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The role of water circularity in the food-water-energy nexus and climate change mitigation

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ABSTRACT

By 2050, the global Earth population will reach 10 billion, leading to increased water, food, and energy needs. Availability of water in sufficient quantities and appropriate quality is a prerequisite for human societies and natural ecosystems. In many parts of the world, excessive water consumption and pollution by human activities put enormous pressure on this availability as well as on food and energy security, environmental quality, economic development, and social well-being. Water, food/materials, and energy are strongly interlinked, and the choices made in one area often have consequences on the others. This is commonly referred to as the "water-food-energy" nexus. These interconnections intensify as the demand for resources increases with population growth and changing consumption patterns, and Humanity continues using a linear economy model of 'take-make-dispose'. The nexus makes it difficult for governments, public and private organizations, and the public, to set and follow a clear path towards a sustainable economy i.e., "meeting the needs of the present without compromising the ability of future generations to meet their own needs". Humanity best chance at mitigating climate change, and shortage of resources is to harness the value of water as much as possible.

This paper reviews the latest publications about the water-food-energy nexus and climate change, putting numbers into perspective, attempting to explain why water circularity is part of the key factors to accelerate the transition from a linear economy to a circular economy, and to meet the UN Sustainable Development Goals, and how circularity can be implemented in the water sector.

1. Introduction

In 2016, the World Economic Forum asked some experts to rank potential global threats to human life according to their likelihood and impact [9]. Energy and water shortages were identified as two of the five top risks facing the world in the next decade. By 2050, the global population will reach 10 billion, leading to increased food, water, and energy demand. The global size of the water market (water treatment, distribution plant and equipment for domestic and industrial use) was estimated at $557 billion in 2013. Even allowing for market growth since this estimate, the annual global energy market (valued at around $6 trillion) considerably overcasts the importance of the water market. But has energy priority over all other commodities in the run to ensure resilience of humanity and a sustainable planet for centuries to come? Nothing is less certain and the impossibility to prioritise energy over food or water is commonly referred to as the 'water-food-energy nexus'. This nexus makes it difficult for governments, public and private organizations, and the public, to set and follow a clear path towards a sustainable economy i.e., "meeting the needs of the present without compromising the ability of future generations to meet their own needs" as defined by the United Nations (UN) in 1987. This nexus can only be solved by making our global economy more 'circular' as shown in this paper, which reviews the latest publications about the water-food-energy nexus and climate change, putting numbers into perspective, attempting to explain why water circularity is part of the key factors to accelerate the transition from a linear to a circular economy, and how circularity can be implemented in the water sector.

2. The water-food-energy nexus

Humanity's ability to fulfil its basic needs is based on the availability of food/materials, energy and water (commodities). The exchange of these commodities is ensured by the world's economy, that is "the process or system by which goods and services are produced, sold and bought". Water, food/material and energy are strongly interlinked: water is necessary to produce, and transport all forms of energy to some

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Abbreviations: CCS, Carbon Capture and Storage; CE, Circular Economy; CHP, Combined Heat and Power; DO, Dissolved Oxygen; DS, Dry Solids; GHG, GreenHouse Gas; MBR, Membrane BioReactor; MBBR, Moving Bed Biofilm Reactor; N, Nitrogen; P, Phosphorus; PE, Population Equivalent; PV, PhotoVoltaic; SBR, Sequencing Batch Reactor; SCADA, Supervisory Control And Data Acquisition; SDG, Sustainable Development Goal; UN, United Nations.

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extent; and energy is required for the collection/extraction, treatment and distribution of water. In the same way, both water and energy are required to produce, transport and distribute food. And food (and/or crops) is sometimes used to produce energy in the form of biofuels. These interconnections imply that the choices made in one domain have often direct and indirect consequences on the others, which lie at the heart of what has become known as the "water-food-energy" nexus. The nexus intensifies as the demand for resources increases with population growth and changing consumption patterns. Meanwhile, major global trends – climate change and competing land-use patterns – restrict the ability of existing systems to meet the growing demand in a reliable and affordable manner. The nexus affects the extent to which water, energy and food security can be simultaneously achieved.

3. Issue with current economy model

Since the beginning of the industrial revolution, global consumption and resource use has followed a 'take-make-waste' approach i.e., a "linear economy model". Whilst this model has enabled tremendous economic and societal growth, it has also unfortunately induced huge overconsumption to the detriment of planetary resources and health. As of 2020, Humanity has now breached two major milestones: 100 billion tonnes of materials enter the global economy every year, of which only 8.6 % is recycled back to the economy [2]. And in 2017, the threshold of human activities causing 1 °C global warming has been exceeded (1.1 °C reached in 2020) [2]. A few impacts of our current 'linear economy' are described in the sections below for some of the main commodities in our economy.

3.1. Plastics

As of 2019, 99 % of plastics raw material base came from fossil fuels [17]. In 2019, the National Geographic wrote an article [16] stating that 91 % of plastic was still not recycled. And in 2021 still only a fraction of our plastic waste – 14 %, according to a report by the World Economic Forum and the Ellen MacArthur Foundation [7] – got recycled. Only 2 % was "effectively recycled"; that is, converted into an equally useful item. However, most recycled plastic were "downcycled" into something less useful than before.

3.2. Fashion

A 2017 Industry report [19] estimated that, in 2015, the global textiles and clothing industry was responsible for the consumption of 79 billion m^3 of water, 1,715 million tons of CO_2 emissions and 92 million tons of waste. Textiles are estimated to be the largest source of synthetic fibres in the oceans with microplastics shedding into the water system every time clothes are washed. A single 6 kg domestic wash has the potential to release as many as 700,000 fibres [19]. These fibres end up in wastewaters but as explained in Section 10.1.5, current conventional wastewater treament plants cannot remove them efficiently. Therefore they inevitably end up in our oceans, sadly absorbed by marine fauna and ultimately make up part of our food. Less than 1 % of material used to produce clothing is recycled into new clothing [7]. Textile production is a major contributor to climate change. The fashion industry produces 10 % of all humanity's carbon emissions and is the second-largest consumer of the world's water supply [43]. That's more emissions than all international flights and maritime shipping combined! Washing clothes, meanwhile, releases 500,000 tons of microfibers into the ocean each year — the equivalent of 50 billion plastic bottles [43].

3.3. Food

Food is wasted throughout the supply chain from production all the way to final household consumption. Food that never gets eaten represents a waste of resources such as land, water, energy, soil and seeds. A 2019 report [6] estimates that around 931 million tonnes of food waste were generated in 2019, 61 % of which came from households, 26 % from food service and 13 % from retail, suggesting that 17 % of total global food production may be wasted (11 % in households, 5 % in foodservice and 2 % in retail).

4. What the future looks like

4.1. Basic needs 2050

By 2050, energy demand will have increased by 80 %, food demand by 50 % and water demand by 55 % [13] due to predicted population growth. Availability of freshwater in sufficient quantities and appropriate quality is a prerequisite for human societies and natural ecosystems. In many parts of the world, excessive water consumption and pollution by human activities put enormous pressure on this availability as well as on food and energy security, environmental quality, economic development and social well-being. Competition over freshwater resources has been increasing during decades due to a growing population, economic growth, increased demand for agricultural products for both food and non-food use, and a shift in consumption patterns towards more meat and sugar based products. So in how much stress is Earth to fulfil our water needs?

4.2. Planetary boundaries

In 2009, a group of scientists proposed the concept of 'planetary boundaries' [35] (to assess parameters such as P,N, and freshwater availability, or climate change impacts, amongst others) where the threshold, or tipping point, is the value at which a very small increment of the control variable (like CO_2) triggers a larger, possibly catastrophic, change in the response (global warming). Tipping points of several planet boundaries have now long been exceeded. In 2009, the research paper [4] stated that the upper limit of accessible freshwater resources was estimated at ~ 12,500–15,000 km^3/year and water scarcity reached when withdrawals of freshwater exceeded 5,000–6,000 km^3/year. At the time of this paper, withdrawals of freshwater amounted to ~ 4,000 km^3/year, whereas consumptive use was ~2,600 km^3/year, leaving Humanity with some margin for manoeuvreing. However, in 2015, this boundary was reviewed to a lower threshold of 4,000 km^3/year by a new study [56] indicating that the remaining safe operating space for water may be largely committed already to cover necessary human water demands in the future up to 2030–2050.

4.3. The water-energy-food nexus and the UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) have set an ambitious agenda for society, government and businesses. Water has a dedicated goal in SDG6 (ensure availability and sustainable management of water and sanitation for all) and its attainment relies on contributing to and benefiting from the attainment of other SDGs, especially SDG12 on circular economy (ensure sustainable consumption and production patterns). The resolution of the food-energy-water nexus is the center piece of achieving the 17 SGDs. In particular, production of food,energy and water rely significantly on the exploitation of common, finite and increasingly degraded water and land resources. Policies and measures put in place to meet the targets established under each individual goal may therefore compromise the achievement of the other targets [24].

Practically, CO_2 emissions and - to a lesser extent - water footprint both increase with GDP (see Fig. 1).

Nearly half (48 %) of cumulative CO_2 emissions over the last quarter century can be attributed to just the richest 10 % of the globe, whilst the poorest 50 % were responsible for only 7 %, when SDG 10 promotes the reduction of inequalities. Unfortunately, lower income nations who

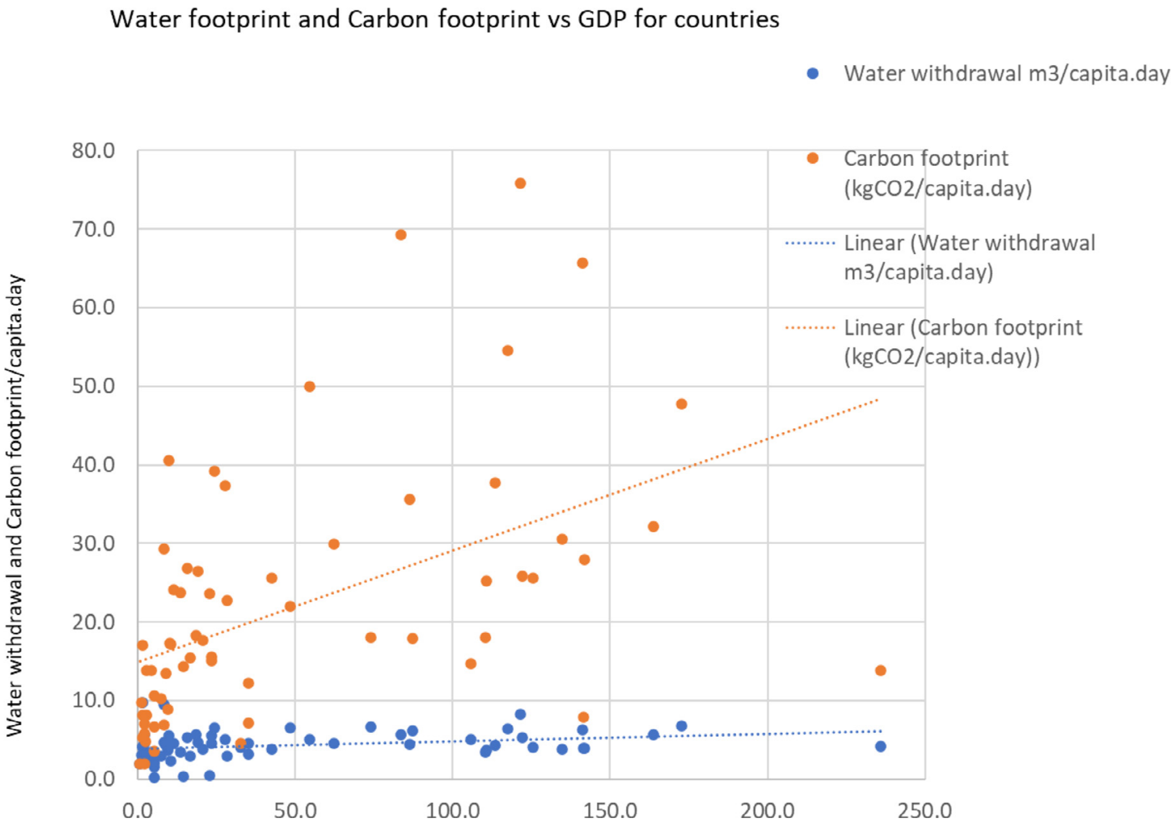


Fig. 1. Based on [31,50–53] – Water footprint 2011, Carbon footprint 2018, Population 2020, GDP 2020.

contribute the fewest emissions are also most vulnerable to the impacts of climate change. Therefore, solving SDGs 6, and 7 would help solving SDGs 5,10 and 16 by ensuring reduced inequalities, genre equality, and peace and justice.

5. Global carbon footprint vs global water footprint

In 2014, primary energy production and power generation accounted for roughly 12 % of total worldwide water withdrawals (producing less than 3 % of the carbon emissions), while energy produced 73 % of the carbon emissions (See Fig. 2).

Because of its low value-to-bulk ratio and high cost of transport, water is not commonly traded internationally or over long distances. Consequently, water has no international price, unlike oil, gas and coal which are widely traded but with regional price differences, reflecting their transport and distribution system [12]. Whereas energy is often managed nationally, water is managed regionally or locally. And while the water sector remains largely public, the power sector remains largely private. A drop of water, a piece of land, or a kilojoule of energy cannot be traded using the same criteria. What might appear to be an efficient policy in one dimension can be harmful for the others, and different ways of exploiting water and land or producing energy place different stresses on the other resources.

However, wastewater remains an undervalued resource, all too often seen as a burden to be disposed of or a nuisance to be ignored. This perception needs to change to correctly reflect its value – as wastewater is a potentially affordable and sustainable source of water, energy, nutrients, organic matter and other useful by-products.

5.1. Water footprint vs carbon footprint for different sectors of the economy

The following sections present a comparison of carbon and water footprint for different sectors of the economy, bringing to light the weight of water withdrawals in comparison to carbon footprint for these sectors. This section is not deemed to be exhaustive or representative of the whole economy but only to give a few values for our current linear economy model.

5.1.1. Fashion industry

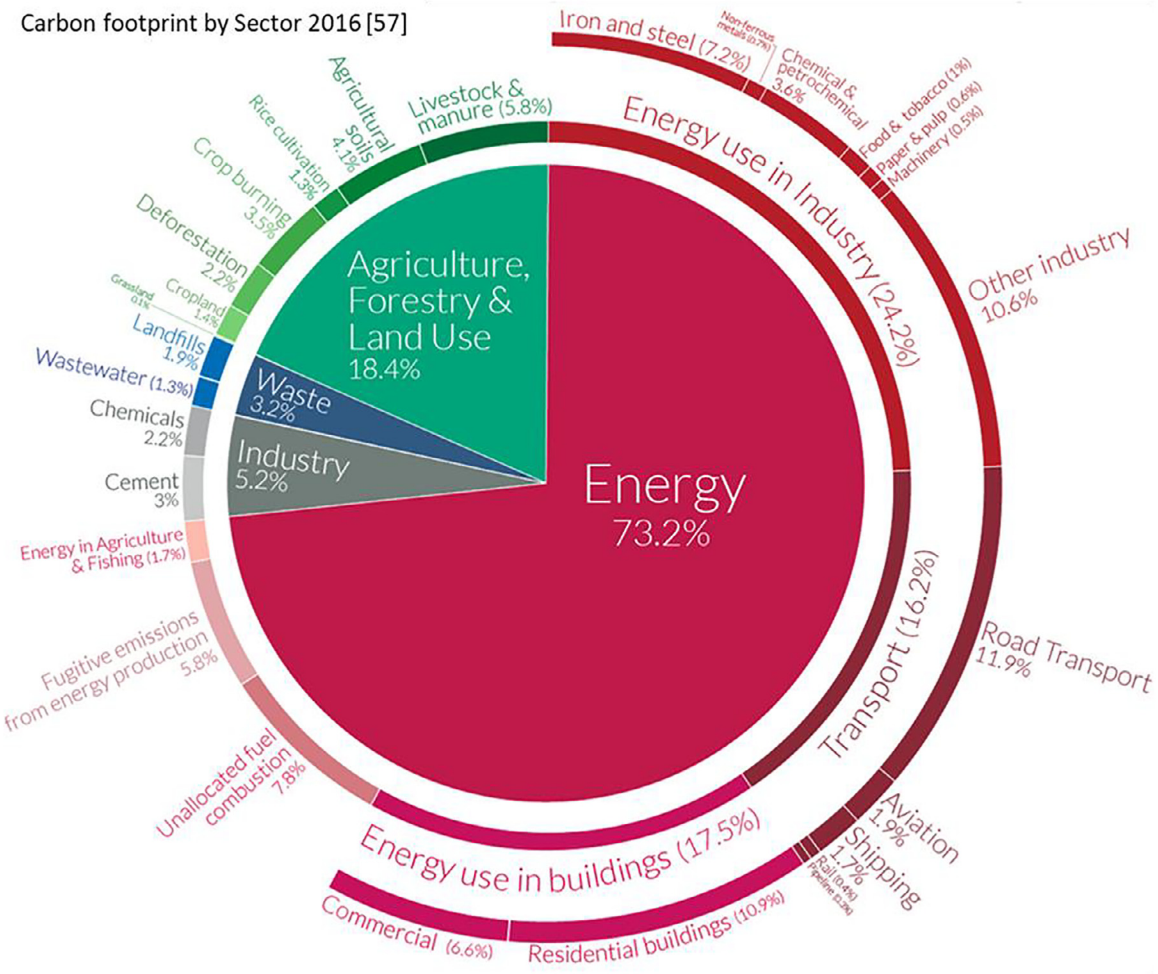
Textile production (including cotton farming) uses around 93 billion m^3 water /year [7]. However, the current economy is only efficient at recycling about 12 % of these textiles to the same quality material, which means that 88 % of produced textiles end up in landfill, incineration or lost in the manufacturing process, some of it ending up in our wastewaters (see Section 3.2). As per [15], the average lifetime of a piece of clothing in the UK is 2.2 years! That means that overall, 37.2 billion m^3 of water are wasted due to the Fast Fashion industry every year. That represents 1 % of the freshwater planetary boundary. To put things into perspective, the production of one cotton shirt consumes enough water for one person to drink at least eight cups per day for three-and-a-half years and the production of a pair of jeans consumes enough water for one person to drink eight cups per day for 10 years [37,38,40]. The fashion industry therefore needs to move away from a Fast Fashion consumption model as well as find a way to transition to a more sustainable economic model.

5.1.2. Agriculture sector

Below, on Fig. 3, are represented the carbon footprint, the water footprint and the land footprint of some agriculture products and their cumulative footprint.

It comes with no surprise that amongst main food products, red meats such as beef, sheep, or pork rank as the highest environmental impact, whereas most fruits and vegetables are at the bottom of the chart. But more specifically, it can also be observed that a lot of the most carbon intensive food products are also some of the most water footprint and land intensive at the same time. Overall, in Europe, the

Carbon footprint by Sector 2016 [57]



Water footprint by sector (2014) (based on [12]

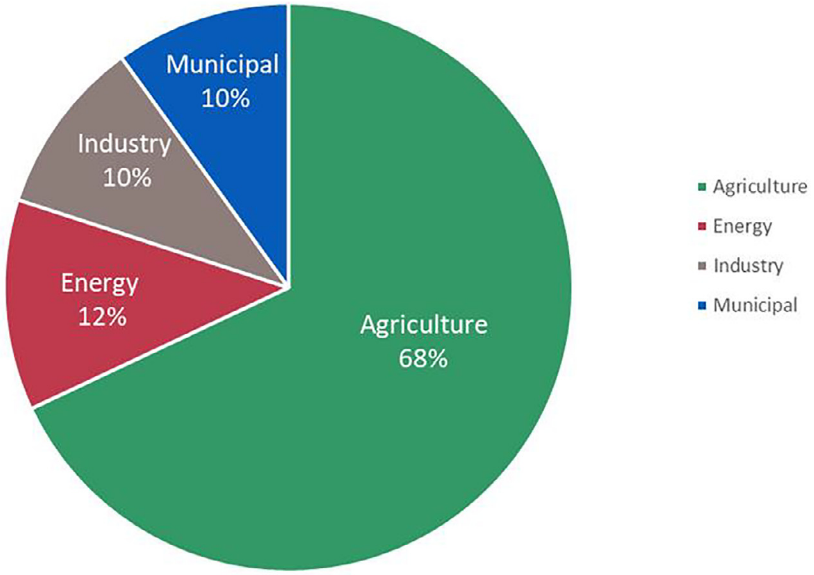


Fig. 2. Global carbon and water footprints.

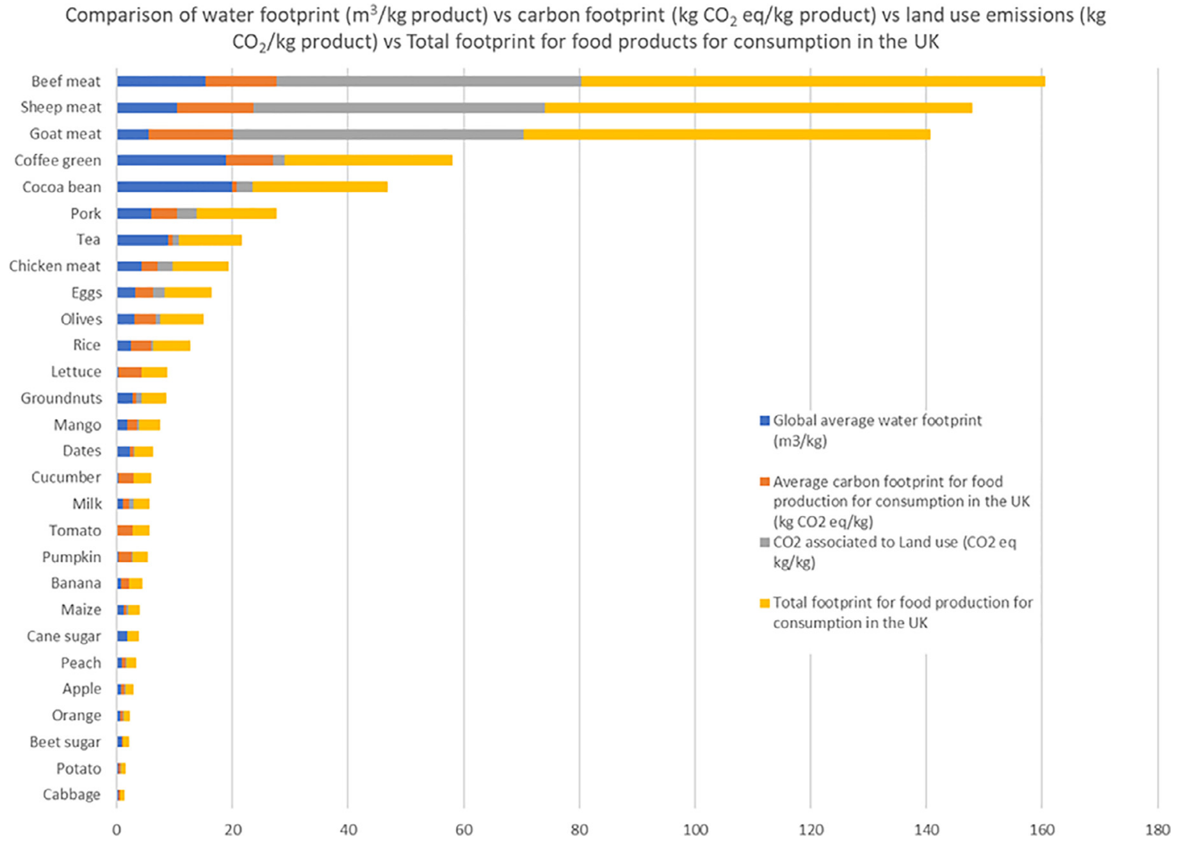


Fig. 3. Comparison of water footprint, carbon footprint and total footprint for food products for consumption in the UK – Based on [18,32,36].

manufacturing of food products consumes an average of about 5 m^3 water/pers.day [11]. With as much as 1.3 billion tonnes of food waste annually, 250 km^3/year of water is being lost due to food waste worldwide [59], which represent 6.2 % of the freshwater planet boundary wasted by the food industry alone. Humanity needs to do something about the food waste issue as well.

5.1.3. Beverage industry

From Fig. 4 below for the beverage industry, it can be observed that the more refining processes used, the more carbon and water footprints generated. Also worth be noted: although CO_2 emissions from bottle manufacturing is logically identical for all alcoholic drinks, the proportion it plays in the total CO_2 emissions is different for each alcohol type. This proportion is largely determined by the process emissions, except for beer where malt production (agricultural impact) is producing extensive quantities of CO_2 emissions compared to wine and spirits.

Lastly, proportionally, beverage manufacturing has a much higher water footprint than the corresponding carbon footprint.

5.1.4. Motor vehicles industry

An interesting study [45] reports about the water footprint of three car models of Volkswagen over their full life cycle. It is estimated that the water consumption along the life cycles of the three cars studied amounts to 52 m^3 (Polo 1.2 TDI), 62 m^3 (Golf 1.6 TDI), and 83 m^3 (Passat 2.0 TDI) and is related to the car size. And almost 78 million cars were produced worldwide in 2018 [60]. In all three cases, 95 % of the total water consumption lies in the raw material extraction and production stage of the car (as opposed to the use and end-of-life stages). As per [5], the carbon footprint of a new car is: 6 tonnes CO_2 eq: Citroen C1, basic range; 17 tonnes CO_2 eq: Ford Mondeo, medium range and 35 tonnes CO_2 eq: Land Rover Discovery, top of the range. Doing our maths tells us that limiting new material extraction is at the core of solving the nexus.

5.1.5. Building materials

Cement production contributes more CO_2 than aviation fuel (2–2.5 %) [62] and is not far behind the global agriculture business (12 %) [57]. If the cement industry were a country, it would be the 3rd largest emitter in the world. If steel were a nation, it would be the 5th largest producer of carbon emissions in the world [44]. However, water consumption is not to be ignored for some common building materials as represented in Fig. 5. Once again, that shows the importance of looking at carbon footprint and water footprint concomitantly and holistically rather than in isolation.

5.1.6. Metals extraction

The expected lifespan of fresh supplies of metals such as lead, tin, zinc, gold and silver is about 20 years according to Refs. [41] and [63], after which the Earth's underground supplies will run out or no longer be economical to mine. Other metals have 50 years and at the most less than 100 years reserve. Another alarming prediction for our future economy, our dependance on metal resources and our planet's future.

6. Energy to power the water sector vs water to power the energy sector

6.1. Water for energy production

Water use for energy production represents a critical element of the water–energy nexus. The energy system of today, dominated by oil, coal and natural gas, is water intensive, requiring substantial water inputs for fuel extraction, processing, transport, transformation, end-use and, where applicable, decommissioning [14]. Looking closer at the share of water consumption for various energy carriers, it can be observed that fossil-fuel based power and energy production is the biggest water consumer, which gives another good reason to phase out fossil-fuel

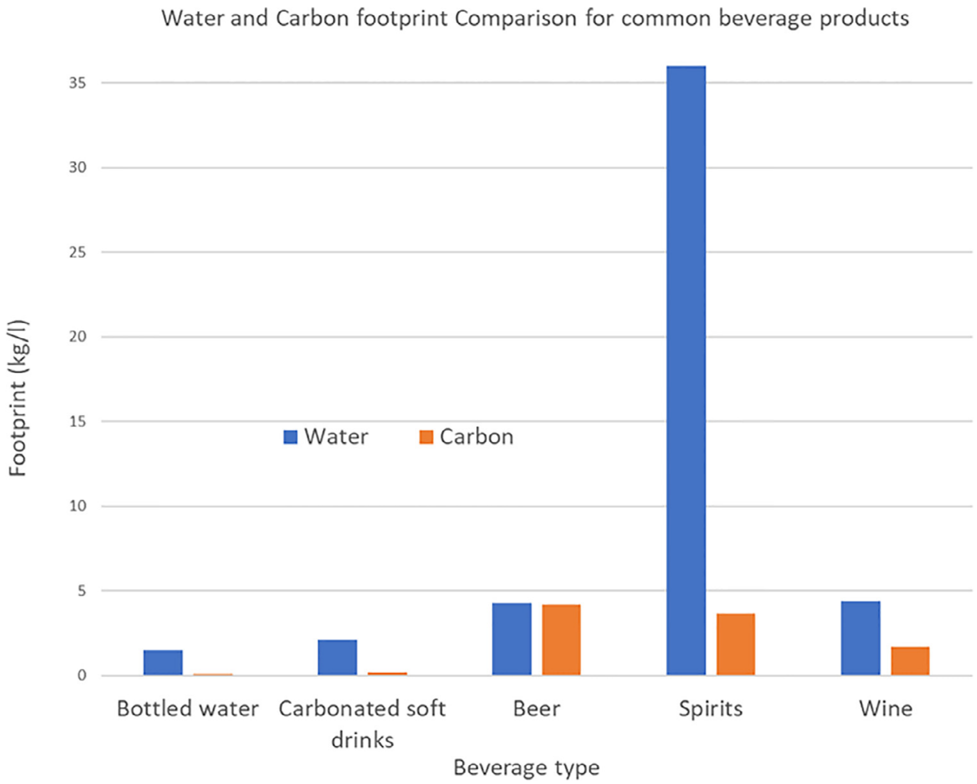


Fig. 4. Water and carbon footprint comparison for common beverage products – Based on [45–49].

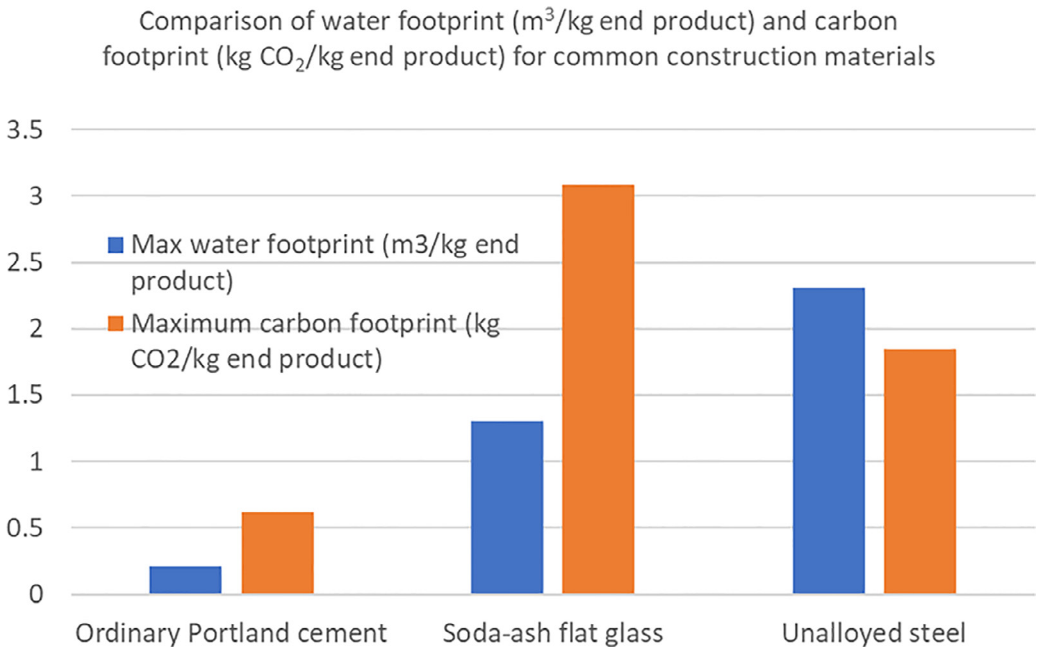


Fig. 5. Comparison of water footprint and carbon footprint for common construction materials – Based on [28,57,44,63].

power and to transition to green technologies. Power generation is by far the largest source of energy-related water withdrawals, with biofuels being the first primary energy carrier production water consumer and potentially competing with crops for food [9]. Water is also crucial for producing fuels such as coal, uranium, oil and gas and for cooling purposes in most power plants. It can also be used as the driving force for hydroelectric and steam turbines.

6.2. *Energy for water production*

Water production also consumes energy. Municipal wastewater treatment in particular is energy intensive. After personnel, energy in most cases represents the main cost for water utilities. Biological processes as part of secondary treatment dominate electricity use on wastewater treatment and collection [9]. In 2016, the total energy con-

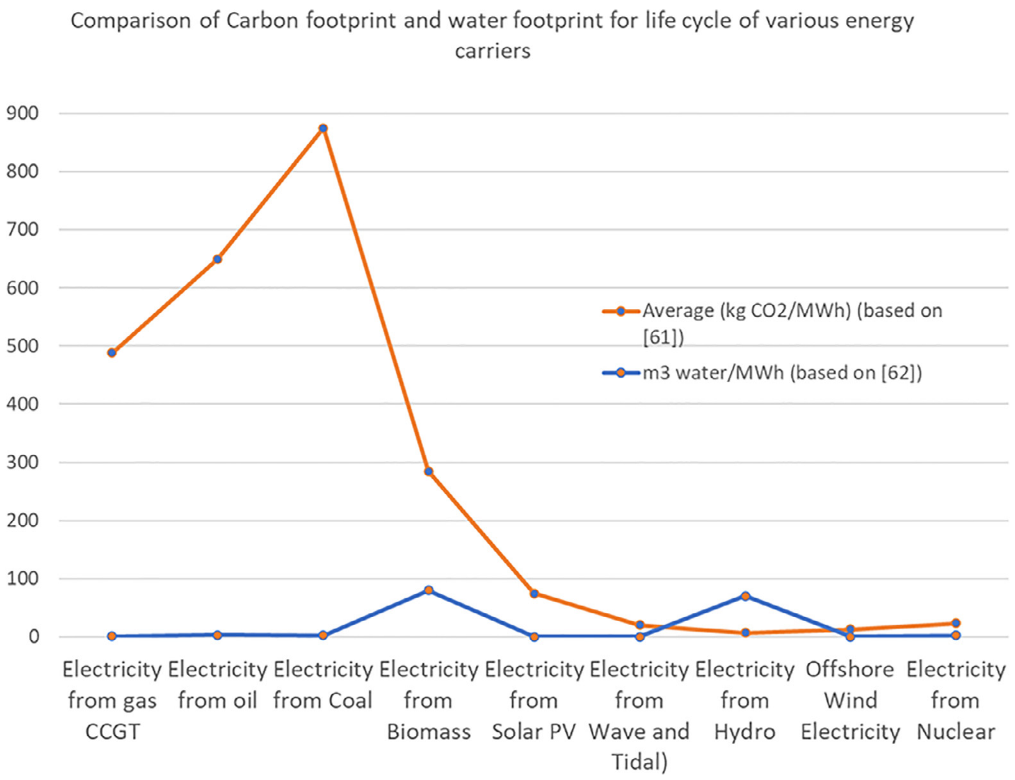


Fig. 6. Comparison of carbon footprint and water footprint for various electricity production systems – Based on [54,55].

sumption of the wastewater sector was approximately 1 % of the world's total (Fig. 2).

6.3. Interdependence energy-water

The relationship between water and energy is well understood. In most energy production processes; water is a key input. Conversely, energy is necessary to sustain and improve water services. From Fig. 6, it can be observed that, as expected, coal burning power systems have the largest carbon footprint of all the electricity generation systems. On the other hand, the water consumption for the various electricity production systems varies much less than the CO_2 emissions, with electricity from biomass (due to biomass irrigation requirements) and electricity from hydro being the biggest water consumers [54]. As with all low carbon technologies, nearly all the emissions occur during the manufacturing and construction phases, arising from the production of steel, concrete and plastic materials. These account for 98 % of the total life cycle CO_2 emissions.

On the water side, most thermal power plants require water for cooling; water is also an important factor in the extraction of fossil fuels. Only wind and solar power exert almost insignificant pressures on water demand. Consequently, the fuels or technologies used to achieve the clean energy transition could, if not properly managed, increase water stress or be limited by it. Furthermore, as with conventional energy technologies, renewables also make use of natural resources, and theirs demand in terms of land and water, in particular, can be significant. Renewable energy deployment can therefore be associated with cross-sectoral trade-offs, such as agricultural production and water supply.

This highlights the importance of considering the full life cycle when assessing the sustainability of energy production technologies.

7. The global economy

Material handling and use (metals, energy carriers) accounts for the vast majority (70 %) of GHGs emitted [2]. This proves how vital it is to look beyond the narrow energy focus of the current climate pledges (material resources amongst others) to make a real impact.

As of today, most renewable energy policies and projects are not explicitly designed to exploit synergies and very often, one sector is favoured over the others, and that clearly is the energy sector. The key steps to achieving the SDG objectives include decarbonization of the energy sector through greater deployment of renewables, measures for increased energy efficiency in buildings, a focus on a circular economy, protection of ecosystems and biodiversity, adoption of a green and healthier agriculture system and increasing uptake of electric vehicles, amongst others. But is enough done about the water sector and its coming crisis?

8. A new economic model – the circular economy

The circular economy concept has been evoked for many years as an alternative to our current linear economy and cannot be traced back to one single date or author, as several authors have contributed to refining and developing the concept since the 1970s. Today's economy principles should draw on the fact that in nature, materially closed systems have to recycle to avoid collapse. Circular economy should be based on 3 main principles (Based on Ellen McArthur foundation), which are: (i) design out waste and pollution; (ii) keep products/materials in use; (iii) regenerate natural systems.

The seven societal needs and wants of humanity include housing, nutrition, mobility, consumables, services, healthcare and communication. Providing mobility, housing and nutrition to the world accounts for almost 70 % of global emissions [2]. The remaining 30 % of emissions is produced from communications, services, consumables and healthcare. However, as per report [2] published in 2021, our current economy is only 8.6 % circular. So, "although we only need to almost double circularity to close the emissions gap by 2030″ as stated by Circle Economy organization report [2], our global economy still remains tangled in outdated 'take-make-waste' practices.

9. Circular economy governance and regulations

Despite this potential for improvement, legacy infrastructure and current regulatory priorities (often focused on the cheapest outcomes) are driving linear, unsustainable practices which do not get anywhere close to optimising reuse and recovery. Low-carbon technologies already exist to fully decouple the global economy from fossil fuels, but progress is failing at the political level and part of the reason for that is that conventional economics fail to identify the environmental costs of production. Fossil fuels currently have approximately 5 to 1 subsidy advantage over renewable energy in terms of explicit subsidy. But there are also implicit subsidies – those subsidies arising from lack of accounting for negative downstream impacts in the economy – in particular – impacts on the environment and natural capital.

The implementation of efficient economic, social, and environmental policies which can prevent the degradation and depletion of water resources implies that the total value of these resources must be measured and incorporated into the decision making process [10].

In this sense, if we consider water treatment as a productive process in which a desirable output (treated water) is obtained together with a series of undesirable outputs (suspended solids, nitrogen, phosphorus, etc.) then a shadow price can be calculated for these undesirable elements. The quantification of these shadow prices would enable an estimation of the avoided costs resulting from the removal of pollutants during wastewater treatment. These avoided costs would represent an estimation of the economic value of the minimal environmental benefits obtained from the treatment process.

Based on all considerations above, the section below analyses in which ways shadow prices could be reduced and how the water sector could become more circular.

10. Circular economy opportunities in the water sector

Water industries worldwide are intrinsincally based upon circular systems (e.g., water, carbon, nitrogen and phosphorus cycles). However, the global water industry is currently processing many of these resources in a linear fashion, and is missing the opportunity to optimize circular economy approaches through maximising resource reuse and recovery at every stage of its interaction with the water cycle. Wastewater can also be a cost-efficient and sustainable source of energy, nutrients, organic matter and other useful by-products [3]. Ultimately, the pollutants in wastewater are food to other systems. Waste and water management are crucial enablers of the circular economy, as recovering materials or energy from wastewater is necessary to close loops and provides a continuous stream of resources.

There are several ways to make the water sector contribute to a more circular economy. The approach to water circularity should start from the top of the waste hierarchy (4 Rs) with water use reduction all the way down to recovery of energy, and materials from wastewater.

Water use reduction, reuse and recycling methods have been around for decades. However, the recovery aspects of wastewater are much newer and not all available at commercial scale yet. This paper focuses on these latter technologies rather the former ones which have already been covered at length in other papers.

10.1. Material recovery opportunities

According to report [3] and to put the scale of the opportunity of wastewater into perspective, globally we produce an estimated 9.5 million m^3 of human excreta and 900 million m^3 of municipal wastewater every day. This waste contains enough nutrients to replace 25 % of the nitrogen currently used to fertilize agricultural land in the form of synthetic fertilizers, and 15 % of the phosphorus, along with enough water to irrigate 15 % of all the currently irrigated farmland in the world (some 40 million hectares). At the city scale, the wastewater from a city of 10 million people contains enough recoverable plant nutrients to fertilize about 500,000 hectares of farmland – which in turn could produce about 1.5 million tons of crops [3]. Wastewater is therefore a treasure that has not been exploited completely yet.

10.1.1. Nutrient recovery: high-value products from microalgae

Green microalgae have the ability to capture sunlight, nutrients and CO_2 and produce clean water, O_2 and biomass. The biomass produced as a by-product of wastewater treatment can be used as a feedstock to manufacture high-value bio-products such as next generation bio-fertilizers, bioplastics and biofuels.

Potential high-value products from algae biomass are: proteins for aquaculture and livestock feed; omega-3 oils and potent phytonutrients (anti-oxidants, vitamins) to maximize health and productivity; biofertilizers and biostimulants; biofuels; bioplastics; green neutraceuticals and functional foods. Microalgae can be produced on non-arable land, often using saline water. This offers the ability to enhance feed security, drought proof the live stock sector, support the expansion of the aquaculture industry and enable sustainable regional development and job creation while reducing CO_2 emissions. One acre of algae can remove up to 2.7 tons per day of CO_2 [68]. As a comparison, an acre of mature trees can capture 2.6 tons of CO_2 per year [71]. That makes algae potentially 300 times more efficient at capturing CO_2 than trees, with additional potential for circular economy practices.

10.1.2. Metal recovery

Metals and other inorganic compounds in wastewater present opportunities not only for recovery of high-value by-products, but also for reducing health concerns and environmental pollution caused by their disposal. Metal in sewage water comes from different places such as slow erosion of jewellery, use of metals in medicines and disinfectants, emissions from engines catalytic converters. Effluents from mining and electrical industries can contain certain traces of heavy metals (e.g., gold, silver, nickel, palladium, platinum, cadmium, copper, zinc, molybdenum, boron, iron and magnesium). Ending up in sludge often used as agricultural fertilizers, metals pose a problem with sludge content and future bans for agricultural use. Ecofriendly ways to extract metals would help material recovery and use of sewage sludge as fertilizers. Also, with regards to carbon emissions: recycling gold has been shown to be 300 times less carbon intensive than mining it for primary production [64]. All is therefore in favour of recovering metals from wastewater.

10.1.2.1. Metal recovery from sewage

"Sewage is a mine of gold" so to speak. A 2017 study [23], involving 64 wastewater treatment plants across Switzerland, concluded that an estimated 95 pounds of gold rush through Switzerland's sewage pipes and its pumping stations each year. That's about $1.8 million dollars of sewage-covered gold. They also estimated that about 6,600 pounds of silver flows through those pipes, which is worth about $1.7 million, according to Bloomberg. Although probably due to the large number of precision equipment manufacturers in the vicinity, the wastewater treatment plant still represents a good potential for material recovery. Since 2009, a sewage treatment facility in Tokyo that has already started extracting gold from sludge has reported a yield rivalling those found in ore at some leading gold mines (concentration higher than 40 times that of a leading gold mine) [26] with the extraction of 1.89/2 kg of gold/t flysh ash from incinerated sludge. A 2015 study [25], estimated that a city of 1 million inhabitants flushed about $13 m (£8.7 m) worth of precious metals down toilets and sewer drains each year. A model incorporating a parameter to capture the relative potential for economic value from biosolids revealed the identity of the 13 most lucrative elements (Ag, Cu, Au, P, Fe, Pd, Mn, Zn, Ir, Al, Cd, Ti, Ga, and Cr) with a combined value of US $280/ton of sludge.

As of August 2021, researchers from two Brussels universities have succeeded in extracting particles of gold, platinum and other metals from the sewers of the city [41]. The project is due to run until February

2022, with researchers hoping eventually to be able to extract 10 kg of gold from the sewers in a year, and one kilo of platinum which at today's prices represent sums of $555,900 (€473,501) for gold and $32,853 (€27,978) for platinum.

10.1.2.2. Metal recovery from produced water

Produced water contains chemicals and metals such as sodium, chlorine, calcium, potassium, strontium, magnesium, barium, boron, lithium. Li is a valuable metal, broadly known for its current application in the energy-storage sector, in Li-ion batteries. If Li was recovered with 50 % efficiency from produced water from a gas field with a water volume production range of 1,000–1,200 m^3/d and a concentration of 80–120 mg/l (common composition), that would represent a recovery of 50 kg/d. To put things into perspective, Lithium in phone battery is 2, 3 g weight on average [1]. That gives a rough idea of how many phone batteries could be produced from recovery of resources from produced water. Lithium cost was $16,500/t in 2018, which highlighs the potential for recovery from produced water, as that would mean no need to build new wells for extraction thereby reduce costs for Li recovery. On the emissions side, lithium mining releases around 15 t CO_2/t Li extracted [65], which therefore would be avoided thanks to recovery from wastewater.

At the time of this report, Li can be sustainably recovered from oil and gas produced water by utilizing Li recovery technologies such as adsorbents, membrane-based processes, and electrolysis-based systems. Lithium is considered a "hot" commodity and the importance of research into its recovery from produced water is indicated by the number of junior mining companies involved. However technologies are not yet commercially achieved.

In March 2019, MGX Minerals Inc and Eureka Resources, LLC have signed a letter of intent to form an exclusive joint venture to recover lithium from water produced at a non-conventional shale oil and gas sites in the eastern United States.

10.1.3. Fertilizers' production from sewage treatment sludge

The two objectives of wastewater sludge treatment are sanitization and stabilization to reduce numbers of pathogens and putrescibility, respectively. Hence treatment of sludge significantly reduces potential health hazards and risk of odour nuisance. In the UK, sewage sludge is treated by processes to generate conventional or enhanced biosolids products which are suitable for recycling to agricultural land. The practice of taking biosolids from sewage treatment plants out to farmland for recycling started more than 50 years ago and is very well researched and regulated in the UK. It recycles nutrients and organic matter to the soil thereby achieving agricultural benefit and providing a sustainable and economical outlet for suppliers and farmers where suitable land is accessible. The practice is largely based on the supply and transport of biosolids by water companies or their contractor to farms within economic distance of plants. The limiting factor determining the rate of application is normally the N or P content of the biosolids and the soil N and P content.

Both the treated biosolids and other products of the sludge, can be used as a fertilizer (mainly nitrogen and phosphorus components) and soil conditioner (mainly organic matter components). An alternative option can be to reclaim P as struvite (magnesium phosphate mineral) or brushite (calcium phosphate mineral) from sludge, to be commercially used as soil nutrient. Struvite and brushite can be produced in various ways at commercial scale, from digested sludge or ashes of incinerated sludge. It was estimated that, over the next decade, UK water utilities will recycle around 10 million tonnes of dry biosolids to land with a carbon benefit of 12 million tonnes CO_2 [66].

10.1.4. Sludge incineration flying ash recovery

Incineration of sludge is mentioned later as a potential technology for energy saving from municipal wastewater treatment. The process produces flying ash and dust which are separated from the flue gas before it is discharged to the atmosphere. The system produces recyclable by-products (ash and dust) which can potentially be used in road construction, and concrete production as advertised on Veolia website for their sludge fluidised bed incinerator technology [42]. In 2015, a research study identified sewage sludge ash as potential partial replacement of cement in concrete [34], thereby reducing CO_2 emissions from one of the most carbon intensive sector outside of the energy sector (8 % of global CO_2 emissions from concrete industry in 2018 [61]). In 2016, another study concluded that sludge incineration flying ash additions of up to 20 % could be used to produce mortar and concrete without detrimental effects on the final product [29]. Another way to close the loop.

10.1.5. Microplastics recovery

Although metals are the main hazards covered in the Sewage Sludge European Directive 86/278/EEC for application to agricultural lands, new hazards such as organic and inorganic chemicals, anti-microbial resistance and micro-plastics have now been identified and need to be mitigated. Wastewater treatment works are not specifically designed to remove microplastics. However removal by conventional primary and secondary wastewater treatment technologies have shown to be very effective overall and these microplastics will invevitably end up in the sludge. Microplastic in sewage sludge and subsequent application of sewage sludge for agricultural use, may lead to the transfer of microplastics and/or chemicals to soil used in growing food. EU legislation requires sludge to be treated to protect against health hazards, for example by lime stabilization, anaerobic digestion, composting, or thermal drying, but there is limited evidence of these being able to remove microplastics and there is currently no specific regulation for microplastics. Research shows there are 5,250 billion plastic particles floating on the surface of the world's seas and oceans., equivalent to 268,940 tonnes of waste. Recent studies suggest that the financial damage caused by plastics in marine ecosystems amounts to around $13 billion annually [67]. What could we do about it? Certainly plastics recycling is part of the solution. Replacement of conventionnal plastics by biobased and biodegradable plastics is another solution. But being able to recover most bioplastics which end up in our waters may also have an economic benefit ?

10.2. Energy recovery opportunities

There is significant potential for energy savings in the water sector if all the economically available energy efficiency and energy recovery potentials are exploited. Wastewater also contains significant amounts of embedded energy that, if harnessed, could cover more than half of the electricity needs of municipal wastewater utilities.

10.2.1. Energy efficiency and consumption reduction

Optimising operations at treatment plants and through distribution networks can significantly reduce overall energy consumption. Aeration of biological treatment optimization is one of the most important energy demand reduction potential in a wastewater treatment plant. Better DO control of biological processes would greatly improve energy efficiency of these assets as well as greenhouse gas emissions from wastewater treatment plants.

Thermal energy contained in wastewater can be extracted for space heating and cooling. There are several applications of wastewater use for heating/cooling in residential and commercial buildings, public spaces and industrial plants. As well as using treated effluents as a source of renewable energy, utilities can produce their own off-grid renewable energy through wind turbines, solar panels or geothermal energy; or partner with energy suppliers for renewable energy provision from the grid. Such approaches give some security against fluctuating energy prices; a hybrid model of on-grid / offgrid supply is optimal. Solar-based pumping solutions, for example, offer a costeffective alternative to pump sets that run on grid electricity or diesel. Although renewable energy may not reduce the energy intensity of the processes, it may reduce the environmental footprint and can be particularly useful in off-grid applications to increase access to reliable water services. Renewable energy technologies could address some of the trade-offs between water, energy and food, bringing substantial benefits in all three sectors. They can alleviate competition by providing energy services using less resource-intensive processes and technologies, compared to conventional energy technologies [14], as across their life cycle, some renewable energy technologies are less water intensive than conventional options.

Smart systems that enable data collection and analytics can be useful tools to identify improvement potential.

10.2.2. Energy production from wastewater

10.2.2.1. Sludge incineration and heat production

Sludge incineration can provide energy recovery for heating purposes while reducing the quantities of solid waste to be sent to landfill. However relatively low grade heat can be recovered from sludge incineration in comparison with processes such as digestion, or pyrolysis/gasification. Addtionally, the exhaut gases from sludge incineration need to be cleaned prior to discharge to the environment, which makes the incineration process very carbon intensive and capital extensive. However, report [69]-(Fig. 21) shows an energy recovery as electricity from steam turbine of around 0.8 kWh/t DS, based on various sludge incinerators across the UK. And in 2016 in the UK, the greenhouse gas emissions factor for base electricity generation was 0.284 kg CO_2/ kWh [70]. Therefore a 100,000 t DS/year sludge incineration facility with energy recovery would therefore reduce CO_2 emissions by around 22 t CO_2/year.

10.2.2.2. Biogas production

Biogas production through the anaerobic digestion of biosolids for subsequent electricity and heat generation is the most common application of on-site energy recovery in the UK. A substantial portion of the energy and heat demand of wastewater treatment plants can be met through energy recovery from biosolids [11]. Biogas generated can be burnt directly on-site in a Combined Heat and Power (CHP) plant to generate both heat and electricity in a highly efficient process. Part of the heat produced by the CHP plant is used in the digester to heat the sludge, and the power is used in the plant or sold to the grid. For a conventionnal anaerobic digestion with CHP, the amount of recovered electricity would be around 0.82 kWh/t DS [69]-(Fig. 14).

Advanced Digestion (AD) and Thermo Hydrolysis Process (THP) offer the opportunity to produce more biogas than conventional digestion, thereby increasing the efficiency of the single step digestion process, while reducing the amount of sludge to dispose of. For an advanced digestion process with CHP, the amount of recovered electricity would around 1.1 kWh/t DS [69]-(Fig. 19). These technologies have received significant attention, are proven to be cost effective and known to be predictable. Biogas is currently gaining popularity. There are many examples where anaerobic digestion of biosolids alone produces biogas that covers more than 60 % of energy consumed at wastewater treatment plants.

10.2.2.3. Sludge drying

Addtionally, sludge can be dried after the anaerobic digestion step, in order to obtain a dry product which can be easily transported and used as solid fuel. Based on [69]-(Fig. 64), the energy left from the whole process after onsite need coverage could be in the order of 60 % of the sludge energy content, under the form of electricity (1.1 kWh/t DS) and solid fuel (2.1 kWh/t DS).

10.2.2.4. Pyrolysis/Gasification and syngas production

Pyrolysis refers to the decomposition of organic matter at elevated temperatures in the absence of oxygen and under substantially dry conditions. The process employs temperatures between 300 and 1,300 °C, resulting in a biochar (charcoal-like) solid product, a bio-oil formed from ‘condensable’ volatile substances and ‘non-condensable’ gas. Pyrolysis operated under conditions selected to favour the biochar fraction is sometimes referred to as torrefaction, a process intended to generate a solid fuel product.

Gasification is a thermal conversion process that utilizes some amount of oxygen but well below stoichiometric requirements. The products of gasification are very similar to the products of the pyrolysis process, that is solid biochar and gas with gas produced in bigger proportion than with the pyrolysis process. The liquid product (or tar) is minimized or not collected during the conversion process. The synthetised gas from pyrolysis or gasification comprises primarily CO_2 and hydrogen and is called ‘syngas’, which can be directly used for heat and power generation on site. Ultimately, the syngas from the pyrolysis and gasification process can also be purified and treated to separate the hydrogen from the CO_2, in order to sell the pure hydrogen externally, or reuse it for heat and power on site and accelerate the transition to a low-carbon energy production. Pyrolysis and gasification require dry sludge as an input to optimize the energy balance of the system.

Technologies are now reaching maturity for the conversion of wastewater treatment sludge into pure hydrogen and biochar which can be used as solid biofuel. In March 2021, renewable hydrogen systems manufacturer Ways2H Inc. and its shareholder and technical partner Japan Blue Energy Co. announced the completion of a Tokyo facility that will convert sewage sludge into renewable hydrogen fuel for fuel cell mobility and power generation. The waste-to-hydrogen facility, located at the Sunamachi Water Reclamation Center (Tokyo Bay), will process 1 ton of dried sewage sludge per day, to generate 40 to 50 kg of hydrogen per day, enough to fuel 10 passenger vehicles or 25 fuel-cell e-bikes.

Ultimately, it could also be envisaged to produce hydrogen by steam reforming the biogas obtained from sludge anaerobic digestion in wastewater treatment plants. However, a side-product of the conversion processes is CO_2, which would need to go through carbon capture and storage in order to make the process net zero carbon and it is not yet proven to be economically viable.

10.2.2.5. Hydropower

Hydropower is unique because of the large quantities of water required to be stored and uncertainties regarding the amounts of water consumed as evaporative losses from reservoirs as well as hydropower unique environmental and social impacts. Meeting ever growing energy demands will require seeking coherence between water use and climate change mitigation. Hydraulic energy such as placing turbines in wastewater streams can generate electricity, but this process is restricted due to the low-elevation locations of most wastewater treatment plants.

10.2.2.6. Green hydrogen from water

Hydrogen has been mentioned a lot as the energy of the future and a necessary component of the energy transition to achieve the 2030 Paris agreement Agenda. Hydrogen is attracting growing interest from a variety of sectors and stakeholders as a potentially valuable decarbonization tool. The majority of hydrogen produced today is used for oil refining and ammonia production. Despite being the most abundant element in the universe, hydrogen does not exist on its own and needs to be extracted from water via electrolysis or separated from carbon fossil fuels. Both these processes require a significant amount of energy. A wide range of analyses have been reviewed to calculate the amount of water used during the hydrogen production, and by the energy source used to power it (renewables or gas). With a predicted global energy need over 70 EJ of electrolytic hydrogen by 2050, water consumption for hydrogen production will be about 25 billion m^3. That is relatively small compared with the global figure of 2,800 billion m^3 for agriculture (the largest consumer), 800 billion m^3 for industrial uses, and 470 billion m^3 for municipal uses. It would be equivalent to the water use of a developed country with 62 million inhabitants (400 m^3/capita). Even in the most conservative case, where water desalination is used, the water cost (treatment, transport) would be less than 2 % of the total hydrogen production cost and the energy consumption for water desalination would be only about 1 % of the total energy needed for the hydrogen production [20]. However, precious metals such as platinum and iridium are typically required as catalysts in fuel cells and some types of water electrolyser. The technology still uses finite resources and platinum is a rare and precious metal with only around 100 tonnes produced annually from mines in South Africa [30]. Green hydrogen will have to overcome several barriers to fulfil its full potential, amongst which costs. It is unsure whether this will be achievable by 2030.

10.3. Water treatment emissions reduction opportunities

Lastly, circularity considerations would not be complete without looking at the emissions aspects of water treatment plants, as many efforts to reduce carbon emissions such as carbon capture and storage rely on water availability for long-term success. The process emissions from water and wastewater treatment plants are currently receiving much attention with regards to achieving net zero carbon. Main emissions from wastewater treatment process are N_2O and CH_4 which have quite high global warming potentials. It is becoming paramount that these gas emissions are reduced from the plants in order to reach net zero emissions.

10.3.1. Emissions reduction through process optimization

N_2O is mainly emitted from secondary biological treatment [27]. There are different ways of tackling these emissions and one or a combination of many can also be used. Triggers of N_2O production and emissions from wastewater treatment processes are: (i) DO concentration. Oxygen-limiting conditions during nitrification but high dissolved oxygen during denitrification; (ii) extensive aeration leading to stripping of N_2O from the liquid phase to the gaseous phase; (iii) Treatment processes that emit lower levels of N_2O have been associated with higher process performance and a greater extent of total nitrogen (TN) removal. The major strategy proven to significantly reduce N_2O emissions is proper aeration control for optimal DO levels or cycle duration (for SBR), to ensure complete nitrification and/or denitrification and minimize N_2O production, as well as reduce N_2O stripping through extensive aeration. Aeration strategies should be carefully taken into consideration to balance emissions from process operations and energy savings. Optimal DO set-point, applying intermittent aeration, and control aeration rate are also solutions to reducing greenhouse gas emissions from water treatment plants.

CH_4 is mainly generated during the sludge treatment stage [27] i.e., the anaerobic digestion process as well as all subsequent phases of sludge handling, treatment, and storage. Emissions reduction measures for wastewater treatment plants include covering sludge tanks, including sludge treatment works in enclosed buildings with air extraction to an odour control unit or capture of the CH_4 through degassing technology. To put things into perspective once again, a recent Stantec project on GHG process emissions from sewage treatment assets calculated averaged emissions across the whole Client asset base between 0.02 and 0.2 kg $CO_{2\ eq}$/PE.day depending on wastewater and sludge treatment processes and emission factors used. More quantification work is needed in the future but for a 100,000 PE sewage treatment plant, the CO_2 eq process emissions would therefore total to around between 2 and 20 t $CO_{2\ eq}$/year in process emissions. As a reference, there are currently around 17,000 sewage treatment plant assets in the UK [72].

10.3.2. Emissions reduction through carbon capture

CO_2 is emitted from wastewater treatment plants through burning of biogas for heat and power production.

Amongst CO_2 removal approaches, microalgae can efficiently remove CO_2 through the rapid production of algal biomass. In addition, microalgae have the potential to be used in wastewater treatment. The concentration of CO_2 in the atmosphere (only about 0.04 % v/v) is not sufficient to provide carbon for algal growth. Microalgae are naturally able to obtain their carbon from several other sources, including CO_2 from industrial flue gases, and those chemically fixed in soluble carbonate compounds (e.g., $NaHCO_3$ and Na_2CO_3). Waste gases from combustion represent a viable source of CO_2 that can be directly introduced into large-scale microalgae production systems, as they usually contain CO_2 in volume fraction of 5 to 15 %. Algal biomass can convert wastewater pollution into high-value products and simultaneously reduce greenhouse gas emissions [22].

These emissions could also be reduced by carbon capture and storage technology (CCS) if appropriate and economically beneficial to do so. CCS is often presented by energy companies and governements as the new pass allowing us to carrying on burning coal, oil and gas for electricity production. Unfortunately, once again, the water requirements of CCS technologies are often over-looked or have not yet been fully assessed. Depending on the technology, the water footprint of CCS technologies ranges from 0.74 to 575 m^3 H_2O/tonne CO_2 captured [8]. The widespread deployment of CCS to meet the 1.5 °C climate target would almost double the anthropogenic water footprint. Based on the previously stated planet boundary for freshwater, this would likely exacerbate and/or create water scarcity conditions in many regions worldwide. Once again, these numbers show that CCS can only be part of the solution to mitigating climate change and that other more circular solutions will need to be put in place to achieve climate change mitigation.

10.3.3. Offsetting

A tree absorbs 10–50 kg CO_2/year on average, depending on the type of tree and its age. Increasing the Earth's forests by an area the size of the United States would cut atmospheric carbon dioxide 25 % according to [39]. However, using land alone to remove the world's carbon emissions to achieve 'net zero' by 2050 would require at least 1.6 billion hectares of new forests, equivalent to five times the size of India or more than all the farmland on the planet [58]. It is also really hard to show much benefit from afforestation (and/or reforestation) in the line with deadline humanity is struggling with, because there's always the problem of not having enough water to support the rapid growth of these trees. Currently only around 1.57 billion ha of land is arable. Report [21] states that too many governments are relying on carbon offsetting through nature-based solutions. Relying on land-based solutions may worsen poverty and hunger in the coming decades. Although global tree restoration is the most effective climate change solution to date [33], offsetting should only be used as a complement to emissions mitigation and reductions measures to improve the climate situation.

10.4. Technological advances and land savings opportunities

10.4.1. Advances in membrane and other treatment technologies

One of the various aspects of the energy-food-water nexus is also the competition for land. Advances in membrane technologies have allowed the reduction of land use associated with wastewater treatment. Advances in membrane technology have not only reduced human and environmental health risks associated with treated wastewater, but opened new opportunities for wastewater use such as potable reuse. The use of membrane technologies (reverse osmosis, nicrofiltration, ultrafiltration, MBR, MBBR etc.) is becoming increasingly common for tertiary and advanced treatment, especially in developped countries, as membranes continue to improve and operational costs decrease [11], as well as reducing land use, which can then be used for agricultural purpose instead. Membrane technologies offer advantages such as compactness, flexibility and ability to operate reliably under remote control. But membrane technologies are not sustainable due to their high energy demand. Therefore new developments in biological treatment processes (Nereda, Annamox) have also found successful application due to the high efficiencies and low investment and operational costs.

Innovative wastewater monitoring and control systems are also finding application as technologies improve. The most promising technological advances include: innovative monitoring techniques based on new sensors, computerised telemetry devices, and innovative data analysis tools. Research on sensor include mobile applications to operate the SCADA (Supervisory Control and Data Acquisition) system for remote monitoring and control of wastewater systems.

Natural treatment systems (constructed wetlands, sustainable drainage systems (SUDS)) are becoming more attrative as innovative nature solutions to complement existing technological limitations, with research increasingly focusing on natural processes.

10.4.2. Hydroponics/aquaponics/aeroponics

Hydroponics is a type of horticulture which involves growing crops without soil, by using mineral nutrient solutions in an aqueous solvent. The nutrients used in hydroponic systems can come from many different sources, including fish excrement, duck manure, purchased chemical fertilizers, or artificial nutrient solutions. Plants commonly grown hydroponically include tomatoes, peppers, cucumbers, strawberries, lettuces. Hydroponics offers many advantages, notably a decrease in water usage in agriculture. Aeroponics is the process of growing plants in an air or mist environment without the use of soil or an aggregate medium. To grow 1 kg of tomatoes using intensive farming methods requires 400 L of water, using hydroponics, 70 L; and only 20 L using aeroponics. These natural solutions are especially applicable for urban areas, which themselves are a major source of GHGs. In Chicago, "The Plant" installed in a reused old industrial building in the inner city, is harnessing wastes as material input to other processes, taking the output of one process and making it the input to another process, using aquaponics systems waste from fish to feed plants and vice-versa, while cleaning the fish tanks water to reuse it. The Plant is planning to receive food waste from businesses around and put them through anaerobic digestion to sell sludge and liquid as soil amendments, using their biogas for electricity generation to run plants grow lights and fish tank blowers, and heat for building heating. The plant location will also allow to create green jobs in the local community, thereby avoiding long distance commute and providing local food to the community, thereby reducing CO_2 emissions.

11. Future developments and conclusions

11.1. Future developments

Over the past years, lots of scientific papers concurred on the fact that the following factors contribute to some of the barriers to a rapid and just transition to circular economy (CE): culture, market, regulation and technology as a minimum.

The present paper shows that there are lots of available technologies under use or exploration to achieve or tend to a more circular water sector. Without a doubt, more technologies will come up in years to come for the sector.

However the remaining cultural, market and regulatory barriers are no exception for the water sector. Study [73] found that, most notably 'lack of consumer interest and awareness' as well as 'hesitant company's culture appear to be the most pressing CE barriers that slow down and possibly eventually derail the transition towards a CE.

CE business models have difficulties to compete on the market due to competing 'low virgin material prices'.

Targeted governmental interventions regarding the identified market barriers, e.g., the easing-out of subsidies that favour linear products, while, simultaneously, adopting policies that favour circular products are not voted and implemented quickly enough.

Future development should focus on fostering the following economical aspects in order to gain momentum for a more circular economy:

- Create a compelling vision of the CE benefits for the general public and consumers to increase the demand and uptake of circular economy products.
- Promote a wide range of industry benefits for companies and individuals to switch to circular through regional, governmental, and international regulations.
- Embrace and de-risk further innovative technologies in the sector.
- Find suitable markets for sludge/biosolids and products recovered from wastewater and sludge treatment (metals, microplastics,…)
- De-risk the health impacts of going circular in the wastewater sector.

All of the above require strong and durable collaboration across the whole value chain on the international scene: consumers, producers, companies, government and regulatory bodies and more importantly a paradigm shift of Humanity globally.

11.2. Conclusions

By 2050, the global population will reach 10 billion, leading to increased water, food and energy needs. Water, food/material and energy are strongly interlinked: water is necessary to produce, transport and use all forms of energy to some extent; and energy is required for the extraction, treatment and distribution of water, as well as its collection and treatment after use. In the same way, both water and energy are also required to produce food. That implies that the choices made in one domain have direct and indirect consequences on the others. These interdependencies lie at the heart of what has become known as the "water-food-energy" nexus and intensify as the demand for resources increases with population growth and changing consumption patterns.

As a sector based on multiple cycles (water, carbon, nitrogen, phosphorus and sulphur cycle), it may be argued that there are aspects of current water sector which already reflect some circular economy principles. Water companies are increasingly recovering nutrients or/and energy from their treatment processes but there is still a long way to achieve optimum circularity. In the water-energy-food nexus context, all recovery options should be looked at and CO_2 emissions and nutrient recovery should be envisaged concomittently, not favouring carbon footprint over water footprint.

There are several ways to make the water sector contribute to a more circular ecomomy. The approach to water circularity should start from the top of the waste hierarchy with water use reduction all the way down to recovery of energy, and materials. Ultimately, the pollutants in wastewater are food to other systems. So Humanity best chance at mitigating climate change, and shortage of resources is to harness the value of water as much as possible. The technologies already exist to fully decouple the global economy from fossil fuels but progress is failing at the political level and part of the reason for that is that conventional economics fails to identify the environmental costs of production.

Water needs to become a building block of the new low carbon economy and to be looked at holistically and in relation to energy and food:

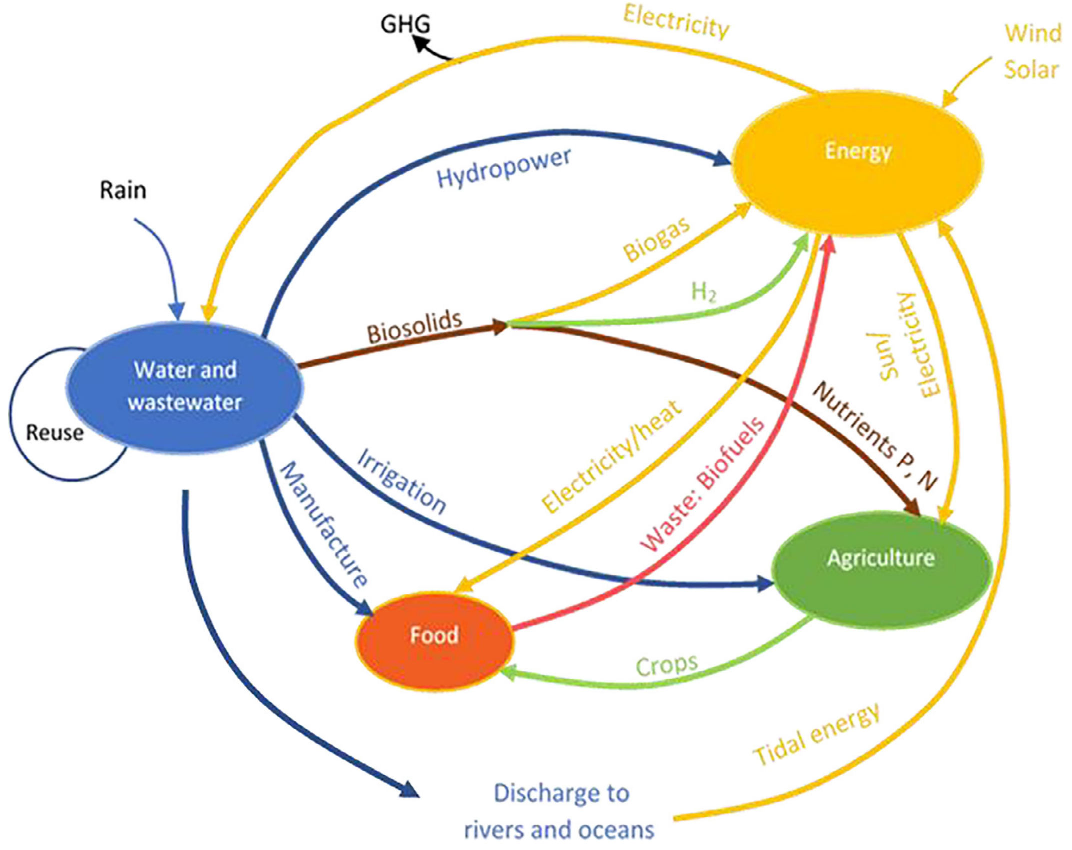


Fig. 7. Circular economy for the water sector in a nutshell.

And it is time to do this now.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2022.100061.

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