting than for cellulosic biorefining. Likewise, public-private partnerships for industrial composting are less relevant as the risks associated with private sector investments are lower, given the centuries of experience in composting.

Nevertheless, there are 'tools' that can be applied to traditional technologies that may result in improved predictability and performance. In particular, recent advances in genomics and the new discipline of engineering biology can open up new avenues of investigation and discovery.

The policy considerations here are therefore a mix of general and specific considerations. The general considerations tend to be about the larger implications around sustainability and creating a circular attitude and future for society. Some of the more specific considerations focus in on specific issues e.g. the need for continuing R&D in what has become known as consolidated bioprocessing.

7.1. Clarify definitions and terminology

The development of common definitions would enable better data collection by both private and public entities. This would help resolve the issue of comparison between different data sources mentioned above.

Biorefinery: The International Energy Agency (International Energy Agency Bioenergy Task 42 Biorefinery, 2012) described a biorefinery as "*the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)*". This definition suggests that biorefineries should produce both non-energetic and energetic outlets. Both primary products and energy-driven processes are considered as true biorefinery approaches provided that the final goal is the sustainable processing of biomass (de Jong and Jungmeier, 2015).

Bioeconomy: lack of an agreed definition is a hindrance. It denies the science input, it complicates the creation of international databases, and may result in possible trade barriers. The OECD 'working definition' of 2009 (OECD, 2009) has been overtaken somewhat as the concept has grown in popularity. In that landmark document, one of the formative documents in bioeconomy thinking, the bioeconomy is defined as "*the set of economic activities in which biotechnology contributes centrally to primary production* *and industry, especially where the advanced life sciences are applied to the conversion of biomass into materials, chemicals and fuels*". It is the implications of biomass utilisation, from regional to global, which have expanded the field of bioeconomy way beyond the contributions of the life sciences.

Bio-waste: most of the statistics do not distinguish between wet and dry weight, so no comparisons can be performed. It is extremely important to clarify the definition of bio-waste. According to the European Commission: "*Bio-waste is defined as biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants. It does not include forestry or agricultural residues, manure, sewage sludge, or other biodegradable waste such as natural textiles, paper or processed wood. It also excludes those by-products of food production that never become waste*." By leaving out forestry and agricultural residues, the tonnages generated will be very different.

Waste disposal: could be changed to allow collection, transportation, sorting in view of its conversion in biorefineries. Effectively, if a material is to be converted in a biorefinery then it should no longer be regarded as a waste but as a resource. If this is done officially, many of the problems around collection and transport would be addressed.

A definition of '*bio-based product*' and a harmonised framework for bio-based products is also needed as a standard for public procurement and business development. Progress has been made by the European Committee for Standardisation (CEN) in the development of a coherent and harmonised standardisation framework for bio-based products, but there is still a need to spread the use of the developed standards with a view to capitalise on their market pull potential. This international cooperation can be done by, for example, exchange of Best Practices and experiences in order to reach a more coherent approach to bio-based products globally. Without it, trade barriers are certain to develop.

An assessment of *biotechnology's competitive potential*, which generally requires an economic model of competing technologies, is also required. For example, the future of zero-carbon transportation depends on whether cellulosic ethanol becomes economical at large scale and whether that can compete with electric vehicles.

For various reasons there is a perceived need for standardised terminology in biotechnology. The ISO Technical Committee TC ISO/TC 276 has an inventory of biotechnology-related terms under development[24]. ASTM already has a standard for terminology in industrial biotechnology[25].

Ultimately, integration of actors across sectors and hence the creation of new value chains is limited by disparity and lack of common terminology and standards. In short what is called for is *commonly agreed vocabulary throughout value chains, from feedstock suppliers to biorefining to downstream actors in the application sectors*.

7.2. Most important instruments for making waste biorefining work

What is singularly the most important national/regional instrument for waste biorefining? A process that leads to a strategy for a nation/region that sets out the feedstocks available, their quantities, the sustainability of their use, the infrastructure needs and a timetable out to a decided date should establish clarity for policy makers and the private sector. In reality, this amounts to a two-pronged strategy: first of all is a (decision-oriented) biorefinery roadmap, which must be followed up by an enablement-oriented action plan. The implementation of each would involve setting up a national/regional leadership council of public and private actors to make sure that milestones are being met.

Above all, the private sector is looking for policy certainty. Companies can invest in many countries, and a lack of policy certainty in any one country can drive investments outside that country. A timeframe of 15-25 years to develop the bio-based industry and establish a competitive advantage over fossil-based production is needed. Fossil fuels still enjoys very large subsidies (International Energy Agency, 2017), the industry has had decades of experience to perfect their processes, supply and value chains, and the operating plants are by and large fully amortised by now.

If society needs a change in production, and bioproduction is seen to have a sufficient 'public good' character, then major changes in society need to take place. It is far from within the private sector interests to 'go it alone', and for decades to come, public investments will be needed to bring about this production revolution. It is necessary, however, to create the policy that delivers greatest cost-effectiveness for the taxpayer, for the policy to be tapered, flexible and with clearly defined end-points so that the industry can make the timely investments that will be needed post-public policy (in a free, competitive market).

7.3. Policy alignment of waste biorefining with sustainability goals

Bioproduction is directly linked to several of the societal grand challenges and policy goals. These are principally, climate change mitigation, energy security and resource depletion. Indirectly, bioproduction can also be linked to food security (as the industrial use of biomass has the potential to impact on food security), soil destruction and water security. Therefore bioproduction touches on the most important human challenges of now and the future, which collectively could be called 'sustainable development', and is therefore directly linked to the United Nations 2030 Agenda for Sustainable Development (General Assembly of the United Nations, 2015).

7.3.1. Waste biorefining addresses several major policy goals

Using wastes materials in biorefining meets several policy goals and challenges:

- It relieves pressure on land, thereby enhancing sustainability
- It avoids the issues around indirect land use change (ILUC) (Van Stappen et al., 2011)
- It avoids issues such as the food versus fuel debate
- It improves public opinion through the first three
- In the case of waste industrial gases, especially CO and CO_2, as well as the above four advantages, this uses GHGs that would otherwise become emissions, i.e. it contributes to science and policy goals around reducing emissions in climate policy
- In the case of MSW all of the above apply (as MSW is converted to methane in landfill sites, and methane is a much more potent GHG than CO_2), and an additional policy challenge is also addressed – the diminishing supply of suitable sites for new landfills, a problem for many countries.

7.3.2. Generic issues around waste utilisation and biorefining

The decision on where to locate a waste biorefinery is not a simple one, despite much discussion about rural locations. There are multiple factors that can be taken into account. A decisive factor may be a decision to include municipal solid waste (MSW) as a feedstock. For a national or regional government to consider waste biorefining, there must be sufficient knowledge of issues described in Table 4.

Table 4. Generic waste utilisation and biorefining issues in decision making for policy makers.

For a national or regional government to consider waste biorefining, there must be sufficient knowledge of
What wastes, and what quantities, are available within a radius of the proposed plant that guarantees sustainability. The main limitation of the use of raw materials from agriculture is related to their typical low economic value and energy density. Long distance transportation is a limiting factor (Mayfield et al., 2007).
What wastes may need to be imported (for example, to maintain year-round operation). The location of the nearest port may be a decisive factor.
What type of biorefinery is to be constructed (the more feedstocks that can be used, the greater the likelihood of success).
What forms of pre-processing are to be used (gasification extends the range of potential feedstocks considerably);
Where the physical location might be (access to different types of biomass, including potentially MSW, public acceptance, NIMBYism (“not in my back yard”).
What agencies can be called upon to gather data.
What new infrastructure will need to be provided (e.g. road, rail, electricity).
The initial roles of the public sector (e.g. loan guarantees to de-risk private investment).
Local waste licensing regulations (e.g. there may be specific prohibitions regarding transport of waste materials).
Risks (e.g. odour, economic, health, environmental).
Implications for existing markets, especially recycling, incineration and industrial composting.
Public perceptions (about waste, industrial plant, brownfield/greenfield policies, GM biocatalysts, effects on local amenities, effects on house prices).
How to make the regulatory framework sufficiently flexible.
Availability of a qualified workforce with the requisite technical skills (Lopolito et al., 2011).
Recycling water and wastewater treatment may be a necessity, and existing policy could be helpful or prohibitive.
Cities understandably may wish to invest in a biorefinery if it brings benefits and jobs to the city itself (Bazancourt-Pomacle, however, is rural/semi-rural and Reims Metropole is one of the consortium of investors). Bazancourt-Pomacle also has Champagne Ardennes and La Marne Conseil Général as investors, and Crescentino had Regione Piemonte. The ground-breaking MSW biorefinery of Enerkem in Edmonton, Canada has the City of Edmonton as an investor. Different investors will have different political agendas, which have to be carefully managed.
Many gaps between R&D, demonstration and prototype production plants (common in many countries).
Bio-based products are often not competitive with petrochemical products (this is not surprising as the latter industry has had decades to perfect its processes and products, and the young bio-based industry needs policy support to make it more competitive).
Lack of consistent political leadership.

7.3.3. Waste biorefining and the UN Sustainable Development Goals (SDGs)

The SDGs have greatly raised the political profile of future sustainability. They should act as the benchmark for creating the CBE to ensure that it is fully aligned with these far-reaching societal goals. Bengelsdorf and Dürre (2017) showed how gas fermentations align with four of the SDGs. This is an analysis that should be possible for any biorefinery development using any feedstock(s), given a standard set of metrics. As long as the alignment can be proven, this should boost public acceptance. It could also be used as a tool for public finance of biorefinery projects: it would help make sure that economic, social and environmental sustainability is embedded within the project rather than just environmental. If the SDGs become a lodestar of the private sector, then waste biorefining should become easier to finance.

El-Chichakli et al. (2016), in describing five cornerstones of a global bioeconomy, note that innovations in the bioeconomy can contribute to meeting more than half of the SDGs. The concept of "*scoring sustainable development goals*" could similarly be extended to the CBE.

7.3.4. Substitution of fossil resources and climate change mitigation

Bioeconomy strategies call for substantial substitution of fossil-based resources (oil, gas and coal) with renewable resources. Many governments have set targets for emissions reductions to meet international obligations, and as a result there has been a drive towards using biomass in electricity generation, for liquid and gaseous fuels. According to the International Renewable Energy Agency, at least 154 countries have set renewable energy targets as of mid-2015 (IRENA, 2015a; 2015). However, there has been much less policy attention to bio-based materials and chemicals.

In June 2015 the G7 outlined the plan to phase out fossil fuels by the end of this century. The G7 text (G7 Germany, 2015) called for as-close-as-possible to a 70% reduction on 2010 emissions by 2050, in line with the overall goals of the Paris Agreement from COP21. Such a major upheaval calls for policy action on many fronts e.g. tax, energy, agriculture, governance, investment. Science and technology quite clearly hold the answers to many of the questions regarding this low-carbon, non-fossil future, as evidenced by the growth of solar and wind technologies.

7.3.5. Soil destruction as a focus for policy makers

"*Soil health and productivity are foundational to the provision of nearly* all *of these life-sustaining services, including food and fuel production, carbon sequestration, water filtration, flood control and biodiversity*"

Sally Collins, USDA (2011)

At the political level the implications of soil destruction and degradation are now being realised. Late in 2017, the UK Environment Secretary Michael Gove warned that the UK is 30 to 40 years away from "*the fundamental eradication of soil fertility*" in parts of the country[26] . Governments need to incentivise farmers to tackle both the loss of soil fertility and the decline in biodiversity. Practices need to promote the ability of soils to produce food while also delivering other key ecosystem services (Holland et al., 2018).

The situation is by no means restricted to the UK. Rather, it is a matter of almost global importance. About one third of the world's soil has already been degraded. Every year, an estimated 12 million hectares of agricultural land, which could potentially produce 20 million tonnes of grain, are lost to land degradation (Beddington et al., 2011). About 2.5% of arable land in China is too contaminated for agricultural use (Chen and Ye, 2014).

Once more there is an issue of reliable data. Global estimates of total degraded land area vary from less than 1 billion hectares to over 6 billion, with equally wide disagreement in their spatial distribution. The risk of overestimating the availability and productive potential of these areas is severe, as it may divert attention from efforts to reduce food and agricultural waste (Gibbs and Salmon, 2015).

7.3.6. Green growth

The policy goals of waste biorefining are also consistent with the Green Growth concept[27]. Green growth has been defined as follows (OECD, 2011b):

"*Green growth is about fostering economic growth and development while ensuring that the natural assets continue to provide the resources and environmental services on which our well- being relies. To do this it must catalyse investment and innovation which will underpin sustained growth and give rise to new economic opportunities*".

The first country that incorporated Green Growth into major policy was the Republic of Korea, with a National Green Growth Strategy, which included three major objectives and ten policy directions (Zelenovskaya, 2012) consistent with climate change mitigation.

7.3.7. Food waste regulation

The timing is very good in many countries to align waste biorefining with young or new food waste regulations. For example, in 2013 the Northern Ireland Assembly introduced food waste regulations[28] that place a duty on food businesses to present food waste for separate collection and ban the landfilling of source-separated food wastes. Additionally the statutory instrument places an obligation on councils to provide receptacles for the separate collection of food waste from households. This final point helps break down one of the barriers to food waste biorefining.

This has created a strong driver for projects that support the development of circular/bioeconomy policies and research. One example of this is the ReNEW project[29] which has demonstrated that more than 13 000 jobs could be created if Northern Ireland moved to a circular economy, identifying "*particular opportunities in food and drink, biorefining and the bioeconomy*" (Pérez-Camacho et al., 2018).

7.4. Waste biorefinery financing

The most common form of financing for biorefinery technologies in the United States is a hybrid of equity, teamed with either federal grants or federally backed loan guarantees. A grant does not need to be paid back, but is subject to a series of technical hurdles. To build biorefineries, both the USDA and USDOE have favoured 20-year loan guarantees.

With a government loan guarantee, the government (the guarantor) promises to assume the debt obligation of a private borrower if that borrower defaults. Loan guarantees are similar to traditional project finance, but the government accepts the technology risk and backs the loan. This streamlines the approval steps and the control.

In Europe the main mechanisms is the public-private partnerships involving matched funding. The loan guarantee mechanism, which has been largely absent in Europe for biorefinery construction, but used frequently in the US, would help debt finance management. At the time of construction of the Crescentino biorefinery in Italy, debt financing was seen as a major difficulty in the overall financing of the construction. Policy makers should be sure that the debt financing strategy is sound before committing public funds. Financial instruments for building public-private partnerships have to be attractive and not overly bureaucratic. Make sure there is gate-staging management to ensure that staged public financing is dependent upon hitting targets.

With the arrival of InnovFin in Europe, it may become easier to finance biorefineries through loan guarantees. The InnovFin-EU Finance for Innovators was launched by the

European Community and the European Investment Bank (EIB) Group in the framework of Horizon 2020. It provides guarantees or direct loans (EUR 24 billion available) to research and innovation projects. InnovFin aims to improve access to risk finance for research and innovation projects; research infrastructures; public-private partnerships; and special-purpose projects promoting first-of-a-kind, industrial demonstration projects (Scarlat et al., 2015). This is a major step in Europe as loan guarantees had previously been missing from the portfolio of funding mechanisms for bioeconomy projects.

Innovative instruments are being developed to finance biorefinery construction, such as green banks established with taxpayer money but operates along the lines of a commercial bank. The concept of the green investment bank, in which investment decisions are based on a sound assessment of a business plan, is growing in popularity (OECD, 2016b). Typical green bank projects include offshore and onshore renewable energy, offshore wind and solar power. An extension to biorefinery projects seems like an easy option, but at present the risks are higher. Other models ought to be considered, and hybrid models may be more effective than any single existing model.

7.5. R&D subsidy

A major challenge in bio-based production, and specifically in waste biorefining, is the multidisciplinary nature of the subject. Research subsidies will have to create not only the new knowledge required, but also the cadre of specialist people. The education system is currently not fit for this multi- and interdisciplinary challenge (Delebecque and Philp, 2018).

Research programmes in biorefining need to be designed with care. There is a need for a balance between upstream R&D that would be more laboratory based, and downstream research activities that are closer to market e.g. satisfying needs to create an industrial ecosystem. There is an obvious need for co-sponsoring of research programmes between various research councils e.g. biotechnology, natural science, engineering, to prevent overlaps and duplication. Programmes like the BBI JU encompass several types of project, from basic research to flagship biorefinery facilities, each with a different funding structure.

It is beyond the scope of the paper to make detailed assessment of R&D needs. Instead, a few priority areas for publicly funded research are highlighted.

7.5.1. Is the right model of R&D&I available?

The greatest technical promise for future biotechnology mobilisation may be the standardisation of engineering biology that allows more rapid and less expensive reduction to practice. However, decades of metabolic engineering for bio-based chemicals and materials have brought many research successes but few commercial-scale products. To address this gap between laboratory and market, there may be a need for new models of R&D&I to speed up the process. Various models, including the public and private intermediate research organisation (IRO) were discussed by Gauvreau et al. (2018).

7.5.2. Building the SMEs and collaborations to meet the challenges

In response to this lack of commercial success, researchers at the Korea Advanced Institute of Science and Technology (KAIST) have recently suggested ten general strategies of systems metabolic engineering to successfully develop industrial microbial strains (Lee and Kim, 2015). Systems metabolic engineering differs from conventional metabolic engineering by incorporating traditional metabolic engineering approaches along with tools of other fields, such as systems biology, synthetic biology, and molecular evolution.

Many companies are competent in one or more of these specialisms, but few can integrate them all into a production process. In this and other fields of biotechnology there is a need for better collaboration between academia and industrial biotechnology companies (Pronk et al., 2015), and far more rapid transfer of knowledge between the public and private sectors.

7.5.3. Consolidated bioprocessing: a continuing need for public R&D funding

In the consolidated bioprocessing (CBP) approach, enzyme activities for the breakdown of (ligno)cellulose are combined with the machinery for making bio-based products within a single bacterial biocatalyst. The US Department of Energy endorsed the view that CBP technology is widely considered the ultimate low-cost configuration for cellulose hydrolysis and fermentation (USDOE, 2006). Achieving CBP in practice is an endeavour of engineering biology to create the correct functionality but also to make the biocatalyst robust enough for use in an industrial process. Of the various possible bioprocessing technologies, CBP may be the most economical in the long run, but productivity is still lacking (Kawaguchi et al., 2016), and requires continued research funding to bring it to fruition.

7.5.4. Reliability, reproducibility and standardisation

"*Our main argument is that adoption of standards is bound to accelerate the transition between contemporary genetic engineering-based biotechnology and the future bio-engineering-based KBBE*."

De Lorenzo and Schmidt, 2018

Concepts such as interoperability, separation of design from manufacture, standardisation of parts and systems, all of which are central to engineering disciplines, have been largely absent from biotechnology (OECD, 2014b). Standards allow decoupling of design from production from assembly from deployment (de Lorenzo and Schmidt, 2018), an essential concept in engineering. They also help to reduce irreproducibility of results which has always been evident in biology and biotechnology (Baker, 2016). In short, the adoption of standards facilitates the scalability, reproducibility and predictability of an engineering field, to which engineering biology is aspiring. To overcome such large hurdles requires public and private cooperation, which can be facilitated by targeted joint R&D programmes.

7.5.5. Biotechnology research automation and public DNA foundries

To achieve the goals of reliability, reproducibility, and standardisation calls increasingly for the automation of protocols and workflows in biotechnology research if engineering biology is to enter a fully quantitative era. Computer-aided design with automation will lead to the ability to achieve scale as has never been possible. Automation will allow researchers to spend more time on experimental design instead of experiment execution.

Complementary to laboratory operation is access to data and DNA through centralised DNA foundries that can be accessed using cloud-based applications (McClymont and Freemont, 2017). The concept is meant to allow many independent low-cost work cells in many institutions, but with cloud access to DNA foundries to carry out complex experimental workflows beyond the means of most organisations.

7.6. A level playing field

Objections to subsidising young technologies of any sort for climate change mitigation can be based on market distortion caused by subsidies. However, there is no such thing as a 'level playing field' between the fossil industries and any of the green industries. The fossil industries are over a century old and fossil fuels subsidies remain high. Each year these subsidies consistently amount to several hundreds of billions of dollars (International Energy Agency, 2017).

Carbon price and carbon taxes seem like the logical ways to raise the large sums required to finance the public contributions of such projects. The purpose of carbon pricing policy frameworks today should be to send clear and credible price signals that foster the low-carbon transition over the medium to long term (OECD, 2015a). Explicit carbon prices can either be set through a carbon tax, expressed as a fixed price per tonne of emissions, or through cap-and-trade systems, where an emissions reduction target is set through the issuance of a fixed number of permits, and the price is set in the market through supply and demand. Pricing carbon emissions through a carbon tax should be a powerful incentive to invest in cleaner technologies and adopt greener industrial processes such as those promised by engineering biology. Classically, emissions should be charged at a price equal to the monetary value of the damage caused by the emissions. This should result in the economically optimal (efficient) amount of CO_2 emissions (OECD, 2016a). However, agreement on the price of the damage remains elusive.

Removing fossil fuel subsidies and pricing the environmental damage of those industries would put a completely different complexion on their economics, and would make arguments against green, sustainable bioindustries much less convincing.

7.7. Regulations, standards and labels for bio-based products pertain to resource efficiency

The regulations and standards approach can also be a tool for market creation through, for example, product registration and life cycle assessment. A way for waste biorefining to win here is the application of rational, harmonised sustainability certification, where currently this area is a patchwork of voluntary schemes that is confusing and lacks the credibility of enforcement.

Regulations governing the use of biomass, especially cascading use, in the various application sectors differ among the sectors and at national and international levels. This can hinder investments in new facilities and R&D into new products and applications. The specific challenge is two-fold.

1. Firstly, there is a need to boost the use of instruments, in particular common standards, reducing barriers to trade in bio-based products among value chains and hence to expand their market potential.
2. Secondly, regulatory hurdles hindering investments into existing and new value chains, products and applications across sectors, have to be removed and establishing a level playing field for bio-based products is a priority.

Standards for bio-based products at international level (e.g. on bio-based content, biodegradability, sustainability and functionalities) will ensure their consistency across sectors. Standards are also central for the development of labels for bio-based products. To be comparable and reliable, sustainability assessments for bio-based products need to be standardised and certifiable. Sustainability criteria for bio-based products and biofuels should be comparable and take into account factors such as the calculation of GHG emissions and criteria for sustainable biomass production.

In the same manner that the Renewable Fuels Standard (RFS) set GHG emissions savings standards along with volumetric mandates for biofuels, environmental targets for bio-based materials may be possible. This might have the effect not only of encouraging the development of the most effective bioplastics, but would also deter early investment in bioplastics with poorer environmental performance. Narayan and Patel (2003) have made an attempt to specify such targets: they recommended that, relative to their conventional counterparts, biopolymers and natural fibre composites should:

- Save at least 20 MJ (non-renewable) energy per kg polymer;
- Avoid at least 1 kg CO_2 per kg polymer; and
- Reduce most other environmental impacts by at least 20%.

The data produced by Weiss et al. (2012) showed that a range of bio-based materials saved, on average, 55 +/- 34 MJ non-renewable energy and 3 +/- 1 kg CO_2 per kg material, thereby easily meeting the suggested targets of Narayan and Patel.

Labelling can play an important role for the commercialisation of bio-based products, providing consumers with clear information on the environmental performance of the products and guiding their purchasing behaviour towards sustainable choices. Labels can also be critical for the uptake of bio-based products by green public procurement. In view of the proliferation of national and international labelling schemes, there are benefits to be attained by associating bio-based products with a successful existing scheme that has a harmonised and standardised approach.

7.7.1. Consider bioplastics within a future strategy for dealing with plastic waste

Bioplastics provide an avenue for the development of a sustainable, circular plastics economy by using alternative feedstocks and offering a wider scope of end-of-life options for plastic products. However, the EU Plastics Strategy proposal fails to suggest concrete legislative measures to capitalise on the benefits of bioplastics. European Bioplastics (2018) has outlined a set of potential legislative measures and actions that will enable bioplastics to fulfil their potential in an evolving plastics economy that must address the serious issues that plastic waste is creating. While these measures[30] pertain to the EU, they may be equally valid in countries struggling with the plastic waste dilemma (effectively all OECD member states and many others).

- Define criteria for applications, where biodegradable plastics are more suitable than conventional plastics
- Promote the use of biodegradable, bio-based materials for the manufacturing of packaging
- Define feedstock sustainability criteria for bio-based plastics
- Ensure sustainability criteria for plastics feedstock are based on a level playing field with fossil-based plastics
- Work towards new, harmonised rules to ensure that, by 2030, 10% of all plastic packaging materials placed on the EU market are bio-based

- Work towards new, harmonised rules to ensure that, by 2030, a range of plastic packaging with food contact (especially perishable foods) or used for the collection of bio-waste can be organically recycled
- Restrict the use of 'oxo-degradable' plastics (see OECD, 2013)
- Consider the implementation of existing harmonised rules, definitions, and labels for industrially compostable plastics.

In the case of drop-in or replacement durable bioplastics, they should be treated in policy the same way as their fossil counterparts as long as they fulfil sustainability criteria, including emissions reductions and reductions in primary fossil energy, such as those suggested by Narayan and Patel (2003).

7.8. Control of illegal practices in raw materials trade

Unfortunately, illegal trading practices are often used in order to circumvent direct control of important secondary raw material flows. For instance, false customs declarations classifying waste as second-hand goods are used to avoid the Waste Shipments Regulation for specific secondary raw material flows (European Commission, 2011). Illegal transboundary waste shipments have also been increasing, although the extent is difficult to measure (European Environment Agency, 2009).

Illegal logging is already costing nations tens of billions of dollars each year, and tropical deforestation contributes 12% of total anthropogenic carbon dioxide emissions globally (Lynch et al., 2013). Therefore, illegal logging works against two founding policy goals of a bioeconomy – economic growth and climate change mitigation. Paying to prevent deforestation is likely to be contentious, but contributions from OECD countries may be less expensive than letting it continue unabated.

Liberia is using novel policy to counter illegal logging aimed at enabling the country and communities to make money from reduced carbon emissions. First, carbon levels are measured in a forest. Then, if the land is not cleared, the carbon that is retained in the forest — or not emitted through clearing — can be sold as offsets. Norway is providing USD 70 million to help Liberia develop the policy framework and create capacity to implement it. It is providing a further USD 80 million to pay for the first carbon offsets (Aglionby, 2016). It will take time to see whether such a system could succeed, but this could be a test-bed for deforestation prevention.

Technology is available that may be adapted to monitoring logging. Arbonaut of Finland has developed the combination of machine vision software and light detection and ranging (liDAR) technology that can be used to assess carbon stocks in tropical forests. It can calculate the amount of CO_2 removed from the atmosphere, entitling a country to payments for carbon capture via forests under the Paris Agreement (Ministry of Economic Affairs and Employment of Finland, 2017).

An increasing transition to a CBE will result in increased flows of primary and secondary raw materials, and governments need therefore to improve the monitoring of illegal trade and measures to prevent/disincentivise it.

7.9. Improved resource efficiency is essential to meet the SDGs

Of the 17 Sustainable Development Goals (SDGs), 12 directly depend on the sustainable economy-wide management of a whole range of natural resources (UNEP, 2016). At least half of the SDGs can be addressed by the use of biotechnology and the bioeconomy. It could be argued that resource efficiency and the bioeconomy have in common at least 9 of these SDGs (2,3,6,7,9,12,13,14,15). In other words, biotechnologies that are demonstrably resource-efficient can address these 9 SDGs. It is in a CBE where the benefits of bio-based resource efficiency can be greatest.

7.10. Resource efficiency improvements are indispensable for meeting climate change targets

There are merits and demerits of applying biotechnologies to climate change mitigation. Much evidence is accumulating that bio-based production to replace fossil-based can generate large emissions savings (e.g. Dammer et al., 2017; OECD, 2014a; Weiss et al., 2012). However, a policy correction should be considered as the vast majority of policy in this area has been directed at energy, for the logical reason that liquid fuels have a large contribution to emissions, as does burning coal for energy. The contributions to emissions of the chemicals and materials industries are not inconsiderable, and here bio-based production not only offers emissions savings but greater contributions in terms of value-added and job creation (Philp, 2015).

Meanwhile those biotechnologies that can be considered to be environmental biotechnologies, while offering essential benefits, also contribute to emissions (USEPA, 2010). For example, aerobic biological wastewater treatment produces GHGs while carrying out essential wastewater purification, and research is being directed to reducing these emissions (e.g. Campos et al., 2016). Current treatment of municipal wastewater accounts for approximately 3% of global electricity consumption and 5% of non-CO_2 GHG emissions, principally methane from anaerobic digestion (Li et al., 2015). Similarly composting of solid organic wastes is a circular biotechnology that is well-established, but results in emissions, and there is scope for improvements (Sánchez et al., 2015).

These environmental biotechnologies suffer from a lack of process control, despite being applied at very large scale (the largest scale deployment of all biotechnologies). Therefore R&D subsidy policy could focus on providing the genomics/digital tools that make these technologies more predictable. Bioremediation is a good example of a full-scale environmental biotechnology that is under-utilised through a lack of process control (Gillespie and Philp, 2013), despite being considered a sustainable remediation technology (Sorvari et al., 2009). There is an urgent need to equip bioremediation practitioners with a suite of –omics techniques to demonstrate the genuine scientific basis that underpins the process, and to improve its predictability (Diplock et al., 2009).

Although still research-based, evidence is accumulating for systems (Dvořák et al., 2017) and cell-free synthetic biology (Karig, 2017) approaches to the bioremediation of recalcitrant pollutants from soil. Such approaches are probably only justified in cases of highly persistent pollutants, but have been hampered by safety concerns associated with the release of genetically modified organisms (GMOs) into the environment. The cell-free synthetic biology approach may circumvent these concerns by allowing deployment of gene networks and metabolic pathways without the risk of replication and spread of new microbial strains in the wild. Nevertheless, on-going, science-based risk assessment should still be a policy priority.

7.11. There are substantial areas of opportunity for greater resource efficiency

Modelling undertaken for UNEP found that resource efficiency combined with climate policy could reduce global resource use in 2050 by 28% relative to existing trends, while reducing greenhouse emissions and boosting income and economic growth. Likewise, bioeconomy offers such opportunities that need to be scrutinised case-by-case using standardised methodology. Data for the resource-efficient CBE have still to be garnered.

7.12. A balance between input and output policy

A policy strategy that relies mainly on the output side of the material and energy cycles is likely to fail in bringing about the necessary and desired environmental changes. The corollary is that significant reductions in the input side through a substantial increase of energy and resource efficiency are likely to be necessary to prevent aggravation of environmental problems due to ecosystem thresholds (Domenech and Bahn-Walkowiak, 2018).

References

Adani, F. (2015), "Availability of bio-waste types (including gases)", Presentation at the joint workshop of the Italian National Technological Cluster of Green Chemistry and the OECD: Bio-waste Biorefining: bio-waste and organic by-products exploitation in multi-purpose biorefinery schemes, Economdo 2015, Rimini Fiera, Italy.

AEE Suisse (2015), *Bois: Une matière première renouvelable avec du potentiel*, (In French). http://www.energie-bois.ch/uploads/tx_ttproducts/datasheet/000_aee_Bois_MatierePrem_aPotentiel.pdf

Aglionby, J. (8 April 2016), "Green revolution aims to stem deforestation in Liberia", Financial Times blog, www.ft.com/intl/cms/s/0/9e596f2e-dbbb-11e5-a72f-1e7744c66818.html#axzz45DdIxzJY

Arsenault, C. (2015), "Only 60 years of farming left if soil degradation continues", *Scientific American*, http://www.scientificamerican.com/article/only-60-years-of-farming-left-if-soildegradation-continues/

Baker M. (2016), "1,500 scientists lift the lid on reproducibility", *Nature* Vol. 533, pp. 452–454.

Beddington, J., M. Asaduzzaman, A. Fernandez, M. Clark, M. Guillou, M. Jahn, L. Erda, T. Mamo, N.V.Bo, C.A. Nobre, R. Scholes, R. Sharma and J. Wakhungu (2011), *Achieving food security in the face of climate change: summary for policy makers from the Commission on Sustainable Agriculture and Climate Change*. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Beloborodko, A. and M. Rosa (2015), "The use of performance indicators for analysis of resource efficiency measures", *Energy Procedia* Vol. 72, pp. 337-344

Bengelsdorf, F.R. and P. Dürre (2017), "Gas fermentation for commodity chemicals and fuels", *Microbial Biotechnology* Vol. 10, pp. 1167-1170.

Bioeconomy (2014), *The Finnish bioeconomy strategy*, http://biotalous.fi/wp-content/uploads/2014/08/The_Finnish_Bioeconomy_Strategy_110620141.pdf

BIT (2016), *Bioeconomy in Italy*. http://www.agenziacoesione.gov.it/opencms/export/sites/dps/it/documentazione/NEWS_2016/BIT/BIT_EN.pdf

Biomass Magazine (2011), "The role of MSW for future biorefineries", http://biomassmagazine.com/articles/6746/the-role-of-msw-for-future-biorefineries/?ref=brm

Blume, D. Kurle, C. Herrmann and S. Thiede (2017), "Toolbox for increasing resource efficiency in the european metal mechanic sector" *Procedia CIRP* Vol. 61, pp. 40-45.

Böhringer, C. and Jochem, P.E.P. (2007), "Measuring the immeasurable – a survey of sustainability indices", *Ecological Economics* Vol. 63, pp. 1-8.

Bosch, R., M. van de Pol and J. Philp (2015), "Define biomass sustainability", *Nature* Vol. 253, pp. 256-257.

Brosowski, A., D. Thrän, U. Mantau, B. Mahro, G. Erdmann, P. Adler, W. Stinner, G. Reinhold, T. Hering and C. Blanke (2016), "A review of biomass potential and current utilisation - Status quo for 93 biogenic wastes and residues in Germany", *Biomass and Bioenergy* Vol. 95, pp. 257-272

Bundgaard, A.M., M.A. Mosgaard and A. Remmen (2017), "From energy efficiency towards resource efficiency within the Ecodesign Directive", *Journal of Cleaner Production* Vol. 144, pp. 358-374

Byrnes, B.H. (1990). Environmental effects of N fertilizer use - An overview. *Fertilizer Research* Vol. 26, pp. 209-215.

Campos, J.L., D. Valenzuela-Heredia, A. Pedrouso, A. Val del Río, M. Belmonte, and A. Mosquera-Corral (2016), "Greenhouse gases emissions from wastewater treatment plants: minimization, treatment, and prevention", *Journal of Chemistry* ID 3796352, http://dx.doi.org/10.1155/2016/3796352.

Chemical & Engineering News (2017), "Calysta raises money for fish food", *C&EN* Vol. 95, p. 10.

Chen R. and C. Ye (2014). "Land management: resolving soil pollution in China", *Nature* Vol. 505, p. 483.

China Go Abroad (2017), *Chinese State Council publishes guidelines on strategic emerging industries during the 13th Five-Year Plan period (2016-20),* http://www.chinagoabroad.com/en/article/22887 .

Circulate (2017), *How Finland is approaching the circular economy*, http://circulatenews.org/2017/04/finland-approaching-circular-economy/

Clarke, W.P. (2018), "The uptake of anaerobic digestion for the organic fraction of municipal solid waste – Push versus pull factors", *Bioresource Technology* Vol. 249, pp. 1040-1043.

Collins, S. (2011), Foreword in: *Sustainable Soil Productivity in Response to Global Climate Change*. *Science, Policy and Ethics*. T.J. Sauer, J.M. Norman and M.V.K. Sivakumar (eds.), Wiley-Blackwell, Chichester, UK.

Conway C., G.S. Amacher, J. Sullivan and D. Wear (2003), "Decisions nonindustrial forest landowners make: an empirical examination", *Journal of Forest Economics* Vol. 9, pp. 181-203.

Cristóbal, J., C.T. Matos, J.-P. Aurambout, S. Manfredi, and B. Kavalov (2016), "Environmental sustainability assessment of bioeconomy value chains", *Biomass and Bioenergy* Vol. 89, pp. 159-171.

Dahiya, S., A.N. Kumar, J.S. Sravan, S. Chatterjee, O. Sarkar and S.V. Mohan (2018), "Food waste biorefinery: Sustainable strategy for CBE", *Bioresource Technology* Vol. 248, pp. 2-12.

Dahmen, N., E. Henrich and T. Henrich (2017), *Synthesis Gas Biorefinery*, In: *Advances in Biochemical Engineering/Biotechnology*. Springer, Berlin, Heidelberg

Dammer, L., M. Carus, S. Piotrowski, A. Puente, E. Breitmayer, N. de Beus and C. Liptow (2017), "Sustainable first and second-generation bioethanol for Europe: A sustainability assessment in the context of the European Commission's REDII proposal", *Industrial Biotechnology* Vol. 13, pp. 292-300.

de Jong, E. and G. Jungmeier (2015), *Biorefinery Concepts in Comparison to Petrochemical Refineries*, in *Industrial Biorefineries and White Biotechnology*, Elsevier, Amsterdam, http://dx.doi.org/10.1016/B978-0-444-63453-5.00001-X.

Delebecque, C.J. and J. Philp (2018). Education and training for industrial biotechnology and engineering biology. *Engineering Biology*, eISSN 2398-6182, doi: 10.1049/enb.2018.0001.

de Lorenzo, V. and M. Schmidt (2018), "Biological standards for the knowledge-based bioeconomy: What is at stake", *New Biotechnology* Vol. 40, pp. 170-180.

De Meester, S., C. Callewaert, E. De Mol, H. Van Langenhove and J. Dewulf (2011), "The resource footprint of biobased products: a key issue in the sustainable development of biorefineries", *Biofuels, Bioproducts and Biorefining* Vol. 5, pp. 570-580

D'Hondt, K., G. Jiménez-Sánchez, and J.C. Philp (2015), "Reconciling agricultural and industrial needs for an Asian bioeconomy". *Asian Biotechnology and Development Review* Vol. 17, pp. 85-130.

Di Maio, F., P.C. Rem, K. Baldé and M. Polder (2017), "Measuring resource efficiency and circular economy: A market value approach", *Resources, Conservation and Recycling* Vol. 122, pp. 163-171.

Diplock, E.E., D.P. Mardlin, K.S. Killham and G.I. Paton (2009), "Predicting bioremediation of hydrocarbons: Laboratory to field scale", *Environmental Pollution* Vol. 157, pp. 1831-1840.

Dobes, V., J. Fresner, C. Krenn, P. Ruzicka, C. Rinaldi, S. Cortesi, C. Chiavetta, G. Zilahy, M. Kochanski, P. Grevenstette, D. de Graaf and C. Dorer (2017), "Analysis and exploitation of resource efficiency potentials in industrial small and medium-sized enterprises e Experiences with the EDIT Value Tool in Central Europe", *Journal of Cleaner Production* Vol. 159, pp. 290-300

Domenech, T. and B. Bahn-Walkowiak (2019), "Transition towards a resource efficient circular economy in Europe: Policy lessons from the EU and the member states", *Ecological Economics* Vol. 155, pp. 7-19.

Dvořák, P., P.I. Nikel, J. Damborský and V. de Lorenzo (2017), "Bioremediation 3.0: Engineering pollutant-removing bacteria in the times of systemic biology", *Biotechnology Advances* Vol. 35, pp. 845-866.

EEA (2013), *EU Bioenergy Potential from a Resource-Efficiency Perspective*, Luxembourg: European Environment Agency No 6/2013, July 2013.

El-Chichakli, B., J. Von Braun, C. Lang, D. Barben and J. Philp (2016), "Five cornerstones of a global bioeconomy", *Nature* Vol. 535, pp. 221-223.

Elia, V., M.G. Gnoni and F. Tornese (2017), "Measuring circular economy strategies through index methods: A critical analysis", *Journal of Cleaner Production* Vol. 142, pp. 2741-2751.

Ellen MacArthur Foundation (2013), *Towards the Circular Economy. Economic and Business Rationale for an Accelerated Transition*, Ellen MacArthur Foundation, Cowes, UK.

Ellmer, K., M. Fuchs, U. Bauer, T. Schneider, P.U. Thamsen, T. Morgenthal, J. Villwock and A. Hanau (2017), "Research project *Simulation Wäschepflege* - Recommendations for improving resource efficiency in the laundry process in households in Germany", *Journal of Cleaner Production* Vol. 153, pp. 539-547

Enascuta, C.E., E. Stepan, I. Bolocan, D. Bombos, C. Calin, E.-E. Oprescu and V. Lavric (2018), "Simultaneous production of oil enriched in x-3 polyunsaturated fatty acids and biodiesel from fish wastes", *Waste Management* Vol. 75, pp. 205-214.

European Bioplastics (2018), *Plastics Strategy–Contribution of Bioplastics to a Sustainable Circular Plastics Economy*, European Bioplastics, Berlin, http://docs.european-bioplastics.org/publications/pp/EUBP_PP_Plastics_Strategy.pdf

European Bioplastics (2017), *Biodegradable Plastics and the Circular Economy in Europe*, European Bioplastics, Berlin, https://www.european-bioplastics.org/biodegradable-plastics-in-the-circular-economy-in-europe/

European Commission (2017a), *Directive of the European Parliament and the Council on the Promotion of the Use of Energy from Renewable Sources (Recast*), COM (2016)767 final/2 2016/0382 (COD). http://eur-lex.europa.eu/resource.html?uri=cellar:3eb9ae57-faa6-11e6-8a35-01aa75ed71a1.0007.02/DOC_1&format=PDF

European Commission (2017b), *Eco-innovation Action Plan – Finland*, https://ec.europa.eu/environment/ecoap/finland_en

European Commission (2015), *Closing the loop – An EU Action Plan for the Circular Economy*, European Commission, Brussels, December 2015

European Commission (2012), *Innovating for Sustainable Growth. A Bioeconomy for Europe*, Directorate General for Innovation and Research. Available at: https://ec.europa.eu/research/bioeconomy/index.cfm?pg=policy&lib=strategy

European Commission (2011), *Opinion of the European Economic and Social Committee on the Access to Secondary Raw Materials (Scrap Iron, Recycled Paper, etc*.). CCMI/078,https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/system/files/ged/6%20ces-ccmi-078_en.pdf

European Commission (2009). *Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources*. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN

European Commission (2007), *Environment Fact Sheet: Soil Protection – a New Policy for the EU*, KH-15-04-014-EN-C. http://ec.europa.eu/environment/pubs/pdf/factsheets/soil.pdf

European Environment Agency (2009), *Waste Without Borders in the EU? Transboundary Shipments of Waste*", EEA report number 1/2009. ISSN 1725-9177. EEA, Copenhagen.

Fadhil, A.B., A.I. Ahmed and H.A. Salih (2017), "Production of liquid fuels and activated carbons from fish waste", *Fuel* Vol. 187, pp. 435-445.

Fava, F., G. Totaro, L. Diels, M. Reis, J. Duarte, O.B. Carioca, H.M. Poggi-Varaldo and B.S. Ferreira, (2015), "Bio-waste biorefinery in Europe: opportunities and research & development needs", *New Biotechnology* Vol. 32, pp. 100-108.

Fehrenbach, H., S. Köppen, B. Kauertz, A. Detzel, F. Wellenreuther, E. Breitmayer, R. Essel, M. Carus, K. Bienge and J. von Geibler (2017). *Biomass Cascades. Increasing Resource Efficiency by Cascading Use of Biomass — fromTheory to Practice. Summary*. Umweltbundesamt, Dessau-Roßlau.

G7 Germany (2015), *Think Ahead. Act Together*, Leaders' Declaration G7 Summit 7-8 June 2015. https://sustainabledevelopment.un.org/content/documents/7320LEADERS%20STATEMENT_FINAL_CLEAN.pdf.

Gaitán-Cremaschi, D., F. Pashaei Kamali, F.K Van Evert, M.P.M. Meuwissen and A.G.J M. Oude Lansink (2015), "Benchmarking the sustainability performance of the Brazilian non-GM and GM soybean meal chains: An indicator-based approach", *Food Policy* Vol. 55, pp. 22–32.

Galloway, T.S. (2016), *Micro- and Nano-Plastics and Human Health*, Chapter 13 in: M. Bergmann et al. (eds.), *Marine Anthropogenic Litter*, DOI 10.1007/978-3-319-16510-3_13.

García, E. Pongrácz, P.S. Phillips and R.L. Keiski (2013), "From waste treatment to resource efficiency in the chemical industry: recovery of organic solvents from waters containing electrolytes by pervaporation", *Journal of Cleaner Production* Vol. 39, pp. 146-153.

Gauvreau, D., D. Winickoff and J. Philp (2018), "Engineering biology and the grand challenges: do we need a new R&D&I model?", *Engineering Biology* Vol. 2, pp. 2-6.

GBEP (2011), *The Global Bioenergy Partnership Sustainability Indicators for Bioenergy*, http://www.globalbioenergy.org/fileadmin/user%5Fupload/gbep/docs/Indicators/The_GBEP_Sustainability_Indicators_for_Bioenergy_FINAL.pdf

Geldermann, J., L.M. Kolbe, A. Krause, C. Mai, H. Militz, V.-S. Osburg, A. Schöbel, M. Schumann, W. Toporowski and S. Westphal (2016), "Improved resource efficiency and cascading utilisation of renewable materials", *Journal of Cleaner Production* Vol. 110, pp. 1-8.

General Assembly of the United Nations (2015), *Transforming Our World: the 2030 Agenda for Sustainable Development*, A/RES/70/1. United Nations. http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

German Bioeconomy Council (2015), *China*, http://biooekonomie.de/sites/default/files/china.pdf

Gibbs, H.K. and J.M. Salmon (2015), "Mapping the world's degraded lands", *Applied Geography* Vol. 57, pp. 12-21.

Gillespie, I.M.M. and J.C. Philp (2013), "Bioremediation, an environmental remediation technology for the bioeconomy", *Trends in Biotechnology* Vol. 31, pp. 329-332.

Glendining, M.J. (2009), "Is it possible to increase the sustainability of arable and ruminant agriculture by reducing inputs?", *Agricultural Systems* Vol. 99, pp. 117–125.

Golden, J.S. and R.B. Handfield (2014), *Why Biobased? Opportunities in the Emerging Bioeconomy*, Duke Center for Sustainability & Commerce and the North Carolina State University Supply Chain Resource Cooperative, for the USDA Office of Procurement and Property Management.

Goodwin, J.A.S. and J.B. Stuart (1994), "Anaerobic digestion of malt whisky distillery pot ale using upflow anaerobic sludge blanket reactors", *Bioresource Technology* Vol. 49, pp. 75-81.

Gore, A. (2013), *The Future: Six Drivers of Global Change*, Random House, New York, US.

Government Offices of Sweden (2016), *Strategy for Sustainable Consumption*, http://www.government.se/4a9932/globalassets/government/dokument/finansdepartementet/pdf/publikationer-infomtrl-rapporter/en-strategy-for-sustainable-consumption--tillganglighetsanpassadx.pdf

Haberl, H., D. Sprinz, M. Bonazountas, P. Cocco, Y. Desaubies, M. Henze, O. Hertel, R.K. Johnson, U. Kastrup, P. Laconte, E. Lange, P Novak, J. Paavola, A. Reenberg, S. van den Hove, T. Vermeire, P. Wadhams and T. Searchinger (2012), "Correcting a fundamental error in greenhouse gas accounting related to bioenergy". *Energy Policy* Vol. 45, pp. 18–23.

Han, J., G.S. Forman, A. Elgowainy, H. Cai, M. Wang and V.B. DiVita (2015), "A comparative assessment of resource efficiency in petroleum refining", *Fuel* Vol. 157, pp. 292-298

Hao, H.-T.N., O.P. Karthikeyan and K. Heimann (2015), "Bio-refining of carbohydrate-rich food waste for biofuels", *Energies* Vol. 8, pp. 6350-6364.

Harrison, S.L., B. Verster, L. Mostert, S. Rumjeet, T. Raper, S. Rademeyer and M. Johnstone-Robertson (2017), *Towards Wastewater Biorefineries: Integrated Bioreactor and Process Design for Combined Water Treatment and Resource Productivity*, Water Research Commission WRC Project No. 2380/1/17, ISBN 978-1-4312-0909-5.

Hatfield-Dodds, S., H. Schandl, D. Newth, M. Obersteiner, Y. Cai, T. Baynes, J. West and P. Havlik (2017), "Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies" *Journal of Cleaner Production* Vol. 144, pp. 403-414.

Heintz, J. and R. Pollin (2011). *The Economic Benefits of a Green Chemical Industry*. In: *The Us: Renewing Manufacturing Jobs While Protecting Health and the Environment*, Amherst, MA: University of Massachusetts Amherst, Political Economy Research Institute, 2011.

Hetemäki, L., M. Hanewinkel, B. Muys, M. Ollikainen, M. Palahí, and A. Trasobares, (2017), *Leading the Way to a European Circular Bioeconomy Strategy*, From Science to Policy 5", European Forest Institute.

Hoffman, J. (2009), "What is greenwashing?", *Scientific American*, April 01, 2009. https://www.scientificamerican.com/article/greenwashing-green-energy-hoffman/

Holland, J.E., A.E. Bennett, A.C. Newton, P.J. White, B.M. McKenzie, T.S. George, R.J. Pakeman, J.S. Bailey, D.A. Fornara and R.C. Hayes (2018), "Liming impacts on soils, crops and biodiversity in the UK: A review", *Science of the Total Environment* Vol. 610-611, pp. 316-332.

Huysman, S., S. Sala, L. Mancini, F. Ardente, R.A.F. Alvarenga, S. De Meester, F. Mathieux and, J. Dewulf (2015), "Toward a systematized framework for resource efficiency indicators", *Resources, Conservation and Recycling* Vol. 95, pp. 68–76.

Huysveld, S., S. De Meester, V. Van linden, H. Muylle, N. Peirena, L. Lauwers and J. Dewulf (2015), "Cumulative Overall Resource Efficiency Assessment (COREA) for comparing bio-based products with their fossil-derived counterparts", *Resources, Conservation and Recycling* Vol. 102, pp. 113–127.

Illinois Environmental Protection Agency (2014), *Illinois Landfill Projections of Disposal Capacity as of January 1, 2014*, Illinois Environmental Protection Agency, Springfield, IL. http://www.epa.state.il.us/land/landfill-capacity/2013/landfill-capacity-report-2014.pdf

International Energy Agency (2017), *World Energy Outlook*, IEA Publishing, Paris/IEA, Paris.

International Energy Agency Bioenergy Task 42 Biorefinery (2012), *Bio-based Chemicals. Value Added Products from Biorefineries*, International Energy Agency, Paris.

IRENA (2015a), *IRENA Renewable Energy Capacity Statistics, 2015*, http://www.irena.org/DocumentDownloads/Publications/IRENA RE Capacity Statistics 2015.pdf.

IRENA (2015b), *IRENA Renewable Energy Target Setting 2015*, http://www.irena.org/DocumentDownloads/Publications/IRENA RE Target Setting 2015.pdf.

Ishizaka, K. and M. Tanaka (2003), "Resolving public conflict in site selection process - a risk communication approach", *Waste Management* Vol. 23, pp. 385-396.

IUCN (2017), *Sustainability of Fish Feed in Aquaculture: Reflections and Recommendations*, https://portals.iucn.org/library/sites/library/files/documents/2017-026-Summ.pdf.

Jacobs, J. (2018), *Europe's Half a Million Landfill Sites Potentially Worth a Fortune, Financial Times*, January 08, 2018. https://www.ft.com/content/0bf645dc-d8f1-11e7-9504-59efdb70e12f.

Jasiński, D., J. Meredith and K. Kirwan (2016), "A comprehensive framework for automotive sustainability assessment", *Journal of Cleaner Production* Vol. 135, pp. 1034-1044

Jin, Q., L. Yang, N. Poe and H. Huang (2018), "Integrated processing of plant-derived waste to produce value-added products based on the biorefinery concept", *Trends in Food Science & Technology* Vol. 74, pp. 119-131.

Ju, M., S.-J. Bae, J.Y. Kim and D.-H. Lee (2016), "Solid recovery rate of food waste recycling in South Korea", *Journal of Material Cycles and Waste Management* Vol. 18, pp. 419–426.

Juntao, W. and N. Mishima (2017), "Development of resource efficiency index for electrical and electronic equipment", *Procedia CIRP* Vol. 61, pp. 275-280.

Kadier, A, Y. Simayi, P. Abdeshahian, N.F. Azman, K. Chandrasekhar and M.S. Kalil (2016), "A comprehensive review of microbial electrolysis cells (MEC) reactor designs and configurations for sustainable hydrogen gas production", *Alexandria Engineering Journal* Vol. 55, pp. 427–443.

Kaparaju, P., M. Serrano, A.B. Thomsen, P. Kongjana and I. Angelidaki (2009), "Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept", *Bioresource Technology* Vol. 100, pp. 2562-2568.

Karig, D.K. (2017), "Cell-free synthetic biology for environmental sensing and remediation", *Current Opinion in Biotechnology* Vol. 45, pp. 69-75.

Kawaguchi, H., T. Hasunuma, C. Ogino and A. Kondo (2016), “Bioprocessing of bio-based chemicals produced from lignocellulosic feedstocks”, *Current Opinion in Biotechnology* Vol. 42, pp. 30-39.

Keegan, D., B. Kretschmer, B. Elbersen and C. Panoutsou (2013), “Cascading use: a systematic approach to biomass beyond the energy sector”, *Biofuels, Bioproducts and Biorefining* Vol. 7, pp. 193–206.

Kellens, K. G.C. Rodrigues, W. Dewulf and J.R. Duflou (2014), “Energy and resource efficiency of laser cutting processes”, *Physics Procedia* Vol. 56, pp. 854-864.

Kirkham, M.B. and B.E. Clothier (2007), “Loss and recovery of research investment for applied sciences: A salutary lesson from New Zealand” *HortTechnology* Vol. 17, pp. 9-13.

KTN (2016), *From Shale Gas to Biomass: The Future of Chemical Feedstocks*, Knowledge Transfer Network, Horsham, UK.

Kutzner, H. J. (2001), *Microbiology of Composting*, In: Biotechnology Set, Second Edition, H.-J. Rehm and G. Reed (eds), Wiley-VCH Verlag GmbH, Weinheim, Germany. doi: 10.1002/9783527620999.ch2n

Langeveld, J.W.A., K.P.H. Meesters and M.S. Breure (2016), *The Bio-based Economy and the Bioeconomy in the Netherlands*, Biomass Research Report 1601, reference number 59015257. Biomass Research, Wageningen.

Lee, S.Y. and H.U. Kim (2015), “Systems strategies for developing industrial microbial strains”, *Nature Biotechnology* Vol. 33, pp. 1061-1072.

Leung, C.C.J, A.S.Y. Cheung, A.Y.-Z. Zhang, K.F. Lam and C.S.K. Lin (2012), “Utilisation of waste bread for fermentative succinic acid production”, *Biochemical Engineering Journal* Vol. 65, pp. 10–15.

Li, W.-W., H.-Q. Yu, and B.E. Rittmann (2015), “Chemistry: reuse water pollutants”, *Nature* Vol. 528, pp. 29-31.

Licht, S., B. Cui, B. Wang, F.-F. Li, J. Lau and S. Liu (2014), “Ammonia synthesis by N_2 and steam electrolysis in molten hydroxide suspensions of nanoscale Fe_2O_3”, *Science* Vol. 345, pp. 637-640.

Liew, F., M.E. Martin, R.C. Tappel, B.D. Heijstra , C. Mihalcea and M. Köpke (2016) Gas fermentation – A flexible platform for commercial scale production of low-carbon-fuels and chemicals from waste and renewable feedstocks. *Frontiers in Microbiology Vol.* 7:694, doi: 10.3389/fmicb.2016.00694.

Liguori, R. and V. Faraco (2016), “Biological processes for advancing lignocellulosic waste biorefinery by advocating circular economy”, *Bioresource Technology* Vol. 215, pp. 13-20.

Lopolito, A., G. Nardone, M. Prosperi, R. Sisto and A. Stasi (2011), “Modeling the bio-refinery industry in rural areas: A participatory approach for policy options comparison”, *Ecological Economics* Vol. 72, pp. 18-27.

Lynch, J., M. Maslin, H. Balzter and M. Sweeting (2013), “Choose satellites to monitor deforestation”, *Nature* Vol. 496, pp. 293-294.

Martinez, G.A., S. Rebecchi, D. Decorti, J.M.B. Domingos, A. Natolino, D. Del Rio, L. Bertin, C. Da Porto and F. Fava (2016), “Towards multi-purpose biorefinery platforms for the valorisation of red grape pomace: production of polyphenols, volatile fatty acids, polyhydroxyalkanoates and biogas", *Green Chemistry* Vol. 18, pp. 261-270.

Massari, S. and M. Ruberti (2013), "Rare earth elements as critical raw materials: focus on international markets and future strategies", *Resource Policy* Vol. 38, pp. 36-43.

Massé, D.I., G. Talbot and Y. Gilbert (2011), "On farm biogas production: A method to reduce greenhouse gas emissions and develop more sustainable livestock operations", *Animal Feed Science and Technology* Vol. 166–167, pp. 436–445.

Mayfield, C.A., C. Darwin Foster, C.T. Smith, J. Gan and S. Fox (2007), "Opportunities, barriers, and strategies for forest bioenergy and bio-based product development in the Southern United States", *Biomass and Bioenergy* Vol. 31, pp. 631-637.

McClymont, D.W. and Freemont, P.S. (2017), "With all due respect to Maholo, lab automation isn't anthropomorphic", *Nature Biotechnology* Vol. 35, pp. 312-314.

Ministy of Economic Affairs and Employment of Finland (2017), *Wood-based Bioeconomy Solving Global Challenges*, Helsinki, Finland.

Morgan-Sagastume, F., M. Hjort, D. Cirne, F. Gérardin, S. Lacroix, G. Gaval, L. Karabegovic, T. Alexandersson, P. Johansson, A. Karlsson, S. Bengtsson, M.V. Arcos-Hernández, P. Magnusson and A. Werker (2015), "Integrated production of polyhydroxyalkanoates (PHAs) with municipal wastewater and sludge treatment at pilot scale", *Bioresource Technology* Vol. 181, pp. 78-89.

Narayan, R. and M.K. Patel (2003), *Review and Analysis of Bio-based Product LCA's*, Institute for Science & Public Policy

Natural Scotland (2016), Making Things Last – A Circular Economy Strategy for Scotland, Scottish Government, http://www.gov.scot/Resource/0049/00494471.pdf

OECD (2018), Meeting Policy Challenges for a Sustainable Bioeconomy, OECD Publishing, Paris, ISBN 978-92-64-29234-5, http://dx.doi.org/10.1787/9789264292345-en

OECD (2016a), Effective Carbon Rates: Pricing CO2 through Taxes and Emissions Trading Systems, OECD Publishing, Paris, ISBN 978-92-64-26011-5, http://dx.doi.org/10.1787/9789264260115-en

OECD (2016b), Green Investment Banks: Scaling up Private Investment in Low-carbon, Climate-resilient Infrastructure, Green Finance and Investment, OECD Publishing, Paris, ISBN 978-92-64-24512-9, http://dx.doi.org/10.1787/9789264245129-en

OECD (2015), Environment at a Glance 2015: OECD Indicators, OECD Publishing, Paris, ISBN 978-92-64-23519-9, http://dx.doi.org/10.1787/9789264235199-en

OECD (2014a), "Biobased Chemicals and Bioplastics: Finding the Right Policy Balance", OECD Science, Technology and Industry Policy Papers, No. 17, OECD Publishing, Paris. http://dx.doi.org/10.1787/5jxwwfjx0djf-en

OECD (2014b), Emerging Policy Issues in Synthetic Biology, OECD Publishing, ISBN 978-92-64-20842-1, http://dx.doi.org/10.1787/9789264208421-en

OECD (2014c), *Sustainable Biomass Drives the Next Bioeconomy: a New Industrial Revolution?*, Report of an OECD workshop, 10-11 June, OECD, Paris, (internal document).

OECD (2013), "Policies for Bioplastics in the Context of a Bioeconomy", OECD Science, Technology and Industry Policy Papers, No. 10, OECD Publishing, Paris. http://dx.doi.org/10.1787/5k3xpf9rrw6d-en

OECD (2011a), Future Prospects for Industrial Biotechnology, OECD Publishing, ISBN 978-92-64-12663-3, http://dx.doi.org/10.1787/9789264126633-en

OECD (2011b), Towards Green Growth: Monitoring Progress: OECD Indicators, OECD Publishing, ISBN 978-92-64-11135-6, http://dx.doi.org/10.1787/9789264111356-en

OECD (2010), OECD Environmental Performance Reviews: Japan 2010, OECD Publishing, Paris, ISBN 978-92-64-08786-6, https://doi.org/10.1787/9789264087873-en

OECD (2009), The Bioeconomy to 2030 – Designing a Policy Agenda, OECD Publishing, Paris, ISBN 9789264056886, https://doi.org/10.1787/9789264056886-en

Onwosi, C.O., V.C. Igbokwe, J.N. Odimba, I.E. Eke, M.O. Nwankwoala, I.N. Iroh and L.I. Ezeogu (2017), "Composting technology in waste stabilization: On the methods, challenges and future prospects", *Journal of Environmental Management* Vol. 190, pp. 140-157.

Orts, W.J. and C.M. McMahan (2016), "Biorefinery developments for advanced biofuels from a sustainable array of biomass feedstocks: survey of recent biomass conversion research from Agricultural Research Service", *BioEnergy Research* Vol. 9, pp. 430-446.

Paillard, H. (2016), "Ever decreasing circles", *The Chemical Engineer* Vol. 899, pp. 38-40.

Parajuli, R., T. Dalgaard, U. Jørgensen, A.P.S. Adamsen, M.T. Knudsen, M. Birkved, M. Gylling and J.K. Schjørring (2015), "Biorefining in the prevailing energy and materials crisis: A review of sustainable pathways for biorefinery value chains and sustainability assessment methodologies", *Renewable and Sustainable Energy Reviews* Vol. 43, pp. 244-263.

Parfitt, J., M. Barthel and S. Macnaughton (2010), "Food waste within food supply chains: quantification and potential for change to 2050", *Philosophical Transactions of the Royal Society B* Vol. 365, pp. 3065–3081.

Pavanan, K.C., R.A. Bosch, R. Cornelissen, and J.C. Philp (2013), "Biomass sustainability and certification", *Trends in Biotechnology* Vol. 31, pp. 385-387.

Pawelzik, P., M. Carus, J. Hotchkiss, R. Narayan, S. Selke, M. Wellisch, M. Weiss, B. Wicke and M.K. Patel (2013), Critical aspects in the life cycle assessment (LCA) of bio-based materials - reviewing methodologies and deriving recommendations. *Resources, Conservation and Recycling* Vol. 73, pp. 211-228.

Pérez-Camacho, M.N., R. Curry and T. Cromie (2018), "Life cycle environmental impacts of substituting food wastes for traditional anaerobic digestion feedstocks", *Waste Management* Vol.73, pp. 140-155.

Philp, J.C. (2015), "Balancing the bioeconomy: supporting biofuels and bio-based materials in public policy", *Energy & Environmental Science* Vol. 8, pp. 3063-3068.

Philp, J.C., A. Bartsev, R.J. Ritchie, M.-A. Baucher and K. Guy (2013), "Bioplastics science from a policy vantage point", *New Biotechnology* Vol. 30, pp. 635-646.

Pickin, J. (2009), *Australian Landfill Capacities into the Future*, Report prepared for the Department of the Environment, Water, Heritage and the Arts, Hyder Consulting Pty Ltd, report ABN 76 104 485 289.

Piotrowski, S., M. Carus and D. Carrez (2018), *European Bioeconomy in Figures 2008 – 2015*, Nova-Institute report, nova-Institute, Hürth, Germany.

Piotrowski, S., M. Carus and D. Carrez (2016). *European Bioeconomy in Figures*, Nova-Institute, Hürth, Germany.

Prazeres, A.R., F. Carvalho and J. Rivas (2012), "Cheese whey management: A review", *Journal of Environmental Management* Vol. 110, pp. 48-68.

Pronk, J.T., S.Y. Lee, J. Lievense, J. Pierce, B. Palsson, M. Uhlen and J. Nielsen (2015), "How to set up collaborations between academia and industrial biotech companies", *Nature Biotechnology* Vol. 33, pp. 237–240.

Randolph, K. and S. Studer (2013), *Biological Hydrogen Production Workshop Summary Report*, US Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office.

Ravindran, R. and A.K. Jaiswal (2016), "Exploitation of food industry waste for high-value products", *Trends in Biotechnology* Vol. 34, pp. 58-69.

RFA (2016), *Fueling a High-octane Future. 2016 Ethanol Industry Outlook*, Renewable Fuels Association, Washington DC, US.

Richter, K. (2016), *A Comparison of National Sustainability Schemes for Solid Biomass in the EU*, Fern, Brussels, Belgium.

RobecoSAM (2012), *Tackling Resource Efficiency Challenges*, RobecoSAM, Zurich.

Röder, M., C. Whittaker and P. Thornley (2015), "How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues", *Biomass and Bioenergy* Vol. 79, pp. 50-63.

Rohn, H., N. Pastewski, M. Lettenmeier, K. Wiesen and K. Bienge (2014), "Resource efficiency potential of selected technologies, products and strategies", *Science of the Total Environment* Vol. 473-474, pp. 32-35

Ryan, M.P. and G. Walsh (2016), "The biotechnological potential of whey", *Reviews in Environmental Science and Bio/Technology* Vol. 15, pp. 479-498.

Sachs, J.D. (2014), "Sustainable development goals for a new era", *Horizons*, Autumn 2014, 106-119.

Sánchez, A., A. Artola, X. Font, T. Gea, R. Barrena, D. Gabriel, M.Á. Sánchez-Monedero, A. Roig, M.L. Cayuela and C. Mondini (2015), "Greenhouse gas emissions from organic waste composting", *Environmental Chemistry Letters* Vol. 13, pp. 223-238.

Scarlat, N., J.-F. Dallemand, F. Monforti-Ferrario and V. Nita (2015), "The role of biomass and bioenergy in a future bioeconomy: Policies and facts", *Environmental Development* Vol. 15, pp. 3-34.

Scharff, H. (2014), "Landfill reduction experience in The Netherlands", *Waste Management* Vol. 34, pp. 2218–2224.

Scottish Enterprise (2015), *A Biorefinery Roadmap for Scotland*, https://www.scottish-enterprise.com/~/media/se_2013/chemical%20sciences/biorefineryroadmapforscotland.pdf?la=en

Searle, S. and C. Mallins (2015) *National Case Studies on Potential Waste and Residue Availability for Cellulosic Biofuel Production in the EU*, An International Council on Clean Transportation. Wasted project report https://www.theicct.org/sites/default/files/ICCT_EU-national-wastes-residues_Feb2015.pdf

Siegmeier, T., B. Blumenstein and D. Möller (2015), "Farm biogas production in organic agriculture: System implications", *Agricultural Systems* Vol. 139, pp. 196-209.

Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, M.J. Figueroa Meza, L. Fulton, S. Kobayashi, O. Lah, A. McKinnon, P. Newman, M. Ouyang, J.J. Schauer, D. Sperling, and G. Tiwari (2014), "Transport". In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sorda, G., M. Banse and C. Kemfert (2010), "An overview of biofuel policies across the world". *Energy Policy* Vol. 38, pp. 6977-6988.

Sorvari, J.R., R. Antikainen, M.L. Kosola, P. Hokkanen and T. Haavisto (2009), "Eco-efficiency in contaminated land management in Finland – barriers and development needs", *Journal of Environmental Management* Vol. 90, pp. 1715-1727.

Spuerk, S., M. Drobe and B.G. Lottermoser (2017), "Evaluating resource efficiency at major copper mines", *Minerals Engineering* Vol. 107, pp. 27-33

Suez Recycling and Recovery UK (2017), *Mind the Gap 2017-2030. UK Residual Waste Infrastructure Capacity Requirements*, Suez House, Maidenhead, UK.

Sussarellu, R., M. Suquet, Y. Thomas, C. Lambert, C. Fabioux, M.E.J. Pernet, N. Le Goïc, V. Quillien, C. Mingant, Y. Epelboin, C. Corporeau, J. Guyomarch, J. Robbens, I. Paul-Pont, P. Soudant and A. Huvet (2016), " Oyster reproduction is affected by exposure to polystyrene microplastics", *Proceedings of the National Academy of Sciences* Vol. 113, pp. 2430-2435.

Swedish Research and Innovation Strategy for a Bio-based Economy (2012), R3:2012 ISBN 978-91-540-6068-9, http://www.formas.se/PageFiles/5074/Strategy_Biobased_Ekonomy_hela.pdf

The Danish Government (2015), Denmark Without Waste – A Waste Prevention Strategy, http://eng.mst.dk/media/164923/denmark-without-waste-ii_wasteprevention.pdf

Tomei, J. and R. Helliwell (2016). "Food versus fuel? Going beyond biofuels", *Land Use Policy* Vol. 56, pp. 320-326.

UNEP (2016), *Resource Efficiency: Potential and Economic Implications. Summary for Policy Makers*, International Resource Panel, United Nations Environment Programme, Nairobi.

UN-Water (2015), *Wastewater management – A UN-Water Analytical Brief*, http://www.unwater.org/publications/wastewater-management-un-water-analytical-brief/

USDA BioPreferred Program (2016), *An Economic Impact Analysis of the US Biobased Products Industry*, USDA, Washington DC.

USDOE (2006), *Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda*, DOE/SC-0095, US Department of Energy Office of Science and Office of Energy

Efficiency and Renewable Energy, Washington, DC, www.doegenomestolife.org/biofuels/.

USEPA (2017), Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2015, EPA 430-P-17-001. United States Environmental Protection Agency, Washington DC.

USEPA (2014), *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012*, EPA-530-F-14-001, February 2014, Washington DC.

USEPA (2010), *DRAFT – Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories: Solid Waste Disposal Wastewater Treatment Ethanol Fermentation*, Submitted by RTI International to the Sector Policies and Programs Division, Measurement Policy Group, US EPA, EPA Contract No. EP-D-06-118.

Van Dam, J. and M. Junginger (2011), “Striving to further harmonization of sustainability criteria for bioenergy in Europe: Recommendations from a stakeholder questionnaire”, *Energy Policy* Vol. 39, pp. 4051–4066

Van Stappen, F., I. Brose and Y. Schenkel (2011), “Direct and indirect land use changes issues in European sustainability initiatives: State-of-the-art, open issues and future developments”, *Biomass and Bioenergy* Vol. 35, pp. 4824-4834.

von Moos, N., P. Burkhardt-Holm and A. Köhler (2012), “Uptake and effects of microplastics on cells and tissue of the blue mussel *Mytilus edulis* L. after an experimental exposure. *Environmental Science and Technology* Vol. 46, pp. 11327-11335.

Weiss M., J. Haufe, M. Carus, M. Brandão, M.S. Bringezu, B. Hermann and M.K. Patel (2012). A review of the environmental impacts of bio-based materials. *Journal of Industrial Ecology* Vol. 16, pp. S169–S181

Wernick, D.G., S.P. Pontrelli, A.W. Pollock and J.C. Liao (2016), “Sustainable biorefining in wastewater by engineered extreme alkaliphile *Bacillus marmarensis*”, *Nature Scientific Reports* Vol. 6: 20224 (2016), doi:10.1038/srep20224.

White House (2012), *National Bioeconomy Blueprint*, http://www.whitehouse.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf,

Wierny, M., A. Coremberg, R. Costa, E. Trigo and M. Regunaga (2015), *Measuring the Bioeconomy: Quantifying the Argentine Case*, Ciudad Autónoma de Buenos Aires: Bolsa de Cereales de Buenos Aires.

World Bank (2013), *Fish To 2030. Prospects for Fisheries and Aquaculture*, World Bank report number 83177-GLB, World Bank, Washington DC.

World Economic Forum (2014), *Towards the Circular Economy: Accelerating the Scale-up Across Global Supply Chains*, http://www3.weforum.org/docs/WEF_ENV_TowardsCircularEconomy_Report_2014.pdf

Zelenovskaya, E. (2012), *Green Growth Policy in Korea: A Case Study*, International Center for Climate Governance, Venice, Italy.

Zeng, X., A.P. Borole and S.G. Pavlostathis (2015), “Biotransformation of furanic and phenolic compounds with hydrogen gas production in a microbial electrolysis cell”, *Environmental Science and Technology* Vol. 49, pp. 13667-13675.

Zhang, Y., M. Goldberg, E. Tan and P.A. Meyer (2016), "Estimation of economic impacts of cellulosic biofuel production: A comparative analysis of three biofuel pathways", *Biofuels, Bioproducts and Biorefining* Vol. 10, pp. 281-298.

Zschieschang, E., N. Denz, H. Lambrecht and T. Viere (2014), "Resource efficiency-oriented optimization of material flow networks in chemical process engineering", *Procedia CIRP* Vol. 15 pp. 373-378.

Endnotes

1 https://ilbioeconomista.com/2018/10/26/an-interview-with-dirk-carrez-bic-in-2050-we-will-live-in-a-circular-bio-society/

2 Gross value added is the value of output less the value of intermediate consumption; it is a measure of the contribution to GDP made by an individual producer, industry or sector; gross value added is the source from which the primary incomes of the SNA are generated and is therefore carried forward into the primary distribution of income account. http://stats.oecd.org/glossary/detail.asp?ID=1184

3 http://www.fao.org/3/a-bb144e.pdf

4 http://www.fao.org/3/a-bb144e.pdf

5 http://www.bbc.com/news/magazine-17353707

6 http://www.aiche.org/academy/videos/conference-presentations/gas-fermentation-industrial-waste-gases-fuel-and-chemicals

7 https://www.theguardian.com/environment/2018/mar/22/great-pacific-garbage-patch-sprawling-with-far-more-debris-than-thought

8 http://www.kansas.com/news/business/article119902263.html#storylink=cpy

9 https://biofuels-news.com/display_news/13070/worlds_first_commercial_second generation_bioethanol_facility_shuts_down/

10 http://www.fao.org/soils-2015/en/

11 https://www.newswire.ca/news-releases/enerkem-and-sinobioway-group-sign-a-c125m-agreement-to-accelerate-enerkems-global-expansion-and-create-a-joint-venture-to-build-over-100-biofuel-facilities-in-china-670436203.html

12 https://www.bbi-europe.eu/projects/agrichemwhey

13 http://www.strategyr.com/MarketResearch/Succinic_Acid_Market_Trends.asp

14 http://www.independent.co.uk/environment/sweden-s-recycling-is-so-revolutionary-the-country-has-run-out-of-rubbish-a7462976.html

15 http://fortune.com/2015/10/20/germany-import-trash/

16 https://sweden.se/nature/the-swedish-recycling-revolution/

17 http://www.consilium.europa.eu/en/press/press-releases/2018/02/23/eu-ambassadors-approve-new-rules-on-waste-management-and-recycling /

18 http://ec.europa.eu/environment/resource_efficiency/index_en.htm

19 http://www.oecd.org/environment/resourceefficiency.htm

[20] https://www.edie.net/news/5/Volkswagen-Group-focuses-on-resource-efficiency-to-help-meet-sustainability-goals/

[21] http://www.oecd.org/env/indicators-modelling-outlooks/resourceefficiency.htm

[22] https://www.ictsd.org/downloads/2012/10/kutas-ppp.pdf

[23] http://www.businessinsider.fr/us/low-oil-prices-hurt-plastics-recycling-2016-4

[24] https://www.iso.org/standard/67886.html

[25] https://www.astm.org/Standards/E3072.htm

[26] https://www.theguardian.com/environment/2017/oct/24/uk-30-40-years-away-eradication-soil-fertility-warns-michael-gove

[27] The concept officially emerged in June 2009, when all 30 OECD member countries at the time (plus Chile, Estonia, Israel and Slovenia) signed a Green Growth declaration. See: http://www.oecd.org/env/44077822.pdf

[28] http://www.irishstatutebook.ie/eli/2013/si/71/made/en/pdf

[29] http://www.nweurope.eu/about-the-programme/our-impact/challenge-3/the-renew-project/

[30] https://www.european-bioplastics.org/eubps-policy-recommendations-to-integrate-bioplastics-in-the-eu-plastics-strategy/