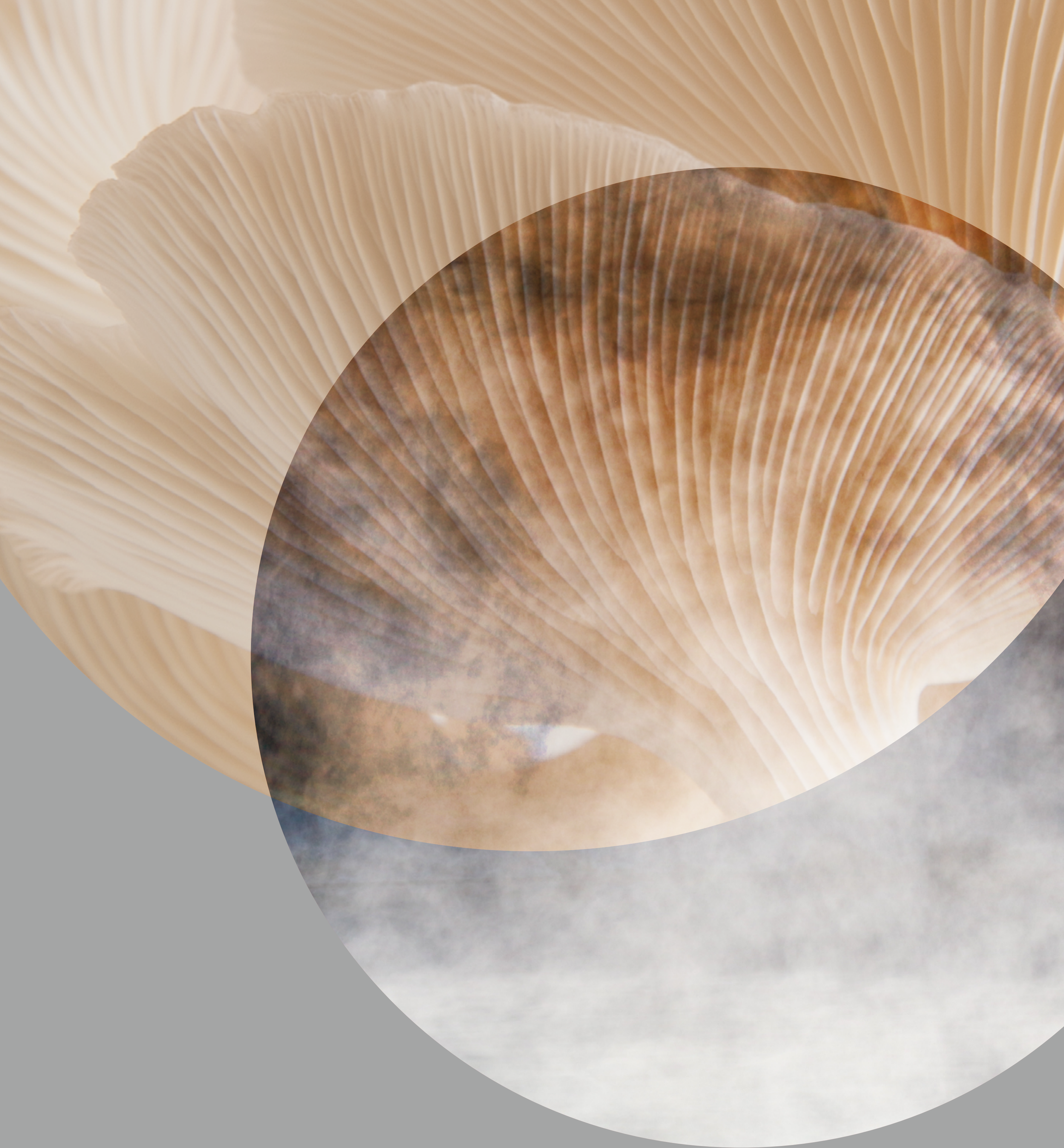

URBAN BIOCYCLES

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BIOCYCLE ECONOMY

The aim of this scoping paper is to present an initial exploration of the circular economy opportunities for the biocycle economy. It represents the first step towards a deeper understanding enabled by a more comprehensive analysis.

The term biocycle in the context of this paper is distinct and separate from BioCycle, The Organics Recycling Authority®, published since 1960 (biocycle.net).

DISCLAIMER

This paper was produced by a team from the Ellen MacArthur Foundation, which takes full responsibility for the paper's contents and conclusions. While the project participants and experts consulted have provided significant input to the development of this paper, their participation does not necessarily imply endorsement of its contents or conclusions.

PROJECT MAINSTREAM

The World Economic Forum and the Ellen MacArthur Foundation launched Project MainStream in 2014. This multi-industry, global initiative serves as the umbrella for this paper. The project is led by the chief executive officers of seven global companies: Averda, Tarkett, Royal DSM, Ecolab, Philips, Suez, and Veolia.

Project MainStream aims to accelerate business-driven innovations and help scale the circular economy (building awareness of it, and increasing impact and implementation). It focuses on systemic stalemates in global material flows that are too big or too complex for an individual business, city or government to overcome alone, as well as on enablers of the circular economy, such as digital technologies.

ACKNOWLEDGEMENTS

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PROJECT MAINSTREAM STEERING BOARD

PROJECT TEAM

Ellen MacArthur Foundation

Andrew Morlet, Chief Executive

Dale Walker, Project Manager (Lead Author)

Nick Jeffries, Research Manager

Aurélien Susnjara, Research Analyst

Sarah Churchill-Slough, Designer

Lena Gravis, Editor

Ian Banks, Editor

World Economic Forum

Dominic Waughray, Head of Public Private Partnership, Member of the Executive Committee

Antonia Gawel, Lead, Circular Economy

Attila Turos, Project Lead, Future of Production

EXPERT INPUT AND CASE STUDY CONTRIBUTORS

Biomimicry 3.8
Janine Benyus, Co-Founder

Biopolus Technologies
Frank Marton, Chief Commercial Officer

Desso
Rudi Daelmans, Sustainability Director

The Ecala Group
Joshua Foss, President

Elemental Impact
Holly D. Elmore, Founder and CEO

Il Bioeconomista
Mario Bonaccorso, Founder and Editor in Chief

Institute for Local Self Reliance
Brenda Platt, Co-Director

International Resource Panel
Janez Potocnik, Co-Chair

Ostara Nutrient Recovery Technologies
Phillip Abrary, Co-Founder, President and CEO

Debra Hadden, Vice President, Marketing and Communications

Peats Soil and Garden Supplies
Peter Wadewitz, Managing Director

Royal DSM
Jeff Turner, Vice President Sustainability

Inge Massen-Biemans, Global Director Business Communications and External Affairs – Science and Innovation

SLM Partners
Paul McMahon, Co-Founder and Managing Partner

Suez
Henry Saint Bris, Senior Vice President Marketing and Institutional Relations

Frédéric Grivel, Vice President Marketing

Laurent Galtier, Development Director

Veolia
Gary Crawford, Vice President – International Affairs

Wageningen UR
Johan Sanders, Emeritus Professor of Biobased Chemistry and Technology

GLOSSARY

Anaerobic digestion: A series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. One of the end products is biogas, which is combusted to generate electricity and heat, or can be processed into renewable natural gas and transportation fuels.

Bioeconomy: Encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy via industrial biotechnology.

Bioenergy: Energy derived from biomass, either as a solid fuel, or processed into liquids and gases. Technologies to generate heat and power include solid wood heating installations for buildings, biogas digesters for power generation, and large-scale biomass gasification plants for heat and power. Includes biofuels.

Biofuel: Any liquid or gaseous hydrocarbon fuel produced from biomass in a short time, i.e. not over geological time as with fossil fuels, and used as a transportation fuel.

Biomass: The biodegradable fraction of products, waste and residues of biological origin from agriculture (including vegetal and animal substances), forestry, fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste. Includes bioliquids and biofuels.

Biorefinery: A facility (or network of facilities) that integrates biomass conversion processes and equipment to produce biofuels, power, and chemicals. The concept is analogous to an oil refinery, which produces multiple fuels and other products from crude oil.

Negative externality: A cost borne by a third party as a result of an economic transaction. This includes any individual, organisation, or resource that is indirectly affected by an activity. Pollution is an obvious example of a negative externality.

Nutrient: A substance that provides nourishment essential for the maintenance of life and for growth.

EXECUTIVE SUMMARY

This scoping paper focuses on the potential of the significant volume of organic waste flowing through the urban environment. The aim is to highlight the opportunities to capture value, in the form of the energy, nutrients and materials embedded in these flows, through the application of circular economy principles. Organic waste - from the organic fraction of municipal solid waste streams and wastewater that flows through sewage systems - is traditionally seen as a costly problem in economic and environmental terms. This scoping paper will explore the idea that the equation can be reversed by designing more effective recovery and processing systems to turn organic waste into a source of value and contribute to restoring natural capital.

Every year, people harvest roughly 13 billion tonnes of biomass globally to use as food, energy and materials. This biomass flows through the 'biocycle economy', as it is referred to in this scoping paper. This part of the economy includes industries that deal with biological materials at different stages of the value chain: for example, agriculture, forestry and fishing at the primary stage; food processing, textile manufacturing and biotechnology in the processing stage; and retail and resource management in the consumption stage. Together, they generate a global value of approximately USD 12.5 trillion, equivalent (in 2013) to 17% of global gross domestic product (GDP).

The biocycle economy's share of the overall economy is much larger in emerging markets, where the majority of growth in per capita consumption is expected. In this context, the volume of biomass flowing through the global economy is set to grow: notably, by 2050, global demand for food is expected to rise by approximately 55%.

While such parameters offer considerable commercial and trade opportunities, they also involve numerous challenges. These include significant structural waste in the biocycle economy (about a third of all food produced globally is lost or wasted), as well as natural capital losses and negative environmental externalities. The volume of greenhouse gas emissions produced by global food waste is ranked third behind China and the US.[1] Land degradation affects roughly one quarter of land globally and costs USD 40 billion per year.[2] Eutrophication, or the accumulation of nutrients caused by surface run-off and the resulting overgrowth of plant life, has created aquatic dead zones all around the world.

At the same time, the economic opportunities are significant. The World Economic Forum estimates that potential global revenues from the biomass value chain – comprising the production of agricultural inputs, biomass trading and biorefinery outputs – could be as high as USD 295 billion by 2020.

Cities, the new powerhouses already generating over 80% of global GDP, will play a major role in addressing challenges and realising opportunities in the biocycle economy. As major concentrators of materials and nutrients, cities aggregate inputs such as food from rural areas into a concentrated urban space. Today, almost none of these materials are looped back into the biosphere, meaning that rural soils are becoming degraded and rely increasingly on synthetic fertilisers, which also creates nutrient imbalances. In theory, nitrogen, phosphorus and potassium (NPK) nutrients recovered from food, animal and human waste streams on a global scale could contribute nearly 2.7 times the nutrients contained within the volumes of chemical fertiliser currently used. Cities produce about 1.3 billion tonnes of solid waste per year, roughly half of which is organic. This figure is expected to almost double by 2025, with 70% of the total likely to be generated in emerging markets.

According to a recent study on residual organic waste in Amsterdam, the Netherlands, high value processing could lead to added value of EUR 150 million, as well as 900,000 tonnes of material savings and a reduction of 600,000 tonnes in CO_2 emissions annually for the city.[3] These benefits can be generated using biorefineries, waste separation and return logistics, cascading organic flows and nutrient recovery.

Some cities have implemented programmes to recover and valorise organic materials, such as those found in food waste and wastewater streams.

1 FAO, *Global Food Losses and Food Waste–Extent, Causes and Prevention*
2 United Nations (2012)
3 Circle Economy, TNO and FABRIC

The volumes of recovered material vary greatly. Milan, Italy now has high rates of recovery, which it uses to generate revenue by producing energy and compost, the decayed organic material used as a fertiliser. Many cities, however, are achieving only low levels of recovery, representing a notable lost opportunity as well as impacting human and environmental health.

Producing concentrated NPK fertilisers is one way of recovering nutrients from organic waste streams, as is using biosolids as compost. Nutrient recovery is attractive as a source of revenue and, importantly, as a contributor to ecosystem regeneration.

Energy recovery from organic waste can offset operational costs, generate revenue, increase the share of renewables in the energy mix and reduce GHG emissions. Anaerobic digestion is the most widely adopted technology in this area and can be applied to a wide range of organic materials to generate biogas, leaving a nutrient-rich substance called digestate. The biogas can either be fed to the gas grid or converted to electricity using conventional thermal power processes.

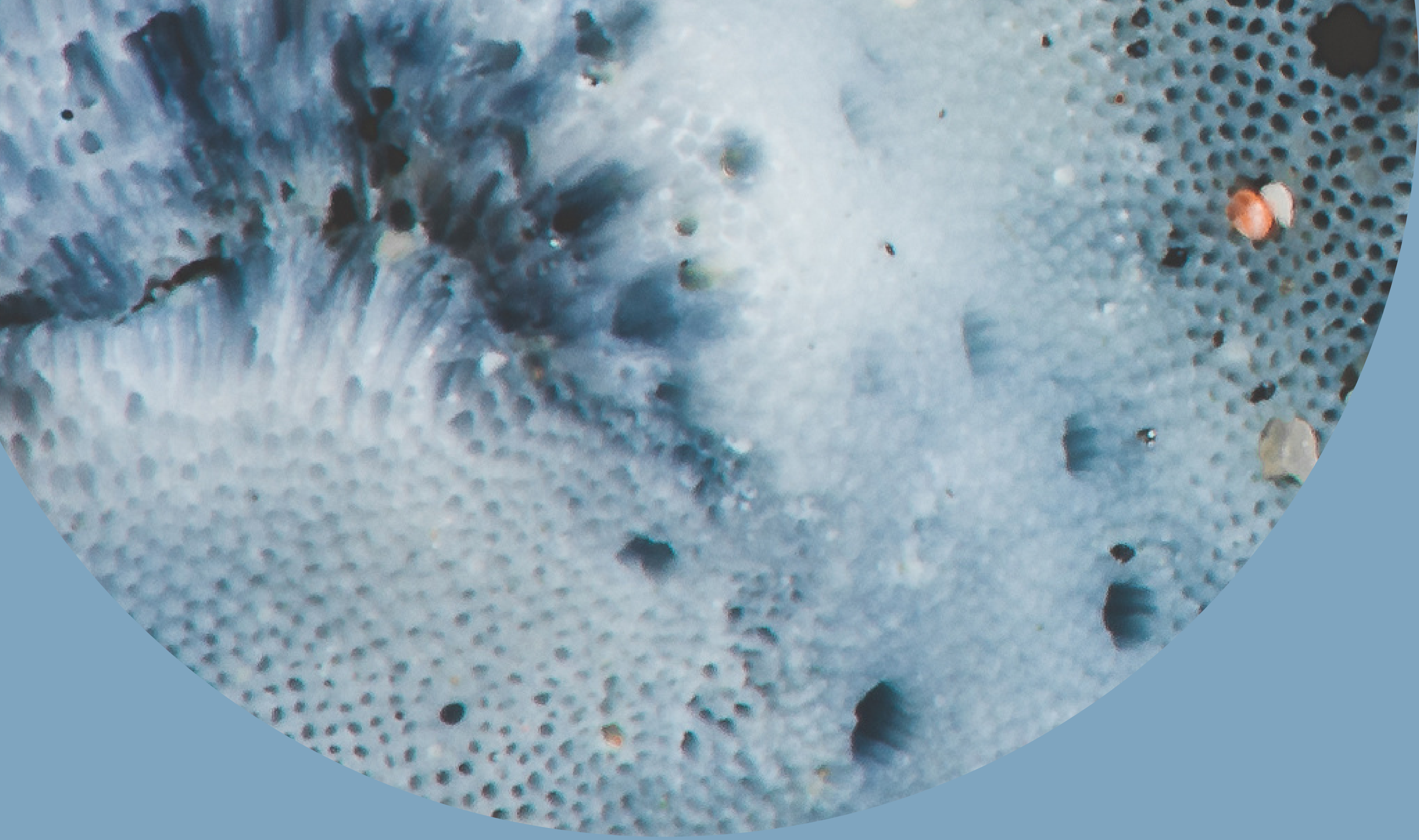
Recovering energy in the wastewater sector is attractive, as it can offset the energy required for treatment. In the best example of this, a plant in Denmark has managed to produce more electricity than it needs for its operations, making it a net exporter of power.

Significant opportunity exists to use organic waste material to manufacture a range of products and materials traditionally derived from fossil fuel sources. Biorefineries could be a central technology in this endeavour. Operating in a similar way to petrochemical refineries, they employ a range of techniques – such as thermal treatment, biological processes and enzymatic conversions – to transform organic feedstock into valuable chemicals and products. Biorefineries have many feedstock options available, spanning solid organic waste and waste water. The options are categorised as first generation (food-based) and second generation (non-food-based), with the latter being particularly attractive as they complement food production rather than compete with it.

The technology is rapidly evolving and as it matures, biorefineries will produce more and more complex chemicals and materials. Succinic acid and polylactic acid (both useful precursors for fuels and lubricants) are already being produced. It is increasingly evident that organic waste can be used to produce competitive alternatives to resources derived from fossil fuels.

Several barriers need to be overcome to shift the system towards one aligned with circular economy principles. These include regulatory barriers – such as inconsistent and ill-fitting definitions of waste, and economic hurdles, including the absence of accurate externality pricing – which tilt the field towards incumbent systems, rather than levelling it for biologically derived materials and energy. Overcoming such barriers will further enable the technological advances required to realise the economic opportunities.

Clearly, there is a high-level opportunity to capture value and increase the contribution of urban biocycles to building natural capital. However, this paper demonstrates the need for further analysis. What is required is no less than the following: to develop the baseline understanding of the urban organic landscape as well as quantify the opportunity; to quantify the private-sector opportunities; to identify the systemic solutions that enable the economic use of recovered nutrients; and finally, to highlight the regulatory levers needed to develop new markets in organic materials.



THE BIOCYCLE ECONOMY

The bioeconomy, or the biocycle economy as it is referred to in this scoping paper, includes industries that deal with biological materials at different stages of the value chain. Such industries include agriculture, forestry and fishing at the primary stage; food processing, textile manufacturing and biotechnology in the processing stage; and retail and resource management at the consumption and end-of-use stages.

The focus of this paper is on flows of organic matter through cities and the opportunities to increase their recovery and enhance their use by applying circular economy principles.

The significance of the biocycle economy

Seen as a whole, the biocycle economy plays a critical role in global economic, human and environmental systems. According to the Natural Capital Coalition, "farmers, traders, wholesalers, food manufacturing companies, and retailers together make up the world's largest sector, generating an approximate global value of around USD 12.5 trillion based on revenue, or 17% of world gross domestic product (GDP) in 2013".[4] In emerging countries, the biocycle economy's proportion of the overall economy is even more significant; for example, the agricultural industry, including crops and livestock, accounts for 22% of Brazil's GDP.[5]

According to the European Commission, the bioeconomy's estimated worth in Europe is approximately EUR 2 trillion in turnover per year, and accounts for more than 22 million jobs. This figure encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy.[6] In Finland for example, the government forecasts its national bioeconomy to grow 4% annually to 2025, increasing economic output from EUR 60 billion to EUR 100 billion and adding 100,000 jobs. The greatest opportunities for growth are expected to be in creating new products and materials, with organic waste streams playing a significant role as raw materials.

4 Natural Capital Coalition
5 Center for Advanced Studies on Applied Economics, University of São Paulo, and Brazilian Confederation of Agriculture and Livestock, Ellen MacArthur Foundation, *A Circular Economy In Brazil: An Initial Exploration* (2017)
6 European Commission (2012)

Pressures on the biocycle economy

Largely because of the linear model of development that has dominated the global economy since the Industrial Revolution, the biocycle economy is now facing major challenges.

Global demand for food is expected to grow by about 70% between 2005 and 2050, increasing the pressure on the availability of land.[7] The growing demand for new biological feedstocks to supply a variety of uses, including biofuels, biomaterials and pharmaceuticals, will further stiffen competition for land. Moreover, the effects of climate change on soil quality and land productivity will exacerbate such challenges.

Significant structural waste, natural capital losses and environmental externalities in the current biocycle economy need to be addressed:

- About a third of all food produced globally, worth roughly USD 680 billion in high-income countries and USD 310 billion in emerging countries, is lost or wasted each year.[8] The volume of greenhouse gas emissions produced by global food waste is ranked third behind China and the US[9]
- Agricultural activities account for almost 70% of global water withdrawals,[10] yet only 40% of this water reaches plants[11]
- Land degradation affects roughly one-quarter of the global land surface; about 75 billion tonnes of fertile topsoil are lost each year, with an estimated annual loss of USD 490 billion[12]
- Industrialised farming practices cost the environment some USD 3 trillion per year (more than UK annual GDP) in negative environmental externalities across the value chain.[13] Many agricultural industries would be unprofitable if such externalities were priced in, as they exceed industry revenue, sometimes many times over[14]
- Fertiliser run-off from the agricultural system leads to nutrients accumulating in rivers, lakes and oceans and eventually to eutrophication, algal blooms and hypoxic dead zones (ocean dead zones now affect 240,000 km^2, an area approximately the size of the UK).[15]

Disrupted nutrient flows

Modern agricultural practices, such as excessive tillage and the use of heavy machinery, accelerate erosion and water runoff, carrying nutrients out of the soil and into water systems. As crops are harvested, nutrients and organic matter are removed; if they are not replaced, soil fertility decreases. Excessive use of pesticides and synthetic fertilisers, which may not contain all the necessary nutrients and organic matter, can also lead to increasing toxicity levels, reducing the soil's capacity to support growth.

As more and more nutrients are lost and soil quality decreases, farmers increasingly turn to the use of synthetic fertilisers. Global demand for fertilisers was estimated at 185 million tonnes in 2014, and is forecast to grow 1.6% a year 2015-2019.[16]

Producing synthetic fertilisers typically involves mining finite resources such as phosphate rock, requires significant energy, and generates GHG emissions. Producing synthetic nitrogen fertilisers, for example, consumes 2% of the world's energy and, in 2007, generated 465 million tonnes of CO_2 emissions.

THE DISRUPTED NUTRIENT CYCLE

The cycling of nutrients is critical for the growth of all plant and animal life on the planet. At its most basic level, the natural cycle sees nutrients such as nitrogen, phosphorus and potassium absorbed from the soil by plants, which are then consumed by animals (including humans). These nutrients are subsequently excreted and returned to the soil, where plants can take them in again.

This cycle, however, has been disrupted by human activity. Each year, societies harvest roughly 13 billion tonnes of biomass globally for food, energy and material purposes. Food, including biomass produced for animal feed, dominates this material, accounting for about 82%, or 11 billion tonnes, of total extracted biomass. This is followed by bioenergy (11%) and materials (7%).[17] Marine fisheries contribute a further 110 million tonnes to the food supply every year.

In addition to farming practices, megatrends such as globalisation, increasing population and urbanisation contribute to disrupt the nutrient cycle. The global food system and trade networks, for instance, can require extracted nutrients to be transported

7 Food and Agriculture Organisation of the United Nations (FAO), *How to Feed the World in 2050*
8 FAO (2011)
9 FAO, *Global Food Losses and Food Waste – Extent, Causes and Prevention*
10 OECD, *Water use in agriculture*
11 European Environment Agency (2012)
12 United Nations (2014)
13 FAO (2015)
14 Trucost (2013)
15 Diaz, R.J. and Rosenberg, R.
16 FAO (2016)
17 Wirsenius, S.

vast distances from their source. Urbanisation leads to nutrients being concentrated and discharged as food waste into solid waste streams, and into wastewater systems as sewage sludge. In Europe, the sludge contains approximately three times more phosphorus than is found in solid waste. Concentration and discharge of nutrients in wastewater systems can also contribute to the eutrophication problem mentioned above.

The crux of the issue is that nutrients are extracted from the biosphere as harvested food, and become concentrated in cities, subsequently causing damage where they are discharged, rather than being beneficially looped back into the soil.

PLANETARY BOUNDARIES[18]

Of the nine planetary boundaries developed by the Stockholm Resilience Institute, five have a direct link to the biocycle economy:

- **Nitrogen and phosphorus flows to the biosphere and oceans**
  The biogeochemical cycles of nitrogen and phosphorus have been radically changed by humans as a result of many industrial and agricultural processes. Nitrogen and phosphorus are both essential elements for plant growth, so fertiliser production and application is the main concern. Human activities now convert more atmospheric nitrogen into reactive forms than all of the Earth's terrestrial processes combined. Much of this new reactive nitrogen is emitted to the atmosphere in various forms rather than taken up by crops. When it is rained out, it pollutes waterways and coastal zones or accumulates in the terrestrial biosphere. Similarly, a relatively small proportion of phosphorus fertilisers applied to food production systems is taken up by plants; much of the phosphorus mobilised by humans also ends up in aquatic systems. These can become oxygen-starved as bacteria consume the blooms of algae that grow in response to the high nutrient supply. A significant fraction of the applied nitrogen and phosphorus makes its way to the sea, and can push marine and aquatic systems across ecological thresholds of their own. One regional-scale example of this effect is the decline in the shrimp catch in the Gulf of Mexico's 'dead zone' caused by fertiliser, transported in rivers from the US Midwest.
- **Land system change**
  Land is converted for human use all over the planet. Forests, grasslands, wetlands and other vegetation types have primarily been converted to agricultural land. This land-use change is one driving force behind the serious reductions in biodiversity, and it has impacts on water flows and on the biogeochemical cycling of carbon, nitrogen and phosphorus and other important elements. Forests play a particularly important role in controlling the linked dynamics of land use and climate.
- **Freshwater consumption and the global hydrological cycle**
  The freshwater cycle is strongly affected by climate change yet human pressure is now the dominant driving force determining the functioning and distribution of global freshwater systems. The consequences of human modification of water bodies include both global-scale river flow changes and shifts in vapour flows arising from land use change. These shifts in the hydrological system can be abrupt and irreversible. By 2050 about half a billion people are likely to be subject to water-stress, increasing the pressure to intervene in water systems.
- **Loss of biosphere integrity (biodiversity loss and extinctions)**
  The Millennium Ecosystem Assessment of 2005 concluded that changes to ecosystems due to human activities were more rapid in the past 50 years than at any time in human history, increasing the risks of abrupt and irreversible changes. The main drivers of change are the demand for food, water, and natural resources, causing severe biodiversity loss and leading to changes in ecosystem services.
- **Climate Change**
  Recent evidence suggests that the Earth, now passing 390 ppm CO_2 in the atmosphere, has already transgressed the planetary boundary and is approaching several Earth system thresholds. The weakening or reversal of terrestrial carbon sinks, for example through the ongoing destruction of the world's rainforests, is a potential tipping point, where climate-carbon cycle feedbacks accelerate Earth's warming and intensify the climate impacts. A major question is how long we can remain over this boundary before large, irreversible changes become unavoidable.

18 Stockholm Resilience Centre

Cities aggregate biological materials and nutrients from rural areas, but return few of them to the agricultural system

Cities as concentrators of organic resources

Cities aggregate biological materials and nutrients from rural areas, but return few of them to the agricultural system. In 2050, it is estimated that over 70% of people will be living in cities, equivalent to 2.5 billion new urban dwellers. Cities consume 75% of the world's natural resources and 80% of global energy supplies, and produce approximately 75% of global carbon emissions.[19] As of 2012, cities produced about 1.3 billion tonnes of Municipal Solid Waste (MSW) globally per year, a figure expected to grow nearly 70% to 2.2 billion tonnes per year by 2025, with 70% of that waste likely to be generated in emerging markets.[20]

FOOD WASTE AROUND THE WORLD

Food waste is a significant issue in both high-income and emerging economies. While the two groups make up relatively similar proportions of global food waste – 56% from high-income and 44% from emerging economies – the stages in the value chain where waste occurs vary significantly. More than half of the food waste in North America, Europe and Oceania occurs at the consumption stage, whereas most of the waste in South Asia, South East Asia and Sub-Saharan Africa occurs at the production and storage stages (the two stages closest to the farm).[21] This contrast indicates the need for tailored approaches to recovering and valorising organic waste in different regions of the world.

However, almost all urban areas, no matter where they are located, experience significant levels of food waste and loss. This is particularly true in emerging economies, which often lack the necessary infrastructure to deal with the problem.[22]

Unrecovered organic streams

Organic material makes up the largest proportion (46% by mass) of MSW. This percentage varies around the globe, and is generally higher in low-income countries (64%) than high-income countries (28%). However, although the fraction of organic waste may be lower in high-income countries, the absolute volumes can be larger. For example, in countries of the Organisation for Economic Co-operation and Development (OECD), the organic fraction of MSW is estimated to be 27%, but because these countries generate 44% of the world's total MSW, their absolute quantity of organic waste is larger than that of any other group.

The rapid population growth and urbanisation expected in low-income countries in the near future will lead to a huge increase in the volume of MSW generated. A large proportion of it will be organic waste, which will drive a significant increase in GHG emissions

19 United Nations Environment Programme – Division of Technology, Industry and Economics (UNEP-DTIE)
20 World Bank
21 Lipinski et al.
22 Ibid.

if landfilled or left to decompose. The decay of post-consumer waste accounts for 5% of total global greenhouse gas (GHG) emissions. Organic waste decomposing in landfills is a major contributor, responsible for 12% of the global emissions of methane, a gas with a greenhouse effect 28 times greater than that of carbon dioxide (CO_2).[23] In emerging countries, 80% of the collected waste is disposed of in open dumps or sub-standard landfill sites.

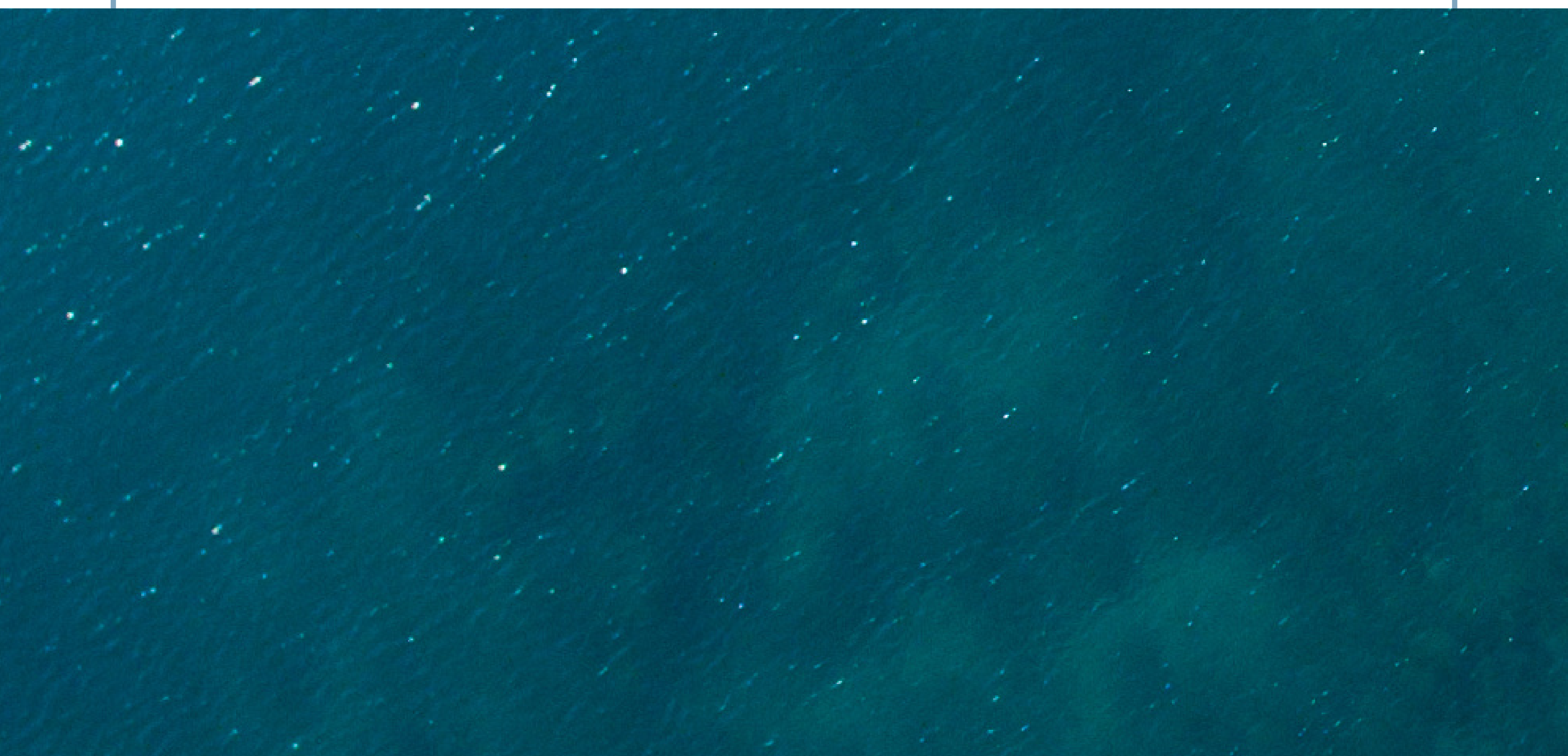
Rather than returning to the soil, the nutrients in these waste streams go largely unrecovered. For example, among the EU-27, 70% of the phosphorus in sewage sludge and biodegradable solid waste is not recovered.[24] Indeed, between 1900 and 2000 the recycling rate of food-derived nitrogen in Paris dropped from 40% to 5%.[25] In Bangkok, an estimated 90% of the 26,000 tonnes of nitrogen that enters the city each year is lost, primarily through the city's waterways.[26] In Kumasi, a city of 1.2 million people in Ghana, 80% of the phosphorus and nitrogen in the 950,000 tonnes of food biomass that enters the city annually is lost because of the lack of collection infrastructure. Those nutrients end up on the streets and in drains.[27] A 2007 analysis showed that about half the nitrogen accumulates in ground and surface water, and about 15% of both nutrients were sent to landfill, with less than 5% ending up in treatment plants. The nutrient value of the uncollected solid and liquid waste would have been sufficient to pay for the city's entire solid waste management costs of USD 180,000 a month.[28]

UNTAPPED RESOURCES IN WASTEWATER

If a value could be attached to the resources in sewage flows, the idea of wastewater treatment would shift from an expensive cost centre to a profit-generating 'resource factory', one that creates a variety of useful end products. "Wastewater is the largest untapped waste category – as big as all solid waste categories taken together. It is a natural starting point for the circular revolution", states Martin Stuchtey in *Rethinking the Water Cycle*.[29] In the circular economy, the flow of biological nutrients can be seen as a series of cascading, value-extracting stages. In a similar way, wastewater could be viewed as a rich soup of energy, carbon, nitrogen, phosphorus and other ingredients that yield different products at different stages. The final and often most valuable product would be clean water, which can be reused or safely returned to the biosphere. A material analysis conducted by the Green Ribbon Commission[30] of Amsterdam's annual wastewater production (the city's population is about 800,000) demonstrates the potential value of urban wastewater.

- Water – 72 million cubic metres (2 billion cubic metres in the Netherlands)
- Organic matter – 40,041 tonnes
- Phosphorus – 577 tonnes
- Nitrogen – 4,140 tonnes
- Heavy metals – 28.8 tonnes
- Pharmaceuticals – 3.1 tonnes

23 Intergovernmental Panel on Climate Change (IPCC)
24 Ellen MacArthur Foundation, SUN and McKinsey Center for Business and Environment
25 Guilbert, S., SupAgro Montpellier - INRA
26 Faerge, J., Magid, J. and Penning de Vries, F.W.T.
27 Drechsel, P., Graefe, S. and Fink, M.
28 Ibid.
29 Stuchtey, M.
30 Struker, A.



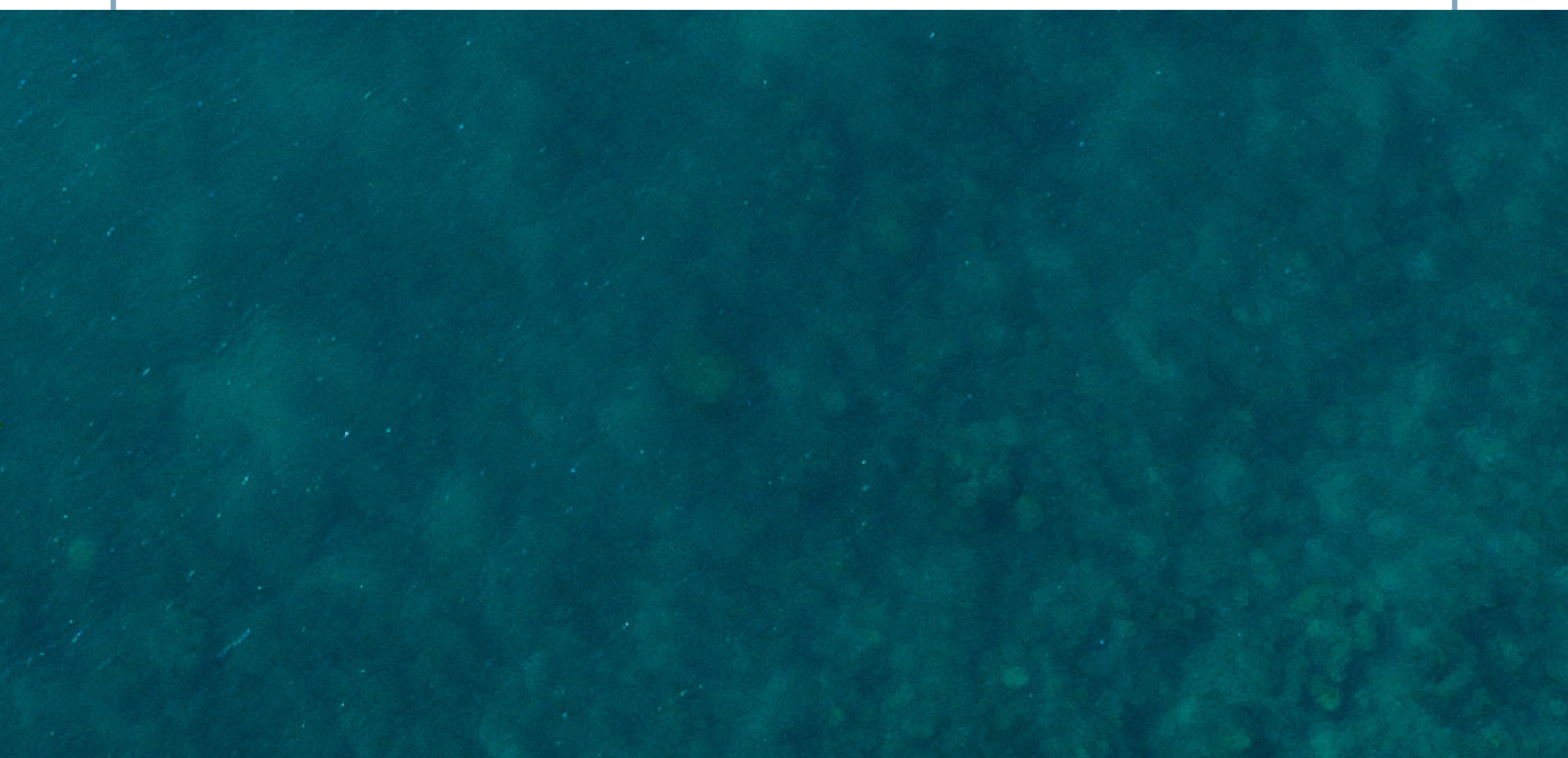
Globally, cities have a huge water 'footprint' – collectively they move about 430 billion litres per day through pipes and aqueducts totalling over 17,000 miles. While cities occupy only 1% of land on earth, the catchment areas that provide them with water cover about 41%. As an example, the watershed supplying New York City is 2,000 square miles, with some drops of water travelling over 100 miles through vast aqueducts before entering the city's water supply. The water supplying Los Angeles, California, travels 230 miles from source to city. Although the demand of cities on their watersheds can affect large areas of land, it goes both ways. Pursuing better farming practices on just 0.2% of farmlands in urban watersheds could improve water quality for 600 million people. Ensuring safe and resilient water supplies in the future for cities is a great and complex challenge; no wonder many experts are calling it a looming crisis.

WASTEWATER IN INDIAN CITIES

Nowhere are the challenges of wastewater more evident than in India's cities. In the next two decades, the country's urban population is projected to grow from 400 million to 600 million. Urbanisation, accompanied by an expanding middle class, will push up per capita consumption. In fact, a 50% increase in the urban population may increase associated annual demand for water by 100%, from 740 billion cubic metres to 1.5 trillion cubic metres.[31] This represents both a challenge and an opportunity for the future. Currently, only 30% of household wastewater is treated; the rest discharges into open drains or the ground, eventually finding its way into aquifers and waterways, both sources of drinking water. A report by the Central Pollution Control Board in March 2015 estimated that Indian cities produce 62 billion litres of wastewater per day, whereas the total treatment capacity is only 23 billion litres.[32] Of this installed capacity, 70% is estimated to be non-functioning because, according to a government spokesman, the cost of energy to run the plants is prohibitively high. All of this puts a huge strain on the national economy, as well as on environmental and public health (one estimate puts this impact at USD 54 billion, or 6.4% of GDP).[33]

The huge future demand from Indian cities, combined with the current non-functioning wastewater systems, suggest that new approaches to wastewater treatment are needed. As Executive Director of the International Water Association, Ger Bergkamp emphasises: "The wastewater treatment plant, as we know it today, is no longer fit for purpose. Major benefits can come from truly rethinking the entire urban water, carbon and energy systems. This approach would be a crucial part of establishing a circular economy in which water and material loops are closed."

31 Subramaniam, B.
32 The Economic Times
33 Alba, D



THE CIRCULAR ECONOMY VISION – HOW TO CLOSE THE NUTRIENT LOOPS

The biocycle in a circular economy

Cities are concentrators of organic materials, with imbalances between inflows and outflows leading to aggregation. While this makes cities the source of large amounts of waste and negative externalities in the current economic model, these resource streams would be captured and valorised in the circular economy model. Ultimately, a city should function like an ecosystem, providing services that are indistinguishable from the surrounding environment. Cities present a major opportunity to implement circular principles in the biocycle economy due to their characteristics, which include large scale of supply, high proximity between stakeholders, and a tech-savvy workforce.

In a circular system, all nutrients would be returned to the biosphere in an appropriate manner. In the urban context, this means nutrients are captured within the organic fraction of MSW and wastewater streams, and processed to be returned to the soil, in forms such as organic fertiliser. The recovery of post-consumer nutrients, coupled with regenerative agricultural practices, would reduce the need to bring in nutrients from non-renewable sources, for example synthetic fertilisers. This would all contribute to developing a regenerative nutrient cycle.

A circular city would run entirely on renewable energy. The power generated by the by-products of treating recovered urban organic waste could be combined with other renewable technologies, such as solar PV and wind. A circular economy's overarching framework distinguishes between two cycles of materials: biological and technical.

Biological cycles contain those materials that can safely cycle in and out of the biosphere. The materials include food, fibres and bio-based construction materials, such as wood. Technical cycles contain flows of materials that cannot be appropriately returned to the biosphere, such as plastics and metals found in myriad products, from engines to washing machines to mobile phones.

Compared with the technical cycle, the opportunities for shifting towards a circular model, and the mechanisms for doing so, have so far been largely unexplored in the biocycle economy.

CIRCULAR ECONOMY DIAGRAM

PRINCIPLE
1

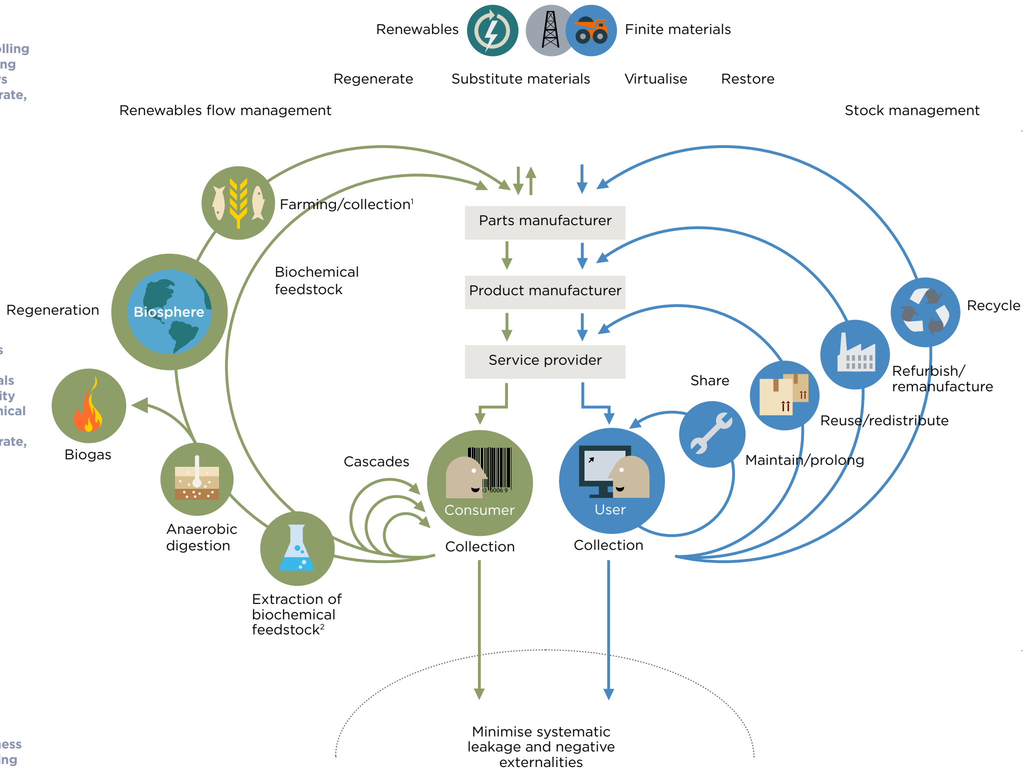
Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows
ReSOLVE levers: regenerate, virtualise, exchange

PRINCIPLE
2

Optimise resource yields by circulating products, components and materials in use at the highest utility at all times in both technical and biological cycles
ReSOLVE levers: regenerate, share, optimise, loop

PRINCIPLE
3

Foster system effectiveness by revealing and designing out negative externalities
All ReSOLVE levers



1. Hunting and fishing
2. Can take both post-harvest and post-consumer waste as an input

Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

Recovering organic waste in cities

Cities around the world have been implementing programmes to recover and valorise organic materials, such as those found in food waste and wastewater streams. However, the approaches to recovery and the volumes of recovered material vary greatly.

Clearly, a significant opportunity exists to increase the recovery of organic material across the board. Well-designed and well-operated integrated waste collection and recovery schemes have been shown to capture upwards of 85% of the organic waste produced. However, average rates are actually far below this. In OECD countries, only 66 million tonnes of organic waste, or 37% of the approximate 180 million tonnes generated in 2013, was either composted or anaerobically digested.

Although municipalities currently view organic waste management as a cost, it could be an attractive source of revenue. A 2013 study by the Ellen MacArthur Foundation, with analysis by McKinsey & Co., highlighted from two perspectives the potential value that could be derived from processing food waste with anaerobic digestion: mitigating the problem of steeply rising landfill costs; and receiving revenues from sales of the derived products, and subsidies for renewable energy. In the United Kingdom, an estimated operating profit of up to USD 172 per tonne could be achieved, including USD 26 from electricity, USD 18 from heat and USD 6 from fertiliser. The feed-in tariff was taken at USD 64, avoided landfill costs were USD 105, and an allowance of USD 45 was made for sorting and processing.

Since 1995, Milan, Italy has worked with large producers – such as restaurants, canteens and grocery stores – to institute in 2012, separate collection of organic solid waste from households. The collection programme now covers the city's entire population and recovers more than 130,000 tonnes of organic solid waste per year, more than any other city in the world with a population of over 1 million.[34] The collected material is used as input for anaerobic digestion and to generate biogas and compost (for more about this initiative, see the 'Milan' box). In the United States, San Francisco and

Seattle have implemented separate household collection of organic solid waste, with San Francisco collecting and recycling or composting 80% of the waste generated by its citizens.

In other cities, separate collection of organic waste is still in the early stages of development. New York City established an organics collection pilot programme in 2013, which now serves approximately 270,000 households. Two years after initiation, 15,850 tonnes of organic material had been collected, nearly 7% of the 2.2 million tonnes generated in the same period. This programme continues to scale up, with the goal of achieving zero waste to landfill by 2030.[35] Overall, however, the recovery rate for organic materials in the United States is low, with the rate for food waste as low as 4.8%. Many cities lack programmes for recovering organic waste at all. Similarly, in the United Kingdom 40% of local authorities do not have a food waste collection scheme.[36]

Returning nutrients to the soil

Urban waste streams represent a significant opportunity to recover nutrients and return them to the soil.

In theory, the recovery of 100% of the nitrogen, phosphorus and potassium in global food, animal and human waste streams could contribute nearly 2.7 times the nutrients contained in volume of chemical fertiliser currently used.[37]

Solutions and technologies already exist, and are being implemented in various locations and at different scales around the world. Such solutions include composting, or the predominantly aerobic, biological decomposition of organic materials. In this process, organisms such as snails, worms, fungi and bacteria help to transform the material over time into humus, a critical component of healthy, fertile soil. Another solution is anaerobic digestion, in which micro-organisms break down biodegradable material in the absence of oxygen.

MILAN: FOOD WASTE RECOVERY IN A DENSELY POPULATED EUROPEAN CITY

In 2011, Milan had an overall collection rate of separated waste of 35%, with food waste only collected from commercial sources such as restaurants and hotels. Considering this level unsatisfactory, the newly elected city government started a programme to produce biogas and compost from residential food waste separated at source and sent to an anaerobic digestion and composting facility.

By January 2015, the total separated collection rate had risen to 54%, with food waste the main contributor. Milan's scheme is distinctive: it now covers the whole population of 1.4 million, making it the largest formal kerbside organics collection scheme in the world.

An information campaign was rolled out before starting the initiative and every household received a kitchen caddy along with a roll of compostable bags made from bioplastic. Collected twice a week, the food waste is delivered to four transfer stations, from where it is transported on the same day to the anaerobic digestion and composting plant to produce biogas and compost.

Every tonne of diverted food waste represents a financial benefit: treating food waste costs about EUR 70 per tonne, while the average disposal cost for residual waste is EUR 100 per tonne. The scheme also prevents food waste from emitting GHGs in landfill sites.

It is effective in producing organic fertilisers rich in nutrients and organic matter, in addition to renewable energy.

Compost and digestate differ in their nutrient content and the availability of those nutrients for uptake by crops. The benefits of applying high-quality compost to soil have been widely documented; they include increasing the organic matter in soil, improving water retention and increasing biological activity. Comparatively less well characterised are the long-term effects of applying digestate, a nutrient-rich substance that remains after anaerobic digestion, on soil organic matter and structure. Generally, compost is viewed as having superior soil-improving qualities, while digestate is better suited as a biofertiliser.[38]

Several cities around the globe employ these processes to treat collected organic waste, with solutions ranging from backyard and community composting schemes to large-scale anaerobic digestion facilities. Examples include the city of Adelaide, Australia, which composts about 70% of its organic waste, and New York City's Compost Project, which provides educational materials to encourage household composting and has set up drop-off sites for community composting.

A person produces an average of 500 litres of urine and faeces every year. As the human body cannot absorb all the nutrients from consumed food, the excreted waste is full of valuable material. In a 2001 study, Swiss analysts estimated that if 100% of these nutrients could be captured in household sewage, nearly 30 million tonnes of nitrogen, 5 million tonnes of phosphorus and 12 million tonnes of potassium could be recovered globally, representing about a third

35 City of New York
36 Waste and Resources Action Programme (WRAP)
37 Ellen MacArthur Foundation, *Towards the Circular Economy, Vol. 2.*
38 ISWA, op. cit.

of the annual total global demand for fertiliser.[39] The Commonwealth Scientific and Industrial Research Organisation in Australia found in a more recent study that "for a city of four million people, the total value of the carbon, ammonia, and phosphorus recovered would be USD 300 million per annum."[40]

Phosphate fertilisers are needed to replace the phosphate that plants remove from the soil. As the global population increases, demand is steadily rising, meaning more crops are cultivated and more meat is consumed (which has a higher 'phosphorus footprint' than vegetables). In the past, the phosphorus cycle was closed; people and animals consumed food and excreted faeces, which were returned to the soil, nurturing it and helping to grow new crops. With shifting demographics, growing cities and 'modern wastewater treatment', this cycle has been broken. Nutrients are not returned to the soil, but instead often end up in natural water bodies causing damage to aquatic ecosystems. While experts differ on the amount of natural phosphate reserves, most agree that they are dwindling (the US Geological Survey estimates that 80 years of phosphorus reserves remain).[41] The price of phosphorus has been very volatile over the past several years; in 2008, it increased by a factor of ten in a matter of months.

A more holistic approach to phosphorus is required to close the loop between food, people and soils, and prevent leakage into bodies of water. Recovering phosphorus from wastewater could be part of this solution.

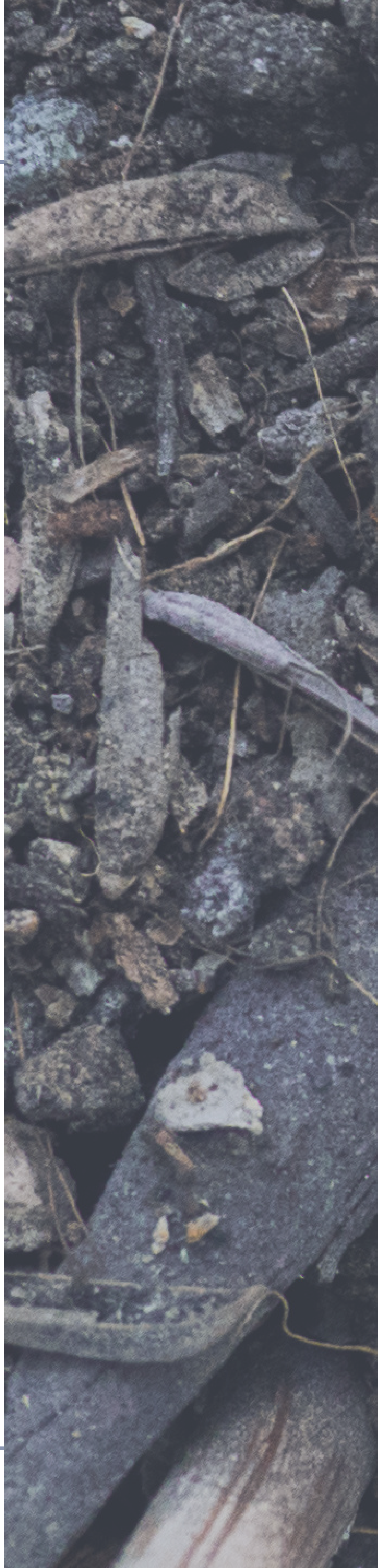
ADVANCED SOLUTIONS FOR INTEGRATED WASTE MANAGEMENT

Suez, the industrial services company, has developed a dedicated integrated solid waste management offer for emerging countries, demonstrating that simple and affordable solutions exist for managing urban organic waste.

These solutions use simple technical modules to convert waste into valuable materials and energy, capturing the full potential of this resource stream. Modules include the following: sorting and separating to recover high-value materials; diverting from landfill and transforming organic waste into new resources, such as fuel, compost and fertilisers; producing energy through the generation of biogas on the landfill site; and optimising intelligent systems to increase energy performance and save empty landfill space.

These services are implemented locally and adapted to suit the local context. In Meknés, Morocco, for example, the rehabilitation and construction of sanitary landfill sites and a new composting plant also included establishing a cooperative to help involve local waste-pickers in the solution.

This integrated approach provides an answer to local waste management needs, protects human health, cleans the urban environment, reduces atmospheric pollution and supports local economic development. Additionally, initial analyses estimate that implementing such solutions would help cut GHG emissions at a cost of less than USD 15 per tonne of CO_2e.



39 Smil, V.
40 Ellen MacArthur Foundation, *Towards the Circular Economy, Vol. 2, p. 45*
41 MIT, Mission 2016: *The Future of Strategic Natural Resources*

In parallel, the regulatory context can play a critical role. Too much nitrogen in effluent can create dead zones, as algal blooms form and lead to hypoxic conditions which suffocate aquatic life. This is the context for many treatment plants in New York City that discharge into the ecologically sensitive Long Island Sound. More stringent effluent quality requirements have led to billions of dollars of investment to upgrade the denitrification capacity of the adjacent treatment plants.

In comparison, San Francisco's East Bay Municipal Utility District discharges effluent into the Pacific Ocean with much less stringent nitrogen permitting. Add to this the unit cost of electricity in California, which is among the highest in the country, and the combination of factors led the utility to modify its plant to process both food waste and sewage. Extra carbon-rich biomass allows it to increase production of biogas, which it converts to electricity to sell to the local grid. Unlike in New York City, the nitrogen and phosphorus resulting from the process, which is normally a cost to recover, is then discharged into the ocean.

While this is not a 'circular' model to be emulated, it does illustrate that constraints in a local context can determine how wastewater treatment plants are designed and operated. The table below summarises the products that potentially can be recovered from sewage flows, along with the associated technology's maturity level and any related case studies.

POTENTIAL PRODUCTS FROM WASTEWATER TREATMENTS PLANTS

GROUP	PRODUCTS	USES	LEVEL OF TECHNOLOGY	CASE STUDY
Water	Potable and non-potable water	Industrial, cooling water, landscaping, agriculture, aquaculture	High	NEWater (Singapore) Gorengeab plant, Windhoek (Namibia)
Energy	Biogas	Heat or electricity generation	High	Odense plant (Denmark) Thames Water (UK)
Treated sludge	Biosolids, biogrout, biochar	Soil conditioning, land reclamation, building materials, nutrients	High	Widespread use
Nitrogen and phosphorus	Phosphates, detergents, phosphoric acid	Fertilisers	High	Ostara – Crystal Green (see the "Ostara" case study)
Cellulose	Recycled cellulose (Recyllose™)	Plastics, insulation, cardboard, construction	Medium to high (a number of installations around the world)	Applied CleanTech*
Algae	Biodiesel, alginates	Fuels, animal feed, paper industry, pharmaceuticals, cosmetics	Low to medium (rotating algae bioreactor prototypes in the US)	WesTech Engineering**
Commercial chemicals	Succinic acid, ethyl acetate, methyl acetate, butyric acid	Platform chemical for many sectors	Low	Integrated BioChem***
Data	Public health data sets	Predicting disease outbreaks, neighbourhood health	Theoretical	MIT Underworlds project****

*Applied CleanTech, Leading the Sewage Mining Revolution
**Griffiths, F
***Integrated BioChem, "Products" [website];
****Massachusetts Institute of Technology, "Underworlds" [website]

An additional approach is through extracting phosphorus and nitrogen from wastewater systems through solutions such as Veolia Water Organics Recycling, Suez's Phosphogreen technology and Ostara Nutrient Recovery Technology's Pearl Process (see Ostara case study). Recovering nutrients from wastewater not only reduces costs for wastewater treatment plants, which face increasingly stringent limits to prevent the harmful discharge of polluting nutrients into adjacent waterways, but also helps such plants eliminate the build-up of struvite scale in pipes. This reduces operating costs and creates a revenue stream for the municipality through sales of high-value fertiliser.

While estimating the potential impact of these solutions is difficult, several indicators point to the scale of the opportunity. In the municipality of Amsterdam, for example, nutrient recovery has been estimated to have a potential value of about EUR 30 million per year. This would reduce the city's CO_2 emissions by 300,000 tonnes and save 75,000 of material.[42]

In the EU, the phosphorus recovered from sewage sludge, meat, bonemeal and biodegradable solid waste amounts to almost 30% of the synthetic phosphorus fertiliser used (92% of which is imported).[43, 44] Considering the low average levels of organic waste recovery across the continent (on average, 40% of organic waste collected in the EU goes to landfill),[45] an increase in organic waste collection could significantly augment the recovery of nutrients and further offset the use of synthetic fertilisers.

In Australia, an additional 13 million tonnes of organic material per year could be diverted from the country's landfills. In fact, diverting just an additional 2 million tonnes would replace 10,000 tonnes of urea, 1,000 tonnes of phosphate and 5,000 tonnes of potassium sulphate, with the resulting yield improvements delivering another USD 30 million in farm revenue. Additionally, it would increase turnover in the organics recovery industry by up to USD 400 million, avoid approximately 2 million tonnes of CO_2e missions and sequester approximately 1 million tonnes of CO_2e in soils.[46]

BARRIERS TO RETURNING NUTRIENTS TO THE SOIL

- It can be difficult to import and export fertilisers and soil amendments derived from organic waste due to trade regulations surrounding the classification of waste products
- Farmers may not recognise the full benefits of using compost and digestate derived from organic waste (such as increased soil carbon and organic matter, improved soil structure and water retention) compared to using synthetic fertilisers
- While decentralising wastewater treatment could dramatically reduce power use and sewer maintenance costs, the economics of nutrient recovery at this small scale are challenging
- It can be difficult to assess the benefits of different wastewater treatment options on a level playing field, for example in the UK fiscal incentives have skewed choices (credits for renewable energy generation value CO_2 emission reduction over nutrient recovery)
- Wastewater treatment technology to recover cellulose and products from algae, for example, is still at the demonstrator stage

CASE STUDY: OSTARA NUTRIENT RECOVERY TECHNOLOGIES

The Pearl technology developed by Ostara is a closed loop nutrient recovery solution. It can recover 85% of the phosphorus and up to 15% of the nitrogen from municipal and industrial wastewater streams, and transform them into a high-value fertiliser. According to Ostara, nutrients crystallise into highly pure fertiliser granules and grow in diameter after the addition of magnesium in a controlled pH setting. Once they reach the size required for standard fertiliser blends, they are harvested, dried and bagged, ready for immediate distribution and sale. The fertiliser recovered by the Ostara process has a distinctive crystalline composition that releases nutrients when acids are given off by growing plant roots. This maximises the efficiency of phosphorus uptake and therefore minimises phosphorus leaching and run-off. The process helps to ensure that the plant absorbs the nutrition, thus contributing positively to the growing cycle as opposed to nutrients being lost in waterways. Capital costs are recouped in 5-10 years through annual savings in chemicals, sludge disposal and maintenance, as well as revenue from Crystal Green fertiliser sales. In addition, the solution helps protect local waterways from nutrient pollution (through lower application and release rates, and lower water solubility) at a time when clean water, food security, fertiliser run-off and growing populations are issues for communities around the globe. The use of one tonne of Crystal Green eliminates approximately 10 tonnes of CO_2e emissions.

42 Circle Economy, TNO and FABRIC
43 Faerge, J., Magid, J. and Penning de Vries, F.W.T.
44 Ellen MacArthur Foundation, SUN and McKinsey Center for Business and Environment
45 European Commission (2010)
46 Australian Organics Recycling Association

Generating bioenergy

Fossil fuels currently provide more than 60% of the energy consumed by OECD countries, while energy generated from waste contributes only 1%.[47] Approximately 10% (50 exajoules) of the total global primary energy supply is provided by bioenergy. Most of that energy is consumed in emerging countries for cooking and heating, using highly inefficient methods such as open fires or simple cook stoves, which have a considerable negative impact on human health (smoke pollution) and the environment (deforestation).[48] A total of 370 terawatt hours (TWh) of bioenergy-derived electricity was produced globally in 2012, which corresponds to only 1.5% of total electricity generated.[49]

Not only are fossil fuels a finite resource, but the significant negative impacts of generating energy from them are also well understood and documented. For instance, coal represents roughly 40% of global energy production[50] and, in 2014, was responsible for 46% of global CO_2 emissions.[51]

One of the core objectives of a circular economy is to ultimately rely on renewable energy sources, be that solar, wind, hydroelectric or bioenergy. The shift away from fossil fuel derived energy towards renewables is already well underway. In 2015, renewables accounted for more than half the total annual additions to global power capacity, surpassing coal in cumulative installed capacity.[52]

Generating bioenergy brings with it the opportunity for decentralised, off-grid energy production at a variety of scales (see the Sainsbury's example below). Emerging markets that have inadequate central energy infrastructure view this as a particularly appealing prospect. Demonstrations of bioenergy generation can be found in rural areas; for example, SNV's Vietnam Biogas Programme constructed over 158,000 domestic digesters, providing energy for about 790,000 rural dwellers.[53]

BIOGAS FROM ANAEROBIC DIGESTION

Anaerobic digestion can be applied to a wide range of organic material (e.g. food waste), generating biogas and digestate as outputs. As well as offsetting fossil-based energy production, the digestate returns nutrients to the soil, reducing the use of synthetic fertilisers. Research has also suggested that digestate increases soil's biological activity, contributing to rebuilding soil quality.[54]

Numerous examples demonstrate how anaerobic digestion is used to treat organic waste and generate electricity:

The United Kingdom has over 200 anaerobic digestion plants, 83 of which use municipal or commercial feedstocks. Planning permission has been granted or sought for an additional 400 plants, indicating the strength of the pipeline that can be delivered with the right support. As of 2016, the United Kingdom has the anaerobic digestion capacity of 617 megawatts of electricity equivalent, enough to power 800,000 homes, and to produce 9 TWh of biogas, which is only 25% of the 35 TWh that could be generated if all suitable feedstocks were used with existing technology. Looking ahead to 2025-2030, the Anaerobic Digestion and Bioresources Association estimates that the generation capacity in the United Kingdom, with new feedstocks and process improvements, could have the potential to generate about 78 TWh.[55] Anaerobic digesters will treat approximately 2.1 million tonnes of food waste and 21 million tonnes of sewage sludge in the country in the 12 months from July 2016.[56]

In Montpelier, France, Suez's Ametyst plant is the largest anaerobic digestion facility in the country, able to treat 173,000 tonnes of municipal solid waste per year, 56,000 tonnes of which is anaerobically digested. The plant generates 19 gigawatt hours (GWh) of electricity and 7 GWh of heat, which is used for 1,500 households in the local neighbourhood of Griselles, as well as the clinical centre of Saint-Roch. In addition, 25,800 tonnes of compost is produced, and applied to public green spaces and local agricultural fields.

At the heart of an agricultural region in northern France, Veolia constructed the Artois anaerobic digestion site in 2012. This unit can reuse organic waste from agriculture (agricultural biomass, chicory roots), the food industry (biological muds, flotation fats, manufacturing off-cuts, meat waste, catering fats, among others), local authorities (grass, canteen waste) and supermarkets (unsellable packaged products). The site is equipped with a complete loop of solutions, from deconditioning to re-use. Packaging, such as cardboard and plastic, is separated from organic material before being sorted and directed to the appropriate recycling units. The annual treatment of 25,000 tonnes of organic waste generates 3.5 million cubic metres of biogas each year and 8 GWh of electricity,

47 ISWA, Circular Economy: *Energy and Fuels* (2015)
48 IEA, *About bioenergy*, (2016)
49 Ibid.
50 IEA, *Energy, Climate Change & Environment: 2016 Insights*
51 IEA, Key CO2 Emissions Trends (2016)
52 IEA, Renewable Energy: Medium-Term Market Report (2016)
53 SNV Netherlands Development Organisation
54 ISWA, Circular Economy: Carbon, Nutrients and Soil
55 Anaerobic Digestion and Bioresources Association
56 Ibid.

A US study found that wastewater treatment plants could meet 10% of the nation's electricity demand

or the amount consumed by 2,700 households. This energy is sold on and injected into the power grid, thus avoiding 2,000 equivalent tonnes of CO_2 emissions each year.

Sainsbury's superstore in Cannock, United Kingdom, is run entirely on power produced from food waste generated by the store. At the end of each day, any unsold food from all Sainsbury's stores across the United Kingdom that is suitable for consumption is given to charities. Some is also turned into animal feed, but any surplus after that is sent to the nearest Biffa anaerobic digestion facility. In the case of the Cannock store, the nearest facility is a mere 1.5 km away. Taking advantage of this proximity, a cable was installed linking the store directly to the anaerobic digestion plant, providing a direct supply of renewable energy produced from the store's own waste and ending its reliance on the grid for day-to-day power supplies. Although the project involved an investment of about £280,000, the retailer estimates annual savings of roughly £140,000 thanks to reduced energy costs.

ENERGY RECOVERY FROM WASTEWATER

Treatment of wastewater follows the same basic steps: removal of solid waste, biological digestion, disinfection and discharge. The process requires significant energy, estimated to be 21 billion kilowatts (kWh) per year in the United States (at a cost of more than USD 1.3 billion) and equivalent to 0.5% of overall demand.[57] About 70% of this is used in the bioreactor stage to produce air and oxygen.

New York City produces 1.4 billion gallons of wastewater each day, which must be treated before being discharged back into local bodies of water. The energy required for treatment is estimated at 500 – 2,500 kWh per million gallons, which equals a daily energy bill of between USD 50,000 – 250,000.[58] Such high power demand requires a reliable power supply, which helps explain why this approach to wastewater treatment has not always achieved success in emerging markets, (see 'Indian cities' box). However, an analysis of the chemical and heat energy in wastewater reveals that it contains up to 14 times more embedded energy than that required for treating it. Approximately 80% of this energy is low-grade heat that is difficult to recover. Yet, if the remaining 20% were converted to biogas and then to electricity at a conversion efficiency of 40%, it would still be theoretically possible to achieve a power-positive treatment plant.[59] One US study found that wastewater treatment plants, taken collectively, could meet 10% of the nation's demand for electricity.[60]

57 Central Intelligence Agency
58 Electricity Local (at USD 0.06 per kWh)
59 Parry, D.
60 Scott, L.

At an individual plant level, the technological front runner in turning theory into practice is in Odense, Denmark. Covering a population of 350,000, the Ejby Mølle treatment plant has achieved 110% self-sufficiency in electricity, meaning the plant produces more electricity than it consumes.[61] Opportunities to optimise this performance have been identified that could lead to even better results.

At the utility scale, Thames Water in the UK saved about £15 million on its 2013 power bills by generating 14% of its energy demand from sewage sludge.[62] For the future, the utility is investing in new thermal hydrolysis equipment that conditions the sludge in a pressure cooker at 160° Celsius, breaking bonds and allowing more biogas to be extracted per tonne of sludge. By using anaerobic digestion along with solar and wind, Thames Water aims to satisfy 20% of its power demand with renewable sources. As well as reducing energy bills, the more efficient conversion means less biosolids at the end of the treatment process. Moreover, it reduces the transport costs required to return the fertiliser-rich organic material back to farmland by GBP 2 million.

This selection of examples in treating wastewater demonstrates current approaches to using organic matter for generating energy. At a macro level, the European Commission has estimated that around 2% of the EU's overall renewable energy target could be met if all organic waste was turned into energy.[63]

LANDFILL GAS TO ENERGY

Capturing landfill gas in sanitary landfills is a transitional solution for energy generation that could be applied when anaerobic digestion is not a viable alternative. Such cases could include cities that have already committed to creating landfills or simply do not have the capital to invest in more complex organic waste processing facilities.

A 2013 report from the Methane Finance Study Group indicated that reductions of 1.6 billion tonnes of CO_2e at landfills would be possible between 2013 and 2020 if a USD 10 or lower incentive were added per tonne of CO_2e.[64]

CASE STUDY: TRANSFORMING LANDFILL GAS TO ENERGY

In the commune of Plessis-Gassot near Paris, Veolia operates the Electr'od site, a successful example of transforming landfill gas to energy that produces the most renewable energy from biogas in France. The plant, designed by Veolia in partnership with Dalkia and Clark Energy, generates 130 GWh of electricity per year, equal to the consumption of 41,200 households (excluding heating) and corresponding to the electricity produced by 40 wind turbines annually. The electricity is sold to the French grid operator and used by households and businesses across the country.

In addition, Electr'od operates as a cogeneration plant, simultaneously producing 30 GWh of thermal energy a year, or the energy consumed by 2,850 households. This thermal energy supplies a new district heating and domestic hot water network, marking the first time a French town has been heated using recovered biogas. The cost of heating that is supplied by Electr'od for those Plessis-Gassot residents connected to the network will be 92% lower than the cost of heating with electricity, and 91% lower than to heating with oil.

BARRIERS TO BIOENERGY GENERATION

- Novel bio-based products cannot be integrated easily into existing supply chains. For example, bioethanol can only be mixed into conventional fuel up to a volume share of about 15%. Bio-based polymers are difficult to integrate into existing polymer value chains, as they may have different properties
- Fossil fuel subsidies reduce the cost competitiveness of bio-energy sources
- The economics of biogas plants are challenged by electricity grids only buying their power at times of peak demand rather than consistently, and by the costs of sorting contaminated organic waste streams

A comprehensive approach: Biorefineries

Biorefineries could become an integral component of urban waste management infrastructure, receiving the organic fraction of MSW as well as wastewater streams, and converting them into valuable materials and products. A diverse set of solutions at multiple scales within the urban environment could be developed to fit local contexts. They could be tailored to suit local needs and the local collection infrastructure, and the content of the incoming organic feedstock would determine which outputs to produce.

Fossil feedstocks are used in oil and petrochemical refineries to produce fuels, chemical feedstocks, plastics and synthetic materials. Significant opportunity exists, however, to use organic waste materials instead to manufacture a range of these products.

61 State of Green
62 Thames Water
63 European Commission (2010)
64 Methane Finance *Study Group Report* (2013)

This is particularly of interest as fossil feedstocks decrease and their prices remain volatile.

AN INTEGRATED SOLUTION

Small- and large-scale biorefineries, located in urban areas close to the source of input material, have both the opportunity and the technologies to make this vision a reality (see the Biopolus and Ecala case studies). Research conducted in the Netherlands estimated that the potential net value created from implementing a network of biorefinery hubs in Amsterdam could total EUR 30 million per year. Furthermore, such a system is estimated to reduce CO_2 emissions by 100,000 tonnes and yield material savings of 25,000 tonnes.[65]

Co-locating these biorefineries with existing facilities, such as wastewater treatment plants, could result in significant benefits from the synergies and cost savings of collection, pre-processing and refining. Research has suggested that such co-locating could result in new capital savings of 20-80%, depending on the level of synergy.[66]

Numerous studies have tried to quantify the potential value of using biorefining processes, usually focusing on specific geographies or product categories. For instance, the World Economic Forum estimates that, by 2050, potential global revenues from the biomass value chain (the combination of produced agricultural inputs, biomass trading and biorefinery outputs) could be as high as USD 295 billion.[67] The United States is capable of producing 90 billion gallons of biofuels to replace oil, meaning that, with improvements in vehicle mileage, the country's vehicle fleet could run solely on biofuel by 2050. The limiting factor is not the supply of biomass, but rather the commitment to oil-focused infrastructure, low oil prices and lack of political commitment.[68]

The market for lignin-derived chemicals (benzene, toluene, carbon fibre), which are in products such as motor fuel, activated carbon and plastics, is estimated to be over USD 130 billion and projected to reach USD 208 billion by 2020.[69]

Biorefineries can employ a range of techniques, such as thermal treatment, biological processes and enzymatic conversions, to transform organic material into valuable chemicals and products. These products are broadly classified into three categories.

Biorefineries have many available options for feedstock. A useful categorisation distinguishes between first- and second-generation feedstocks. First-generation refers to feedstocks drawn from edible biomass, such as corn and sugar cane, while second-generation feedstocks are derived from residual non-food parts of crops, organic waste streams or other non-food sources, such as algae. Second-generation feedstocks have garnered significant interest (see DSM case study) as they not only extract the maximum value from available biomass and turn waste into resources, but also reduce competition for agricultural land.

Biorefineries will start to produce increasingly complex chemicals and materials as the technology matures. Succinic acid and polylactic acid are already examples of this, as plant 'waste' is increasingly seen as offering competitive alternatives to fossil resources. As a consequence, these facilities will become true biorefineries, producing a whole range of valuable products beyond advanced biofuels from feedstocks that were previously viewed, and treated, as waste.

CASE STUDY: DSM – THE CELLULOSIC ETHANOL REVOLUTION

Cellulose is the world's most abundant organic compound and provides the cellular structure for trees, grass and, in fact, all plant life. Producing cellulosic ethanol from biomass has enormous potential as it includes agricultural residues, like corn cobs, leaves, stalks, straw, grasses and waste wood, and even municipal waste.

Project Liberty, the first initiative of POET-DSM Advanced Biofuels, is a 50:50 joint venture between POET, a US-based ethanol producer, and Royal DSM, a

65 Circle Economy, TNO and FABRIC
66 ISWA, op. cit.
67 World Economic Forum
68 Ibid.
69 Smolarski, N.

global science-based company. The project offers substantive proof of the technological and commercial viability of advanced biofuel production using second-generation feedstocks. The Project Liberty plant began shipping cellulosic ethanol at the end of 2015. At full capacity, it will convert 770 tonnes of biomass per day to produce ethanol at a rate of 20 million gallons annually, and later ramp up yearly production to 25 million gallons.

To make cellulosic bioethanol, agricultural residue from corn needs to be pre-treated with acid or heat. Enzymes are added to extract all sugars, proteins and lignin from the plant material. Finally, yeasts 'eat' these sugars and turn them into bioethanol. While the theory is straightforward, the process is exceptionally difficult in practice. The sugar molecules contained in lignocellulose are well protected by tightly packed cellulose chains (part of a plant's natural defence system). Sophisticated biotechnology is required to break down these chains and get to the sugars.

DSM made a major scientific breakthrough in 2008 by identifying enzymes in its strain collection with the desired performance characteristics. Real progress was also made in developing an enzyme system particularly effective at breaking down lignocellulose into component sugars.

CASE STUDY: BIOPOLUS

Metabolic hubs redesigning urban metabolism could support cities in investing directly in effective organic treatment solutions that close water, food and nutrient loops, and generate energy, all while bringing about social benefits. Biopolus is looking to create an interconnected network of water recycling associated with energy production and organic products growing in its metabolic hubs.

These aesthetic hubs are suited to all types of settlements, ranging from industrial parks to luxury residential communities and slums. Thanks to high modularity in size, layout and function, they can fit into any environment, as part of a new construction or as a retrofit. Modules provide functions suited to the local community's context, such as generating energy, treating water, recovering nutrients, and even providing bathroom blocks and laundry facilities. The Aero. Green aeroponics module, for instance, adopts a special lightweight and mobile method of urban farming, allowing the hub to produce healthy, nutritious food for a large population and where water is scarce and space is limited.

Each individual hub can be set up to serve any city from 5,000 to 50,000 people. Using metabolic network reactor technology, a microecosystem with more than 2,000 species, including bacteria protozoa, invertebrates and plants, turns the hubs into a living factory. The modular hubs require up to 60% less land and save up to 35% in operational costs compared to traditional solutions.

CASE STUDY: THE ECALA GROUP

Integrated Utility Hub Ecala, a restorative infrastructure design, development and advisory firm, employs a whole-systems approach to guide public, private and social sectors to circular and net positive outcomes. Its Integrated Utility Hubs (IUH) incorporate industry leading technologies for resource recovery, water purification, energy generation and food production within a single, closed-loop facility. The IUH creates no adverse smells, noise or pollution, and can be placed in locations ranging from dense, high-income urban areas to remote villages, delivering services directly to local communities. Additionally, modular and scalable hubs can be designed to fit within International Standard Organisation shipping containers, allowing them to be deployed rapidly to assist with disaster relief in remote regions or communities. The core functions and production capabilities of a city-scaled IUH are:

- Waste: Processes 600 tonnes of unsorted MSW per day, with an 80-95% recovery rate

- Water: Purifies 5 million gallons of wastewater per day to potable levels, without using chemicals
- Energy: Generates emissions-free baseload electricity for 20,000 households, or pure hydrogen for 14,000 vehicles, from a combined heat, hydrogen and power system
- Food: Produces 1 million pounds of fresh fish and 4 million heads of lettuce per year, using 98% less space and 95% less water than conventional farming
- Public asset: Incorporates public amenities, including food markets, cafes, offices, laboratories and exhibition spaces

CASE STUDY: BILLUND BIOREFINERY

The Billund Biorefinery, an award-winning project in Denmark that combines environmental technologies in water treatment and biogas in one full-scale demonstration project. Using Exelys, Veolia's proprietary thermal hydrolysis and anaerobic digestion technology, the plant simultaneously treats the wastewater from Billund's 70,000 residents, as well as 4,200 metric tonnes of organic waste from agriculture, industry and local households.

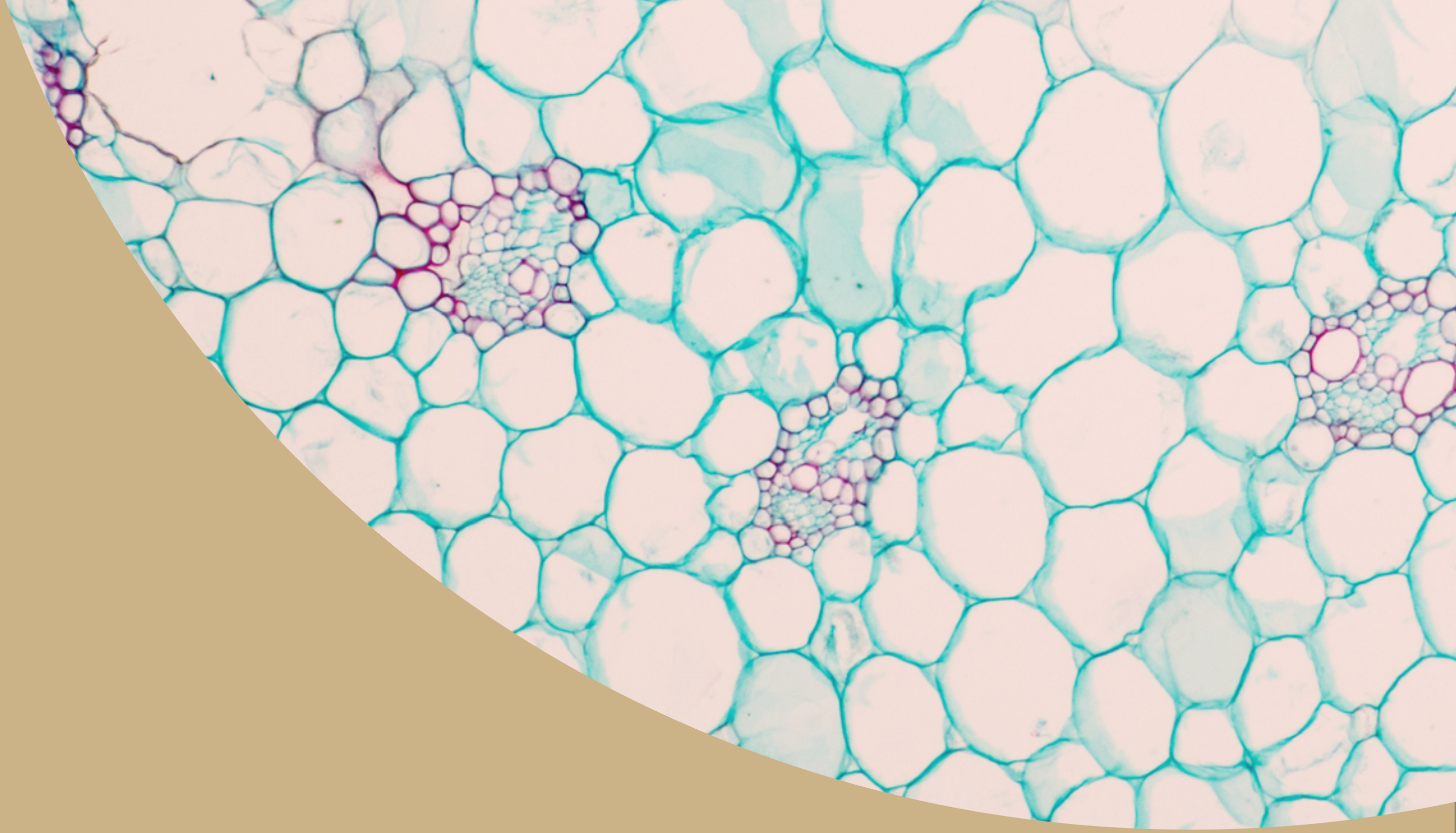
The biogas generated is transformed into electricity and heat, and the nutrients are utilised in a very effective and odour-free organic fertiliser. The plant produces more than enough energy from biogas to run its own treatment process. Furthermore, the process opens up possibilities of using interesting by-products, such as phosphorus (for fertiliser) and bioplastics.

Benefits:

- Producing biogas from the biowaste and treatment sludge that provides heat and electricity for the site
- Producing organic fertiliser for agriculture, and bioplastics for industry
- Discharging treated water into the neighbouring stream
- Creating a city-country-industry loop
- Reducing the environmental footprint

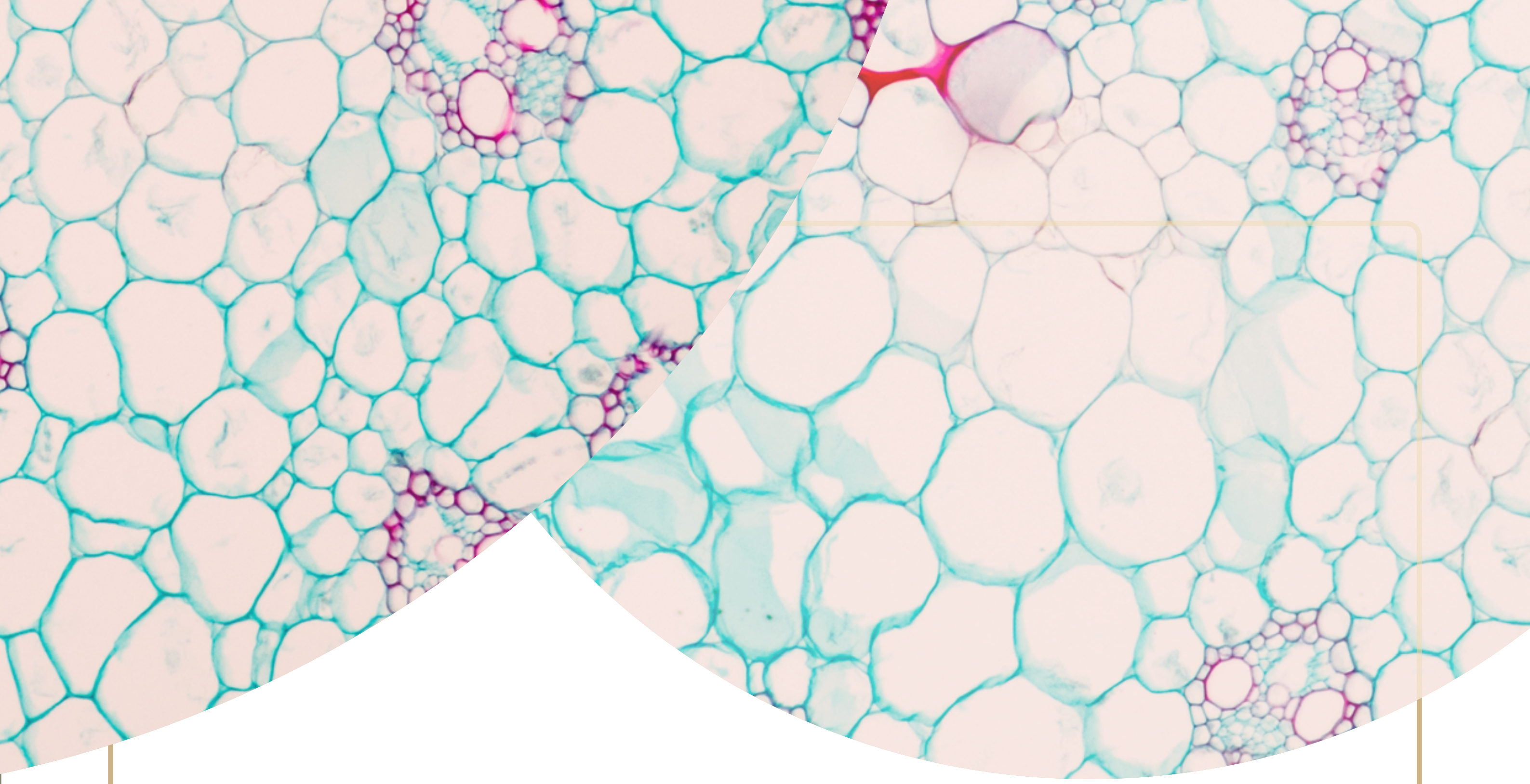
BARRIERS TO DEVELOPING BIOREFINERIES

- Across OECD countries, waste streams are regulated to ensure they do not harm the environment or human health. While serving their intended purpose, these regulations can prevent by-products being used as resources. They take the form of:
    - Stringent controls and administrative costs on owners, transporters and processors of organic waste
    - Restrictions on moving and using waste streams that impede their integration into established non-waste processes
- Fossil fuel subsidies reduce the cost competitiveness of bio-based products
- Venture capital interest in biorefineries has been declining as funders come to understand the large capital requirements, and uncertainty on long-term profitability in the face of short-term government incentives
- In contrast to oil refineries, it is difficult to guarantee a supply to a biorefinery of feedstock of consistent quantity and quality, since the type and quantity of organic waste changes over a year



CONCLUSION

Vast potential exists in shifting towards a circular economy in the biocycle, ranging from scaling up regenerative farming practices to producing algae for making biobased materials. This paper has focused specifically on opportunities for valorising post-use urban nutrients and biomass by applying currently available technologies.



- By 2025, cities are expected to produce 2.2 billion tonnes of solid waste globally per year, almost double the 2012 levels. About 1 billion tonnes of this will be organic waste, based on current non-organic/organic ratios
- The decomposition of post-consumer waste creates 5% of total global greenhouse emissions. A major contributor to this is organic waste decomposing in landfills, which generates 12% of global methane emissions. (Methane gas has a greenhouse effect 28 times greater than that of CO_2)
- Growing populations and increasing urbanisation could lead to a significant rise in organic waste generation (and its associated negative impacts). This is particularly acute in emerging economies, which are expected to generate 70% of global waste by 2025. In these markets, organics, the primary generators of methane, are estimated to make up 60% of the waste, and 80% of collected waste is currently disposed of in open dumps or sub-standard landfill sites
- Significant opportunities exist to valorise post-use urban organic waste, including the development of high-value products and materials in biorefineries, the creation of energy from biological sources and the capture of nutrients to be returned to soils. The capabilities already available to perform these tasks now need to be scaled up to fully realise the potential
- While some cities have shown it is possible to collect up to 85% of organic waste, average collection rates are low around the globe. This highlights the big opportunity to increase collection rates and valorise recovered material
- The decision of whether to collect organics separately has important implications: for integrating them in residual waste collection systems, for the quality of the collected waste and, therefore, for the opportunities to recover value from organic material through additional processes, such as biorefining. Data collected during the development of the European end-of-waste proposals for compost and digestate indicated that only separately collected organic wastes could be used as feedstocks to manufacture quality products; contamination levels and poor quality of mixed-waste-derived outputs were too high for use as an unrestricted product.[70] However, technological innovations have increased the quality of mixed-waste derived outputs, which remain options when source-separate collection cannot be implemented

Cities around the globe are beginning to recognise the value embedded in organic material flows, and many have put systems in place to capture that value. Implementation, however, is sporadic; approaches vary significantly, and levels of success are wide-ranging. A systemic shift in how to deal with urban organic waste is required to realise the full value.

70 European Commission, (2014)

ABOUT THE ELLEN MACARTHUR FOUNDATION

The Ellen MacArthur Foundation was established in 2010 with the aim of accelerating the transition to the circular economy. Since its creation the charity has emerged as a global thought leader, establishing the circular economy on the agenda of decision makers across business, government and academia. With the support of its Core Philanthropic Funder, SUN, and Knowledge Partners (Arup, IDEO, McKinsey & Company, and SYSTEMIQ), the Foundation's work focuses on five interlinking areas:

EDUCATION

Inspiring learners to re-think the future through the circular economy framework

The Foundation has created global teaching, learning and training platforms built around the circular economy framework, encompassing both formal and informal education. With an emphasis on online learning, the Foundation provides cutting edge insights and content to support circular economy education, and the systems thinking required to accelerate a transition.

Our formal education work includes Higher Education programmes with partners in Europe, the US, India, China and South America, international curriculum development with schools and colleges, and corporate capacity building. Our informal education work includes the global, online Disruptive Innovation Festival.

BUSINESS AND GOVERNMENT

Catalysing circular innovation and creating the conditions for it to flourish

Since its launch, the Foundation has emphasised the real-world relevance of the circular economy framework, recognising that business innovation sits at the heart of economic transitions. The Foundation works with its Global Partners (Cisco, Danone, Google, H&M, Intesa Sanpaolo, NIKE Inc., Philips, Renault, and Unilever) to develop scalable circular business initiatives and to address challenges to implementing them.

The Circular Economy 100 programme brings together industry leading corporations, emerging innovators, affiliate networks, government authorities, regions and cities, to build circular capacity, address common barriers to progress, understand the necessary enabling conditions, and pilot circular practices, in a collaborative, pre-competitive environment.

COMMUNICATIONS

Engaging a global audience around the circular economy

The Foundation communicates cutting-edge ideas and insight through its circular economy research reports, case studies and book series, using multiple channels, web and social media platforms. It uses relevant digital media to reach audiences who can accelerate the transition, globally. The Foundation aggregates, curates, and makes knowledge accessible through Circulate, an online information source dedicated to providing the latest news and unique insight on the circular economy and related subjects.

INSIGHT AND ANALYSIS

Providing robust evidence about the benefits of the transition

The Foundation works to quantify the economic opportunity of a more circular model and to develop approaches for capturing its value. Our insight and analysis feeds into a growing body of economic reports highlighting the rationale for an accelerated transition towards the circular economy, and exploring the potential benefits across stakeholders and sectors.

The circular economy is an evolving framework, and the Foundation continues to widen its understanding by working with international experts, key thinkers and leading academics.

SYSTEMIC INITIATIVES

Transforming key material flows to scale the circular economy globally

Taking a global, cross-sectoral approach to material flows, the Foundation is bringing together organisations from across value chains to tackle systemic stalemates that cannot be overcome in isolation. Plastics was identified through initial work by the Foundation with the World Economic Forum and McKinsey & Company as one of the value chains most representative of the current linear model and is, therefore, the focus of the Foundation's first Systemic Initiative. Applying the principles of the circular economy, the New Plastics Economy initiative, launched in May 2016, brings together key stakeholders to rethink and redesign the future of plastics, starting with packaging.

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