A Review of Current Knowledge

Circular Economy in the Water Sector

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This review is one of a series of Reviews of Current Knowledge (ROCKs) produced by FWR. They focus on topics related to water supply, wastewater disposal and water environments, which may be the subject of debate and inquiry. The objective of each review is to produce concise, independent scientific and technical information on the subject to facilitate a wider understanding of the issues involved and to promote informed opinion about them.

CIRCULAR ECONOMY
IN THE WATER SECTOR

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CONTENTS

FIGURES

TABLES

GLOSSARY

BSI	British Standards Institute
CIWEM	Chartered Institution of Water and Environmental Management
DWF	Dry weather flow
EASAC	European Academies Science Advisory Council
FOG	Fats, oils and grease
GHG	Greenhouse gases
Ofwat	Water Services Regulation
OPEX	Operational expenditure
PE	Population equivalent
PFD	Process flow diagram
PV	Photovoltaics (e.g., Solar PV panels)
STC	Sludge treatment centre
TOTEX	Total expenditure
VFA	Volatile fatty acids
WaSC	Water and Sewerage Companies
WRAP	Waste and Resources Action Programme
WTW	Water treatment works
WwTW	Wastewater treatment works

Review of Current Knowledge

1. Introduction

This Review of Current Knowledge describes the circular economy and how it relates to the water industry. It has been structured to explain:

- *why* the circular economy is needed for business optimisation for UK water utilities
- *what* the theoretical and actual basis is for its adoption
- *how* it is driven by physical, real world factors
- *what* considerations and approach constitutes good practice for a water utility deploying circular economy measures in its operations.

The circular economy is an economic strategy based on minimising the production of waste and recycling material resources utilised in economic activity.

This introductory section describes what an economy is and what it does in relation to the environment in physical terms. It defines the linear economy and its inefficiencies. It briefly explains current economic models and their deficiencies so that water utility policymakers can be aware of the current range of economic opinions they may encounter and have a context for understanding the range of economic theory available while making policy decisions.

The origins of the circular economy can be traced back to Kenneth Boulding's investigations into the attributes of an 'open economy' in the late 1960s. In classical economics an open economy is presumed to possess unlimited resources for its production and unlimited sinks for its wastes, in comparison to a 'closed economy', a 'Spaceship Earth' economy as described by Boulding, which is subject to real physical limits. While Boulding did not create the term 'circular economy' his 'Spaceship Earth' economy (Boulding, 1966) defined the need for a real economy to recycle materials due to the level of resource demand and waste production that could occur in a physically isolated system.

The concept of the need for increased resource and waste efficiency over the long term for an intensively productive economy was formalised in 1989 by the work of Pearce and Turner (1989) with their description of how the environment (the natural world) was the source of the material resources used in economic production whilst simultaneously being the receptor for all wastes produced by economic activity.

This led to the concept of the circular economy which is now most familiar in the definition offered by the Ellen MacArthur Foundation (https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy): the circular economy is 'an industrial economy that is restorative or regenerative by intention and design.' In comparison, the global economy as it now functions, operates as a predominantly linear process of resource extraction, processing and use associated with a high level of energy input that culminates in a high intensity of waste production entering the environment (Ellen MacArthur Foundation, 2013a, 2013b, 2014).

The deficiencies of circular economy theory arise from the same flaw that lies at the heart of classical macroeconomic theory – they both lack reference to the macroscopic physical basis of all systems provided by thermodynamics.

This omission of thermodynamics leaves the concept of a circular economy open to critique, based on its lack of a formal physical basis. For example, there are absolute limits to material recycling set by thermodynamics. The lack of a thermodynamic description for most of the circular economy propositions described above also fails to recognise the critical role energy plays in any economy, from subsistence level to post-industrial and beyond. The European Academies Science Advisory Council reviewed circular economy concepts and commented on the physical constraints for current propositions for circular economy material recycling in this regard in 2015 (EASAC, 2015). Water utility policymakers and business strategists need to be aware that the criticisms that are given of circular economy measures do not invalidate the need for circular economy measures.

Thermodynamic analyses are now available for macroeconomic growth theory and where used they have supported the resource efficiency goals set by circular economy theory.

1.1. A brief review of the academic context for a circular economy

Water utility policymakers and water utility business strategists should ideally be aware of where risks arise for business planning from use of different economic models. The current criticisms that are offered for circular economy measures do not invalidate the need for circular economy in water industry services and this section of the report will briefly describe why.

Contemporary economic theory consists of several schools, ranging from neoclassical economics, which is based on classical economics but reinterprets classical economic theory based on neoliberal economic theory, to other schools that place economics within the context of physical environment and hence make allowance for impact on the environment. Neoclassical economics in effect regards the environment as irrelevant to the sustainability of economics due to how some of its key doctrines function (such as utility, substitution, externalities and discounting). In comparison, there are two sub-disciplines of contemporary economics which take the environment into account and relate its resources to the economy. These are:

- environmental economics and
- ecological economics.

These two schools of thought differ in their methods and consequently, in their conclusions. Environmental economics overlays classical economic theory, which has no physical science basis with consideration of environmental impacts. In contrast, ecological economics locates economics within a physical world model which leads its adherents to conclude that there are flaws in the doctrine of substitution. The ecological economists' world-view requires conservation of natural capital for economic use and assumes the *economic* need and linkage to resource sustainability is strong rather than weak.

Ecological economists provide solutions to the flaws in discounting and externalities of neoclassical economics. An externality is a cost (negative eternality) or benefit (positive externality) rising from a service or goods production that affects a third party who did not chose to be affected by that activity. The corrections to these assumptions provided by ecological economists are now also familiar to water industry asset planners as ecosystem service values and natural capital values. Ecological economics is the only economic sub-discipline which incorporates thermodynamics in its economic models.

The circular economy as an economic model sits between environmental economics and ecological economics but its considerations and goals identify most closely with those of the ecological economists (e.g., Boulding, 1966; Kneese et al., 1970; Daly, 1994, 1997; Ayres, 2007). The circular economy has not yet been formalised in terms of thermodynamic analyses which leaves it open to criticisms arising from lack of such analyses. For example, it is not physically possible to achieve 100% recycling due to thermodynamic constraints (EASAC, 2015). 'Zero waste' is more about attractive terminology than physics. In comparison, ecological economics has recently used thermodynamic analyses to form its economic models, especially in the work of Robert Ayres (*e.g.* Ayres, 1998; Ayres et al., 2002; Ayres, 2004; Ayres and Warr, 2009).

Some ecological economists also critique the circular economy due to their perception that it legitimises the errors of neoclassical economics through lack of a fully integrated physical (thermodynamic) and economic model for itself, which can lead it to overestimating its environmental benefits (e.g., Zink et al., 2017). Another point of criticism is that the reliance of circular economy interventions on Cost-Benefit Analyses (CBA) to demonstrate their worth itself embodies uncertainty: a major flaw in the doctrine of externalities is that capital investment projects in services and production do not cover all downstream and upstream costs and a better environmental sustainability approach could be provided by an ethical, societal approach to setting economic constraints (e.g., Hislop and Hill, 2011).

2. The global economy and the role of the water sector within it

*This section describes the interrelationships between the economy and the environment and defines the physical role of the water sector in the global economy. This section summarises the status of physical systems analysis of an economy and **presents the evidence for the need for introduction of circular economy measures** to restructure local economies and hence the global economy.*

2.1. The physical (thermodynamic) characteristics of an economy and their consequences

Thermodynamics gives us the basis for a physical, macroscopic analysis, of the economy. As an introduction to the main considerations, the key relationships for any physical system is as follows:

First law:

The quantity energy (heat) is defined as (atomic/molecular) motion of a system:

$$\Delta Q = \Delta U + \Delta W$$

where: ΔQ = heat added to system, ΔU = internal energy of the system and W = the work the system can do

The energy of a system is conserved, i.e. kept in balance and cannot be consumed. If energy is applied coherently it can do *work*. The internal energy of a system is not structured (coherent) and hence is not able to perform physical work.

Second law:

The second law describes how for an isolated system, its total entropy is constant. However, the *active* physical world consists of non-isolated, *interacting* systems and in all spontaneous processes, the entropy of a system and its environment increases over time. This allows the physical work a system can do to be defined in terms of:

$$E = T_0 \, \Delta S^{tot}$$

where: E = 'exergy'- the fraction of system energy able to perform work, sometimes described as 'ordered motion' and represents the maximum work the system can do, T = ambient temperature, ΔS^{tot} is the total system entropy- meaning the entropy of the system we are describing and its environment, such that

$$W = E - T_0 \, \Delta S^{tot}$$

where: the physical work a system can do is 'W', E = 'exergy'- the fraction of system energy able to perform work, T = ambient temperature, ΔS^{tot} is the total system entropy

It is important to note that these systems behaviour descriptions are defined *in relation to the system's environment* (through energy expressed as ambient temperature T_0).

Why does **exergy** and **entropy** matter to any business operation? The **exergy** of a physical system sets a limit to the work it can perform and, unlike energy, exergy is not conserved. Exergy is only in balance for reversible processes, but in the real world of interacting physical systems the physical processes are all *irreversible* which means that exergy is not in balance**.** The *total exergy input to an economic system, including water company operations, will always exceed its output*. Exergy is *consumed* in economic operations including water utility operations. Energy and work drive the economy (Ayres and Warr, 2009).

The **entropy** of a physical system is simply a measurement of the **dispersal** of energy and materials by that system. Consequently, systems that are undispersed, that is, those which are highly structured and complex, are very low entropy systems. Systems whose energy and materials are highly dispersed are high entropy systems. *As entropy has to remain balanced between a system and its environment*, this means that if a physical system doing work reduces energy dispersal and material dispersal by increasing structure/complexity, *it exports entropy to the environment*. For any economic activity, the business operation itself disperses energy and materials (*wastes*) into the environment, increasing entropy in the environment.

Entropy has material resource quality implications as well as environmental impact implications (waste dispersal), as measure of dispersal is also the inverse of the *resource quality* of a material resource or an energy resource.

The circular economy is a philosophy for increasing **resource use efficiency** *and hence reducing exergy consumption and managing resource entropy in the economy*.

Another aspect of the second law is that:

$$I = E / T_0$$

where: I = information content of system – its physical structural information (total structural information including structural complexity), E = 'exergy'- the fraction of system energy able to perform work (*e.g.* Gibbs energy, Helmholtz free energy, enthalpy) , T_0 = ambient temperature

Hence exergy is both a measure of the **work** *a system can perform and a measure of the* **work outcome**, because it is also a measure of the physical information in a system, in terms of how a system is *physically structured*. Poorly structured systems are low exergy; highly structured and complex systems have high exergy. Another way of understanding this relationship is to consider that it takes *more* physical work to build a more complex physical structure than to build a simple physical structure. This applies to both physical production activity and to services. It applies to an output that is a manufactured product assembled from raw materials (the output has higher physical information content than the input resources) or a service industry report based on data analysis (the output has higher information content than input data resources). Production and service provision are both ultimately physical transactions requiring work. Applying this consideration to an economy, a manufacturing production process or service operation typically produces outputs of increased complexity compared to the inputs while simultaneously dispersing waste energy (e.g. heat) and waste materials. The exergy of the outputs has typically increased over that of the input resources and exergy has also been consumed in the process because physical work had to be done to create those structural changes.

This implies that *exergy analysis* also has the potential to reveal the returns for operational efficiency and environmental sustainability from *information utilisation activities* such as data analysis, complex systems analysis, use of real time control systems and even staff training to increase operational knowledge. *For a water utility operation, information can be utilised to increase resource use efficiency (circular economy goal).*

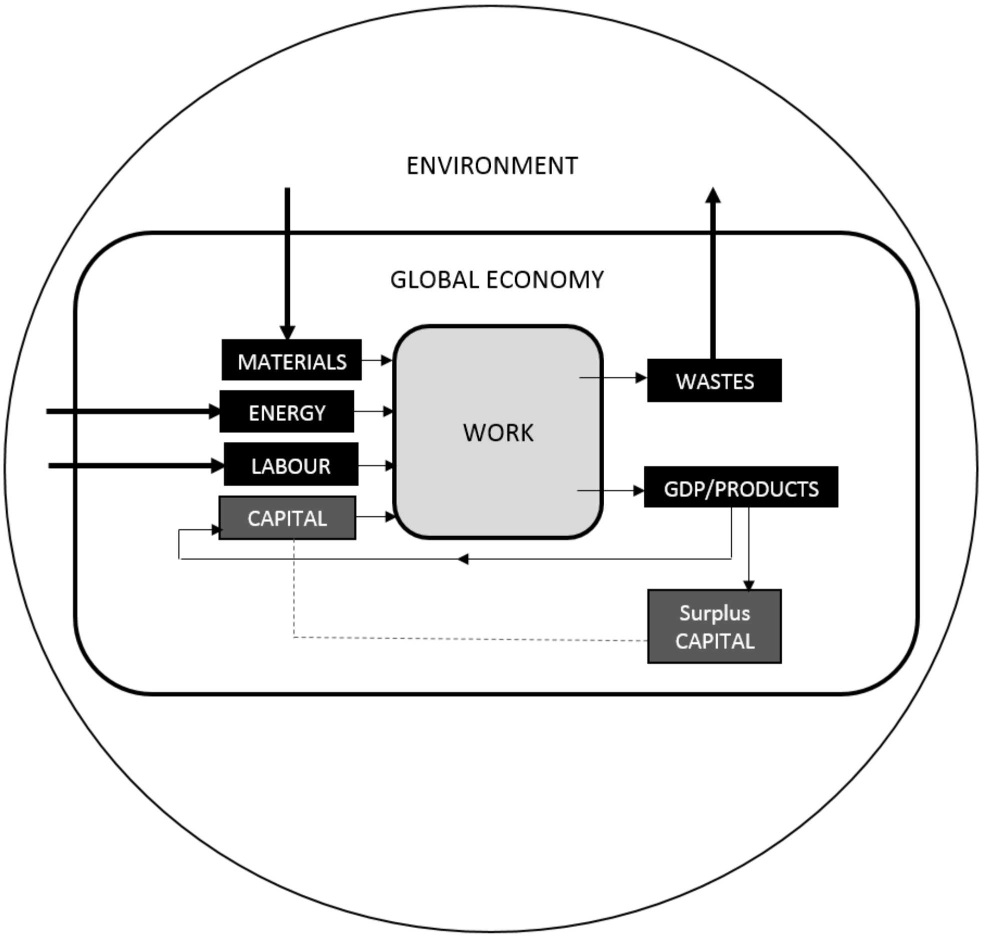


Figure 1 An economy as a thermodynamic system
Source: Reproduced from Palmer and Alford (2018)

The context for the laws of thermodynamics is that they are a description of how the universe started (its initial system condition as a high energy density pure state) and its subsequent behaviour as a system (energy and material dispersing). The dispersal of energy to a larger number of physical microstates is the driver of chemical reactions. Therefore thermodynamics is macroscopic and applies to all economic activity. A physical system has boundary conditions and state conditions that define its behaviour. An economy can be physically defined as a thermodynamic system in which work is carried out for production and service provision. Production activity itself exerts material demands for energy resources and raw materials while requiring capital and generating surplus capital (all summarized schematically in Figure 1).

A boundary drawn around economic activity sets a relationship between economic activity and the environment. The material and energy resources are obtained from the environment and wastes from economic production are discharged into the environment. Thermodynamics requires an entropy balance to be maintained between the economy and environment. The work done in economic activity defines the economy as a low entropy system. To maintain an entropy balance between systems, the economy therefore disperses high entropy energy and materials (waste energy, e.g. heat and waste materials) into the environment.

Widespread uptake of circular economy principles will be more likely if a ‘gold standard’ for business case analysis is available. From a physical science viewpoint, such an approach would be dependent on at least broadly understanding the exergy flows through a water company operation. For water utilities, **exergy analysis** could be a critical innovation in objective assessment of current linear economy water utility business practice and its comparison to circular economy interventions. Exergy analysis of any given water utility operation as described in Section 4 of this ROCK could minimize the risk and maximise the returns for circular economy interventions in water businesses.

The critical insight from thermodynamic analysis of global production and service provision is that both are processes that typically increase physical structural complexity and both have a demand for exergy, while producing wastes dispersed into the environment. *Economic activity is typically a process of low entropy generation which in turn generates high entropy in the environment (for example, Mahbub et al., 2017).* This means that economic activity is inherently a challenge to the Earth’s environment which needs to be managed to avoid or minimize its harms accumulating to levels that are disruptive for society and too destructive of natural capital.

A more accurate description of natural capital is that it constitutes the sum of the material resources the economy depends upon, now and in the future. The risk to the future economy is dealt with by sustainability considerations.

Accumulated erosion of natural capital due to failure to manage the adverse physical impacts of economic activity robs value and diversity from any future global economy. The wastes that economic activity dissipates into the global environment include the greenhouse gas (GHG) emissions driving climate change. Referring to water industry history, it was accumulated damage to environmental systems (river ecosystems) during the Industrial Revolution in the UK which led to the creation of the water industry, to secure water resources at minimum public health risk and mitigate human and industrial waste impact on the environment.

2.2. Consequences of the mechanised economy for the environment

The global economy is a multicomponent economy constructed of multiple national economies, within which internal trade in goods and services occurs and between which external trade in goods and services occurs. The economies with highest per capita productivity as currently defined by GDP (gross domestic product) are mechanised economies. The highest current per capita productivity for goods and services has been achieved by increasing the amount of work that an individual unit of labour, a person, can achieve through technology developments in mechanisation. The definition of mechanisation used in this ROCK is physical science based and broad: it includes Information Technology in services. This is necessary because information utilisation is an operational efficiency intervention that can provide increased resource use efficiency and thus can provide a basis for water utility circular economy interventions.

Increasing per capita productivity through mechanisation has a profound resource demand implication: it increases the per capita energy demand of production and has led to global production to be close-coupled (inelastic) with regard to energy use (Figure 2). In other words, high GDP productivity per capita is critically dependent on energy.

In general, the component economies of the *global economy* are managed to compete on productivity to maximise surplus capital, wealth creation and human development goals for each towards their manager’s political objectives. This has replicated the per capita resource-intense, linear and growth orientated economic model favoured by neoclassical economics globally. However, the structure of the current global economy has profound resource implications for *economic* sustainability:

(i) It increases the per capita energy demand of production and has led to global production to be close-coupled (inelastic) with regard to energy use.

(ii) Resources drawn from the environment are dissipated back into it as high entropy wastes, which means that any future reuse of them requires even more work than the extraction of the original resources. *Resource quality* is being degraded by the economy over time and in future more energy will be required to fuel the extra work needed to utilise material resources the *linear economy* has dissipated into the environment.

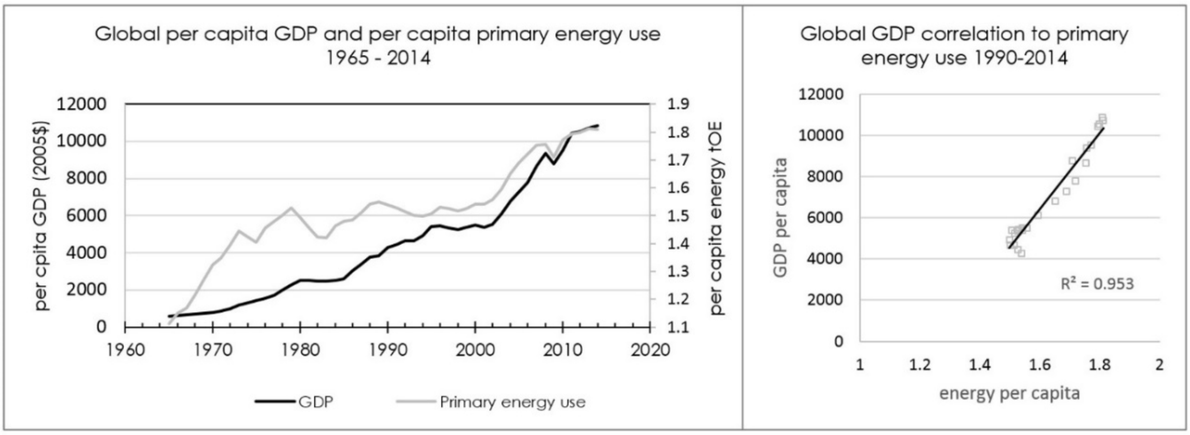


Figure 2 Global per capita production and energy use
Source: From Palmer (2018a)

The increased productivity mechanisation has delivered has resulted in convergence between energy use and production (Figure 2) and because the bulk of global energy is currently fossil-fuelled this has also resulted in close coupling (high inelasticity) between greenhouse gas emissions and productivity (Figure 3), which is the source of current anthropogenic climate change (Palmer, 2018).

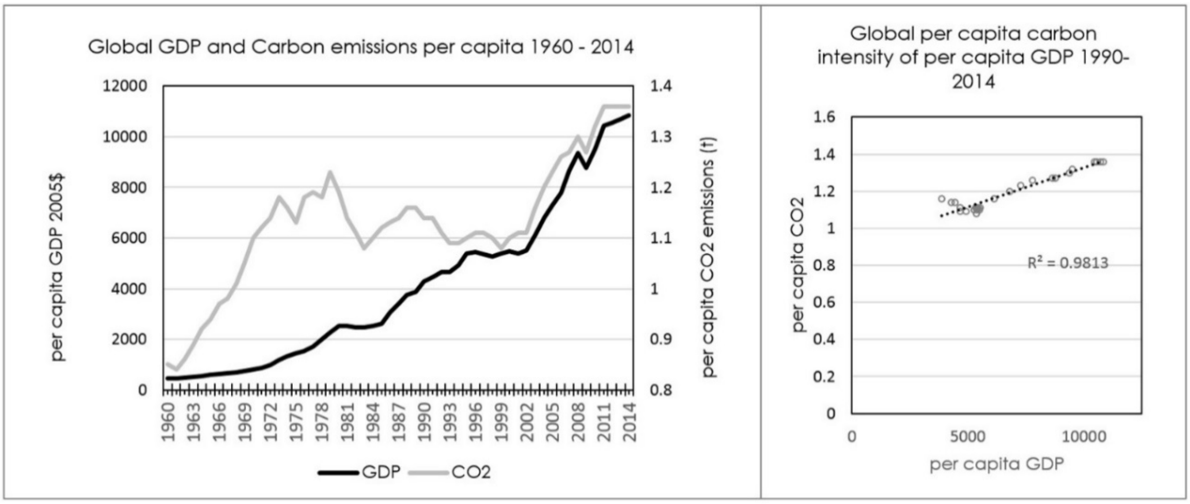


Figure 3 Global per capita carbon dioxide production and productivity
Source: From Palmer (2018a)

The global mechanised economy and its high demand for energy results in commodity costs being tightly linked to energy costs. Over time, the intense global demand for fossil fuel energy has exhausted the fossil fuel resources that were highest quality and easiest to obtain. Fossil fuel resource trends have consequently followed the thermodynamic model implied by Figure 1 with substitution of lowest cost fossil fuel resources for higher cost resources once the latter become exhausted, leading to decreased Energy Return on Investment (Figure 4).

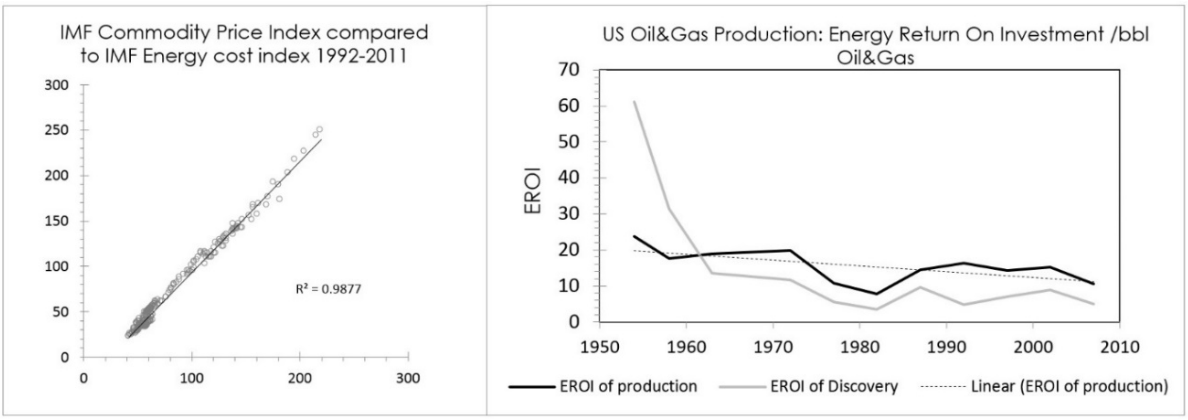


Figure 4 Global commodity price as a function of energy price and decreasing Energy Return on Investment (EROI) for global fossil fuel resources over time
Source: From Palmer (2018a)

This pattern of resource quality erosion in the long term is a consequence of the thermodynamic behaviour of the economy. It is occurring with other high demand resources such as metals (Palmer and Alford, 2018). The entropy and exergy balance that the current global economy maintains with its environment (the Earth) creates an intensity of demand that translates into an erosion of quality of high-demand material resources that has become apparent within a single human lifespan. For example, the demand for key resources is now growing super-exponentially (Rustad, 2012).

The burden placed on the global economy from the long-term erosion of resource quality, caused by dissipation of materials into the environment, is a future need for *increased work* in order to recover and recycle dissipated resources and mitigate any harms done by economic activity. That consequence leads to another: increased energy demand for the global economy going forwards. The most immediate global risk that arises from these considerations is how tightly coupled climate change and energy use currently are and the need to mitigate climate change due to its damage to natural capital.

Our planet is not an isolated physical system in energy terms due to a huge influx of solar energy. Solar energy is a critical energy flow into the Earth as it (via photosynthesis, plant growth and death) has driven the biogeochemical accumulation of carbon in the Earth as fossil fuels over millions of years. Climate change is the result of those accumulated carbon fossil resources now being intensively consumed by our economy, such that the rate of waste carbon discharge to our atmosphere is approximately four orders of magnitude higher than the rate at which those carbon resources were deposited, releasing CO_2 into the atmosphere at an unprecedented intensity.

On a material resource basis, the global economy functions in practical economic terms as an isolated system. For example, currently the lowest cost for transporting just 1kg of mass into orbit with the latest reusable technology is US$2,720. The Earth's range of biotic and abiotic (geochemical) systems recycle materials. The doctrine of externalities has created a cost-benefit approach in conventional economics that fails to value key resources and only pays attention to short-term operating costs. It is this accounting failure in conventional economics that has hidden the full costs of the linear economy. Now that those costs are mounting rapidly and becoming obvious in too many areas, resource accounting has been revised to include natural capital assessments and ecosystem service valuations. This is one of the drivers for the circular economy. With climate change as just one example of adverse impact, it is clear that humanity can no longer easily afford to subsidise the current inefficiencies of the linear economy for the benefit of high returns for businesses that do not bear the full costs of the operations (Palmer, 2018; Palmer and Alford, 2018).

Managing the thermodynamic risks inherent in how the economy functions thus requires energy use to be decoupled from climate change and consequently, for energy use to be decoupled from the use of fossil fuels. The entropy implications of how the global economy works also demonstrate how resource inefficient the linear economy is.

The principal reasons for these risks to the global economy only recently being recognised are:

(i) Economic development has fed back into advances in education and health services that only in the last century translated into a global rate of population growth that was exponential. This occurred during a period within which technology development increased the level of mechanisation and rate of production per capita and its demand for resources to an exponential level.

(ii) Neoclassical economics does not take account of the cost and value of the environment and the natural capital the global economy depends on for its resources.

2.3. Conclusions on the Water Industry need for Circular Economy measures

In simple terms, current models of the global economy fail to describe its physical behaviour. When the factors identified by ecological economics are considered and when the circular economy is subject to thermodynamic assessment, its suggested interventions are largely supported by such analyses.

The circular economy is part of the restructuring required to render the global economy both economically and environmentally sustainable in the long term.

3. The Circular Economy and the UK

This section describes the potential roles of the circular economy within the UK economy.

The potential for circular economy measures to correct some of the resource inefficiencies of the currently linear UK economy are well established from circular economy advocates such as the Ellen MacArthur Foundation. Figure 5 is the Ellen MacArthur Foundation's own system diagram for the circular economy.

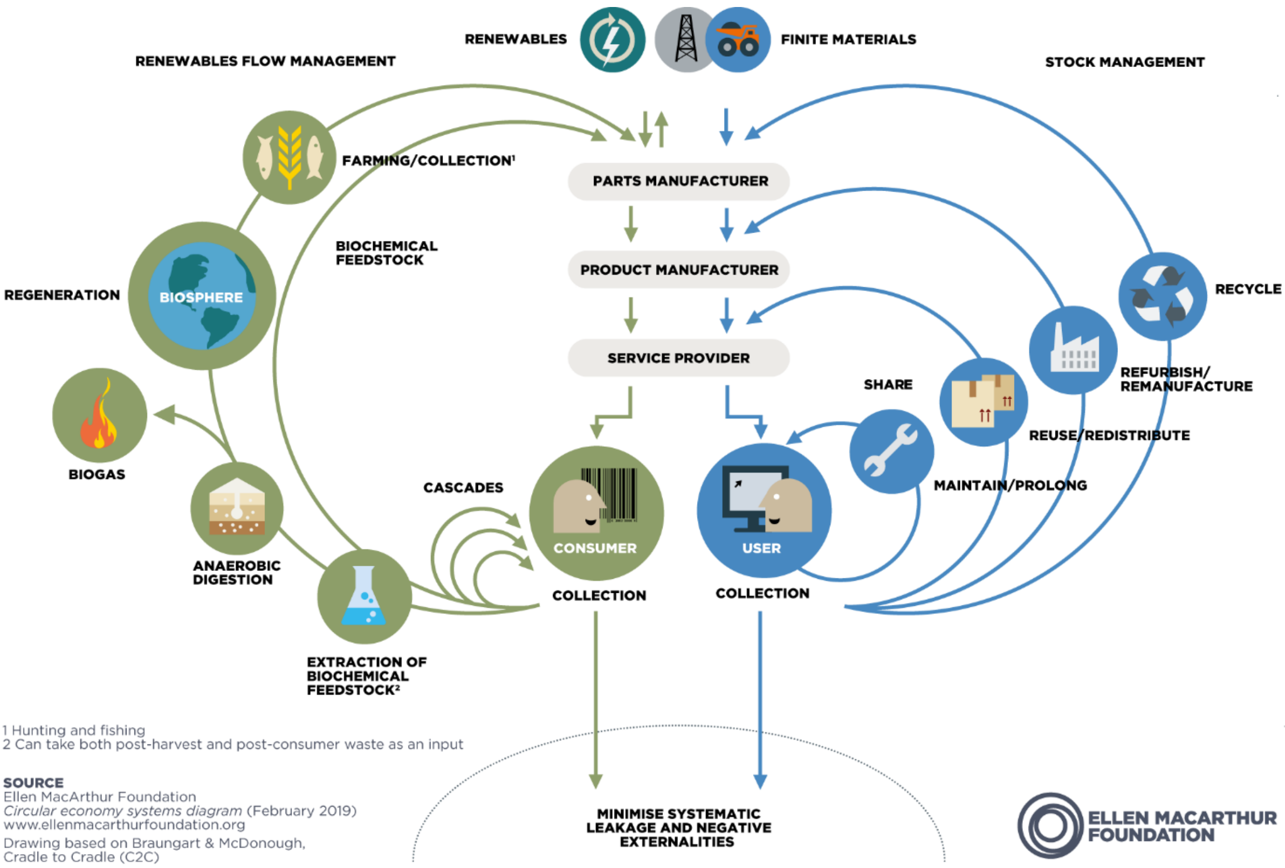


Figure 5 The Circular Economy System Diagram. Ellen MacArthur Foundation
Source: https://www.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail

The linear economy consists of a linear extract-process-use-dispose sequence for its material resources. This carries significant risks for sustainability of the global economy because the current linear economy:

- uses the environment as a sink for wastes and hence allows economic and societal damage from environmental disruption, such as anthropogenic climate change, to accumulate.
- fails to account for the environment being the source of resources used in production (does not account for long term economic sustainability).

- is managed on the basis of a neoclassical model of operation which presumes all material resources are substitutable when in fact, at the level of chemistry of elements, there is a diversity and difference between the properties of elements (and some compounds) that implies that *some are not functionally replaceable by others*; e.g., phosphorus is an essential element for life and is simply not substitutable.
- operates under the doctrine of externalities which simplifies costs by not providing full cost accounting for costs incurred downstream of production. Consequently, because the true costs of production including environmental and societal risks are not internalised, costs of production are currently underestimated. *This means that the market cannot act, as it is meant to, as a corrective mechanism on price, because current linear economy prices are inaccurate.*

Strategic resources such as phosphorus also create an argument for restructuring the UK economy towards a circular economy to best manage *resource security* (Hislop and Hill, 2011). In contrast to the current UK economy being dominated by linear economy practices, proponents of the circular economy seek a range of interventions which would minimize the entropy transfer from the economy to the environment, based on the approach described by the Ellen MacArthur Foundation (Figure 6).

Figure 6 **Ellen MacArthur Foundation: circular economy vision and approach**
Source: https://www.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy

Circular economy interventions seek to uprate the resource-inefficient linear economy into one that can provide a long term sustainable basis for the global economy by designing production to take account of externalities, maximise reuse life by increasing the time resources are kept in use in the economy and allowing natural capital the space and time to regenerate.

Allowing natural capital to regenerate also requires the circular economy to decouple the inevitable energy intensity of current productivity per capita from fossil fuel use as energy resources – to mitigate *climate change*. It is very important for water utility business managers to recognise that circular economy interventions are not confined to use of material resources but also require optimum use of renewable energy resources, not least because wastewater treatment operations in particular are a source of renewable energy generating opportunities.

3.1. Current UK circular economy regulation, perceived benefits and risks

Prior to Brexit, the UK was subject to EU regulation and policy on the circular economy. It is unclear at this time if the UK will continue to follow EU regulations on the Circular Economy although that would help minimise future trading barriers with the EU. However, the EU has undertaken significant work in assessing and beginning to plan for circular economy interventions in the EU economy and as such provides a model of good practice that the UK may choose to adopt and redevelop to its own requirements in the future. In the UK, WRAP (Waste and Resources Action Programme) has undertaken analyses of material flows in the UK economy (WRAP, 2010a) and made an assessment of the potential benefits of circular economy interventions in the UK economy (WRAP, 2010b) based on the following production and consumption interventions:

- lean production (production with a lower material requirement)
- existing asset reuse or repurposing
- increasing product retention and decreasing working product disposal as waste
- increasing the proportion of products leasing (compared to product buying)
- reducing waste in production and service provision.

WRAP analysed the effect of such production and consumption interventions on the UK economy between 2010 and 2020 and predicted such circular economy interventions could reduce the UK economy demand for materials by 30 million tonnes and reduce the UK's waste production by 50 million tonnes in 2020 (a 20% reduction in waste generated) while recycling 20 million tonnes of materials into the UK economy.

The period 2000–2010 during which the UK used a policy instrument, an increase in landfill tax due to landfill capacity limitations, achieved a significantly larger increase in material recycling into the economy (70 million tonnes) which leads WRAP to conclude that 'easy wins' in recycling within the UK economy have already been secured (Figure 7).

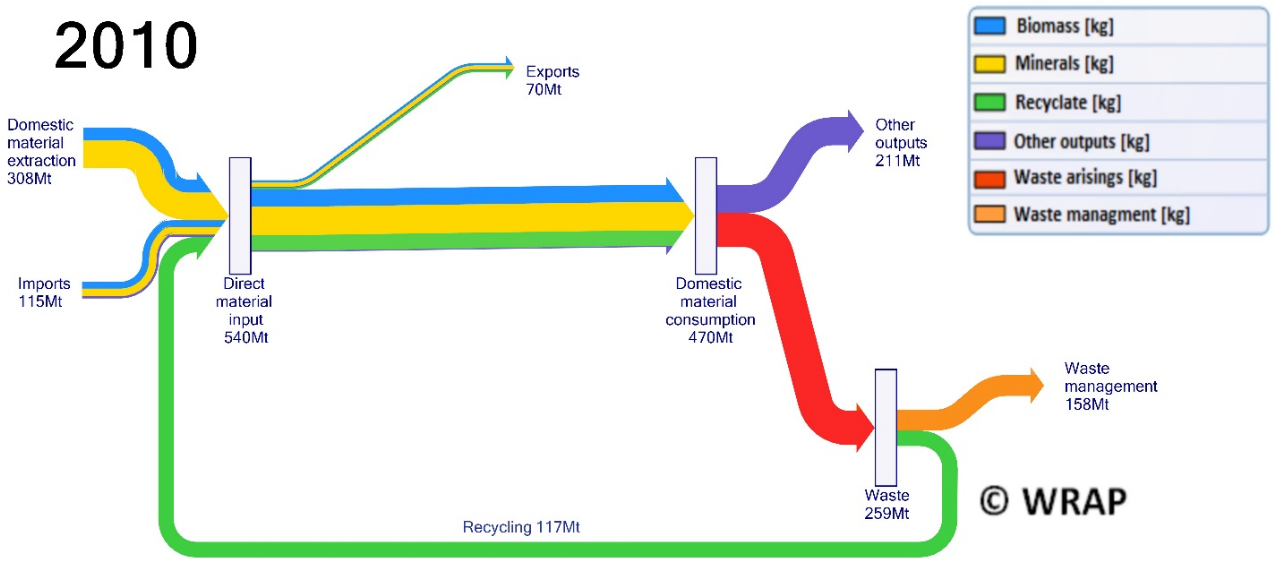


Figure 7 WRAP Sankey Diagram of material flows in the UK economy in 2010 (WRAP, 2010a)
Source: http://www.wrap.org.uk/content/wraps-vision-uk-circular-economy-2020

A key tool for use in initiating resource efficiency in use in the UK is the waste hierarchy which allows businesses to minimise their waste production (Figure 8).

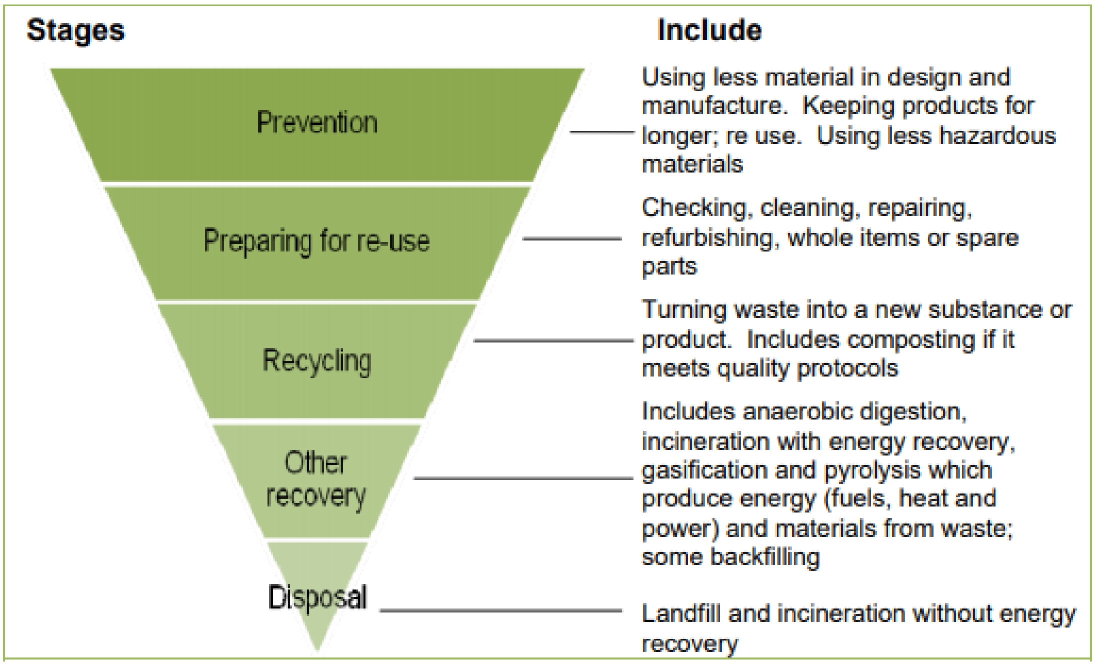


Figure 8 The Waste Hierarchy. (Defra, 2011)
Source: https://www.gov.uk/government/publications/guidance-on-applying-the-waste-hierarchy

In 2015 the EU introduced a legislative circular economy package. The circular economy package consists of an action plan and a schedule for introduction of a range of legislative proposals, including proposals for a directive on waste, a directive on packaging waste, a directive on electrical and electronic waste, and a landfill directive. This range of regulation is supported across the EU by various EU funds (€5 billion from waste management funds and national level investments and €650 million from the EU Horizon 2020 fund).

The cost benefits justifying these policy initiatives in cost terms are net savings of €600 billion or 8% of EU total business turnover. These cost benefits principally arise from **material resource efficiency improvements** which have been valued at €630 billion for industrial production within the EU, based on material resource demand being reduced by 17-24% for the EU (EU, 2015). The linkage to *climate change mitigation benefits* for these interventions has been estimated to also provide a 2–4% reduction in total EU carbon emissions. The overall impact on the EU economy is estimated to provide a boost to GDP of 3.9%. In 2018, the EU published new targets for waste recycling which updated the 2015 targets (Table 1).

Table 1 EU recycling targets for municipal waste

By 2025	By 2030	By 2035
55%	60%	65%

The 2018 regulation updates include new separate collection rules aimed at increasing the quality of secondary raw materials and their uptake. The 2018 provisions also allow for development of an EU market-wide strategy for plastics to systematically reconfigure plastic production and use.

The EU Circular Economy legislation foresees more use of effective economic instruments (incentivisation of circular economy interventions) including taxation and subsidy introduction; the EASAC (European Academies Science Advisory Council) favours taxation of linear economy inefficiencies in resource use (EASAC, 2015).

The EU has identified the following range of circular economy interventions:

- reducing the quantity of materials required to deliver a service
- lengthening products' useful life
- reducing the use of energy and materials in production and product use
- reducing the use of materials that are hazardous or difficult to recycle in products and production processes
- creating markets for secondary raw materials (recyclates)
- designing products that are easier to maintain, repair, upgrade, remanufacture or recycle (ecodesign)
- developing reuse and use extension support services for consumers (maintenance/repair services, etc.)
- incentivising and supporting waste reduction and high-quality separation by consumers

- incentivising separation, collection systems that minimise the costs of recycling, and reuse
- facilitating the clustering of activities to prevent by-products from becoming wastes (industrial symbiosis)
- encouraging wider and better consumer choice through renting, lending or sharing services as an alternative to owning products, while safeguarding consumer interests (in terms of costs, protection, information, contract terms and insurance aspects).

The UK has signed up to the EU's Circular Economy Package (EU, 2020). The UK and its devolved administrations will need to translate these actions into their own domestic plans and policies including, in England, the Industrial Strategy and Clean Growth Strategy, National Infrastructure Delivery Plan and the 25-Year Environment Plan, which should ideally be drawn upon to develop a focused programme following the Resources and Waste Strategy.

3.2. Risks and barriers

The current inaccuracies inherent in conventional Cost-Benefit Analyses of economic activities affect market price, which is lower than it would be if environmental and societal costs were internalised. This translates into payback periods appearing longer for circular economy interventions than they are on a full accounting basis, which is a barrier to investment. If externalities such as natural capital are considered in per capita wealth, wealth per capita has been shown to *decline* even as GDP per capita increases (Dasgupta, 2010). To compensate for these barriers, any cost benefit analyses carried out by water utilities for circular economy interventions should ideally include some reference to ecosystem service values and natural capital values and how they are affected by a linear economic activity compared to a circular approach.

Another barrier cited for circular economy interventions is lack of information and awareness (Purnell, 2019). This ROCK is provided to help the water sector overcome that barrier. Other information that will help water utility managers adopt circular economy interventions is readily available, such as the CIWEM Circular Economy Policy Position Statement, CIWEM reports and open access resources such as the Ellen MacArthur Foundation website, the Defra website, WRAP website, etc. (see References Section for links). Some of the barriers in the wider economy cited for circular economy interventions (EASAC, 2015) such as skills gaps, consumer consumption behaviour and access to recycling centres have less effect on developing circular economy opportunities within water utility operations, because water companies also present an internal market for some resources that can be recovered. These potential advantages for water utilities adopting circular economy measures will be described in Section 4.

The broad objective of circular economy measures is to make the global economy more sustainable in its use of resources and to minimise net resource use. That aim is also subject to a rebound risk. A rebound effect occurs when increases in efficiency result in an increase in overall demand and consumption because the efficiency increases, thus reducing costs.

The rebound effect is one of the criticisms ecological economists (e.g. Zink et al., 2017) make of circular economy interventions; it is a potential risk but one best managed by appropriate government policy and regulation in the wider UK economy and is best mitigated in the UK water sector by dividing initial water sector circular economy measures between internal markets and external market opportunities (see Section 4.5).

Some practitioners of circular economy interventions do not currently deploy a macroscopic physical systems analysis (based on thermodynamics) or sufficient econometric or economic and macroeconomic analyses in their assessments of risk and benefits of circular economy interventions. A minimalist approach creates a higher risk investment project due to the significant information gaps in neoclassical linear economy business case risk assessments which are examples of investment risk assessments based on limited information. Better investment risk assessment can be readily provided with the right techniques and approach. A comprehensive risk and benefit assessment for circular economy interventions is not necessarily one that requires a highly extended study; it is one that has a fundamental (physical) systems basis to incorporate key physical principles while having a large enough *range* in its assessment of risk.

Circular economy interventions are physically based on resource efficiency measures. Such interventions suggest competitive advantages arising from *operational efficiency gains* for water utility and other businesses assessing circular economy interventions. Circular economy interventions are opportunities to secure competitive advantage. Micheal Porter's analysis of competition between businesses (Porter, 1979) is a standard method for assessing the competitive status of a business, including water utilities in the UK. Five forces analysis is based on rivalry between existing competitors in a market being affected by supplier bargaining power and customer bargaining power, substitution of resources and new market entrants. This analysis of competition is useful for water companies operating in England and Wales because these water utilities have their performance compared *relative to each other by Ofwat* and are also subject to Ofwat Outcome Delivery Incentives (ODIs), as part of the England and Wales commercial regulatory oversight of water service provision. Figure 9 illustrates the risks to most UK water utilities of non-participation in circular economy interventions.

Porter's method for assessing competition and the risk of competition between water utilities in this case, is still relevant and readily uprated to take account of the latest innovations in the markets that water utilities operate in (Brujil, 2018). This applies to both current leaders and current poor performers in water services provision because as Porter states: "…ultimately, the only way to sustain a competitive advantage is to upgrade it - to move to more sophisticated types".

The risk and opportunity inherent in the introduction of circular economy measures into water utility businesses is that they can improve operational efficiency which translates into competitive advantage. For water utilities, this is a strong incentive to participate in circular economy measures because they are regulated and formally appraised by the commercial regulator on their relative performance.

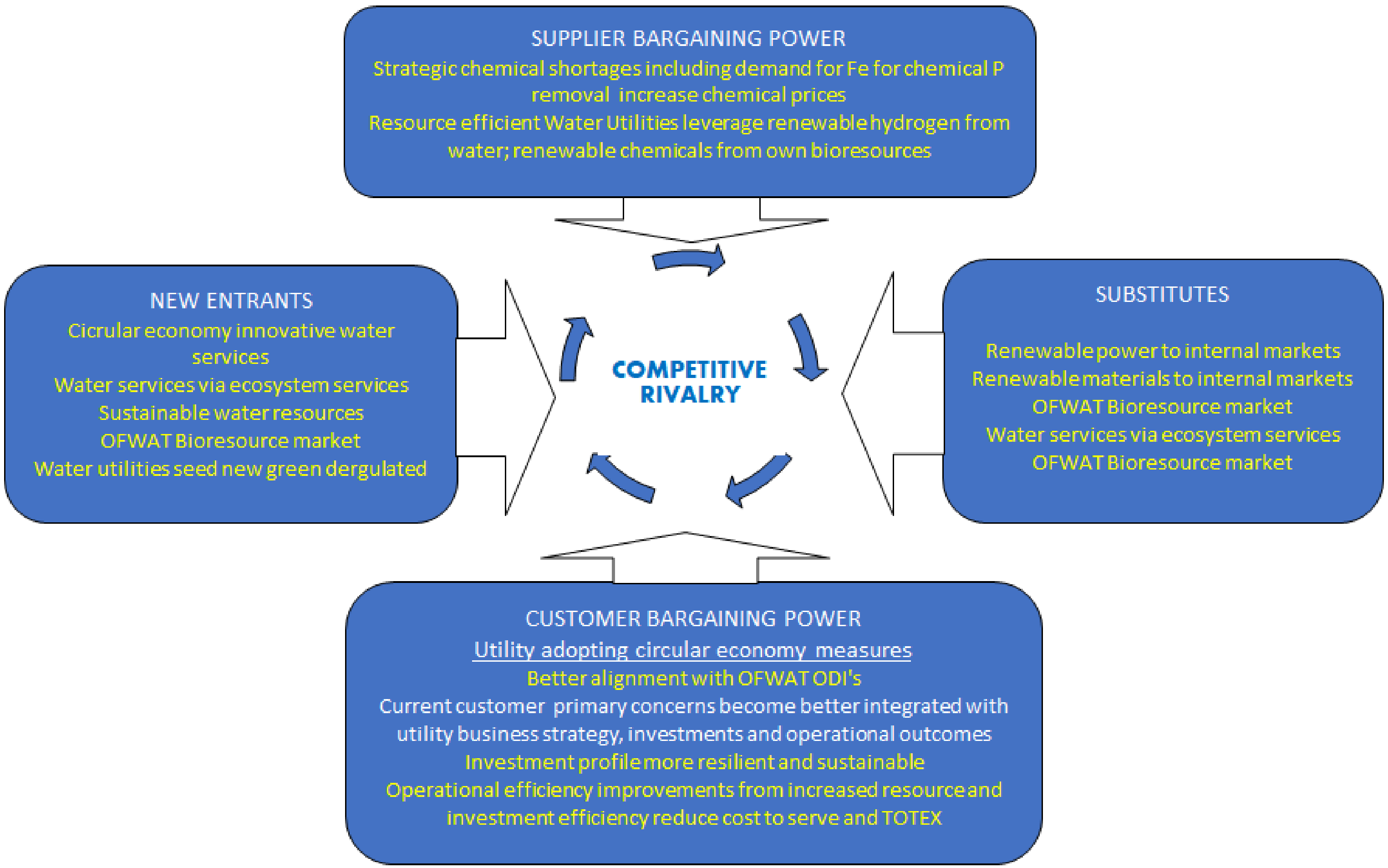


Figure 9 **The risks of not adopting circular economy interventions for UK water utilities**

Notes: An analysis of competition for water utilities using Porter's Five Forces, considering Circular Economy interventions. Porter's Five Forces can be adopted to include resource efficiency advantage that could arise from adoption of circular economy measures and increases is sustainability by competing water utilities as well as the latest advances in information technology and customer satisfaction interventions. Failure to participate in circular economy investment risks an operational performance gap emerging for non-participants.

Review of Current Knowledge

Evidence currently available (Ambec et al., 2013) is that sustainability (a central goal of circular economy measures) is a driver of competitive advantage due to increased environmental regulation driving innovation (Porter, 1998; Porter, 2008).

4. UK Water Industry and the Circular Economy

Challenges facing UK water utilities include pressure on water resources, including their quality, aspirations for increased receiving water quality, customer satisfaction, the emerging impact of anthropogenic materials (such as xenobiotics and microplastics) and the regulatory challenges from Ofwat to reduce operating costs (reduce TOTEX) and meet a series of service quality targets. Water utilities in the UK have also committed to GHG emissions reduction and operating carbon footprints in line with UK government targets.

The circular economy is an approach to business that increases resource efficiency and conserves natural capital: it has a core philosophy of doing 'more with less'. *The circular economy and its principles should therefore be of primary interest as a business realignment and improvement approach for UK water utility business managers because circular economy principles are consistent with the performance targets of UK water utilities.*

The **Ellen MacArthur Foundation** has carried out a collaborative study that set out a view of how the water sector could adopt circular economy measures in the CE100 Group White Paper (2018). The 2018 White Paper uses a 'systems perspective' which is important for understanding how different systems in the environment interrelate on a conceptual level based on assumptions, but does not provide a macroscopic physical model. Consequently the 2018 White Paper lacks a systems engineering description and any supporting complex physical systems analyses (such as agent-based modelling) that can link investment and operations on a physical basis.

The 2018 White Paper for water and the circular economy needs to be understood in terms of its intent and scope: it is a work in progress and describes itself as such, in that it represents an initiative between the Ellen MacArthur Foundation, water service providers and others (CE100 – Circular Economy 100 group) to introduce the circular economy and its potential benefits to their businesses.

Any criticisms that may be made of the 2018 White Paper do not diminish its usefulness for UK water utilities as:

(i) an introduction to the circular economy for water businesses and the concepts used in the circular economy

(ii) an introduction to the philosophy of the circular economy in a water sector context

(iii) an introduction to a system analysis approach within the water sector as the conceptual basis for circular economy measures.

Although the White Paper's case studies are summaries of a range of potential interventions rather than methods, they are sufficient for introducing water utilities to the circular economy and some of its potential interventions. The core principles are:

- designing out waste externalities
- keeping resources in use
- regenerating natural capital.

4.1. The basis for water business circular economy interventions

For water operations the 2018 White Paper concentrates on water resources management, as shown in Figure 10, which is a system map for water resource use.

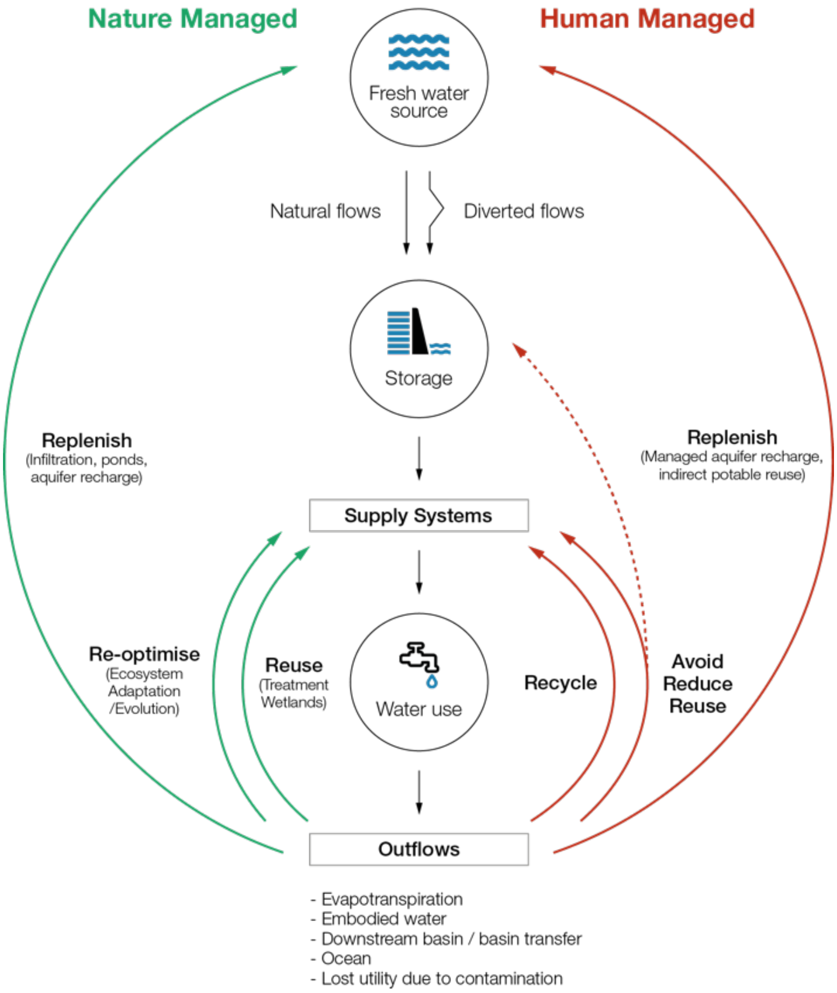


Figure 10 Ellen MacArthur Foundation Water and Circular Economy White Paper (2018)

The current abstraction and use of water resources is described as a take-use-discharge linear resource use and Figure 10 is the CE100/2018 White Paper proposal for sustainable water resources management. There are two routes proposed for how water resources are managed: the water abstraction and processing current route which CE100 term the 'human' route and an alternative 'natural' route where the 2018 White Paper is proposing that water resource utilisation is makes use of the ecosystem services provided by natural systems.

The general ecosystem services the 2018 White Paper identifies for a 'Nature-Managed System' are:

- **Re-optimisation** (apparent meaning: keeping water in natural system circulation to maintain an ecosystem and its biodiversity).

- **Reuse** (apparent meaning: the inherent water pollution remediation 'ecosystem service provision' offered by existing ecosystems).
- **Replenish** (apparent meaning: the water cycle and how water cycles back into the environment).

The 'Water Resource System Diagram' shown in Figure 10 compares the natural water cycle to the water cycle that is subject to human intervention. The 2018 White Paper identifies the key issues with regard to the latter being unsustainable water resource management, namely:

- abstracting freshwater above its natural rate of replenishment
- water loss due to distribution and end-use inefficiencies (water losses and inefficient irrigation)
- water pollution and how pollution limits its utility.

These factors all contribute to the erosion of water quality which in turn translates into erosion of ecosystems. One of the risks in the approach as presented in the 2018 White Paper is lack of prioritisation. Many measures exist to assess the quality and ecosystem service potential of an aquatic ecosystem but in outcome terms, one cited in the 2018 White Paper is biodiversity. Biodiversity in terms of water quality is currently regulated through the environmental quality standards for different types of aquatic environment which is administered by the Environment Agency in England and associated regional authorities, as set by legislation. Biodiversity risk factors include rate of change in the environment; in mathematical terms strong natural selection pressure erodes biodiversity. This is the reason conservation measures seek to conserve a range of environmental characteristics for an environment, because any living system defines itself in terms of its genotype's useful information and hence phenotype, *in reference to its environment* (Palmer, 2018). Prioritisation is an issue in sustainability because there are a range of physical changes presently imposed on all Earth's ecosystems from human economic activity and *the most disruptive at present is climate change*. Consequently, water utility circular economy interventions should consider their effect on climate change risk (e.g. Rose et al., 2012) and not just be based on managing material resource quality.

The circular economy interventions for water resource management suggested by the 2018 White Paper include the following:

- **Avoid** water use where possible (water efficiency measure).
- **Reduce** use (increase water use efficiency).
- **Reuse** (maximise water reuse opportunities).
- **Recycle** (recycle water where possible).
- **Replenish** (return water to the environment to conserve and sustain water resource capacity).

These proposed general measures are then placed in the context of other systems in the 2018 White Paper by creating and mapping three archetypal city types to three archetypal water basin types described as arid lower plains, lush green middle plains and upper highlands, to create a menu of interventions as follows:

- arid lower plains: water reuse and water substitution
- lush green middle plains: water treatment and reuse and water substitution
- arid lower plains: water reuse and water substitution.

These proposed general measures provide a good narrative for an approach to circular economy interventions. For water utilities to translate the 2018 White paper into actionable projects, metrics and methods, including engineering protocols, need to be developed. Secondly, the systems approach needs formalising so that it is actionable on projects and can be effectively translated into systems engineering.

The 2018 White Paper does not present a physical science basis for its concepts which would in turn help in quantifying risk of non-sustainable operations. However, there is a macroscopic basis on which this could be provided for resource use by using thermodynamics to consider the potential changes of entropy between the interacting systems. Although entropy is formally measured for a system at equilibrium, entropy is also estimated for open systems undergoing system changes. An entropy approach would also introduce more rigour into the systems analyses by requiring it to set the physical boundary conditions for the systems being considered and by formalising how the systems interact physically. This approach has already been developed for the environment and for complex production systems in an economy by ecological economists (Szargut, 1997; Gutowski and Sekulic, 2011; Bakshi et al., 2011).

4.2. Approaches and methods for water business circular economy interventions

This section covers a macroscopic approach to describing water business operations that best serves consideration of circular economy interventions. This produces a systems description that applies to all water business operations that circular economy interventions may be considered for and links the water business operation to the environment. A formal approach and a set of analysis tools is necessary to manage the uncertainties, risks and omissions in standard economic analyses described earlier in this Review of Current Knowledge. Any water or wastewater operation can be described as presented in Figure 11, which is the physical systems analysis of Figure 1 for any economic operation respecified for a water or wastewater operation.

The simplest but most complete way to describe the impact of water company operations on the environment that recognises the wider significance of circular economy measures, is to describe them in terms of physical systems. All water company operations are open, non-equilibrium dissipative processes that interact with the environment as described in Figure 11. Water utilities use dissipative structures in their service provision. They require energy and material resources for both service work and the treatment provided by fixed capital assets, the latter requiring investment and maintenance capital.

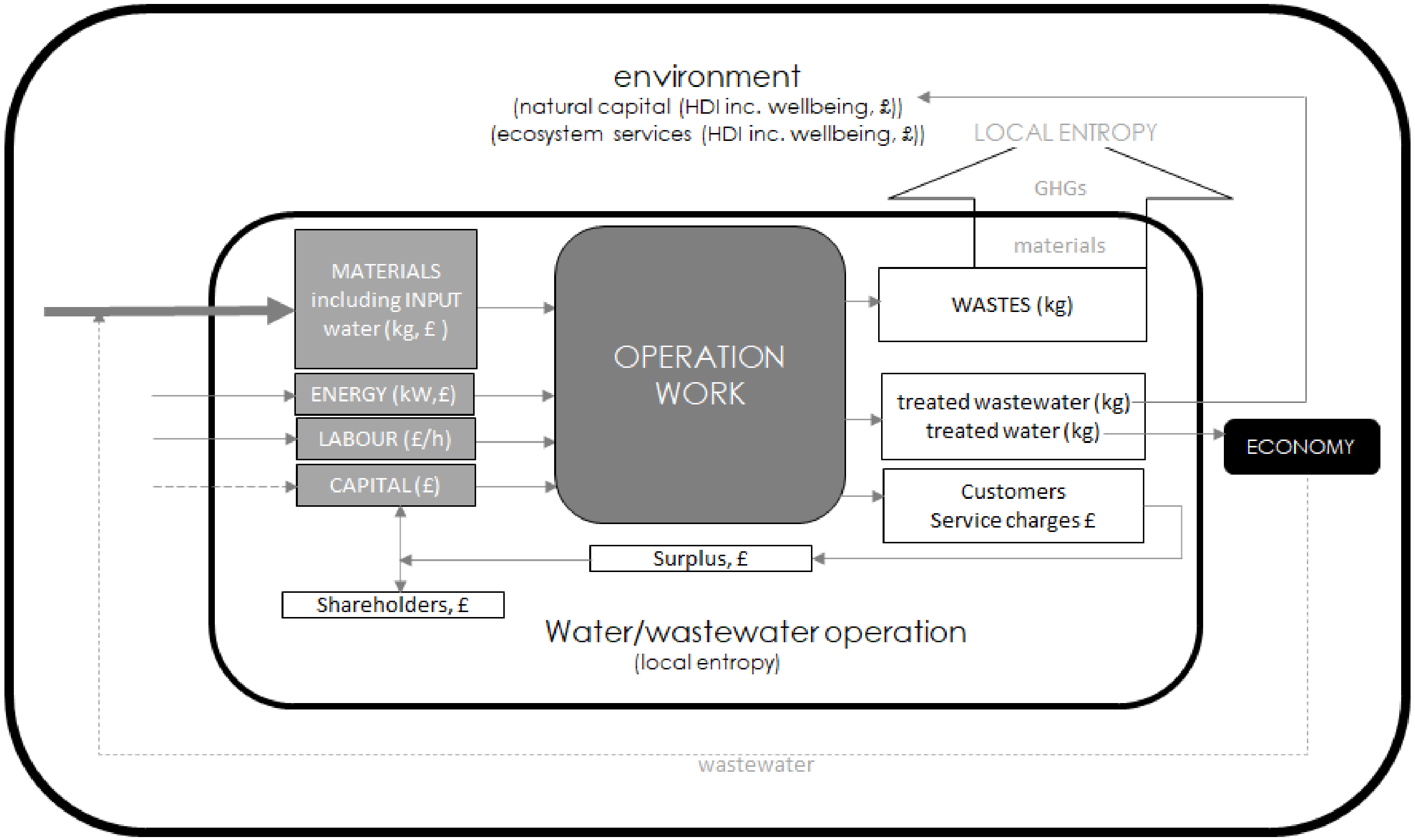


Figure 11 Universal physical systems diagram and econometric flowsheet for a water or wastewater business operation

Notes: Description provided is for the UK water industry, hence shareholders are included as part of the operation. In thermodynamic terms a *water utility operation* is an open system interacting with its environment, consuming manufactured material resources and using manufactured technology resources to perform the work required for the service defined by the operation. Therefore, the operation consumes resource exergy and discharges low exergy/ high entropy wastes to the environment. The magnitude and rate of that process impacts the environment; by reducing exergy consumption of the water utility operation (by increasing resource utilisation efficiency); *circular economy interventions can reduce environmental impact of the water utility operation and increase its sustainability*...

Treated water is used in the capital assets, the latter requiring investment and maintenance capital. Treated water is used in the economy for the population and all water-requiring operations in the economy. When potable water is used in the economy, as a universal solvent and a liquid, it acts as a carrier for dissolved waste materials and suspended particulate wastes which accumulate in wastewater and requires work by treatment assets to remove to levels set by regulation. In the environment, water is a critical part of Earth's biogeochemistry, through the water cycle.

The water operations system is an open system exchanging materials and energy with the environment. Thermodynamics dictates that the use of material and energy resources in the water business operation creates wastes (such as heat and materials wastes). Water company operations (like other operations in the economy) are structured operations and the whole structure is dissipative, dispersing waste materials and energy into the environment.

The physically structured nature of economic operations means that they tend be high exergy consumers and intense entropy producers. In theory, circular economy interventions should reduce the exergy consumption and entropy transfer to the environment of water company operations. Exergy efficiency and exergy flow can be used as an indication of the quality of the resources after use and can provide a comparison point between operational alternatives provided by linear economy options and circular economy options.

Local equilibrium for this system is a sufficient approximation of its status. Establishing the entropy of the system is not practical given information currently available but is also not necessary for our purposes. Use of exergy data will allow a relative assessment of entropy risk to the environment for the economic efficiency of a current linear approach to the operation described in Figure 11, compared to the economic efficiency of a circular economy approach. This is sufficient for water utility business decision-making purposes. Such an evaluation will require additional analysis and needs to include consideration of local environmental natural capital and local ecosystem services and critical global risks such as climate change contribution.

The physical system diagram of Figure 11 for a water utility operation describes a complex system with feedbacks and interdependencies, so an accurate assessment of the relative advantages and disadvantages of a circular economy intervention in an operation needs to use sufficient information to understand the risks inherent in that complexity. For example, where circular economy interventions increase resource efficiency or extend the life of a resource in the economy, in some cases the resource efficiency measures include return and recycle interactions in which *work* is substituted for the extraction of primary resources from the natural capital of the environment. That work may also draw on resources and will require energy resources. If the energy resources for recycling work are renewable, there is minimum impact from that element of increased resource efficiency. If, however, the energy resources utilised in that process are fossil-fuelled there is a sustainability and biodiversity risk associated with the extra energy use. It is this complexity that requires the range of assessments presented in Table 2.

Table 2 Assessments required for good practice accounting of standard (linear economy) operations compared to circular economy alternatives

ASSESSMENT	TYPE	INFORMATION SOURCES
System Diagram	Overview diagram for the operation and its interaction with environment	Generic example in Figure 11. Process engineering outputs - process flow diagram (PFD) or block flow diagram
Materials Balance	Mass Balance for all material resources (mass, kg) (£ cost)	Process engineering calculations, mass balance, PFD, P&ID (piping and instrumentation diagram)
Energy Balance	Energy Balance for all energy resources (kW) (£ cost)	Process engineering calculations, mass balance, P&ID, functional design specification, function design specifications, mechanical equipment schedules, electrical schedule, single line diagrams, operation & maintenance manuals, materials schedules, operational performance data for existing operations, statistics of compliance and risk on output quality for operation, operational performance headroom for existing operations. Example of mass and energy balance approach in Figure 12.
Mass and Energy Balance	Integrated mass and energy material balance (kg, kW)	
Sankey Diagram: Energy	Visualisation of energy flows kW	
Sankey Diagram: Materials	Visualisation of material flows (kg, tonne)	
Operational Flow Diagram	Comprehensive resource flow diagram for operation describing interaction with local environment	
Carbon Footprint	Climate risk from operation (kg) (£ cost); $kgCO_2e$/person served	Carbon accounting tools; kg CO_2e* for total GHG emissions; also per capita ($kgCO_2e$ per person served by operation), also tonnes CO_2e over lifetime of operation. Carbon cost (£/year; £ total for life cycle)
Sankey Diagram: GHG emissions	Visualisation of sources of climate risk	Carbon accounting tools and materials balance (mass per day)
Water Footprint	Efficiency of water resource use (litres/person served)	Water footprint tools; total mass and volume of *fresh* water used in operation, also per capita (litres fresh water per person served by operation)
Natural Capital	Impact of operation on natural capital in local environment (£)	Natural capital lists, metrics and values available in the public domain
Ecosystem services	Impact of operation on ecosystem services in local environment (£)	Ecosystem services lists, descriptions, metrics and values available in the public domain
Total Operating Cost	Total OPEX of operation (£)	Designer's operating cost estimates augmented to total operating costs of operation including carbon costs, net of cost benefits and including effect (any on-costs) from impact on natural capital, ecosystems
Capital Costs	Capital costs of operation (£)	Designer's capital cost estimates for new equipment or infrastructure; capital maintenance costs
Whole Life Cost (WLC)	Whole Life Cost (£)	Whole Life Cost including inflation sensitivity test
TOTEX	TOTEX (£)	Capita enhancement cost plus capital maintenance cost plus OPEX (operational expenditure)
Investment payback	Payback on Capital invested (years)	Based on OPEX benefits introduced versus capital cost or TOTEX capital

*CO_{2e} is the carbon equivalent of the total greenhouse gas emissions from an operation.

Water utility practitioners of circular economy interventions will need to keep in mind that the problems that arise from linear economy approaches are caused by the *lack of information* that neoclassical economic assessments allow in establishing business cases, as described in Sections 1 and 2 of this ROCK.

Table 2 presents the range of information that should be accounted for in comparing circular economy interventions to linear economy investments and operations. If the metrics and indicators described in Table 2 do not provide an obvious or sufficient difference between a proposal for standard (linear) operational option and circular economy alternatives, it may be because there is not enough overall information on *environmental impact risk* and *sustainability* being taken into account in the assessment of options for the operation. There are two other measures that can be deployed to test the environmental impact of a linear versus circular option for a water utility operation. These are consideration of the *exergy flow* of the operation (an analogue of entropy for it) and the assessment of *an indicator of limits to resource substitution*.

At present an **entropy (exergy) risk assessment** between options can be carried out as a qualitative risk assessment based on the familiar risk matrix approach, by comparing environmental impact and sustainability of options for the *exergy* indicators of a water utility project (Figure 13):

- Ecological economists have begun to use entropy/exergy assessment as register of resource quality (e.g. Bakshi et al., 2011), with publications providing a source of information in this regard. Formalised life cycle assessments for types of resources are now also available (Driesmal et al., 2016) and models for entropy transfer between production processes and the environment (Faber et al., 2013). These resources can also be referred to for some *resource use impact* data.
- Exergy is another means of measuring resource quality which is linked to entropy (entropy describes the dispersal of exergy into the environment). Exergy assessment for a water utility operation could be estimated using the method described by Gong and Wall (Wall and Gong, 2001; Gong and Wall, 2001).

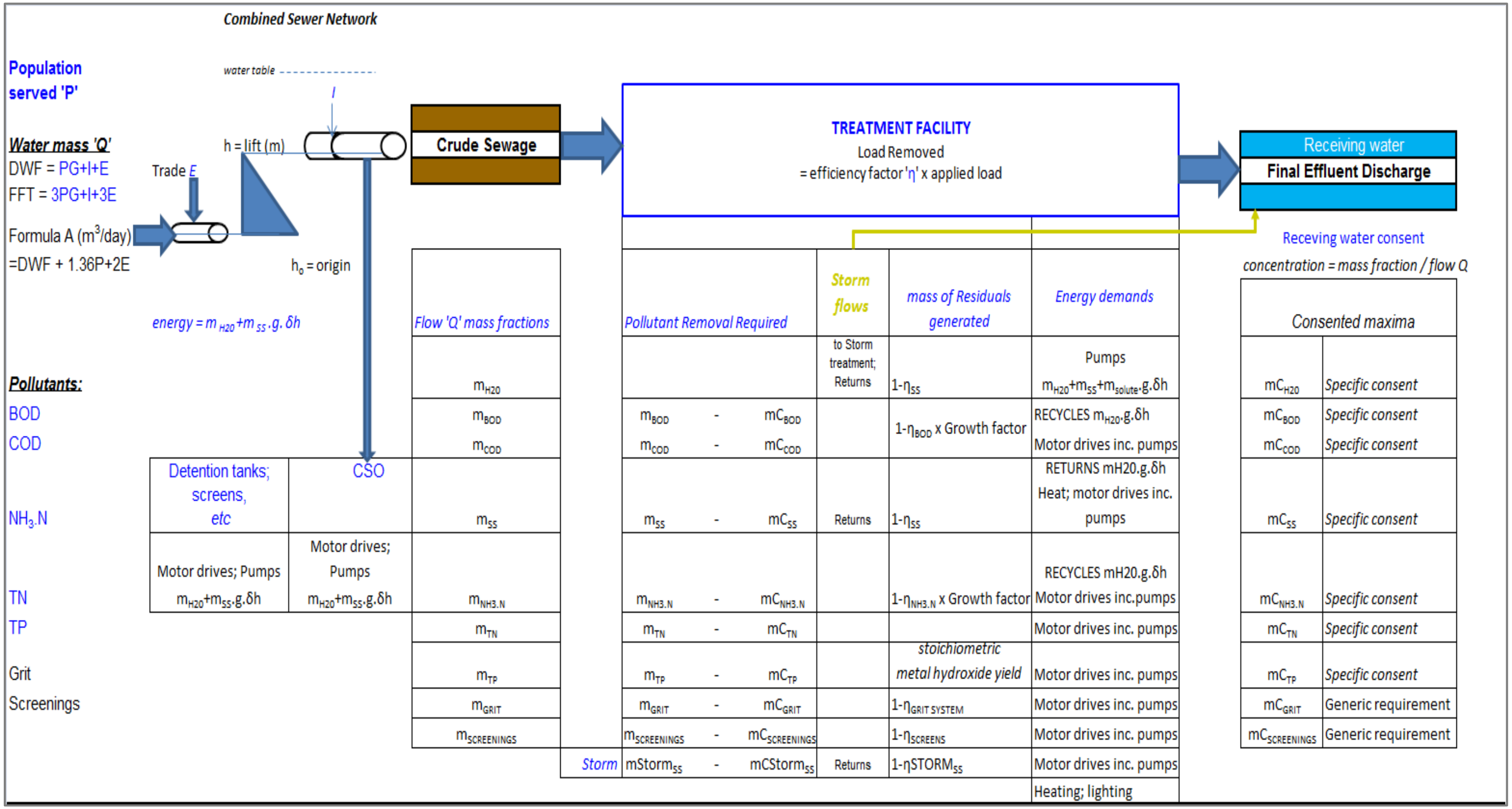


Figure 12 Example Mass and Energy Balance for Wastewater treatment

Notes: The same approach would be used to link a materials (mass) balance to their associated energy demands in water treatment.

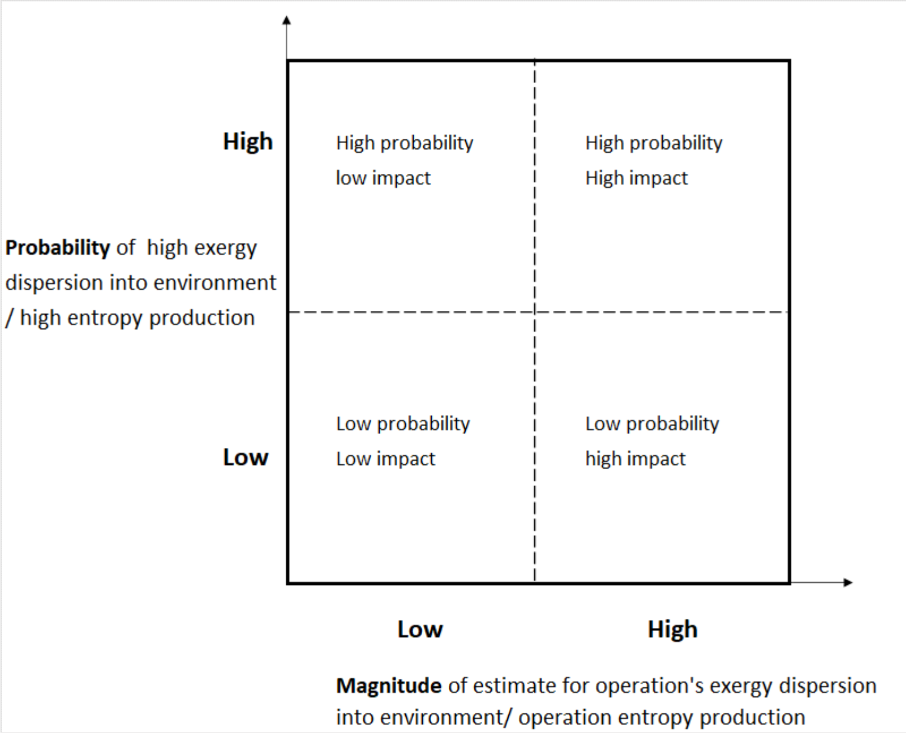


Figure 13 Operation options exergy/entropy risk qualitative assessment for water utility environmental impact risk/sustainability risk.

Notes: Consideration of how many resources are utilised and the efficiency with which they are utilised, with reference to any published exergy data for resource use with particular attention being paid to the fossil fuel use and carbon footprint of the operation, will allow a qualitative risk judgement based on the magnitude likely entropy export to the environment. Exergy is both an indicator of resource quality and a physical quantity whose dispersal describes entropy. The position of options relative to each other on the chart would determine relative risk (lower probability and/or lower risk impact with preference for low impact) in terms of environmental impact and sustainability. Analysts may also consider operation intensity (exergy transfer rate to the environment) as an indicator for biodiversity risk.

Quantitative assessments may also be attempted if sufficient reference data is available for the risk assessment. As entropy describes the dissipation of energy and materials into the environment, an *exergy* index of all resources used will provide an analogue of the entropy generated by the operation (Ayres and Martinàs, 1995; Wall and Gong, 2001; Gong and Wall, 2001) and critical resource sustainability. **A quantitative approach to entropy risk to the environment from a water utility operation could be provided by comparing the *exergy efficiency* of a current option to a circular economy option** (e.g. method of Gong and Wall, 2001). The advantage of the Gong and Wall exergy balance approach (Gong and Wall, 2001) to describing exergy/entropy impact on the environment is that it can be visually summarised either in the form of a Sankey diagram for exergy that includes the exergy destruction inherent in the operation (Gong and Wall, 2001, Figure 4. Net Exergy Analysis, p225) or a Life Cycle or systems life cycle exergy timeline (Gong and Wall, 2001, Figures 5 and 6. p226).

- Consideration of exergy and entropy provides an overview of environmental impact risk for investment cases that is currently omitted. Materials resources coming into the economy and human population are utilised and dispersed into the terrestrial environment, the aquatic environment and the atmosphere (Ayres and Martinàs, 1995; Wall, 1977; Wall and Gong, 2001; Kleidon et al., 2010). Note that the entropy transferred to the environment (exergy flux into the environment) by the human population and the economy is already partially costed as the cost of wastewater treatment by water utilities and as nominal carbon emissions costs.

- *An **exergy analysis** for a water utility operation can also identify how and where circular economy interventions might be most effective as the 'hotspots' (most intensely exergy destructive aspects) of an operation in its use of resources will be potential targets for circular economy interventions. A Sankey diagram for exergy (e.g. Gong and Wall, 2001, Figure 4. Net Exergy Analysis, p225) or a life cycle or a systems life cycle exergy timeline (e.g. Gong and Wall, 2001, Figures 5 and 6. p226) would be tools for this form of analysis.*

- *An **exergy analysis** for a water utility operation can also quantify the efficiency of use of information, information technology and its effects overall in managing the exergy efficiency of the operation – because utilisation of physical system structural data (information) is also quantifiable using exergy analysis and it can reveal the leverage that accurate information use provides for a given water company operation for its overall exergy efficiency.*

- The operational exergy destruction of most water utility operations will include the consumption of chemicals, including fossil fuels. The exergy of chemicals in the environment following their discharge to it is calculable (see Wall and Gong, 2001).

- Dispersion of wastes into the environment can reduce ecosystem service capability of certain ecosystems or reduce the natural capital of resources available. As an example for the UK water industry, the local accumulation of metals and hazardous xenobiotics (human-made chemicals) may prevent the use of sewage biosolids as agricultural fertilizer in the UK which also removes some phosphorus from beneficial recycling to food production.

- *An **exergy analysis** for a water utility operation can also quantify the likely biodiversity risk of an operation. Information for all biological systems is defined by the environment – it is environmentally relevant information that biological systems act on as information in terms of natural selection (Palmer, 2018). Strong selection pressure suppresses diversity and time is a factor in selection pressure. A high intensity operation with a very high **rate** of exergy flow into the environment carries a latent high risk of reducing biodiversity in a local (water) environment.*

Another worthwhile additional risk factor for physical economy accounting and circular economy assessment is *substitution risk* (here meaning the risk of a resource being *totally unsubstitutable)*. The best candidate chemical element for this is phosphorus (P) and its footprint (phosphorus impact). Phosphorus is an example of a *non-substitutable resource* and at present is the most significant non-substitutable resource on Earth due to its utilisation by all living systems. Consequently, the assessment of the operation should consider Total Phosphorus (TP) footprint (TP impact). The material balance for the operation should include phosphorus and account for the influx and efflux of Total Phosphorus from the operation and account for the effect on P of the operation in the local environment i.e. is it bioavailable or has it been removed from the local P cycle. This would be best visualised by a dedicated Sankey diagram, for TP flows.

If these two further metrics are deployed there is also an argument that the full and complete assessment of a circular economy option should at least consider the risk of a circular economy rebound effect. The most simple approach to this risk is for the project team to use the information resources prepared for the project assessment as described in Table 2, to review if, and to what degree, the circular economy intervention may increase resource consumption as a result of any increase in resource utilisation efficiency and to evaluate the impact in terms of carbon, water and phosphorus footprint of any such increase in operational consumption.

4.3. Asset technology considerations when undertaking water business circular economy interventions

The range of challenges facing the operations of UK water utilities includes:

- increased population, especially in some urban areas (treatment operations intensification driver)
- population decreases in some locations
- industrial load decreases due to closure of industries and reduced industrial capacity, and from national and local economy disruptions (e.g. 2008-09 financial crisis impact, 2020 COVID-19 pandemic economic disruption, etc.)
- local water resource quality
- local water resource quality: meeting the nutrient challenge and especially the phosphorus WINEP (Water Industry National Environment Programme) challenge
- local water resource quantity
- over-abstraction stressing local water resource environments, ecosystems and depressing biodiversity
- reduced business and per capita water use reducing rates of return to sewer under dry weather conditions that increases concentrations of polluting chemicals, creating increased operation process risk through changes to treatment processes mass transfer
- some xenobiotics (anthropogenic chemicals) being associated with negative health risks or negative environmental impact, leading to their regulation and a requirement for their processing being added to water treatment and/or wastewater treatment (treatment operations intensification driver)

- climate change; the national legislation and regulation for its management and the UK water utilities own carbon targets and their implications for utility energy policy and use
- climate change and shifts in weather trends, including the length of dry weather flow (DWF) periods, the intensity and persistence of precipitation and the effects of such challenges on the performance and efficiency of treatment operations, from source to network, to treatment facility
- climate change and shifts in weather trends and how those affect water resource availability
- 'cost to serve' and Ofwat regulation of it.

Circular economy initiatives have potential benefits to offer for this range of challenges in terms of both operational efficiency and resilience, because circular economy initiatives take account of upstream and downstream risks both in space (the upstream environment for an operation and the downstream environment for that operation) and in time (sustainability risk).

Circular economy interventions are aimed at increasing resource efficiency and are consistent with developing a systematic and systemic approach to obtaining operational efficiency improvements across a water utility asset base (Figure 14).

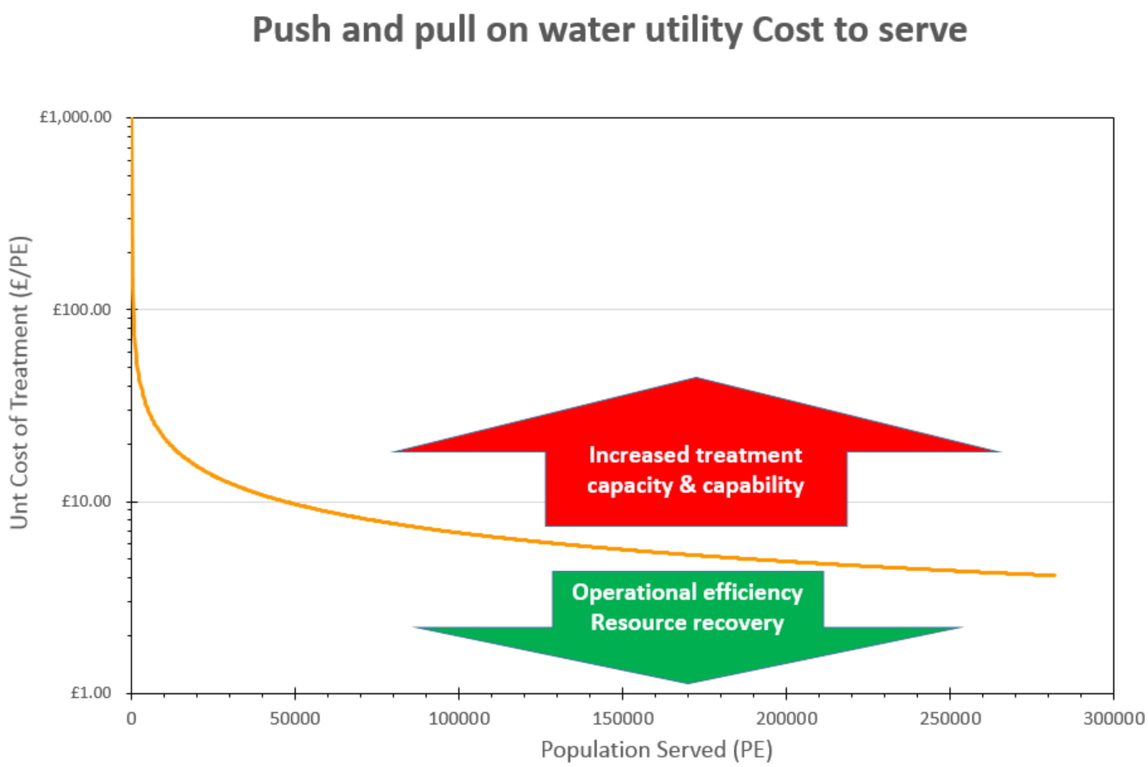
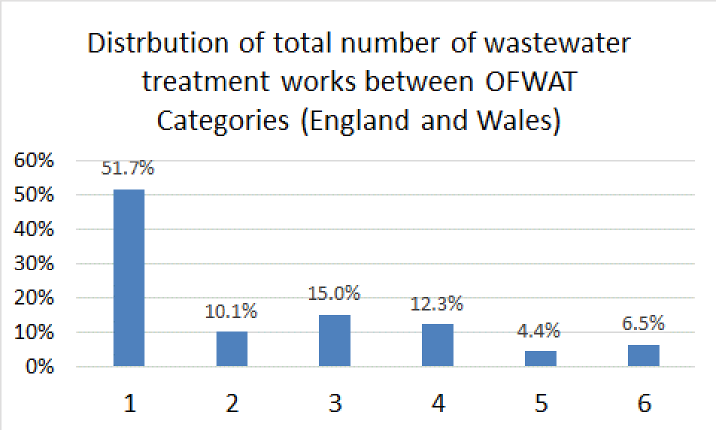


Figure 14 UK Water utility operating challenges and their effect on 'cost to serve'
Notes: The effect of persistent increased capacity and increased capability demands on water utility assets and their operating costs (Palmer, 2019).



OFWAT WwTW Size Bandings	Population Equivalent
1	0 – 250
2	250 – 500
3	500 – 2,000
4	2,000 – 10,000
5	10,000 – 25,000
6	>25,000

Figure 15 Wastewater Asset Profile (UK Water Utilities)

Notes: In municipal wastewater treatment in the UK, small works make up the largest number of the total number of treatment works. Similar trends occur in water treatment plants (see Figure 16). Wastewater treatment in the UK also includes the operation of 393,460 km of sewer network.

The water industry based in England and Wales is also under ongoing review of its 'cost to serve' and the performance of these water utilities is subject to Ofwat commercial regulation, and the performance of these utilities is partially judged *relative* to each other (refer back to competition risk in Section 3.2 and Figure 9).

These challenges suggest that the circular economy should become a standard approach for all UK water industry utilities operations across their asset bases.

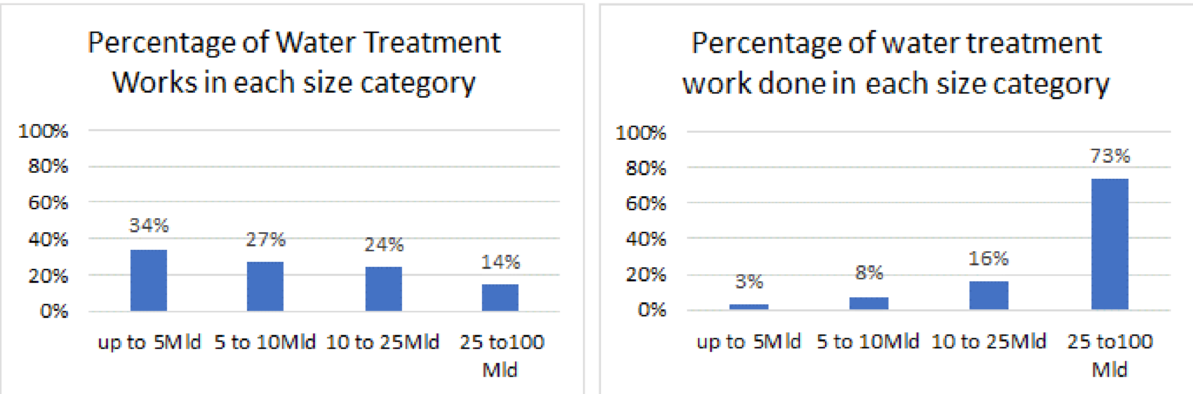
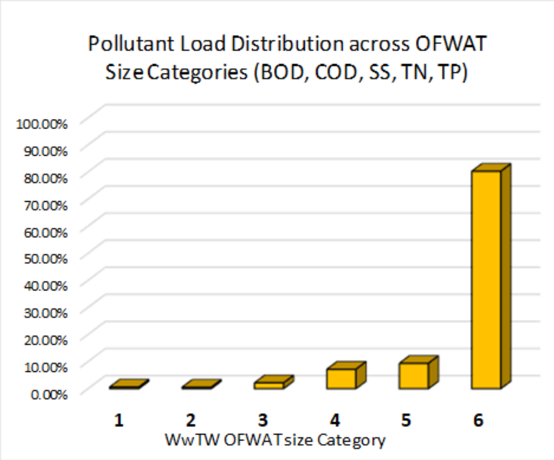


Figure 16 Water Asset Profile (UK Water Utilities)

Notes: For water treatment the same trend in works' size is seen as for wastewater treatment. This is due to the same underlying demographic driver for form of service provision. Small works make up the largest number of the total number of treatment works but when ranked on size category, a small proportion of the total works' number carries out the bulk of abstraction and water treatment. The total number of water treatment works in the UK is presently 1,433. Water treatment in the UK also includes operation of 5,195 water service reservoirs and operation of 416,175 km of water distribution networks.



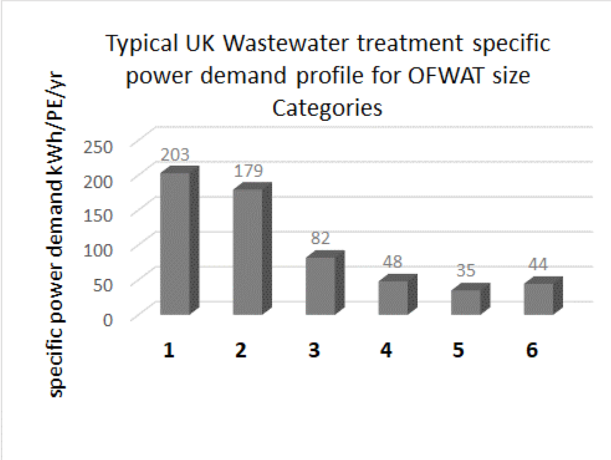


Figure 17 Asset and Treatment Work Profiles (UK Water Utilities)

Notes: Despite representing less than 10% of the total number of treatment works, the largest works do most of the treatment. As treatment work is done by larger units at larger works, the power demand per person served decreases due to economies of scale. Similar trends occur in water treatment plants. The largest water and wastewater treatment works process the largest mass flows and hence present opportunities for the quickest paybacks on circular economy resource efficiency measures, including increased resource efficiency and recovery of materials of value from processing residuals such as water treatment waste sludge, wastewater treatment grit and screenings, and wastewater treatment waste sludges.

The distribution of water treatment and wastewater treatment assets follows demand for both service lines and that *demand density* is set by demographics and the location of water resources. The demographic population service factor is the geographic distribution of the human population, also considering the industrial and commercial service demand for water and wastewater treatment. The demographic distribution of population is the primary determinant of demand density. Large urban centres present the highest demand density and are served by the largest water and wastewater treatment facilities. For wastewater treatment services Ofwat uses a size categorization (Figure 15) for evaluation of wastewater treatment assets. In both water treatment operations and wastewater treatment operations, average costs to serve per person or *population equivalent* (PE) served decrease as water and wastewater throughput increases (Figure 17). There is a range of efficiencies of scale seen in water utility operations that translate into those *economies of scale* for 'cost to serve' for a given population/PE:

- technology scale efficiencies: larger processing technology units process larger mass flows per unit, *spreading the work done in treatment over larger populations served*
- different technologies have different treatment work efficiencies: some are only cost effective in capital investment terms at small scale applications relative to others
- as work done is spread over larger populations served, so the electrical power demand of mechanical treatment systems is also spread over larger populations served
- labour costs are spread over larger populations served

- bulk chemical procurement can lower the cost of chemicals; chemical transport for large deliveries are more transport cost efficient
- transport costs are spread over larger masses to transport supporting the use of large, more efficient transport units; transport costs are spread over populations served
- operational on-costs, like maintenance and administration, are spread over larger populations served.

Ofwat also uses a technology categorization for evaluation of wastewater treatment assets for different forms of treatment. Many of those forms of treatment are commonly served by the biotreatment technologies shown in Table 3. The reason why biotreatment is ubiquitous and universal in large-scale wastewater treatment is that it uses the growth of microorganisms in designed environments (bioreactors) to degrade organic carbon, remove ammonia and remove phosphorus. Biotreatment is thus based on using a self-regenerating catalyst and consequently is the lowest cost treatment process for large volumes of water. The principal waste stream from biotreatment currently managed by utilities is the surplus biomass the process generates.

Table 3 Ofwat Technology Categories for Wastewater Treatment

(Works) Treatment Type	Technology Description
PRIM	**Primary treatment** (typically primary sedimentation)
SAS	(primary treatment plus?) **Secondary** biotreatment (**Activated Sludge**)
SB	(primary treatment plus?) **Secondary** biotreatment (**Biofiltration**)
TA1	**Tertiary treatment** by lagoon/natural system or similar, with (primary treatment ?) and secondary biotreatment by activated sludge
TA2	**Tertiary treatment** by tertiary filtration or similar and/or additional tertiary treatment with (primary treatment?) / secondary biotreatment by activated sludge
TB1	**Tertiary treatment** by lagoon/natural system or similar, with (primary treatment ?) and secondary biotreatment by biofiltration
TB2	**Tertiary treatment** by tertiary filtration or similar and/or additional tertiary treatment with (primary treatment?) / secondary biotreatment by biofiltration

The trends shown in Figure 18 result from large technology units processing larger mass flows per unit and how they consequently distribute their electrical power demand over larger populations served, hence reducing ‘cost to serve’ with size of application. Technologies differ; some technologies do more work than others due to their intensity of operation, such as the low footprint, intensive BAFF (biological aerated flooded filters) with their backwashing capability.

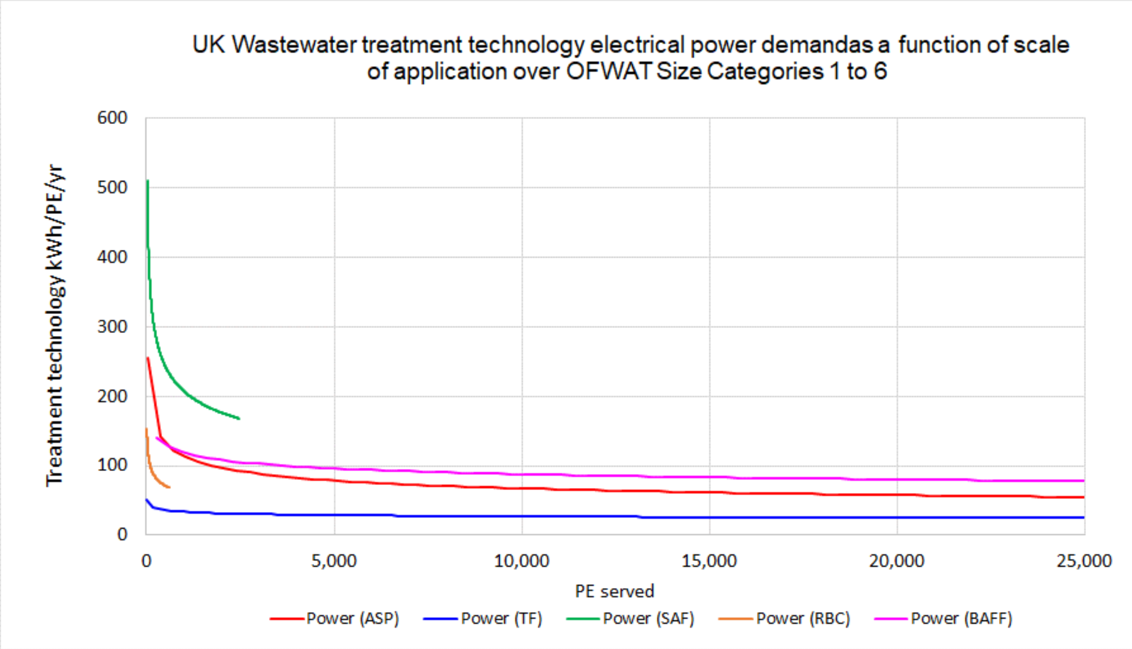


Figure 18 Wastewater treatment work electrical power demand technology profiles for increasing scale of operations for activated sludge (ASP), trickling filters (TF), submerged aerated filters (SAF), biological aerated flooded filters (BAFF) and rotating biological contactors (RBCs).

Notes: Similar trends occur in water treatment without the same level of reliance on biotreatment seen in wastewater treatment. The fundamental difference in approach arises from the need to exclude microorganisms in water treatment.

Technology for water industry assets has been developed based on empirical design. This design approach has been driven by market economics with the unit cost per mass of wastewater treated being low compared to industries such as pharmaceuticals where design is often mechanistic because the high value per mass of product supports more intensive design and more design input.

Affordability is now a major driver in the UK water industry and technology development needs to provide solutions that are commercially and environmentally sustainable in the long term. The fact that treatment technology assets are a mixture of civil, mechanical and ICA (instrumentation, control and automation) asset components is an economic driver rendering technology development typically incremental as water and sewerage companies (WaSCs) cannot afford to prematurely write off significant fixed assets. The longest lived (50–60 year) civil elements are often the more expensive and thus often force technology development to be incremental, unless a greenfield site development option is available.

These economic factors will need to be challenged if there is any step change in technology upgrading to occur. What this means for projects is that the whole-life costs and investment business cases will need to factor in cost risks currently minimised or absent in some water utility cost assessments for operations.

For example, the cost benefit calculations for recovering phosphorus from sewage by phosphorus precipitation P recovery systems (e.g. Ostara Pearl, NutReSys, etc.) at large wastewater treatment works with a phosphorus consent and anaerobic digestion (e.g. struvite harvesting) may omit the benefit of increased pipework and pump life and reduced headloss due to struvite fouling of pipework that would otherwise occur without P recovery in place. This is a significant capital maintenance benefit from an operational efficiency gain that should therefore be *included* in the cost benefits associated with this circular economy intervention.

4.4. Key economic considerations for water business Circular Economy interventions: Scale of operations

For water treatment and wastewater treatment, large treatment works have the largest mass flows and do more processing work than small works, while also achieving best treatment and best 'cost to serve' on a per capita basis due to economies of scale (Figure 19).

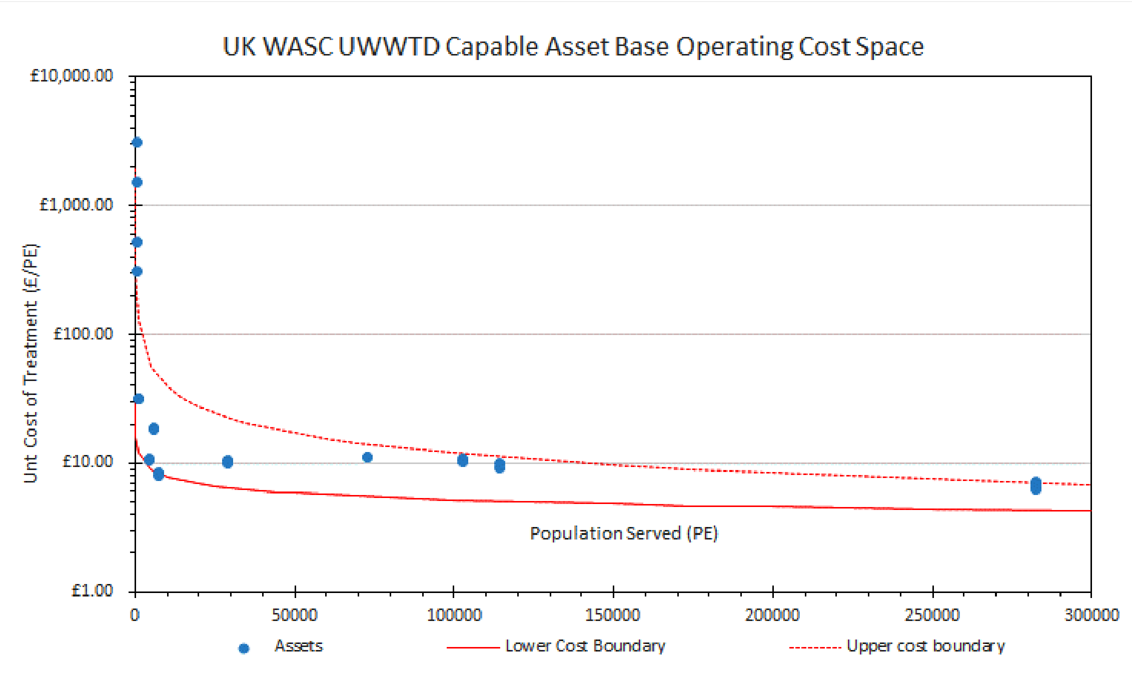


Figure 19 UK municipal wastewater treatment 'cost to serve' as a function of scale of operation.
Notes: The cost efficiency trend best fits a power-law relationship resulting from the economies of scale described above. Large works have the largest mass-flows of energy and material resources, so circular economy interventions to increase resource use efficiency and recover materials of value promise the best initial project returns for circular economy interventions at large sites.

The largest mass-flows present the greatest cost reduction opportunities for circular economy resource efficiency measures, which implies an advantage in deploying these at large works where the technology base is otherwise efficient compared to smaller sites due to economies of scale.

Large works also tend to possess more waste streams than smaller facilities and many smaller wastewater treatment facilities currently transport their wastes to large wastewater treatment works where they can be more economically processed. Large wastewater treatment works that operate as sludge processing centres thus have parallel processing across multiple streams which creates more opportunities for integrated resource recovery and interacting resource efficiencies. For example, where a large scale wastewater treatment works has anaerobic digestion installed on the wastewater sludge stream, that process also represents an internal sink – an internal market – for low grade heat recovered from the wastewater stream.

Large water or wastewater treatment works with multiple treatment requirements and multiple streams, including internally generated mass-flow such as sludge liquor streams, are therefore also opportunities for multiple integrated resource efficiency and value recovery initiatives that both maximise resource efficiency and value recovery potential through a series of aggregated process efficiencies. Interventions can be synergistically combined as described in the previous paragraph for anaerobic digestion. Aggregated marginal benefits accruing from multiple circular economy measures that include a principal value intervention, are more likely to be available at large treatment facilities with multiple streams.

Smaller treatment facilities require a redevelopment of the current operating basis of technology to increase their returns on investment in circular economy interventions (see Section 5).

Summary of scale issue: *economies of scale dictate that the best returns in investment of resource efficiency investment for current assets will come from the largest water treatment and wastewater treatment facilities, and these will also deliver the largest sustainability benefits per project as they deal with the largest mass-flows. This means that water utilities can identify initial projects for optimum returns based on facility/operation size. However, on a local basis, small projects are always locally important. Resource efficient technology development (e.g. psychrophilic anaerobic whole-stream treatment for wastewater treatment) is likely to play a key role in increasing the returns for circular interventions for smaller operations.*

4.5. Key economic considerations for water business Circular Economy interventions: Market balance and business risk

Both large and small water treatment works/wastewater treatment works have significant exergy inflow and exergy consumption. The energy resources and material resources that are utilised in treatment are part of a materials and energy balance within which water coming into treatment also acts as a carrier for materials that need to be removed to give production quality water or wastewater of the required quality. Materials removed by treatment processes can potentially be recovered and processed to recover value from them. Value recovery can be provided both in terms of energy and materials.

In water treatment the influent water abstracted is typically of a high level of quality so the potential for energy recovery from feed water is most likely to come from physical measures such as energy recovery turbines. For water treatment works, the best prospects for value recovery are likely to come from new technology for treatment of residuals (principally water sludge generated in treatment). For water treatment the most significant resource utilisation efficiency gains overall that deliver best sustainability are likely to come from new approaches to water resource utilisation and management but there is still a basis for potential value recovery from waste streams at large water treatment plants.

In comparison, municipal wastewater is characterised by the chemical and physical attributes of human wastes. These have sufficient organic carbon content to make energy recovery possible. On small wastewater treatment works, technology is now being developed that could recover energy from whole-stream treatment with that technology. At large wastewater treatment works this shift in technology is not necessary if the treatment plant includes anaerobic digestion, because residuals recovery at these facilities is already energy efficient (Palmer, 2014). Both water and wastewater treatment requires physical work, operating with treatment systems which have substantial mechanical equipment that has a large energy demand. Consequently, there is an opportunity for renewable energy generation in water treatment or wastewater treatment for energy that can be used in the treatment operation, to reduce its operational carbon footprint and contribute to utility carbon targets and make savings on power purchased. This is an example of an internal market for a recovered resource. Any displacement of grid-supplied electricity will consequently create a cost benefit equivalent to the current power grid sale price for that power supply, plus the value of the carbon emissions reduction to the utility. In comparison, selling renewable electricity recovered from water utility operations on the external market cannot achieve the same value as the internal market, because other organisations pass the cost of their operations, on-costs, risk and margin onto the product value. For example, while the internal market for electricity displacement is typically 10p/kWh, the external market will only pay approximately 45% of that for renewable power to the power generating utility.

The internal market for circular economy interventions that provide renewable energy is strong as the work requirements and associated energy requirements of treatment are high. The water sector uses approximately 2% of UK national power demand. The internal market demand for this resource has longevity: treatment energy demands are likely to increase rather than decrease in future, due to population growth and due to any need for additional treatment to remove more pollutants in future and/or remove them to a higher degree. Any strong internal market for recovered resources that circular economy interventions secure should be used by a water utility in preference to the external market because:

- demand on the internal market is well understood and managed by the water utility itself
- external markets are higher risk to trade in than internal markets, especially under volatile market conditions
- external markets typically set contract requirements that introduce risks that internal market use of a resource do not, such as minimum supply requirements and penalties for non-performance on supply,

- external markets will involve introduction of on-costs, margin, etc. from other organisations involved in trading the commodity which reduce the value to the utility
- these risk factors tend to reduce the value of the resource being recovered, reducing the return on any investment and increasing the payback period for the investment.

In summary, circular economy interventions seek to increase resource efficiency, through:

(i) **Increasing the resource utilisation efficiency** of an operation, hence reducing the resource demand of the operation including the resource demand used to make the mechanical systems utilised in an operation (also reduces the resource use intensity of an operation).

(ii) **Increasing the life of resources in the economy**, which translates into increasing the operational life of resources used in water utility operations, (also reduces the resource use intensity of an operation).

(iii) **Reducing the net resource demand of an operation** by recovering resources from wastes which the current operation generates and recycling them in the economy.

These interventions have a common *physical* accounting basis in thermodynamics, provided by exergy flow. It can *fully* account for the resource cost of a project and operation in physical terms where the complete exergy data is available. Currently it is not, and is unlikely to be so in the future. However, even partial exergy analysis is a major improvement in resource analysis because it defines a project and operation in relation to its environment through physical systems analysis and because it gives a better explanation for capital costs and the use of resources in the construction of capital assets for a project. Although the current linear economy costing approach fails to incorporate externalities in its costs, market capital costs still do partially reflect *history* of physical structure production.

5. Water treatment: Circular Economy Measures

The core philosophy of the circular economy is maximising the efficient use of resources. Increasing resource efficiency is achieved by increasing the efficiency of use of a resource. Recycling materials into the internal economy of the water utility or into the wider external economy increases efficiency of use of a resource, and prolonging the life of viable operational assets is a resource recovery intervention as it prolongs the life of those materials in the economy.

Multiple circular economy interventions can aggregate benefits (in thermodynamic terms because the exergy benefits from multiple interventions are summated) so the best circular economy interventions will not usually consist of one change in operational practice or one isolated upgrade of technology. For water utilities, those resources include energy and materials. Energy efficiency interventions are hence also circular economy interventions and should always be considered as part of circular economy assessment due to the impact on climate change. Exergy theory also accommodates the use of information to leverage increased resource efficiency. Consequently, obtaining more information on an operation and using that information to increase the efficiency of an operation is a circular economy intervention that is part of the multiple interventions that should be deployed in circular economy best practice. *Therefore, online data acquisition, real time control and use of online information and technical experts are also part of circular economy improvements.*

Circular economy approaches in water treatment have currently been considered in some depth for management of water resources but are relatively undeveloped in terms of resource efficiency and resource recovery for water treatment operations.

Systems engineering will provide best engineering practice for water utilities for redeveloping assets in circular economy interventions.

Figure 10 in Section 4.1 presented the Ellen MacArthur Foundation/CE100 Group view of water resource management. There are two routes proposed for how water resources are managed: the water abstraction and processing current route which CE100 term the ‘human’ route and an alternative ‘natural’ route in which attention is focussed on water resource services that can be secured through use of ecosystem services provided by natural systems.

This strategy can provide a water utility with a platform for new business development including use of natural systems and ‘engineered’ natural systems for functions currently only managed defensively by UK water utilities – such as flood risk management.

These approaches can help water utilities meet service performance goals such as:

- water resource sustainability and minimizing or avoiding abstracting freshwater above its natural rate of replenishment

- better management of water losses due to distribution losses and end-use inefficiencies (water losses and inefficient irrigation) through a new focus on water utilisation efficiency
- proactive interventions in flooding prevention schemes that can provide their own ecosystem services
- management of water pollution risk and how pollution limits its utility.

Examples of circular economy water resource management with artificial and natural systems that UK water utilities could adopt – subjection to regulation – are given here.

<u>Circular economy interventions in the water resource abstraction arena of operations</u>

Total water demand often rises in modern cities as the result of population increase even if specific water demand remains at a similar level to today or reduces. Reduction in per capita water use *is* possible: Spain and Denmark, for example, have reduced per capita consumption to 100 l/hd.day from higher levels without greywater recycling or rainwater harvesting through water efficiency measures (Waterwise, 2016).

Increased water efficiency measures could lead to wastewater becoming more concentrated. Although per capita water demand and return to sewer demand will most likely decrease in future, significant population increase in major city areas will increase the total water demand for such communities.

As water demand rises and water supply becomes more constrained, sewer mining may emerge as an acceptable reuse, if local point use of water is reserved for recreational facilities using water for irrigation, for example. Such systems have been successfully applied in the Middle East (or other countries with much scarcer water resources), often as part of a centralised treatment system for a whole city rather than fully decentralised localised treatment. In future, possible microsystem developments could include household recycling and rainwater capture leading to reduced rate of return to sewer, more industrial pre-treatment for energy and resource recovery by industry, sewer capital maintenance 'debt' plus the risk of sewer flooding will combine to increase the risk of separation of foul sewage from municipal drainage systems.

- **Example:** Direct water reuse for potable water

Direct water reuse was first introduced in the Namibian capital, Windhoek, in 1969 because of a severe drought. Initially, direct reuse incorporated blending with the few resources available: average exposure to reclaimed water was 292 days over a 17 year period. A 1987 review of quality control studies showed that drinking water quality conformed to accepted standards. Subsequently, direct water reuse has increased to 100% for the catchment served by the New Goreangab Water Reclamation Plant. This is currently the only plant in the world that produces recycled water of a potable standard for direct use in potable systems. Since 2002, Namibians have been able to supply 100% of their potable water demand from recycled water from a new 21 Ml/d ultra-filtration plant. An effective public awareness campaign by Namibian authorities, combined with a lack of a viable alternative potable source, has enabled the practice of direct water reuse to be widely accepted by Namibians.

- **Example:** Water reuse in water-limited regions:
  Middle East water reuse for irrigation or recharge (replenishment)

There are many large scale reclaimed water projects in the Middle East due to water limitations where the alternative to water resource limitations is desalination. Reuse typically occurs in the Middle East via either indirect potable reuse or, more typically, for agricultural or horticultural irrigation. A megaproject example is the Sulaibiya Wastewater Treatment and Reclamation Plant in Kuwait. Sulaibiya supplies reclaimed water from municipal wastewater to industry, agricultural irrigation and aquifer recharge. The facility is designed to ultimately meet 26% of Kuwait's entire water demand, by providing approximately 82% of Kuwait's 142 million cubic metres per annum non-potable water demand. The wastewater source is Kuwait City and the project has an initial capacity of 375,000 cubic metres per day municipal wastewater, extendable to accommodate up to 600,000 cubic metres per day. The project cost approximately US$430 million and is serviced by a BOT (build-operate-transfer) contract in which the winning bid from the successful concessionaire, UDC, set a water supply tariff of US$0.47/ cubic metre. On this basis the projected revenue for UDC over the thirty year concession is in excess of US$2000 million. In Qatar, the wastewater treatment carried out for the capital Doha, and its drainage system, is all intended for reuse as irrigation water to standards set for irrigation equivalent to current international irrigation water quality standards by the Doha Public Works Authority (PWA). The Doha Drainage System currently serves a residential population of 641,000 with several municipal wastewater treatment plants and a separate treatment system PWA have established for industrial wastewater, to safeguard the irrigation end-use intended for recycled treated effluent.

- **Example:** Water Reclamation/US Practices

In the United States, several states suffer water stress and California has sponsored projects for water reclamation including indirect potable reuse by treated wastewater being supplied to aquifers or reservoirs. A 2007 survey of these projects concluded that all US potable water supplies were now allocated and competition is now developing for reclaimed water. The survey also concluded that the technology to exploit these resources was already available: the limiting factor to its development was public resistance. As for direct reuse in Namibia, successful indirect potable reuse projects required careful public engagement from inception to delivery and into operation.

In addition to the circular economy interventions practised in artificial systems, there are options for circular economy interventions in water resource management for water utilities that arise from the use of natural systems. The CE100 Water Group has identified the following ecosystem services being available for a water utility employing 'Nature Managed Systems' for water resource use:

- **Re-optimisation** (keeping water in natural system circulation to maintain an ecosystem and its biodiversity)
- **Reuse** (inherent water pollution remediation offered by a natural system)
- **Replenishment** (cycling water back into the environment).

- **Example:** Replenishment: Managed Aquifer Recharge

Aquifers can be recharged with good quality final effluent from municipal wastewater treatment by using infiltration basins. The treatment achieved in infiltration is best assessed by piloting the wastewater discharge via a pilot scale infiltration system to establish the filtration and other further wastewater quality improvements obtained by use of infiltration basins. Trialling will also help identify the required system maintenance and its costs. This is a potential circular economy intervention that could be adopted to recharge or minimize the stress on over-abstracted aquifers. For example: San Luis Rio Colorado, Sonora (Humberto et al., 2018)

- **Example:** Replenishment: Water stress alleviation:
  CE100/Ellen Macarthur Foundation Reference project - Italy Canal Replenishment (Bologna)

The water utility Hera and local authorities are operating a canal replenishment scheme to ensure that local agriculture has access to water for irrigation by uprating part of the local municipal wastewater treatment plant discharge and using that flow to balance the flows in two canals from which local farmers also withdraw flows for irrigation.

- **Example:** Upstream water risk management and catchment risk management:
  CE100/Ellen MacArthur Foundation Reference project - Upper Tana-Nairobi Water Fund.

The Tana River supplies 95% of Nairobi's 4 million residents and feeds the country's agricultural areas. For the last 50 years forest clearance of the previously forested slopes of the Upper Tana catchment for use by agriculture has created severe solid washout conditions leading to high annual desilting costs. The Nature Conservancy established the Upper Tana Water fund in order to reduce the loss of the ecosystem services that forests provided for the Tana water catchment. The fund and its partners worked with nearly 15,000 farmers providing the training, resources and equipment that converted local farming practice to minimize spoil loss. In thermodynamic terms, any solution developed further upstream of problem emergence has an inbuilt exergy efficiency advantage as the further downstream of a process a problem is allowed to progress, the greater the exergy flow is and the greater the work requirement is to provide a solution. Upstream water risk management projects on the scale of a river catchment should be adopted by water utilities as catchment-based approaches are more integrated and resource efficient due to their opportunity to intervene at source and manage pollutant masses across their entire catchment distribution. *In the UK, the Water Framework Directive (WFD) encourages catchment-based solutions.*

Water Efficiency Education

Water utilities can encourage water efficiency in their customer base at end-use by combining metering with advice to customers (tailored to household, industrial and commercial uses) on how to reduce water demand and billing, and providing water footprint related information. If such information is also supplemented with information providing context for how investment costs and billing may rise if water demand is not minimized, and that overview also incorporates the negative effects of local water stress on customers' local water-resource environment and its associated biodiversity, it is more likely to encourage good water management at end-use.

Water utilities should also take opportunities to introduce water efficiency measures in their own use of water in their operations and where possible cite the environmental benefits from such interventions, to lead any such initiatives by example.

Consultation and proactive customer engagement on the advantages to all stakeholders of increased water reuse should also be used to initiate and develop water reuse pilot projects for water resources. Water utilities can do so by working with institutions such as Water UK, British Water, CIWEM, UKWIR and the Ellen MacArthur Foundation/CE100, as well as with local universities active in water research and development of the circular economy in the local economy.

Water Reuse Guidelines

Until this year, one of the barriers to water utilities implementing water reuse projects was the lack of European Standards for water reuse. This year, the EU published its first EU-wide regulations for water use *Regulation (EU) 2020/741 on minimum requirements for water reuse.* In addition, UK water utilities can refer to these UKWIR reviews of water reuse options:

- UKWIR Report 14/WR/29/3 (2014): Establishing a robust case for final effluent reuse: an evidence base
- UKWIR Report 14/WR/29/4 (2015): Establishing a robust case for final effluent reuse: testing the UK regulatory framework
- UKWIR Report 05/WR/29/1 (2005): Framework for developing water reuse criteria with reference to drinking water supplies.

Water UK has published a guidance document for water reuse in households ('Water reuse systems, guidance and advice', Water UK and Home Building Federation) which reference the British Standards (2009, 2010) for household water recycling. This is an example of a guidance document that water utilities could make available on their own websites, supplemented with their own advice to their domestic customers or they could provide advice in media campaigns to encourage water reuse by their domestic customers. Water utilities can obtain other water reuse guidance for water reuse initiatives from Water UK, Defra and the Water Efficiency in Buildings Network.

Partnerships with Commerce and Industry: Water Utility-Industrial User Synergy

The cost of water for industrial and commercial users is likely to rise in future with rises in the cost of energy and materials, due to demand increasing. Climate change itself is a driver for increased water demand unless mitigated by water resource efficiency measures. These risks create an opportunity for UK WaSCs to provide water efficiency and related resource efficiency and recovery services for industrial customers. Energy services developed for water resource efficiency for use in industry could also then be applied to water treatment and wastewater treatment operations, and methods such as PINCH analysis (e.g. Brouckaert and Buckley, 2002) used in utility operations as systems engineering tools.

Treatment at source by industry also reduces the overall cost of treatment of recalcitrant materials, xenobiotics and priority pollutants if wastewater streams containing them can be treated at the production site before they become diluted with other wastewater streams. Some technologies already exist for both resource recovery from processing such streams (e.g. wet oxidation and supercritical wet oxidation). In the latter case, energy and material recovery is possible (for example, the AquaCritox process).

The CE100/Ellen Macarthur Foundation White Paper of 2018 also provides three examples of industry reducing significant local water demand to reduce its water costs (one for a power station, Matimba Power Station in South Africa moving to lower water use for cooling; two for textile companies increasing their water use efficiency and reducing their water demand – in Tirupur and Taiwan).

Several industries already practice their own pre-treatment of wastewater before discharge to sewer, to include energy recovery, such as breweries. Renewable energy recovery can be extended to on-site material and energy recovery including water recycling, to minimise operational costs for industrial users. For industrial customers, especially those with organic waste streams, significant energy and operating cost benefits can accrue from a resource recovery approach which also incorporates water efficiency measures and water reuse across their production facility.

There is guidance available for industrial water users considering water reuse (e.g. Waste and Resources Action Programme (WRAP, 2010c).

5.1. Circular economy interventions in the water treatment area of operations

Circular economy interventions seek resource efficiency, which is why systematic application of circular economy principles and solutions in water treatment can inculcate a culture of operational efficiency in water treatment operations for water utilities.

Systems engineering will provide best engineering practice for water utilities for redeveloping water treatment assets in circular economy interventions.

In Section 4 of this ROCK, long term asset development drivers were discussed. They can be summarised in terms of the major trends for circular economy technology deployment and development in water treatment as follows:

(i) Large water treatment works have capacity (mass flow) advantages in terms of resource efficiency and any possible resource recovery. This material flow factor provides asset managers with an economic Pareto efficiency that can be exploited in planning: less than 20% of the total number of (large) water treatment works do more than 80% of the overall water treatment work across the asset base. These large works present the best opportunity (market entry point) for converting the water utility water treatment business line to a circular economy operation for the smallest number of projects. As such, systematic circular economy interventions in this population of water treatment works would allow a water utility to uprate the bulk of its water treatment assets to circular economy operations in the quickest time.

(ii) The circular economy principle of keeping assets in the economy for as long as possible combined with operational efficiency supports water utilities return on capital and securing best TOTEX outcomes.

- **Example**: *Systems engineering approaches: minimizing the physical structural energy and operational efficiency e.g. materials demand of projects.* **Projects maximizing the efficient use of resources are circular economy interventions.**

There is a generic basis for circular economy interventions in water treatment in terms of reducing the exergy demand of building the physical structures that constitute the assets. Circular economy measures seek to increase the resource efficiency of an operation and will change the water utility operation into one having a lower exergy burden which may also provide an asset with a lower exergy intensity. The advantage this gives the water utility is that the operation can provide ‘more for less’ – it is uprated to a lower TOTEX operation through increasing the efficiency of its resource use. **A circular economy intervention that thermodynamically achieves a lower exergy demand for an operation and/or a reduced exergy intensity is a project that obtains ‘more for less’.** There are many generic examples already pursued as best practice by water companies including energy efficiency projects. **Digital monitoring and control systems** such as real-time control provide an *operating system feedback* that can react to changes in process flow and load, further increasing the efficiency of use of a resource. In **chemical dosing**, real-time control is also able to optimise chemical demand in response to changes in demand of the treatment process, on the same basis. Resource efficiency improvements can also be secured by *managing resource value variation*, for example through managing supply and demand cost risks in the external market by measures such as Demand Side Response for electrical power (e.g. UKWIR best practice on demand side response, see Figure 20).

UKWIR Energy Demand Management Tool

Intervention Summary Dashboard

Average Daily Energy Profile

Baseline		32,033	kWh/d
Intervention		31,714	kWh/d
Difference		*-319* ▼	*kWh/d*
Baseline	£	3,270	daily
Intervention	£	3,222	daily
Difference	-£	*47.92* ▼	*daily*

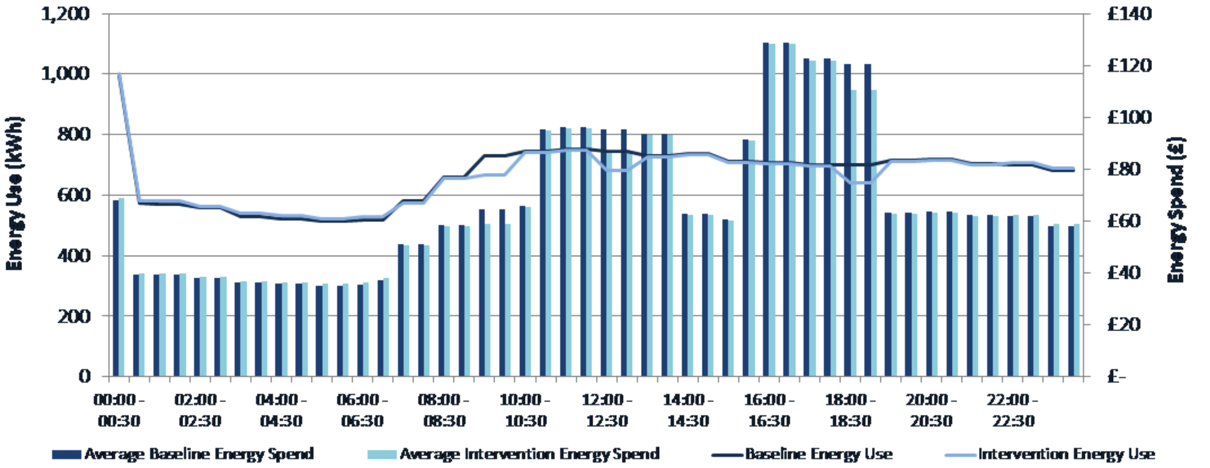
(Using annual average cost rate)

Grid Demand Response Summary

Grid Demand Benefit	£	534	/yr
Grid Demand Respons	£	21	/yr
Difference (Net)	-£	*513* ▼	*annually*

Annual Summary

Baseline	£	1,193,441	annually
Intervention	£	1,175,438	annually
Difference	-£	*18,003* ▼	*annually*
Baseline	£	4.4202	/PE
Intervention	£	4.3535	/PE
Difference	-£	*0.0667* ▼	*/PE*



	Jan.	*Feb.*	*Mar.*	*Apr.*	*May.*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*	***Total***
Grid Demand Response Benefit	£ 133	£ 133	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 133	£ 133	**£ 534**
Grid Demand Response Cost	£ 5	£ 5	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ 5	£ 5	**£ 21**
Difference (Net Benefit)	*-£ 128*	*-£ 128*	£ -	£ -	£ -	£ -	£ -	£ -	£ -	£ -	*-£ 128*	*-£ 128*	*-£ 513*

Return to Intervention Generator

Figure 20 Example of UKWIR Demand Side Response intervention for a water treatment works

Notes Reducing total annual energy demand by 21.4% for a 440MWh/year demand and delivering a 34% saving on power cost (in this example worth £171.8k/yr for the plant capacity shown) Stantec/AMERESCO.

- **Example**: *Systems engineering approaches: optimizing the maintenance requirements of assets.*

For circular economy interventions, maintenance should not be optimised simply to keep down maintenance cost viewed in isolation, but rather to optimise maintenance in terms of impact on the environment through its lifetime and to optimise the lifetime of the asset to keep it in service as long as possible. In circular economy interventions, maintenance costs should never be considered in isolation but only optimised in terms of project whole-life cost over the project lifetime, to also include accounting for externalities such as local environmental impact and global environment impact (e.g. climate change impact/carbon emissions).

- **Example**: *Systems engineering approaches: Water Resource efficiency projects.* **Projects maximizing the efficient use of water within water utility operations**

Any project or intervention that optimises resource efficiency – either energy or materials, will change the water utility operation into a one having a lower exergy burden and may provide an asset with a lower exergy intensity. The advantage this gives the water utility is that the operation can provide 'more for less' – it is uprated to a lower TOTEX operation through increasing the efficiency of its resource use and this principle also applies to systematic use of water footprint data in water utility operations and to inform customers of the risks of water wastage. Increased deployment of monitoring and control systems in water distribution networks, more use of new digital services for water supply management including real time control system incorporating feedbacks on operational efficiency and underperformance alarms, supported by appropriate (expert-led) big data analyses of water supply efficiency, should all be deployed systematically in water supply operations (and water treatment) to systemise water production and supply resource efficiency measurement. This should include widespread use of a water footprint efficiency measure showing, for example, cost to abstract a cubic metre (approximately a tonne) of water, cost to supply a cubic metre of water to end-use, and the litres of water lost between abstraction and end-use.

- **Opportunity**: *Water treatment resource recovery: energy and reagent recovery*

Water under supercritical conditions can be used to obtain complete oxidation of wastes. This process is termed Super Critical Water Oxidation (SCWO) and it can eliminate all organic content and the potential energy of the organic material can be utilized via energy recovery. SCWO itself has a high energy demand, requiring water at high pressure and temperature, and hence to achieve a positive energy output (produce an energy surplus) requires an organic content higher than 3% for the waste feedstock. The energy produced can be recovered as steam or hot water. The AquaCritox process is an example of this technology. Supercritical conditions for water are attained at 221 bar and 374^{o}C. The AquaCritox process consists of a waste (sludge) holding tank, high pressure transfer pump (250 bar) into the supercritical reaction chamber at 400^{o}C. The supercritical reactor attains 600^{o}C with oxygen injection. Process heat is provided by use of natural gas and surplus energy is recovered through a steam boiler/economiser. Water treatment sludge fed into the process is fully oxidised. The inorganic components remaining after SCWO for recovery from water treatment waste sludge for reuse include the metal coagulants and phosphorus. This technology is currently supported by an EU strategic technology development budget and has eight ongoing projects for energy and resource recovery globally, worth €200MM. The process is also applicable to wastewater sludge.

- **Opportunity**: *Water treatment resource recovery: mining waste sludge for coagulants*

Water treatment operations use significant amounts of coagulants based on metals. These metals are present in the waste sludge from water treatment. This waste could present a source for metal coagulants for wastewater treatment operations using chemical dosing for phosphorus removal after minimal processing (washing, acid washing, etc.).

- **Opportunity:** *Resource recovery: electrolysis of water for renewable energy recovery*

Hydrogen is currently being developed as the basis of an island energy economy for the island of Orkney and is a central element in national energy supply planning for Japan. The technology that has most advanced hydrogen as a renewable fuel recently is water electrolysis to form hydrogen. This is a possible application for surplus water production or an alternative resource generation from potable water produced from water treatment. For water treatment works adjacent to existing wind farms and/or with land available for solar PV panel deployment, renewable power could be used in a joint venture with renewable power suppliers to generate hydrogen from demineralised potable water by electrolysis during periods when renewable power generation exceeded demand. Alternatively, in future, a large water treatment operation might invest in its own solar PV, wind power and energy recovery turbines to meet site power demands and periods of surplus power generation, store energy as hydrogen for later reuse via fuel cells.

6. Wastewater Treatment: Circular Economy Measures

The core philosophy of the circular economy is maximising the efficient use of resources. Increasing resource efficiency is achieved by increasing the *efficiency of use* of a resource, including reducing the demand for it in an operation and also achieving a net increase in the resource value balance for an operation by recovering materials of value from wastes generated in the operation.

Recycling materials into the internal economy of the water utility or into the wider external economy increases *efficiency of use* of a resource and prolonging the life of viable operational assets is a resource recovery intervention as it prolongs the life of those materials in the economy.

Multiple circular economy interventions can aggregate benefits (in thermodynamic terms because exergy benefits from multiple interventions are summated). Energy efficiency interventions are hence also circular economy interventions and should always be considered as part of circular economy assessment due to the impact of climate change.

Obtaining more information on an operation and using that information to increase the efficiency of an operation is also a circular economy intervention. Therefore, online data acquisition, real-time control and use of online information and technical experts are also part of circular economy improvements.

Circular economy interventions seek resource efficiency. There are two principal approaches to increasing resource efficiency:

(i) Increasing the efficiency of the utilisation of the resource (for example, increasing the specific efficiency for how the resource is used, increasing its lifetime in the economy, recycling, etc.). For material resources this includes improving the efficiency of processing work as that reduces work required per kg of resource the operation needs, which in turn reduces energy demand for any mechanised operation, consequently also delivering climate change mitigation benefits.

(ii) Converting wastes produced into resources of value (e.g. application of the waste hierarchy, Figure 8, Section 3) from which value can be recovered. That value can be recovered in the external market or can be recovered, typically at lower risk to value in the same water utility operation or another water utility operation – that constitutes an internal market for the resource recovered. For some resources net value can only be recovered in the water utility – they only have a positive internal market value as a resource.

A consequence of the second value proposition (resource recovery) is that wastewater treatment offers more opportunities for circular economy interventions than water treatment because wastewater carries a far high concentration of materials and so presents a greater material source than water. The UK water utilities that will be able to exploit these opportunities are the 10 Water and Sewage Companies (WaSCs) in England and Wales and the two other WaSCs serving Scotland and Northern Ireland.

Systems engineering will provide best engineering practice for water utilities for redeveloping wastewater treatment assets in circular economy interventions.

The Ellen MacArthur Foundation/CE100 Group White Paper of 2018 describes how a systems approach should integrate parts of the wider economy when considering circular economy interventions, such as likely developments in urban development. This is good practice – the equivalent of future-proofing asset development for water utilities, meaning that resilience is then built into the consideration of circular economy interventions. Such assessment should also consider at least the general direction of technology development trends. One of the major current trends for technology development for water utility operational efficiency comes from obtaining more operational information – Information Technology advances.

Consideration of ***operational resilience*** *in circular economy interventions is a key factor in sustainability as it minimises the risk of asset stranding, of assets being prematurely written off – which results in extra use of resources than was necessary for an operation. Best practice for consideration of operational resilience requires it to be broadly based and to include consideration of climate change risks.*

A possible future scenario for wastewater treatment in the UK is one of reduced domestic flows combined with decentralisation at small to medium works and rationalization/ consolidation of urban assets to maximise returns for bioresource recovery.

Climate change and marginal increases in sewage temperature will also increase the risk of sewer septicity and odour, especially when combined with the risk of longer DWF periods and increased sewer bed mass accumulating in those periods in summer. This combination of factors will reduce the efficiency and increase the difficulty of operation of conventional gravity sedimentation based primary treatment.

The sewer network of the future could be digitally integrated and controlled from the sewage works (see section on control and data systems) with most operations automated. Any sewers with balancing capacity, as in sewer tanks, or sewer storage volume, will be fully monitored and integrated with operations at the sewage treatment site. In future, the sewer bed and sewer temperature and ORP (oxidation reduction potential) and ammonia and organics levels will be monitored within the sewer system at key points. This might include turbidity measurements and/or solids probes and estimated levels, volumes and hence mass of the sewer bed. Resilience monitoring and management systems would be expected to take such information and use it to configure a RAG (alarm signal) status for treatment plants operating risk based on current plant capacity (such as solids processing headroom) against the sewer bed level/DWF period duration.

Control and data systems

In future it is likely the operational information management for wastewater treatment will become more integrated between sewer network, treatment and receiving waters, and that the sewer could be monitored and controlled as far as possible to maximise treatment plant resilience and headroom. Plant headroom is a dynamic, shifting property in practice and can increase or decline based on the performance of individual treatment units in series and their actual real time capacity and availability. One method of setting headroom is to set a static threshold. The problem with the static target approach is that the safety margin is then always set and may often be excessively high, resulting in average cost to treat being higher than would be the case if a lower safety margin could be utilised.

Dynamic benchmarking provides an answer by shifting both the performance register and the baseline in response to actual plant status in real time. There are already dynamic benchmarking systems deployed successfully in the water industry (e.g. Figure 21). In future, utilities will need to capture data and keep online, real-time assessments of the status of their facilities and their assets, most likely through centralised data systems serving both the water and wastewater asset bases.

Incremental investment approaches, to maximise returns on capital, have delivered lower cost solutions for new wastewater quality drivers in the past. In future it is possible that semi-autonomous plant will have emerged facilitated by digital technology and IT, including real time control (RTC) systems in which plants will be self-diagnosing in the sense that sensor array used by AI (artificial intelligence) can direct proactive intervention in plant operation. This could significantly increase resilience. Operational staff are still essential in these scenarios but repurposed as proactive plant managers and monitoring and control systems specialists.

Optimised information production and management will increase the range and number of circular economy interventions a UK water utility can make.

- **Case Study** for economies of scale in resource recovery from wastewater treatment

Physical Systems' Constraints on Asset Investment Strategy. For a small works upgraded to anaerobic whole-stream treatment, the likely cost of such technology translation and the savings deliverable from asset operating costs overall from smaller works operating costs, would tend to be minor in terms of overall cost of operation of *the whole asset base*. Psychrophilic anaerobic whole-stream wastewater treatment has already been shown to be less cost effective than a combination of primary treatment, activated sludge and advanced digestion facility for works above 300,000 PE capacity even without including re-aeration costs for the discharge. On smaller works which lack primary treatment and/or anaerobic digestion, or advanced digestion, psychrophilic anaerobic whole-stream wastewater treatment can contribute a positive energy above that of the current technology baseline.

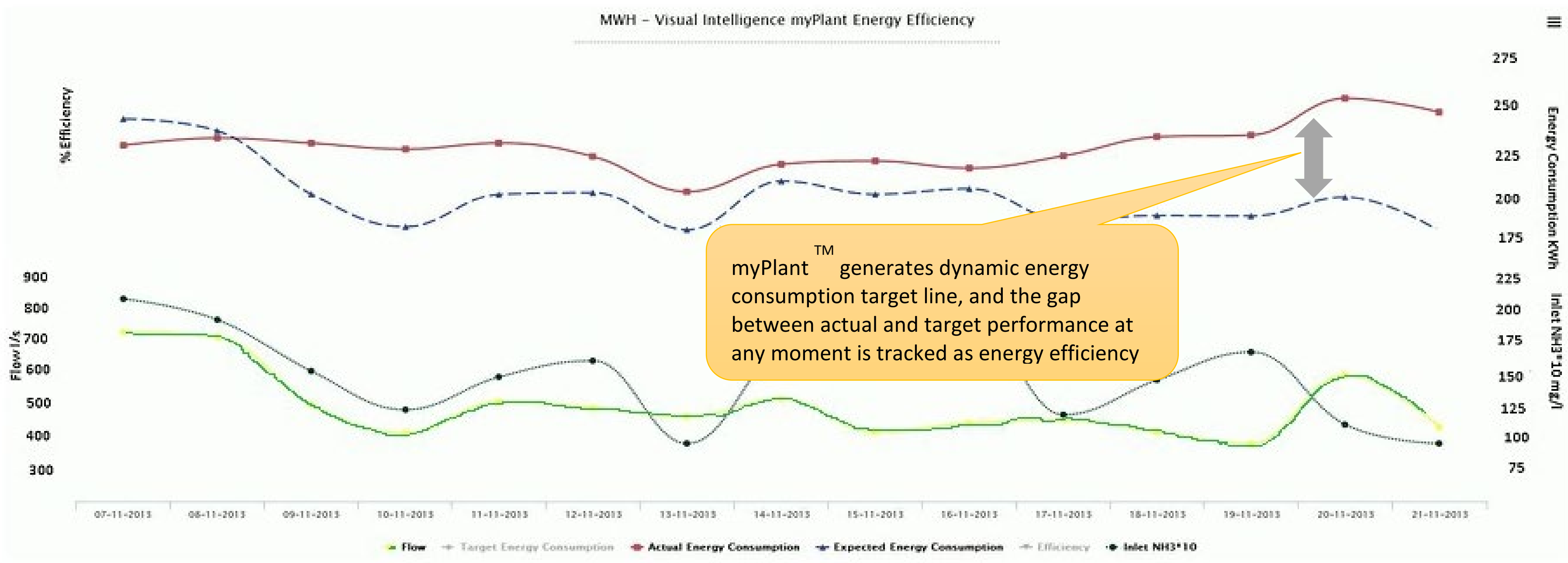


Figure 21 Example of dynamic benchmarking in wastewater treatment by use of a digital twin (myPlant)

Notes: Digital technology is also a platform for achieving circular economy benefits by increasing the resource efficiency of operations.

6.1. Circular economy interventions in the wastewater treatment area of operations: wastewater treatment

As mentioned in Section 5.1, circular economy interventions seek resource efficiency, which is why systematic application of circular economy principles and solutions in wastewater treatment can inculcate a culture of operational efficiency in wastewater treatment operations for water utilities. Systems engineering will provide best engineering practice for water utilities for redeveloping wastewater treatment assets in circular economy interventions.

In Section 4 of this ROCK, long-term asset development drivers were discussed. They can be summarised in terms of the major trends for circular economy technology deployment and development as follows:

(i) Large wastewater treatment works have capacity (mass flow) advantages in terms of resource efficiency and resource recovery. This material flow advantage also presents water utility asset managers with a capital investment (and TOTEX) economic Pareto efficiency. These large works present the best opportunity (market entry point) for converting the water utility wastewater treatment business line to a circular economy operation for the smallest number of projects. As such, systematic circular economy interventions in this population of wastewater treatment works would allow a water utility to uprate the bulk of its wastewater treatment assets to circular economy operations in the quickest time.

(ii) The circular economy principle of keeping assets in the economy for as long as possible combined with operational efficiency supports water utilities return on capital and securing best TOTEX outcomes.

(iii) Small to medium wastewater treatment works have capacity (mass flow) restrictions on their resource recovery opportunities. Gathering resources from multiple small works faces the same transport challenges (costs) as current UK WaSC sludge businesses experience (see Section 6.2.1) and transport is also a significant carbon emissions burden. Technology development is needed that can secure a higher degree of resource efficiency and resource recovery at the small to medium capacity treatment site while also maximising the asset value of any existing assets. The most probable technology development that could meet these targets across most of these facilities is psychrophilic whole-(wastewater) stream digestion. Its use for treatment of organic carbon removal then frees up existing, low energy demand assets such as trickling filters for repurposing for nitrogen removal (principally nitrification).

(iv) Large Wastewater treatment works that are also large Sludge Treatment Centres have capacity (mass flow) advantages and a co-located internal market for renewable power, renewable energy and even some renewable materials (such as VFAs (volatile fatty acids) for Bio-P removal) that makes them a high value opportunity and lower risk investment target for maximising circular economy opportunities.

There are a range of more sustainable wastewater treatment options already deployed that UK water utilities could adopt, with the examples shown.

- **Example**: *Systems engineering approaches: Operational efficiency projects.* **Projects maximizing the efficient use of resources are circular economy interventions.**

Any project or intervention that optimises resource efficiency – either energy or materials, will change the water utility operation into one having a lower exergy burden and may provide an asset with a lower exergy intensity. The advantage this gives the water utility is that the operation can provide 'more for less'. *A circular economy intervention that achieves a lower exergy demand for an operation and/or a reduced exergy intensity will operationally obtain 'more for less'***.** Generic examples of best practice by water companies include energy efficiency projects. Most wastewater biotreatment is currently aerobic due to the pollutant concentrations and temperature of municipal wastewater and the relative efficiency of aerobic microorganisms so **aeration** is a good generic example. The resource in demand is oxygen and uprating the efficiency of the oxygen delivery system for an aerobic biotreatment process reduces the work required to transfer the oxygen to wastewater which translates into a lower energy demand which confers both local resource efficiency advantages that are seen as reduced OPEX and global environmental impact reduction through reduced energy demand reducing fossil fuel use for electrical power. As with water treatment (Section 5), **digital monitoring and control systems** such as real-time control provide an operating system feedback that can react to changes in process flow and load, further increasing the efficiency of oxygen use (see previous Figure 20 for explanation). In **chemical dosing**, real-time control is also able to optimise chemical demand in response to changes in demand of the treatment process, on the same basis. Resource efficiency improvements can also be secured by *managing resource value variation*, for example through managing supply and demand cost risks in the external market by measures such as Demand Side Response for electrical power (e.g. UKWIR best practice on demand side response).

- **Example**: *Systems engineering approaches: optimizing the maintenance requirements of assets*

Similarly to water treatment (Section 5), for circular economy interventions, maintenance should not be optimised simply to keep down maintenance cost viewed in isolation, but rather to optimise maintenance in terms of impact on the environment through its lifetime and to optimise the lifetime of the asset to keep it in service as long as possible. In circular economy interventions, maintenance costs should never be considered in isolation but only optimised in terms of project whole life cost over the project lifetime, to also include accounting for externalities such as local environmental impact and global environment impact (*e.g.* climate change impact/carbon emissions).

- **Example**: *Systems engineering approaches: maximizing returns from primary treatment by microbubble DAF (dissolved air flotation)*

Primary treatment is one of the lowest carbon footprint treatment operations on a mass-for-mass basis, with the lowest operational carbon footprints of any other treatment operation. This is because the process relies on gravity to do its treatment work via sedimentation of particulates, and in municipal wastewater that removal of solids also accounts for almost half the oxygen demand load. Despite these high sustainability factors the process has a large footprint which translates into a high resource demand to construct the capital assets, and its performance also varies with hydraulic loading rate according to Stokes Law (due to it being a sedimentation process). The other performance risk associated with primary treatment is that for sewer networks where there is biological activity in the sewer, the septicity associated with that can cause production of hydrogen sulphide. In fact, when sewage temperatures rise in summer in temperate zones, sulphate reducing bacteria and their septicity can become established in the primary tank sludge blanket, especially if the hoppers are not desludged often enough. The problem with such activity is that sulphate-reducing bacteria form hydrogen sulphide and the largest surface area for the gas microbubble to form on is the solids in the sludge blanket. Buoyant solids can rise in the tank reducing PST (primary settlement tank) solids capture and the rising solids form a surface scum, often with odour being an associated problem. In tropical climates septicity in the primary tanks is closer to the norm. One answer to these issues is to move to uprate existing primary treatment to microbubble DAF. Primary treatment microbubble DAF has an instantaneous tiny production that in effect creates a foam that is highly effective at trapping solids in the DAF float – to 90% primary solids removal. The process is thus resilient to septicity risk, has a lower footprint and it can be retrofitted within existing primary tanks.

- **Example**: *Systems engineering approaches: Upgrading secondary treatment by integrating process intensification with resource recovery*
  Nereda low footprint biotreatment with biopolymer recovery

The Nereda process is a granular media based biotreatment in which large granular media formed under high specific organic loading is deployed for biotreatment. The high organic loading for media production results in a high proportion of heterotrophic activity occurring via floc-forming heterotrophic bacteria, including GAOs (glycogen accumulating organisms) and PAOs (phosphate accumulating organisms) which all have the genetic capability for exopolysaccharide (EPS) formation. The granule is thus a bead composed of EPS and bacteria and is larger and denser than activated sludge floc, resulting in high biomass densities (8 to 15 g/l compared to 1.5 to 4 g/l for activated sludge). Consequently, the process has a much smaller volume and footprint than activated sludge and it can be and is deployed in tanks as fast settling media bed. The Nereda process operates as a fed batch process like a sequencing batch reactor (SBR), but with fast settling media. It consists of reactors capable of being operated in a fill and draw manner, with flow introduced under the media bed, giving a plug flow process. This is followed by an aeration phase in which there is some expansion of the media bed; after aeration the media rapidly settles with good separation due to its density, so no decanting is required. The production of EPS by this system is a resource for recovery and Nereda now provide a ‘Kaumera’ system for value recovery from the excess biomass via a Kaumera Extraction Installation, as now deployed at Zutphan WwTW and Epe’s WwTW in the Netherlands. On a thermodynamic basis, Nereda offers the following advantages:

(i) It minimizes the exergy expended on a project to build the physical structures that provide the required treatment capacity because it is a combination of low footprint, high biomass concentration and a relatively simple structure for what it can achieve.

(ii) It has an operational efficiency advantage in being a media-based technology that does not require continuous solids sedimentation in separate settlement tanks or a decanting arrangement which confers a marginal resource efficiency advantage in operation.

(iii) It also allows for resource recovery of EPS as a material resource by the Kaumera Extraction Installation.

These resource advantages give the process an advantage in exergy efficiency over standard technologies. The combined exergy advantages in terms of the structure and capital cost and the net operational OPEX that can be obtained by maximising resource efficiencies translate into lower exergy projects – which means the local water environment gets the environmental protection it needs for a project that exerts less environmental burden on the global environment.

- **Example**: *Systems engineering approaches: upgrading existing activated sludge at large sewage treatment works that include anaerobic digestion*
  Maximising the life of existing assets

If designers and operators exploit the inherent strengths of the activated sludge process, it has the potential to persist as a mainstay of urban sanitation beyond the twenty-first century, for large urban applications at least. This is because the mass and energy balance for a conventional flowsheet for large works (≥250,000 PE) with primary treatment with energy recovery via biogas utilisation, combined with optimising the energy efficiency of the activated sludge process, can provide a better energy balance overall than converting the same plant to whole-stream anaerobic treatment (Palmer, 2014). A water utility can minimise activated sludge energy demand by optimising the number of aeration tanks and their capacity, optimizing the DO (dissolved oxygen) setpoints, operating at the optimum mean cell residence time (MCRT – sludge age) and optimisation of the internal pumping profile. The limit to these conventional approaches to energy efficiency is that they are only able to reduce whole works power demand by 20% on average. To extend activated sludge energy efficiency savings to 30% or greater, a more aggressive approach is required. This needs aeration and RAS (return activated sludge) flow to be minimised and best practice process monitoring and control to be deployed. Minimising aeration demand requires primary tank performance to be maximised. Biosorption capacity should be designed for, to minimise rbCOD (readily biodegradable chemical oxygen demand). The latter can be achieved through introduction of a selector or anoxic zones. Use of real time control systems can offer increased process energy efficiency and increased performance stability.

An example of this best technology practice approach is described in Figure 22. The interventions summarised in Figure 11 can reduce power demand for the process to 18-23 kWh/PE.yr for the whole works from a 32-80 kWh/PE.yr baseline. Efficient downstream waste processing in digestion then provides good energy recovery by use of combined heat and power (CHP) which at 250,000 PE gives an energy balance around the energy neutrality level. Alternative activated sludge flowsheets, such as the AB-activated sludge system at Strass WwTW, can achieve energy neutral operation at 200,000 PE when low energy demand liquor treatment is incorporated in the WwTW flow-sheet. Uprating anaerobic digestion to advanced anaerobic digestion can increase sludge processing throughout for the same footprint and further improve the energy balance. Even further energy recovery is also possible (e.g. heat recovery from final effluent).

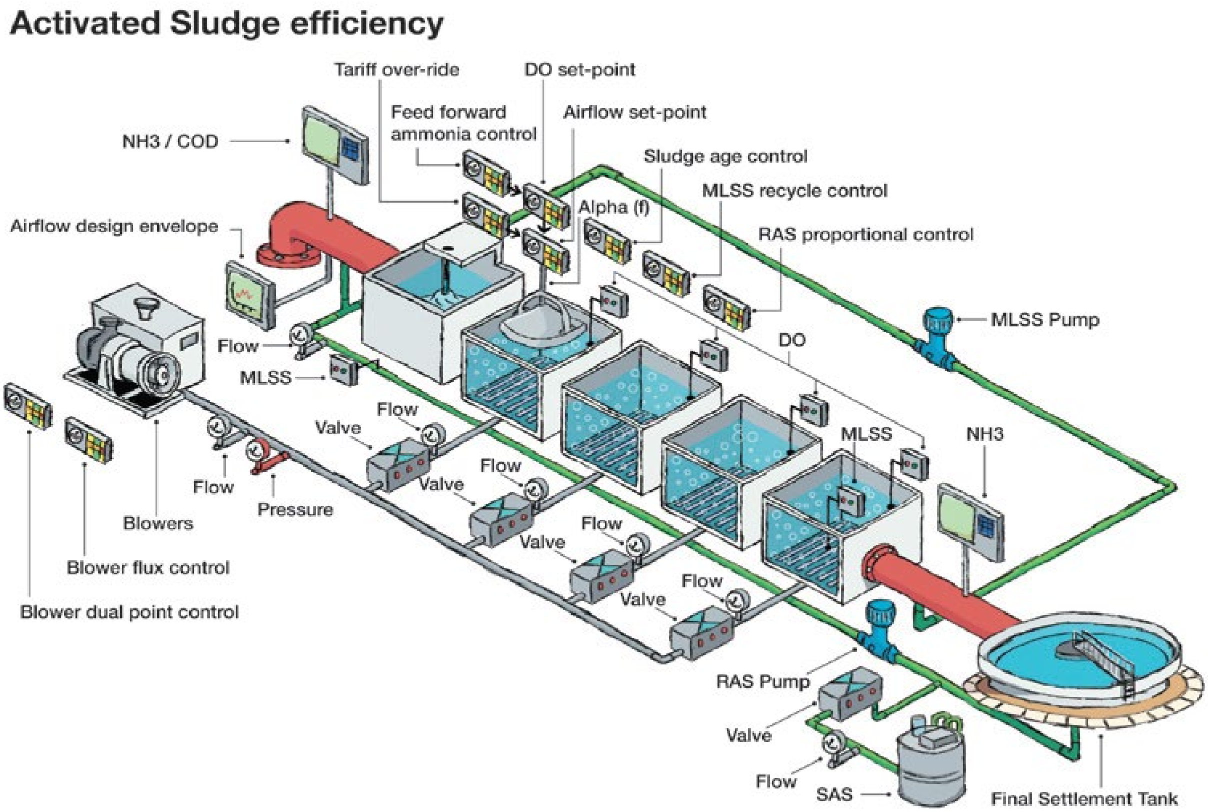


Figure 22 Optimizing activated sludge resource efficiency (oxygen and pumping demands) at large municipal wastewater treatment plants (Palmer, 2014).

- **Example**: *Systems engineering approaches: Upgrading side-stream/return stream treatment to high resource efficiency processes*
  Maximising the life of existing assets by introducing new tertiary or side-stream treatment units and/or resource recovery

Liquor return streams from treatment residuals' processing can add significant loads to wastewater treatment that can put plant operating headroom at risk. Introduction of efficient side-stream treatments are an opportunity to restore headroom in the main plant capacity and possibly recover resources. A range of technologies is now available to do so. For resource efficient side-stream/return liquor stream treatment, the SHARON process and DEMON process are available. Alternative processes under development that could provide resource recovery as ammonia include ammonia membrane treatment and ammonia stripping. Cranfield University have developed an ion exchange process for ammonia recovery and phosphorus recovery that could recover both in this application.

- **Example**: *Systems engineering for asset upgrading to keep existing assets in service longer by uprating their treatment efficiency*
  Tubli Water Control Centre, Bahrain

Tubli Water Control Centre was failing to meet its required wastewater quality compliance due to increase flow and load from an increase in the population served. The impact on the local water environment affected by the plant discharge (Tubli Bay) was oxygen sag, odour and high nutrient load impact which are all drivers for reduced biodiversity in that ecosystem . The existing activated sludge plant was uprated without increasing its landtake by adding Bluewater Bio HYBACS units to the front-end stages of the activated sludge plant. On a thermodynamic basis, this was a highly resource-efficient upgrade that translated into increased operational efficiency at the same time as minimizing the new physical structural build requirements. The latter translated into optimized returns on the capital investment to achieve the required performance improvements from the existing facility. The existing facility performance was significantly improved to well within the compliance requirements.

- **Example**: *Resource Recovery:* Grit recovery

Grit removed from wastewater treatment by grid removal systems is problematic if treated as a waste by a water utility as its likely disposal route is to landfill which creates an on-cost in combined transport and disposal costs wastes. The alternative is to recycle grit for use in the local economy. Grit cleaning systems are now readily available from a variety of suppliers to allow water utilities to twin them with their large WwTW grit removal systems and recover the grit fraction for which there is a reuse market. In the UK the principal reuse market is by local authorities for road gritting in winter. Typical value recovered is of the order of £5/tonne grit.

- **Example**: *Resource Recovery*: Composting of screenings

Grit and screenings combined create a significant residuals disposal on-cost for municipal water treatment operations in the UK. Wessex Water currently recycles its grit and screenings from Avonmouth WwTW as compost, generated by a composting process twinned with the grit and screenings discharges from the screens and grit removal systems of Avonmouth WwTW. The composting process reduces the mass and volume of the final product which is a sanitized, stabilised compost that can be used in agriculture.

- **Example**: *Resource Recovery*: Recovery of cellulose

There is large cellulose load present in crude municipal wastewater which originates as toilet paper and related cellulose-rich products. This cellulose arrives at the wastewater treatment works as fibre, of which a significant amount can be recovered by fine mesh (<0.35mm aperture) filtration. The approach was pioneered in the Netherlands. Currently, Salsnes filters can be used for cellulose capture in primary treatment and the cellulose recovered returned to the economy if processed. Primary treatment fine filtration on this basis can achieve an organic load reduction equivalent to an activated sludge power saving of up to 40%. However, the recovery of cellulose also reduces the volatile solids available for energy recovery and any other downstream material recovery associated with anaerobic digestion. If the existing facility includes value recovery via digestion this loss of value from that route needs to be accounted for in evaluating this resource recovery option.

- **Example**: *Resource Recovery*: Recovery of enzymes and/or bioplastics precursors from biotreatment waste sludge

Imperial College has begun to develop approaches for recovering the organic chemicals present as substrate storage in biotreatment bacteria – in particular, recovery of enzymes and recovery of the polyhydroxyalkanoates (PHAs) and polyhydroxybutyrates (PHBs) that can be used as feedstocks for producing bioplastics. There are bioplastics manufacturers currently seeking suppliers of feedstock material. Bioplastic manufacturers include Biome, Novamont and Biotec. The Bio-based and Biodegradable Industries Association (BBIA) maintains a website which provides links to bioplastic manufacturers. Plastics and microplastics currently have a huge environmental impact globally as they do not degrade and hence accumulate in ecosystems and, in the case of microplastics, bioaccumulate in organisms. This market therefore has a premium value in that the manufacturers in the market will be substituting standard non-degradable plastics with biodegradable bioplastics, which is a significant sustainability gain. Bioplastic feedstock recovery and/or enzyme recovery could be a resource opportunity consideration for water utilities as part of a diverse resource recovery option portfolio. Diversity of potential resources recovered should be maintained in resource recovery options to maximise business flexibility and minimize risk.

- **Example**: *Resource Recovery*: Recovery of phosphorus

Phosphorus is a strategic resource which is not substitutable, is essential for life and is needed in agriculture, so its usage has significant sustainability and resource security implications. There are currently a range of technologies that can recover phosphorus from wastewater, including the recent development of ion exchange systems by Cranfield University. The most deployed system for phosphorus recovery at present is based on precipitation of ortho-phosphate in anaerobic digestion liquors as struvite ($MgNH_4PO_4.6H_2O$) which is a mineral fertilizer with a market in UK agriculture. Currently, the market value of recovered phosphorus as struvite does not cover the cost of its recovery. Due to economies of scale, a business case with a 5-year payback or less could be secured for P recovery as struvite at municipal wastewater treatment works of 250,000 PE or more that also has anaerobic digestion and a wastewater treatment phosphorus consent of 2mg/l or less for which the operation doses metal coagulant (typically a ferrous or ferric salt in the UK; occasionally aluminium). The value return is not from the value of phosphorus recovered alone but for that plus the savings in metal coagulant that result from phosphorus being removed (recovered as struvite) from return liquors. A circular economy view of phosphorus recovery should also take into account (i) the value of the increased lifetime of digester pipework due to the reduced level of precipitated phosphorus fouling that occurs when phosphorus recovery is operating and the benefits on energy demand through pump headloss associated with the same issue and (ii) should also consider its sustainability in the wider UK economy i.e. the impact of recycling recovered phosphorus on meeting the needs of UK agriculture.

- **Example**: *Resource Recovery*: Internal market opportunities for material resource of value

Diversity of potential resources can maximise business flexibility and minimize risk but identifying resources of value for internal use in operations is the lowest risk option of all for resource recovery because the water utility will then manage both demand and supply and avoid eternal market volatility for the value of the resource recovered. The primary internal markets in municipal wastewater operations are renewable power, oxygen and chemical flocculants. Other internal markets exist, especially now for sustainable phosphorus removal which requires Bio-P which is often limited in the UK by VFA concentrations, as well as methanol. This market already exists and is well established for renewable energy recovery from sludge treatment and is a very robust value proposition due to the ubiquity of power demand in operations and climate change issues.

The following resource recovery interventions might also serve an internal market in municipal wastewater treatment:

- replacing potable water use in internal operations with final effluent; adding minimal treatment to a final effluent supply (e.g. in-line sieve, hydrocyclone) to assure its minimum quality requirement for water reuse applications
- VFAs from AAD plants (short detention, have higher VFAs than long detention conventional digesters) dewatering liquors dosed to biological P removal processes
- water treatment waste sludge; use as coagulant (after minor acid wash?)
- biogas upgrading: use of recovered carbon dioxide as a pH control reagent for biotreatment
- electrolysis of final effluent; return oxygen to aerobic biotreatment
- treatment of waste activated sludge to produce a flocculent to replace artificial polyelectrolytes (ultrasonication and chemical conditioning; dosing with metals from water treatment waste sludges)
- biochar from pyrolysis of digested sewage sludge as an adsorption media.

- **Example:** *Flood protection***:** Wallasea Island Wild Coast (natural system for flood protection)

This coastal reconstruction project is an example of a project creating ecosystem services by planning and building an ecosystem. The project used 3 million tonnes of waste clay from the Crossrail excavations in London to build a large constructed wetland to provide flood protection for Wallasea Island in Essex, via a clay-walled series of lagoons with sluices to manage water flow. The system also provides a protected tidal wetland salt marsh environment, enhancing and preserving the biodiversity associated with the tidal wetland.

- **Opportunity:** *Resource Recovery*: Fats, oils and grease and anaerobic digestion

Fats, oils and grease (FOG) tends to increase energy recovery in anaerobic digestion because it has a high biogas production potential per kg. FOG biogas potential is 800m^3/tonne. Where FOG is removed in FOG tanks, it should be fed to digestion, preferable via an insulated, trace heated buffer tank that will avoid grease precipitation at low temperatures in winter. In most municipal wastewater applications FOG is part of the primary sludge make, as primary tanks with scum baffles and scum recovery systems are recovering materials that are largely FOG. Where a wastewater treatment facility has primary tanks and anaerobic digestion capacity, the primary tanks should always be fitted with scum baffles and a scum recovery system that divert the scum to anaerobic digestion.

- **Opportunity:** *Resource Recovery*: Low grade heat recovery from final effluent

There is an internal market for low grade treatment at municipal wastewater treatment facilities where sludge treatment by anaerobic digestion is deployed, to augment digester heating. That heat recovery can be provided by in-pipe heat exchangers such as those manufactured by Uhrig and used in local authority district heating in Germany. This type of exchanger is easily installed in a final effluent pipeline for example. The best location for heat recovery is on final effluent to avoid any risk of reducing the temperature in biotreatment.

- **Opportunity:** *Flood protection*: By artificially constructed natural wetlands to minimise climate change risk in water utility customer areas

The Environment Agency (EA) currently operates several flood protection schemes in the UK that involve managed local wetlands whose principal ecosystem service provisions are flood protection (by allowing land areas to flood when the flow in the local waterways exceeds their carrying capacity) and increasing or conserving local biodiversity. An example is the River Ouse flood scheme on the Cambridgeshire/Norfolk border which creates an international habitat for migrating waterfowl. UK water utilities should consider land purchase for proactive flood protection projects for flood risk hotspots in their service regions to divert the land from use for housing and human habitation to be repurposed as flood management ecosystems. The planning and design of the ecosystem would be dependent on the local ecosystem profile and local biodiversity stress, and would be designed to create operational jobs in the local economy. Such projects could range from managed water meadows in river plains to tidal salt wetlands in estuaries. Operational employment roles would consist of those required for water system management through built natural wetlands and those required for managed biodiversity conservation or expansion. These could range from small schemes based on reintroducing flood control via reintroduction of beavers, of which examples now exist in the UK, up to larger managed wetlands that could be integrated into a wider service provision to include irrigation water storage for local agriculture in areas that are also seasonally water-stressed. One economic vehicle possible for multiple projects of this nature for a water utility that could draw on venture capital partnerships would be a non-regulated ecosystem design and management company for food protection and biodiversity management. In future such projects could also include flood impoundments designed to recharge stressed watercourses and stressed aquifers. In urban areas, circular economy measures for flooding will favour sustainable drainage systems (SuDS).

In general there are business synergies and new business that UK water utilities could secure in schemes, such as artificially created ecosystems for flood protection and irrigation water provision, because they would begin to integrate and circularise the water business from water resource management to wastewater production and food management risk.

6.2. Circular economy interventions in the wastewater treatment area of operations: the sludge business/bioresources market.

The bioresources market proposed by Ofwat is a critical opportunity for UK water utilities to maximise circular economy interventions based on resource recovery.

Ofwat seeks to maintain affordability and minimise 'cost to serve' wherever possible. This goal is why Ofwat seeks to promote competition between the 10 WaSCs in England and other WaSCs for which it is responsible for their commercial regulation. As part of this mission, Ofwat is now developing a non-regulated competitive 'sludge market'; the 'bioresources market'. This concept is a key market entry point for circular economy interventions as it is already a market developing and successfully applying circular economy measures.

The bioresources market represents an opportunity for UK WaSCs to leverage operational efficiency gains from circular economy interventions that meet sustainability prioritisation targets such as climate change (through providing opportunities for renewable energy recovery) with the advantage of an established and significant internal market existing for use of any renewable power generated. This area of investment opportunity presents a strong platform for additional circular economy investment that also increases operational sustainability and operational resilience. The bioresources market is also rich in opportunities for materials recovery and reuse with opportunities for some materials recovery and reuse also being in the utility wastewater treatment internal market – such as VFA production to facilitate Bio-P removal in extensions of existing wastewater treatment assets rather than relying on unsustainable linear economy chemical dosing for phosphorus removal in wastewater treatment.

Analysis of risks and opportunities for sludge recycling by any WaSC needs to begin with an examination of the status quo of its asset base and analysis of the status of the landbank. The typical sludge recycling flow for a UK WaSC to agricultural land as an outlet for biosolids was approximately 76% in 2013, with seven water and sewage companies 91% or more reliant on this route. Amongst the risk factors that affect a WaSC's sustainable landbank is its end-user profile and how dependent it is on one agricultural general outlet (e.g. proportion of arable end-use versus grassland application).

Participation in the Ofwat bioresources market is a circular economy operation because the basis for competition on 'cost to serve' is based on operational efficiency in that market which is already predominated by resource use efficiency and resource recovery.

6.2.1 Sludge market risks and opportunities for water utilities in the UK bioresources market

Ofwat are seeking an open market in sludge services to decrease operating costs for UK water utilities via competition. The competitive efficiencies underlying this market are based on resource efficiency and resource recovery opportunities. Operating costs for water utilities currently operating sludge businesses can be aggregated into three operating cost categories, as Ofwat states:

- sludge transport
- sludge disposal
- sludge treatment

The first value proposition in water utility sludge businesses is the value proposition the sludge business was founded on in the UK water utilities; that of minimizing the cost of disposal of its principal residuals (captured crude sewage waste solids and surplus biotreatment biomass). The present lowest costs are associated with producing quality biosolids for use in agriculture.

This is a highly resilient value proposition in circular economy terms because it returns material resources to UK food production, including the strategically scarce resources of phosphorus and nitrogen. Nitrogen is otherwise manufactured mainly by the Haber process for fertiliser but this has a large energy demand and hence climate change issues. These sustainability risks dictate that any value recovery innovations should seek to preserve the biosolids to land recycling route in future due to resource security issues as well as current cost advantages.

If waste accumulation in sewage sludge in the form of microplastics puts this route at risk, there are already technology solutions for that risk. However, the recycling of phosphorus to agriculture from sewage sludge is an existing strategic circular economy measure for the UK so even if microplastics or any similar threat to this recycling route emerge and are legislated upon, phosphorus from sewage sludge should still be recycled into agriculture through uprated processing. See Figure 23 for the relationships between costs and value recovery opportunities for water utilities participating in the bioresources market.

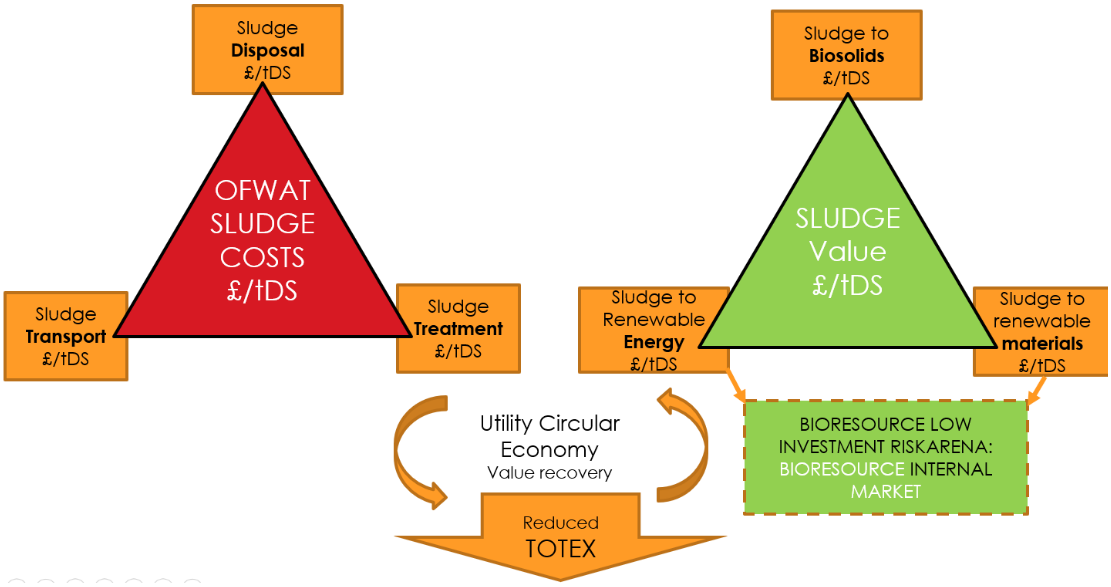


Figure 23 UK water utility sludge business (bioresources market) principal costs and principal circular economy interventions for value recovery.

The resource recovery hierarchy for bioresources is:

- Minimize disposal costs by converting final outputs from waste to product: existing best practice to maximize the agricultural reuse route for beneficial recycling of N and P.
- Recover renewable energy from sludge by maximizing sludge destruction during its conversion to an energy source: anaerobic digestion, advanced anaerobic digestion or Advanced Thermal Treatments (incineration with energy recovery, gasification, pyrolysis).
- Recover materials of value from sludge (an area under development, currently limited to P recovery at very large works) (Palmer 2017).

The transport cost element of the sludge business is a function of the number of small wastewater treatment works from which a utility needs to transport sludge to a sludge processing centre, and the number of large urban communities it serves, as this creates the investment basis for large centralised wastewater treatment works which have economy of scale advantages in processing wastewater treatment residuals (see Figure 24). Biosolids can be produced as a Class A quality for agricultural end-use from advanced liming (Figure 25, brown line), which costs more than standard liming but neither reduces the sludge mass presented to treatment – in fact they increase it due to the lime dose required.

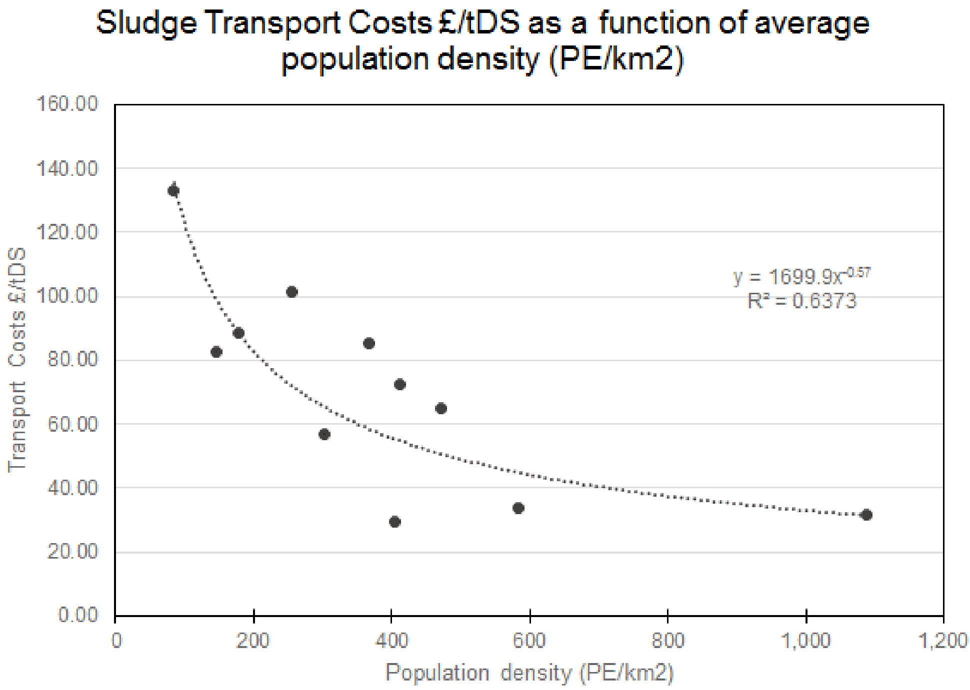


Figure 24 UK demographic cost factors and operating cost: variations in transport costs in the UK bioresources market with population density for each water utility

Consequently, even advanced liming has a limited scale of operation because it increases the total mass of material for disposal. This only makes it viable where a utility has mainly small-scale operations across its asset base.

If biosolids are produced via Mesophilic Anaerobic Digestion (Figure 25, orange line), the output for agricultural recycling is a Class B biosolid, but output mass of sludge is actually reduced in the process by converting it to biogas from which heat and electrical energy can be recovered. The resource efficiency advantages of that process create a lower operating cost than liming which is also subject to economies of scale.

Different sludge treatment technologies provide different resource recovery values for sludge treatment and these in turn translate into having different scales of operation (see Figure 25).

Technology improvements in the resource efficiency of anaerobic digestion to the more intensive advanced anaerobic digestion (AAD) allowed anaerobic digestion to produce a Class A quality biosolid while producing energy recovery by increasing volatile solids reduction. When renewable energy subsidies became more significant in the UK market, several water utilities invested heavily in AAD to maximise their value recovery for technology which could also further reduce their carbon footprint through enhanced renewable generation. In Figure 25 this 'dash for AAD' is represented by the blue line and reflects both lower cost trend and the technologies' increased resource efficiency over conventional mesophilic anaerobic digestion and its deployment at medium to large wastewater treatment sites.

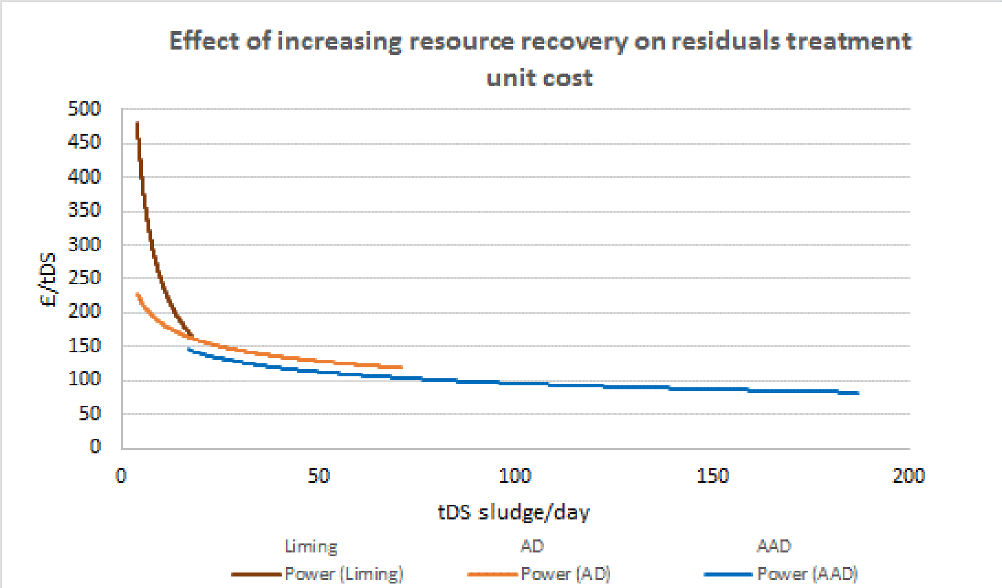


Figure 25 UK bioresources market: resource treatment technologies value effects on cost efficiency and its variation with scale of operation (Palmer 2018)

Notes: These costs exclude capital

Economies of scale are much more pronounced for asset building (asset creation) than they are for asset operations for the simple thermodynamic reason that a massive amount of work has to be done to build complex physical structures, and the creation of assets also consumes a large amount of energy and materials through the production history (total resource life cycle) of all the component parts of the new asset (Figure 26).

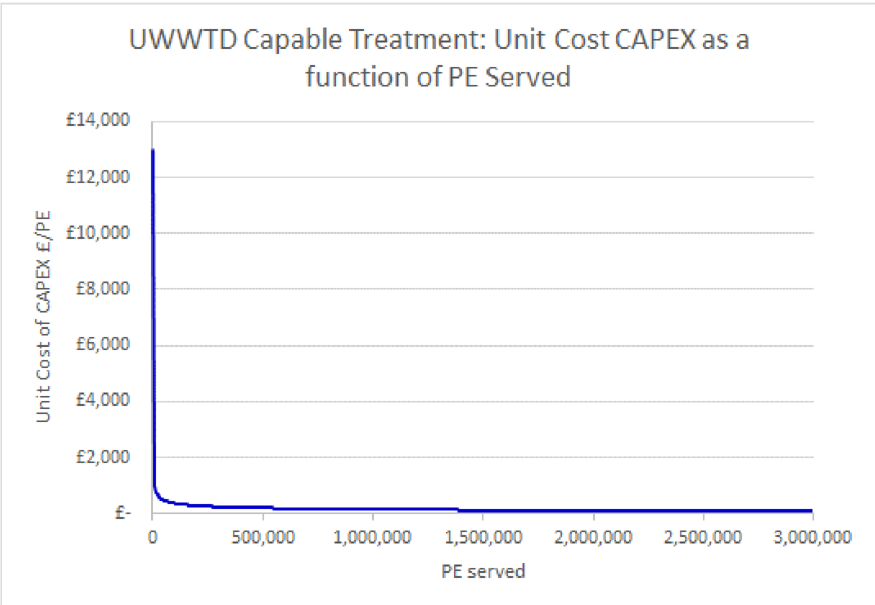


Figure 26 UK wastewater treatment capital costs for EU urban wastewater treatment compliance and the effect of economies of scale (Palmer, 2018)

Notes: The power-law trend is even more pronounced for capital costs than operational costs due to embedded work costs for all resources

This physical economic production factor can be otherwise understood as ‘embedded exergy’ or ‘embedded work and resources’. This is a key consideration for circular economy measures because it implies that Ofwat’s low TOTEX approach and encouraging water utilities to maximise operational efficiencies to reduce ‘cost to serve’ has a physical basis. New complex physical structures (capital assets, Figure 26) have a resource history and work history that gives a greater exergy and resource impact than continuing and improving an existing operation. There are obvious physical limits to this – entropy is also driving a need to maintain those assets in satisfactory working condition.

6.2.2 UK WaSC sludge business history and risks emerging from bioresources competition

Ofwat’s main tool for managing WaSC billing is through WaSC TOTEX reporting and monitoring. This creates a point of convergence between the open sludge market and TOTEX reduction. Sewage sludge is the principal residual from wastewater processing and its disposal costs now contribute significantly towards wastewater treatment costs due to the closure of the sea disposal route and scarcity and rising cost of landfill, unless it is beneficially recycled into agriculture where end disposal can be secured at low cost or even at marginal cost-benefit for the water utility in return for the benefits in nutrient (N and P) recycling and organic soil conditioning to agricultural end-user, compared to their total reliance on comparatively expensive industrial fertilisers.

Anaerobic digestion (AD) was first deployed in the water industry to reduce the total sludge mass for disposal and increase the microbial quality of recycled sludge. However, by the 1990s the rise in electricity prices had significantly increased the value of the by-product of AD – biogas - as a fuel for renewable power generation, such that a boom in digestion capacity occurred in the UK water sector.

Sewage sludge is now in effect a renewable resource that a WaSC can invest in the processing of to displace the cost of electricity and thus reduce their power costs and operational carbon footprint (Figure 27). This creates an internal revenue stream from sewage sludge based on power cost and carbon regulation cost savings that can contribute towards TOTEX reductions, in which typically a WaSC still has the potential to generate more biogas from sludge treatment.

Even where AD capacity covers all sludge production for a UK WaSC, there is typically still the potential to reduce TOTEX through investment in new technology such as advanced digestion and investment in improved operational efficiency.

The risk from the open sludge market is that any WaSC with several sludge treatment centres (STCs) that offer significant economies of scale through their size, and maximise the reduction in treatment cost for sludge further through optimal technology deployment would operate at a much lower UCT (Unit Cost of Treatment e.g. £/tDS sludge) i.e. ‘cost to serve’.

These competitive factors mean that the risks and opportunities in the sludge market are not as simple as those related to adjacent facilities where one WaSC has capacity and another does not. Where this occurs, the WaSC whose asset is in that state may decide to set a local contract for sludge processing and disposal with another water utility or private company.

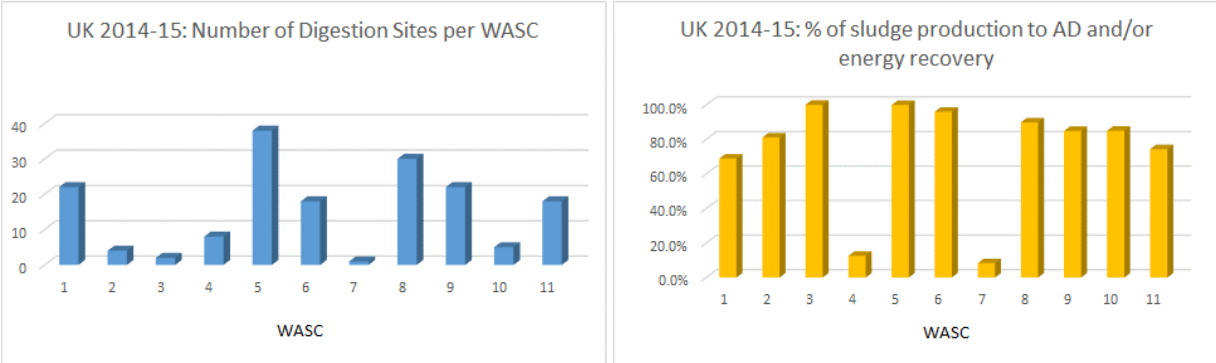


Figure 27 UK water Industry variations in deployment of anaerobic digestion and renewable energy recovery from sewage sludge

Notes: There is significant variation between the 10 English and Welsh WaSCs in the level of investment in sludge processing facilities, in terms of sludge mass reduction, renewable energy generation from biogas and sludge product quality. This in turn affects the net cost of sludge processing and disposal which translates into product cost to customer (here meaning sludge end-user) and customer uptake of the sludge recycling product, when the sludge market opens. Competitive advantages in these areas will be an advantage in competition for the landbank between customers that could proceed beyond common boundary sites. For example, a company with significant quantities of low cost high quality sludge product could afford to transport it further to access a landbank outside its region.

The most competitive service provider in an open sludge market for a UK WaSC is another UK WaSC with the bulk of its sludge production occurring in very large STCs and its resources spread across a moderately sized geographic area, one which has already invested in optimisation of energy recovery.

Competing WaSCs will tend to create a more aggressive competition for sewage sludge than external businesses because of the internal markets they possess for some resources – especially renewable energy. *Water utilities maximising internal market demand for recovered resources also have lower value volatility than any seller to an external market because they also manage demand and can manage supply against demand.*

This value and price certainty is also augmented by the renewable power generated, removing operational carbon costs associated with grid power and contributing to reduction of the operational carbon footprint for the WaSC. These internal markets are not available to non-WaSC market entrants – which creates a competitive disadvantage for them. This competitive disadvantage is also increased by the ability of WaSCs to attract comparatively low-cost capital compared to non-WaSC businesses.

6.2.3 Bioresources market risks and opportunities from disruptive technology

There are a range of emerging technologies that can further increase the energy recovery from sewage sludge, including the various forms of advanced digestion and post-digestion energy recovery in Advanced Conversion Technologies (gasification and pyrolysis of sewage sludge for syngas production) (see Figure 28).

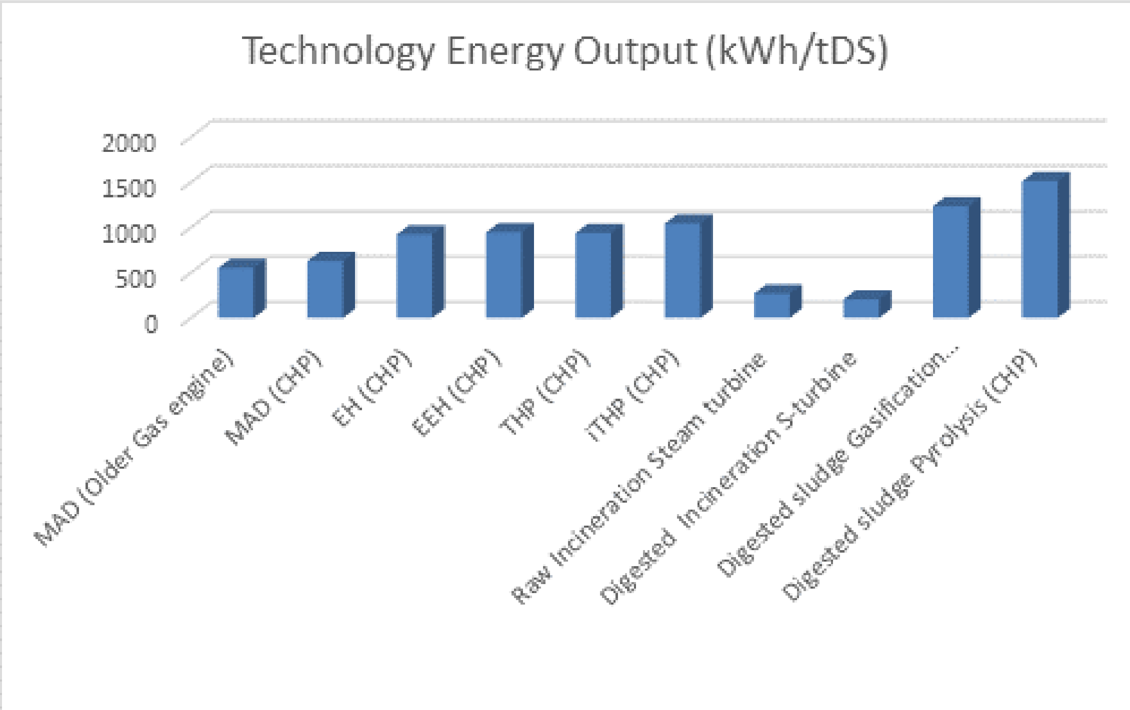


Figure 28 Technologies now in operation in the global water industry or at full-scale piloting for energy recovery from sewage sludge.

Notes: For WaSCs with very large sludge treatment centres (STCs), advanced technologies provide a route to further increasing energy value recovery from sewage sludge, while further reducing the total mass of sludge for which final disposal is required. Digested sludge pyrolysis, for example, also provides investment resilience (future-proofing) because it can provide a means for microplastic destruction in return for renewable energy and opens a route for hydrogen recovery. Under this scenario, phosphorus could also return to land for agriculture in bio-char which may also have a carbon sequestration role.

Deployment of such technologies is likely to be pioneered by WaSCs with large/very large STCs. Since the closure of ROC (renewable obligation certificates) incentivisation, large scale processing is the optimum platform for deployment of such technologies. Drivers for such technology deployment extended beyond long-term energy cost increases. If the open sludge market becomes established it will most likely increase competition based on product quality.

Such competition favours WaSCs with large, concentrated urban populations and hence having a large part of the wastewater service base served by large sewage treatment works and STCs (see Figure 29).

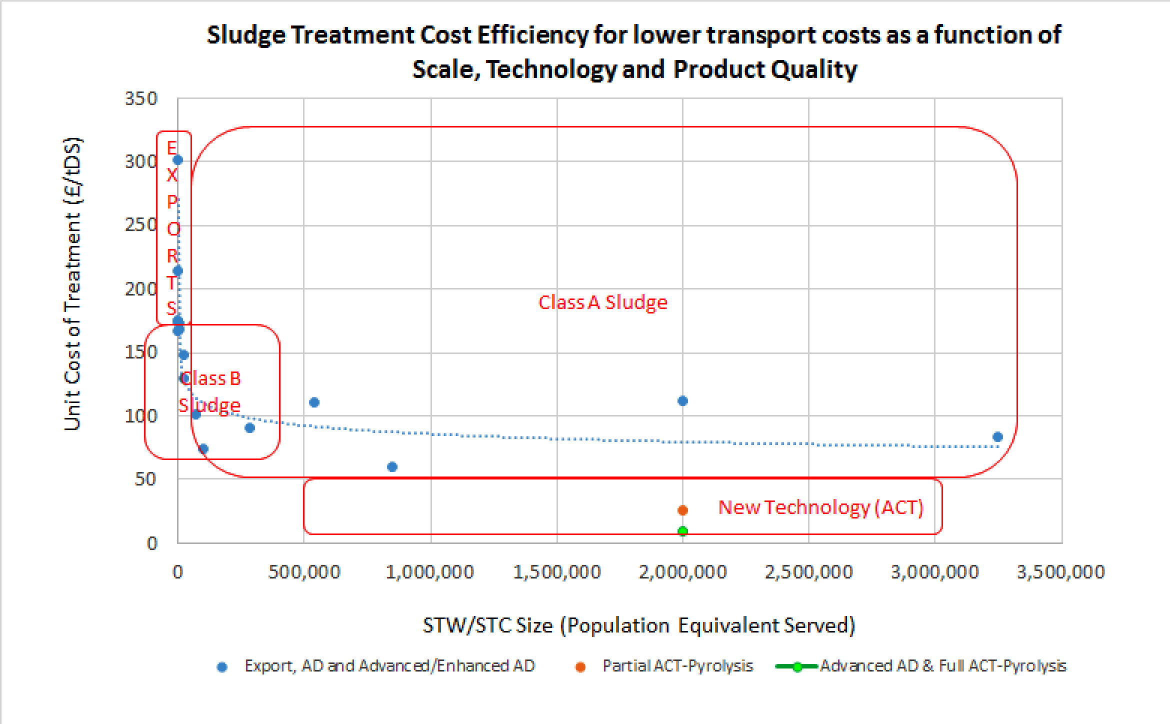


Figure 29 UK water Industry scale of operations for sludge processing and the relationship between scale of operation, technology deployment and biosolids quality

Notes: The thermodynamics of mass processing result in the best economic 'cost to serve' arising from large single sewage treatment facilities. This in turn also means that the best investment platform for technologies that can further increase renewable energy recovery from sewage sludge are very large single STCs. When the 'cost to serve' across the asset base is taken into account, large STCs minimise 'cost to serve' with conventional technologies but also maximise opportunities to introduce new technologies to further increase the cost efficiency of sewage treatment through resource recovery and creation of internal revenue streams.

The emerging technologies that can further reduce the 'cost to serve' across the sludge processing asset base for WaSCs include those for value recovery from sewage sludge shown in Figure 28, plus gas-to-grid for cleaned biogas production. However, gas-to-grid has several risks not associated with renewable electricity generation including that it is less beneficial than renewable electricity for a WaSC due to its external market risks.

The likely trend for fuel and electricity prices for WaSCs up to 2050 - previously described - is likely to encourage further investment in value recovery systems and extend them towards fuel production and use as an energy reserve, as per the integrated circular economy systems engineering blueprint for a large STC presented in Figure 30.

Maximising value for money requires energy resources gained from sludge processing to be utilised at peak tariffs and for internal markets. External sales of renewable electricity to the grid, for example, are currently only 40% (approx.) of the value of internal use (displacement) of power purchased from the grid. The key to maximising the value of renewables for a water utility is to minimise risks and cost, and maximise value.

- **Example**: *Resource Recovery*: Resource Hub/Biorefinery Concept
  Integrating optimized energy recovery with optimised material resource recovery.
  Advanced thermal technologies (ATTs)/advanced conversion technologies (ACTs) with integrated downstream processing to maximise resource recovery.

A large sludge treatment centre that can operate as a resource hub introduces multiple opportunities for resource recovery. In the first instance the site anaerobic digestion capacity should be uprated to Advanced Digestion to maximise the resource efficiency returns from sludge processing. Further energy recovery can be obtained from digested sludge pyrolysis or gasification close coupled with a high efficiency dewaterer and low temperature sludge drier. The site return/side-streams on a large STC allow for ammonia recovery and phosphorus recovery by any of the available technologies – potentially including thermal technologies due to the optimisation of energy recovery. The STC has now become a resource hub and can be further developed towards being a biorefinery by maximising the internal market of the co-located wastewater treatment plant, including options such as final electrolysis as a renewable fuel, with recovered oxygen used in aerobic wastewater treatment. Technologies that can move the facility toward biorefinery status are:

- Diversion of biogas to a methanogenic bioreactor in which methanotrophs store large PHA concentrations – the methanotroph biomass is harvested for PHA recovery for bioplastic production. Reactor liquors with any methanol produced diverted to denitrification carbon supply on wastewater treatment (technology at pilot development level in the US).
- Development of enzyme or PHA/PHB recovery, the latter as feedstock for sale to bioplastics manufacturers.
- PHA recovery or enzyme recovery from SAS.
- VFA returns to Biological P removal.
- SAS ultrasonication with mild acid conditioning/metals dosing to create a polyelectrolyte for use in sludge treatment.
- Pyrolysis biochar as a soil conditioner or for metals' recovery via micro-incineration.
- Micro-incineration of biochar with energy recovery and metals' recovery wet processing (now under development in Germany).

Asset Resilience: the use of the ACTs (gasification or pyrolysis) also provides a means to process digested sludge if the route to agriculture becomes restricted due to risks such as microplastics in sludge. Figure 30 provides a systems diagram for this concept.

For the system engineered example (Figure 30), the Biorefinery/Green Industrial Hub Systems Engineering Blueprint has been designed to deliver all circular economy targets (increased resource efficiency, recycling, resource recovery including renewable energy, increased sustainability and increased resilience) to benefit a water utility in terms of reducing its 'cost to serve', increasing its sustainability and reducing its operational carbon footprint. The resilience is provided by 'future-proofing' through providing resource diversity and providing a resource recovery platform that allows the water utility the opportunity to participate in future in high market potential resources (e.g. hydrogen).

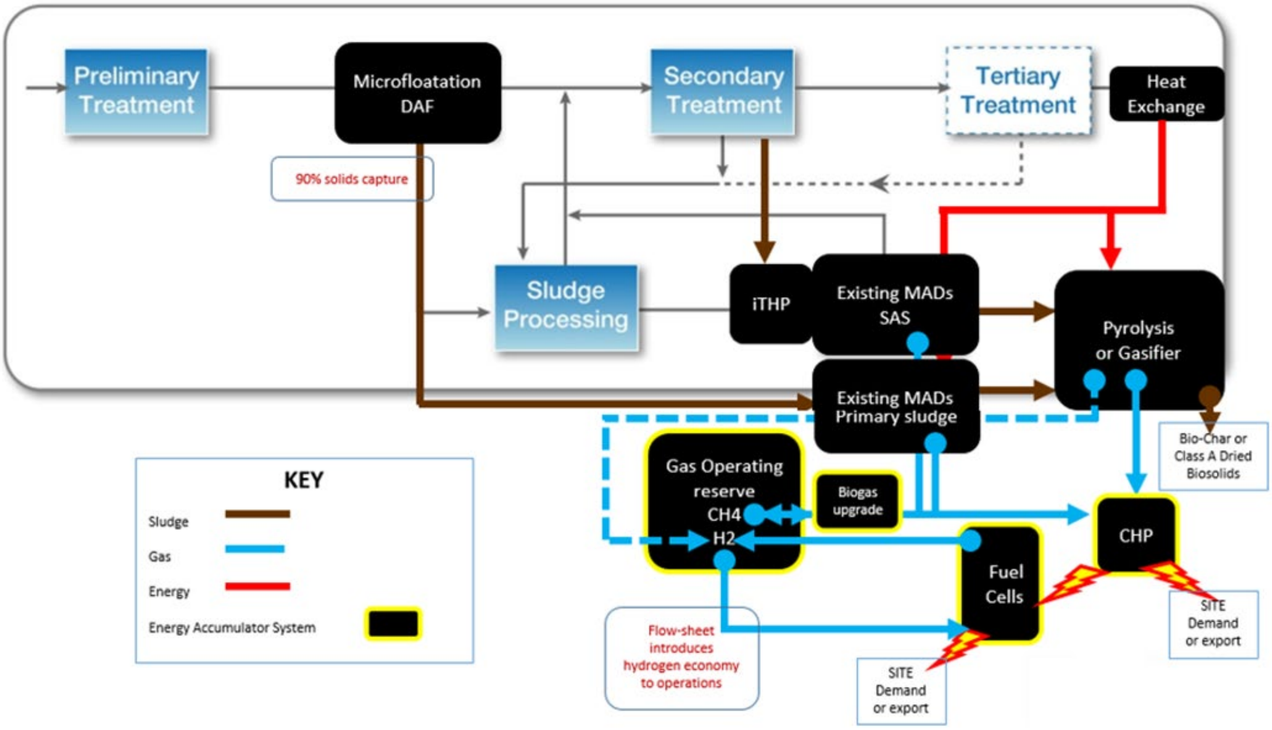


Figure 30 UK bioresources market - Biorefinery/Green Industrial Hub Systems Engineering Blueprint

Notes: Integrated resource efficiency and aggregated marginal resource efficiency benefits minimise exergy consumption and maximise circular economy returns for capital invested, while providing a technology platform that is resilient in the way it extends the benefits of existing MEA/existing assets value by leveraging optimum circular economy benefits from them.

Fuel can be used as an energy store for a combined Demand Side Response investment and hedge against future sludge transport costs. The earlier this type of system is deployed, the greater the OPEX savings potential through the 21st century. Biogas is a source of biomethane, and hydrogen is produced by electrolysis of water during normal operations to create a fuel for storage (compressed hydrogen or biomethane). That fuel can then be called upon during peak power demand via hydrogen fuel cells for hydrogen. The internal market maximises the return of value to the water utility, and even surplus exported power is best utilised on a power line if sent to the nearest wastewater treatment works to displace grid power use there. Only if that latter option (internal power line) is not economic in whole life cost terms, is sale of power to local business likely to be economic, due to value differences on power sale and return via the National Grid.

For renewable electricity and fuel generated from electricity via electrolysis of water and fuel cells (hydrogen economy), maximising the value of electricity comes from servicing the water company wastewater treatment internal market for electricity. This has the added advantage of avoiding cost variations and contract risks (administration costs, security of supply provisions) that an external market and external customers would require.

- **Example**: *Esholt WwTW – Integrated Water, Waste and Resource Recovery (IWWRR)*

YWS are developing Esholt Wastewater Treatment Works (WwTW) in Bradford as a resource centre for local businesses and residential housing adjacent to Esholt WwTW, based on AAD at Esholt STC being a renewable energy source, local residential property and commerce and industry being renewable energy customers, and repurposing existing redundant assets on the WwTW as the basis, creating local natural capital. The scheme was based on value creation on a wider basis than normal for cost-benefit analysis for a WwTW. For Esholt WwTW, the value assessment was more broadly based in the local environment and community and examined how the WwTW could integrate its products and services with needs in the adjacent area. This led to combined housing development (Esholt eco-village) and local business integration, providing a local market for Esholt WwTW products and services. Examination of how the WwTW could return value within this locale and community also led to repurposing redundant sludge lagoons as natural wetland for flood alleviation.

7. Conclusions

The circular economy is ‘an industrial economy that is restorative or regenerative by intention and design.’ (Definition from Ellen MacArthur Foundation).

To be able to achieve the aims of regeneration and restoration, the relative performance of current water utility linear operations needs to be carefully assessed relative to proposals for circular economy operations. As circular economy approaches do not necessarily *assure* the most sustainable outcomes, ‘intention’ needs to be tested. There are tools and service providers available to do such complex system analyses for water utilities.

Circular economy interventions have a physical basis provided by thermodynamics that could be advantageous to water companies. A physical systems approach provides an overview and is robust in risk terms because it considers how systems interact. The best approach to resource efficiency and improving operational efficiency always assesses the whole operation: for example, the whole wastewater treatment facility for a wastewater treatment works. This is necessary because there are possible synergies between some interventions and/or inefficiencies when multiple interventions are combined. The circular economy is therefore also an opportunity to ingrain systems thinking into asset management and asset investment for water utilities and for them to increase the efficiency of their engineering services by moving towards systems engineering.

The thermodynamic basis of the circular economy is optimising exergy efficiency. This should make it of interest to UK water utilities because this approach will give the best outcomes for the performance metrics set by Ofwat. Maximum exergy efficiency means maximum efficiency in operation combined with maximum returns on physical structures deployed – which means maximising asset life and minimizing capital invested in the physical structures needed to perform the operation.

The circular economy is a best practice for overall water utility business.

Circular economy approaches to operations would also help create an inherent culture of operational efficiency in water utilities, one that delivers outcomes that are better assured to be sustainable.

There are barriers that water utilities need to be aware of and manage. If the goal of ‘a restorative’ industrial operation is restoration of ecosystem services and conservation of existing biodiversity, lack of information is a risk. This arises from the current economic model predominating in most government economic planning being classical/neoclassical economics which does not assign value to the environment and its natural capital. Those views are now being challenged because of the immediacy and global impact of climate change on the environment, biodiversity *and* the global economy, but standard cost-benefit analysis simply does not account for the economic value of the environment.

Consequently, circular economy project assessments need to be costed on a wider range of criteria (such as described in Section 3 of this ROCK).

A consequence of thermodynamics is that economic operations discharge materials to the environment. The nature of the materials discharged from the economy, and the *intensity* of the discharge risks reduction in biodiversity because intense natural selection pressure reduces biological diversity. We see this now in our own lifetimes through the impact of climate change.

A key element in creating a more circular UK economy is reconfiguration of national energy infrastructure. This is essential to the UK meeting its present carbon emissions commitments and is another example of why water utilities should not wait on government policy to act in securing benefits from circular economy measures, including renewable energy generation benefits, for themselves. One of the key areas of circular economy opportunity for UK WaSCs is the Ofwat bioresources market. The Ofwat bioresources market is a resource market, and oversight and encouragement of its competition by Ofwat means that it should drive resource efficiency and innovation in resource recovery. This makes it the strongest current market environment that water utilities are currently participating in to outcompete each other in terms of resource efficiency. It also presents promising opportunities for resource recovery and resource recovery innovations. As such, it is an area which successful bioresources market water companies could 'mine' for their own current best practice in engineering solutions development for asset upgrading and maintenance.

7.1. Circular economy innovative approaches required to increase circular economy interventions in water utility operations and overcome barriers

There are already a range of technologies developed and under development for circular economy interventions in water utility operations, in resource recovery. There is no lack of technology development on the market, but there is lack of an overview that allows circular economy benefits to be planned for in the long term (on an asset base relevant timeline e.g. 25 years, not restricted to 5 years). Ensuring a long-term, capital-efficient approach for circular economy resource efficiency interventions will make them more attractive to water utilities.

The main barrier *within* the water sector to systematically introducing the circular economy into water operations is the lack of a utility circular economy strategy and policies to support any such strategy. This ROCK has explained the physical basis for how the circular economy provides benefits to economic operations, and how the optimum benefits and asset resilience for a water utility is provided by a strategy for the use of circular economy technology development. To maximise capital returns on investment in circular economy measures, those interventions need to be integrated through time and space to avoid asset write-off due to restricted circular economy opportunity development.

For water utilities, exergy analysis would be a key analytical innovation for objective assessment of current linear economy water utility business practice and its comparison to circular economy interventions. Exergy analysis of any given water utility operation as described in Section 4 of this ROCK could minimize the risk and maximise the returns for circular economy interventions in water businesses. Circular economy initiatives have potential benefits to offer for this range of challenges in terms of both operational efficiency and resilience, because circular economy initiatives take account of upstream and downstream risks both in space (the upstream environment for an operation and the downstream environment for that operation) and in time (sustainability risk). The water sector has a chance to lead the entire UK economy in establishing this innovative practice in better true cost accounting. Its importance lies in the fact that exergy efficiency is thermodynamically the basis of resource efficiency and is also the basis for cost efficiencies in operations.

Economies of scale dictate that circular economy interventions at large treatment works will deliver the best returns on capital. However, technology developments at the small works level and domestic level will also make circular economy interventions worthwhile due to the value of resource efficiency measures and renewable energy opportunities rising over time.

7.2. The value of circular economy interventions in water utility operations

The core philosophy of the circular economy is maximising the efficient use of resources. Increasing resource efficiency is achieved by increasing the efficiency of use of a resource, including reducing the demand for it in an operation, and also achieving a net increase in the resource value balance for an operation by recovering materials of value from wastes generated in the operation. Recycling materials into the internal economy of the water utility or into the wider external economy increases efficiency of use of a resource, and prolonging the life of viable operational assets is a resource recovery intervention as it prolongs the life of those materials in the economy.

Multiple circular economy interventions should be viewed as the norm for uprating operations as they aggregate benefits. For water utilities, operational resources include energy and materials. Energy efficiency interventions are hence also circular economy interventions and should always be considered as part of circular economy assessment due to the impact on climate change. Information Technology is another key consideration for circular economy interventions. Obtaining more information on an operation and using that information to increase the efficiency of an operation should be routinely deployed in circular economy best practice. Online data acquisition, real-time control and use of online information and technical experts are hence an integral part of circular economy improvements.

The circular economy should become a standard approach for all UK water industry utilities across their operations and their asset bases. This would be best achieved by a systemic approach by water utilities, based on developing a comprehensive strategy for circular economy interventions that creates a circular economy culture in water utility operations. Water utilities need to recognise that circular economy interventions offer the prospect of achieving systematic and systemic improvements in operational efficiency that are synonymous with sustainability, the latter subject to checking the potential outcomes by the metrics described in this ROCK.

8. References.

Ambec S, Cohen MA, Elgie S and Lanoie P (2013) The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Review of Environmental Economics and Policy*, 2013, 7 (1), pp2–22: https://doi.org/10.1093/reep/res016

Ayres RU (2004) Thermodynamics and Economics, Overview. *Encyclopedia of Energy*, 2004, 6, Elsevier Inc.

Ayres RU (2007). On the practical limits of substitution. *Ecological Economics*, 2007, 61, pp115–128: https://doi.org/10.1016/j.ecolecon.2006.02.011

Ayres RU and Martinàs K (1995) Waste potential entropy: the ultimate exotoxic? *Economie Appliquée* XLVIII (2), 95–120.

Ayres RU, Ayres LW and Warr B (2002) Exergy, Power and Work in the US Economy, 1900-1998. Working paper, INSEAD's Centre for the Management of Environmental Resources (CMER); http://terra2000.free.fr/downloads/expowork.pdf

Ayres RU and Warr B (2009) The Economic Growth Engine: How Energy and Work Drive Material Prosperity. Cheltenham UK & Northampton MA, USA

Bakshi BR, Gutowski TG and Sekulic DP (2011) Thermodynamics and the Destruction of Resources. Cambridge University Press, Cambridge: https://doi.org/10.1017/CBO9780511976049

Boulding KE (1966) 'The Economics of the Coming Spaceship Earth'. In: H. Jarrett (ed.) *Environmental Quality in a Growing Economy, Resources for the Future*, Johns Hopkins University Press, Baltimore, MD, pp3-14: http://www.ub.edu/prometheus21/articulos/obsprometheus/BOULDING.pdf

British Standard BS8515:2009 *Rainwater Harvesting Code of Practice*.

British Standard BS8525-1:2010 *Greywater Systems Code of Practice*.

Brujil G (2018) The Relevance of Porter's Five Forces in Today's Innovative and Changing Business Environment. *SSRN Electronic Journal*: https://doi.org/10.2139/ssrn.3192207

Brouckaert CJ and Buckley CA (2002) *Water Pinch Analysis: A Strategic Tool for Water Management in the Food processing industry*. IWA 2002 Water Reuse Symposium (2002)

Daly H (1994) 'Steady-state Economics'. In: *Ecology - Key Concepts in Critical Theory*, edited by C Merchant. Humanities Press, ISBN 0391037951.

Daly H (1997) *Beyond Growth: The Economics of Sustainable Development*. Beacon Press, ISBN 0807047090.

Dasgupta P (2010) Nature's role in sustaining economic development. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.,* 2010, Jan 12, 365(1537) pp5–11.

Defra (2011) *Guidance on Applying the Waste Hierarchy*: https://www.gov.uk/government/publications/guidance-on-applying-the-waste-hierarchy

Drielsma JA, Russell-Vaccari AJ, Drnek T, Brady T, Weihed P, Mistry M and Perez Simbor L (2016) Mineral Resources in Life Cycle Impact Assessment—Defining the Path Forward. *The International Journal of Life Cycle Assessment*, 2016, 21, pp85-105.

EASAC (2015) *Circular economy: a commentary from the perspectives of the natural and social sciences.* European Academies' Science Advisory Council (EASAC).

EU (2020) *Circular Economy Action Plan*: https://ec.europa.eu/environment/circular-economy/

Ellen MacArthur Foundation (2013a) *Towards the Circular Economy, Vol 1. Economic and business rationale for an accelerated transition*. https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an-accelerated-transition

Ellen MacArthur Foundation (2013b) *Towards the Circular Economy, Vol 2, Opportunities for the Consumer Goods Sector.* https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-2-opportunities-for-the-consumer-goods-sector

Ellen MacArthur Foundation (2014) *Towards the Circular Economy, Vol 3, Accelerating the scale up across global supply chains.* https://www.ellenmacarthurfoundation.org/publications/towards-the-circular-economy-vol-3-accelerating-the-scale-up-across-global-supply-chains

Ellen MacArthur Foundation (2018) *Water and Circular Economy White Paper*, 2018.

Ellen MacArthur Foundation (2020) https://www.ellenmacarthurfoundation.org/explore

EU (2015) *Closing the loop - An EU action plan for the Circular Economy*. COM (2015) 614 final: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

Faber M, Niemes H and Stephen G (2013) *Entropy, Environment and Resources: An Essay in Physico-Economics* (second Edition). ISBN-3-540-58984-8

Gong M and Wall G (2001) On exergy and sustainable development – Part 2: Indicators and methods. *Exergy Int. J.,* 2001, 1 (3), pp128–145.

Gutowski TG and Sekulic DP (2011) Thermodynamic Analysis of Resources Used in Manufacturing Processes. In: *Thermodynamics and the Destruction of Resources*, Bakshi BR, Gutowski TG and Sekulic DP, Eds., pp 163-189, Cambridge University Press, New York.

Hislop H and Hill J (2011) *Reinventing the wheel: a circular economy for resource security*. Green Alliance (2011): https://www.green-alliance.org.uk/page_77.php

Humberto HAM, Raúl CC, Lorenzo VV and Ramirez-Hernandez J (2018) Aquifer recharge with treated municipal wastewater: long-term experience at San Luis Río Colorado, Sonora. *Sustain. Water Resour. Manag.,* 2018*,* 4, pp251–260: https://doi.org/10.1007/s40899-017-0196-2

Kleidon A, Malhi Y and Cox PM (2010) Theme Issue 'Maximum entropy production in ecological and environmental systems: applications and implications'. *Phil. Trans. R. Soc. B.,* 2010, 365 (1545).

Kneese AV, Ayres RU and d'Arge RC (1970) *Economics and the Environment: A Materials Balance Approach*. Resources for the Future Inc, Washington, DC. Distributed by John Hopkins Press, Baltimore and London.

Mahbub ME, Souza P, and Williams R (2017) *Int. J. Data Sci. Anal.*, 2017, 3, pp49–60

Palmer SJ (2014) The future of activated sludge in an expensive energy world. In: Activated sludge; past, present and Future (Horan, N. (ed)) Aquaenviro Activated Sludge Centenary Conference, Manchester, 2014.

Palmer SJ (2017) Energy recovery is the key to reducing WaSCs 'Cost to Serve' and Carbon Footprint. *Institute of Water*, Energy Feature pp60-61.

Palmer SJ (2018) *Systems analysis of wastewater treatment intensification*. CIWEM Technical Seminar on Critical Challenges Facing Wastewater Treatment: Wastewater Treatment Intensification. London, December 2018.

Palmer SJ (2018a) *Journal of Biological Physics and Chemistry,* 2018, 18, pp5–20

Palmer SJ and Alford H (2018) A thermodynamic model for the global economy and its implications for macroeconomic theory and policy formulation. *Theoretical Economics Letters*: https://www.scirp.org/journal/paperinformation.aspx?paperid=87595

Palmer SJ (2019) The role of the water industry in supporting sustainable economic growth for an advanced economy and the need for the water sector to maximise circular economy measures to minimise cost increases. 13th European Wastewater Management Conference. 16-17 July Birmingham, UK.

Pearce DW and Turner RK (1989) Economics of Natural Resources and the Environment. Johns Hopkins University Press. ISBN 978-0801839870.

Porter ME (1979) How Competitive Forces Shape Strategy. *Harvard Business Review*, 1979, 57 (2), pp137–145.

Porter ME (1998) *The Competitive Advantage of Nations*. The Free Press. ISBN 0-684-84147-9.

Porter ME (2008) The Five Competitive Forces that Shape Strategy. *Harvard Business Review*, 2008, Jan, 88 (1), pp78–93.

Purnell P (2019) On a voyage of recovery: a review of the UK's resource recovery from waste infrastructure. *Sustainable and Resilient Infrastructure*, 2019, 4 (1), pp1-20: https://doi.org/10.1080/23789689.2017.1405654

Rose M, Stephenson P and Palmer SJ (2012) *Going Green: providing catchment managers with the tools and business processes to measure and improve the sustainability of wastewater catchments*. CIWEM Annual Conference (Water and Environment) 2012, Olympia, London.

Rustad JR (2012) Peak Nothing: Recent Trends in Mineral Resource Production. *Environmental Science & Technology*, 2012, 46, pp1903-1906: https://doi.org/10.1021/es203065g

Szargut J (1997) Depletion of the Unrestorable Natural Exergy Resources. *Bulletin of the Polish Academy of Sciences Technical Sciences*, 1997, 45, pp241-250.

UKWIR Report 14/WR/29/3 (2014) *Establishing a robust case for final effluent reuse: an evidence base.*

UKWIR Report 14/WR/29/4 (2015) *Establishing a robust case for final effluent reuse: testing the UK regulatory framework.*

UKWIR Report 05/WR/29/1: (2005) *Framework for developing water reuse criteria with reference to drinking water supplies.*

Wall G (1977) *Exergy – a useful concept within resource accounting*. Institute of Theoretical Physics, Göteborg, Report No. 77-42, 1977, 58p, ISBN 99-1767571-X and 99-0342612-7: http://www.exergy.se/ftp/paper1.pdf.

Wall G and Gong M (2001) On exergy and sustainable development — Part 1: Conditions and concepts. *Exergy Int. J.*, 2001, 1 (3) pp128–145.

Waste and Resources Action Programme (WRAP, 2010a) *WRAP's vision for the UK Circular Economy to 2020*: http://www.wrap.org.uk/content/wraps-vision-uk-circular-economy-2020

Waste and Resources Action Programme (WRAP, 2010b) *Securing the Future – The role of resource efficiency*: https://www.wrap.org.uk/sites/files/wrap/FULL REPORT v2.pdf

Waste and Resources Action Programme (WRAP, 2010c) *The Rippleffect - water efficiency for businesses. Reducing water through direct reuse or reclamation and reuse*: http://www.wrap.org.uk/sites/files/wrap/guidance_doc_3_water_reclaim.pdf

Water UK and Home Building Federation 'Water reuse systems, guidance and advice' https://www.cambridge-water.co.uk/media/1556/water_reuse_systems_wateruk.pdf

Waterwise (2016) *Save Water* https://www.waterwise.org.uk/save-water/

Zink T and Geyer R (2017) Circular economy rebound. *Journal of Industrial Ecology*, 2017, 21 (3), pp593–602: https://doi.org/10.1111/jiec.12545

9. Sources of Further Information

AquaCritox *Exploiting Super-Critical Water Oxidation for Sludge Treatment* https://ec.europa.eu/environment/eco-innovation/projects/en/projects/aquacritox

Ayres RU (1999a) *Turning Point: An end to the Growth Paradigm.* London: Earthscan Publications, Paperback ISBN 1-85383-439-4.

Ayres RU (1999b) *Products as service carriers: should we kill the messenger – or send it back?* Zero Emissions Forum, UN University, Tokyo.

Blok K, Hoogzaad J, Ramkumar S, Ridley S, Preeti S, Tan I, Terlouw W and de Wit T (2016) *Implementing Circular Economy Globally Makes Paris Targets Achievable*. Circle Economy and Ecofys: https://www.circle-economy.com/resources/circular-economy-a-key-lever-in-bridging-the-emissions-gap-to-a-1-5-c-pathway

Ellen MacArthur Foundation (2015) *Delivering the Circular Economy. A toolkit for Policymakers*: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_PolicymakerToolkit.pdf

Meadows DH, Meadows DI, Randers J and Behrens WW (1972) *The limits to growth: A Report to The Club of Rome*. ISBN 0-87663-165-0

Palmer SJ (2010a). *Opportunities for Water Industry Strategic Investment in Resource Recovery.* AquaEnviro 4th European Water and Wastewater Management Conference: Reducing the Environmental Footprint of the Water Industry (Leeds, September 2010).

Palmer SJ (2010b). *The Kaya Identity and the Enabling Technologies Concept*. I. Chem. E North West: Water Subject Group – Adapting Old Technology for the New AMP (Warrington, November 2010).

Palmer SJ (2010c) Future challenges to asset investment in the UK Water Industry: the wastewater asset risk mitigation offered by minimising principal operating cost risks. *I.W.A. Journal of Water and Climate Change,* 01.1.2010 pp17-35

Palmer SJ (2015) *Challenges for the Operation of Advanced Thermal Conversion*. IWA Sludgetech 2015 (University of Surrey, 2015).

Palmer SJ (2016) *Leveraging the value of sludge for sustainable minimum TOTEX: winners and losers in a sludge market.* IWA Sludgetech 2016 (University of Surrey, 2016).

Palmer SJ and Nair A (2011) T*he Prospects for Phosphorus and Energy Recovery through Tertiary Algal Treatment*. Recovering Value from Wastewater Conference, Aquaenviro (Manchester, April 2011).

Palmer SJ, Nair AJ and White C (2012) *Redeveloping Municipal Wastewater treatment from a fuel management perspective*. 17th European Biosolids Conference, Aquaenviro, (Leeds, November 2012).

Palmer SJ, Ord J, Maclaren J and Nair AJ. (2013) T*he Prospects for Replacing Sludge Incineration with Advanced Energy Recovery Systems and the potential benefits to UK water and Sewage Companies*. 18th European Biosolids Conference, Aquaenviro (Leeds, November 2013).

Product-Life Institute, Geneva (1982) *Cradle to Cradle*: http://www.product-life.org/en/cradle-to-cradle

Stahel W (1982) *The Product-Life Factor*: http://www.product-life.org/en/major-publications/the-product-life-factor

Stern DI (1997) Limits to substitution and irreversibility in production and consumption: A neoclassical interpretation of ecological economics. *Ecological Economics,* 1997, 21(3), pp197–215.

Szargut J (1978) Minimization of the consumption of natural resources. *Bull. Polish Acad. Sci. Technical Sci.,* 1978, 26, pp41–46.

UNESCO *Encyclopedia of life support system (EOLSS)*: https://www.eolss.net/

Water Environment Federation (2014) *Moving Toward Resource Recovery Facilities*. ISBN 978-1-57278-303-4

World Economic Forum (2020) *From linear to circular – accelerating a proven concept*: https://reports.weforum.org/toward-the-circular-economy-accelerating-the-scale-up-across-global-supply-chains/from-linear-to-circular-accelerating-a-proven-concept/