MEASURING THE CIRCULAR ECONOMY OF WATER SECTOR IN THE THREE-FOLD LINKAGE OF WATER, ENERGY AND MATERIALS

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Abstract

Circular economy is gaining increased attention over the conventional "make-use-dispose" model. Researchers, industries and institutions recognise circular economy as an approach to increase the economic growth in a sustainable way. Fundamental principles of circular economy strategies focus on reduce, reuse and recycle in order to close the loops of materials and energy flows and eliminate waste. However, there is still lack of appropriate tools and indicators measuring the circular economy performance of a system. The application of circular economy to water sector changes fundamentally the perception of the water supply chains – water is seen as medium of valuable resources, while water infrastructures are considered as a part of an inter-sectoral value chain system, enabling to revamp existing water systems in an environmentally and economically sustainable way. This paper explores the application of circular economy principles to the water sector in the key interlinked pathways of water energy and materials. Furthermore, it analyses the main environmental and sustainability methodologies and indexes and their suitability for evaluation of the circular economy performance of the water systems.

1. Introduction

The circular economy (CE) concept is gaining increased attention over the conventional "make-use-dispose" model [1], [2]. Fundamental principles of circular economy strategies focus on the reduction, re-use and efficiency of resources utilization [3] ,while boosting economic growth [4] and therefore directly linked with sustainable waste and resource management [5], systems thinking and re-design and "closing loops" of materials and energy flows [6]. A recent review performed by Saidani et al. [7] showed that a universally recognized definition of the circular economy concept is missing, whereas according to the European Environmental Agency (EEA) there are not standardized metrics and monitoring tools to evaluate and support the transition towards circular economy at a company, country and EU level [8].

While circular indicator indexes and methodological frameworks are at a premature stage [7], studies integrating circular economy model in water resources management are even more scarce [9]. According to the report published by Veolia [10], the adaptation of circular economy principles is essential for enhancing water resilience. Efficient implementation and economic benefits of circular water use in Australia have been already demonstrated [11], while Abu-Ghunmi et al., [12] developed a methodological framework to assess the economic drivers, fostering water circular strategies in Jordan. On the other hand, while pressures on re-use and recycling of resources are increasing [13], wastewater treatment plants, acting as wastewater biorefineries can be a key technological platform of circular economy systems introducing innovative technological solutions and moving towards resource recovery approaches in wastewater management.

2. Water in the context of circular economy

2.1. Natural and man-made water cycle

The natural water cycle describes the continuous movement of water underground, land, rivers ocean and atmosphere. It is a driving force for the formation of water resources and vital for the environment [14]. On the other side, the man-made or social water cycles are mainly related to industrial and urban water use supply chains, which consists of water supply, water use/consumption, drainage treatment and reuse [15]. The social water cycle interferes with the natural water pathway by multiple abstractions and discharges of water by the industrial and urban water cycles affecting the water quantity and quality of the water bodies. In order to maintain the environmental health in good condition the withdrawn and consumed water should not exceed the minimum "environmental flow" vital for the ecosystem [16] [17]. However, in some regions the natural replenishment rates are too low, which leads to water stress [18]. Furthermore, the natural water cycle is indirectly influenced by the global climate changes as a result of the excessive expansion of human activities making the water management more and more challenging [19]. Thus, the adoption of circular economy approaches for improving the sustainability of the industry and urban water cycles are of significant importance to maintain the balance between the natural and man-made water cycles. The implementation of measures to control water resource use and existing innovative decentralized energy and water reuse systems can be integrated to deliver circular economy at region or basin level. Other extensive solutions such as forest management and wetlands restoration are also being considered as circular economy strategies to ensure vitality of the watershed and prevent freshwater contamination and reduce flood risk [17].

2.2. Circular economy solutions in water sector

Water is a key enabler and fundamental link amongst Water, Energy and Materials circular pathways [20]. Numerous innovation projects and circular advanced solutions have been applied first-and-once at local scale; however, many of those fragments of circular success have not yet been turned to large scale demonstrations. The recently published United Nations World Water Development report emphasizes the role of wastewater in the circular economy and presents the wastewater management cycle as an integrated 4-step process: (a) source reduction and prevention of pollution, (b) contaminants removal, (c) wastewater re-use and (d) by-products recover [21].

Figure 1 shows an overview of the eight categories of circular economy solutions in the water sector following the three interrelated pathways of water, energy and materials, and their pathway junctions in water service systems. From this perspective, water can be seen as medium of valuable resources and water infrastructure as a part of an inter-sectoral value chain system.

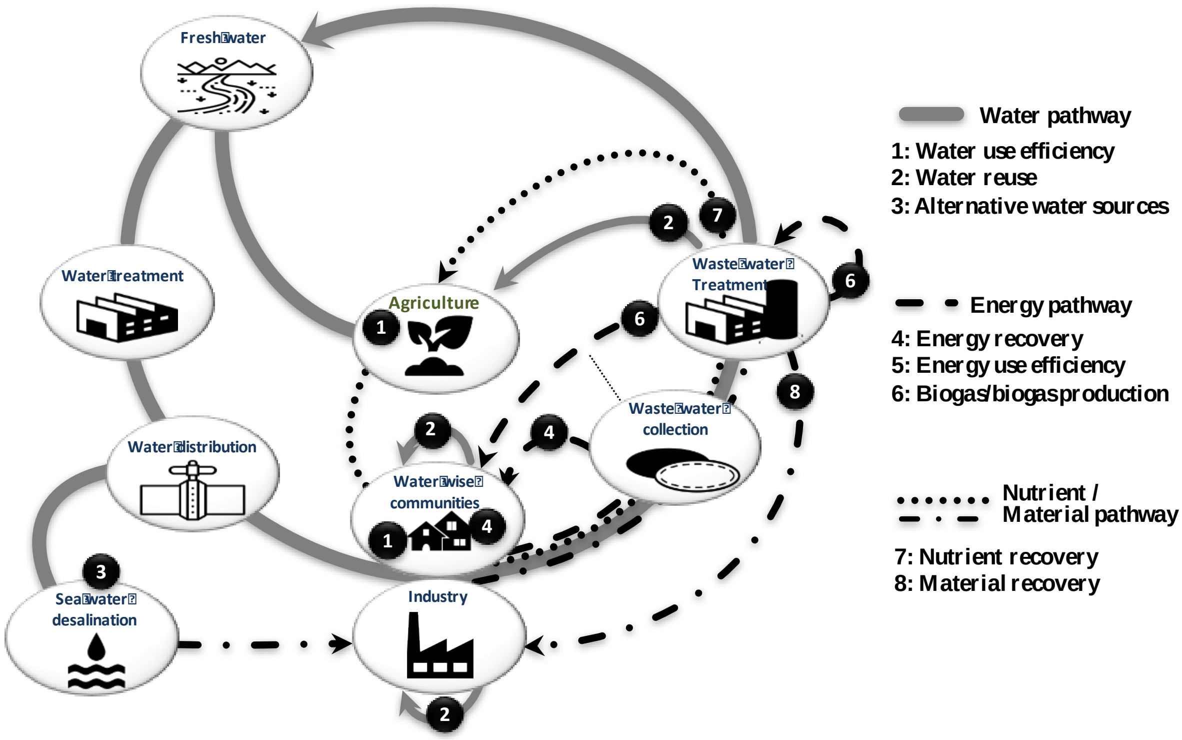

Figure 1 Overview of the potential circular economy solutions in water sector according to the interrelated pathways of water, energy and materials

Besides the compliance with the tight water-related discharge European regulations, the circular economy potential in WWTPs has become a central issue. Figure 1 demonstrates that WWTPs are in the core of the circular economy pathways with high potential of water, energy and materials recovery. However, nowadays the wastewater treatment sector is responsible for 3% of electricity consumption globally [22], while it accounts for 56% of the operational carbon footprint of urban water systems [23].

In the last few years increasing number of studies are focusing on WWTPs and their potential for recovering valuable resources [24]–[28]. Wastewater contains 1.3 MJ/person/day (6.5 MJ/L) in terms of chemical energy [29]. According to McCarty et al. [30], energy efficiency in WWTPs, combined with more efficient utilization of wastewater energy potential can lead to energy positive WWTPs especially when energy recovery potential of the sewage sludge organic carbon is considered [31], [32]. For example, energy self-sufficient WWTPs or even net energy-producing WWTPs have been reported recently, applying co-digestion of wastewater with organic wastes from urban, agricultural, agronomic or industrial sources [33]. The implementation of renewable energy sources (i.e., photovoltaic or wind power) can also be considered to improve the plant’s energy efficiency [34]. Due to its calorific value, the use of dry sludge from WWTP can be also used as an alternative fuel in industrial plants (i.e. cement industry). Additionally, the carbon in wastewater can be utilized for the production of by-products (i.e. biopolymers, chemicals etc.) [35], [36].

Given that wastewater is a carrier of 50% to 100% of waste resources lost, the recovery of these resources is driven by economic, environmental and industrial incentives [36]. Wastewater facilities have the potential to act as loop-closing wastewater biorefineries recovering added-value resources such as chemicals, nutrients, bioplastics, enzymes, metals and water [29], [36]–[39] that can become an input for industries or agriculture, among others (see Figure 1). According to Cordell et al. [40], 20% of the phosphorous consumed is contained in wastewater, while the nitrogen loads in wastewater are equal to 10%-30% of nitrogen required in agriculture [41]. The reuse of these nutrients for irrigation or its recovery as fertilizers reduces the global environmental impact of their industrial production. Furthermore, phosphorous recovery from wastewaters is prioritized, since this nutrient was recently identified as a critical raw material for the European Union.

As shown in Figure 1, one key technology with significant prospects for water and materials recovery is seawater desalination, especially with Forward Osmosis (FO) membranes. Most desalination plants worldwide are based on the Reverse Osmosis (RO) technology which is energy consuming (although the implementation of pressure exchangers reduces considerably the energy demand). The application of FO technology could significantly reduce the mechanical or electric energy demand, since the regeneration of the osmotic solution can be performed using low-temperature thermal energy (i.e. from renewable resources). Moreover, material recovery in desalination plants is also under development. For example, the extraction of salts from desalination brines and its subsequent purification offer the possibility of valorising them as a product with commercial value [42]. Additionally, end-of-life RO membranes of seawater desalination (usually, after 10 years of operation) could be reused for other RO applications that have lower quality specification requirements, instead of landfill disposal [43].

3. Measuring circularity in water sector

Although literature on circular economy in the water use systems is still in its infancy, the concept is gaining momentum in the water sector [20], [44]. However, compared to other product systems, the water sector has not received much attention on the dimensions and measuring the CE performance.

3.1. Review of index based methods measuring the CE in water sector

Recently, Elia et al. [45] reported that existing LCA-based and standardized environmental methodologies (i.e. life cycle assessment (LCA), water footprint (WF)) are able to assess circular economy strategies especially at micro level. The authors developed a decision support-framework for the selection of indicators to assess “conformity” within the circular economy concept. The analysis showed that existing indicators, standalone or combined, are insufficient to quantify the product’s durability increase, which is a significant metric for the transition to circular economy.

However, environmental indicators are key instruments towards the assessment and mitigation of the environmental impacts and the unsustainable freshwater utilisation [46]. A recent report published by EASAC [47] outlines the synergies between existing environmental indicators and circular economy and emphasizes the role of water accounting and water re-use potential. Two approaches have been developed to holistically assess freshwater use, the first one follows a volumetric approach and was developed by the Water Footprint Network (WFN) [48], whereas the second one is based on a Life Cycle Analysis approach as introduced by the Life Cycle Analysis (LCA) community [49]. Towards the Water Footprint assessment, temporal and geographical dimensions should be taken into consideration, along with the identification of water quality and quantity alternations, based on the available hydrological information (BS ISO 14046, 2014). The volumetric and LCA-based WF indicators can provide information on environmental impacts that are related with freshwater use, consumption and degradation and therefore they can complement a circular economy strategy assessment or design.

However, given that circular economy is interlinked with economic growth, social welfare and environmental sustainability aspects [50], existing and new metrics follow different approaches. For example, Di Maio and Rem [51], argued that a circular economy indicator needs to be less complex than an LCA assessment and in line with recent EU policies aiming to foster social and environmental welfare. In order to assess resource efficiency, the conventionally used mass recycling rates should be replaced with a circular indicator index that is based on the value for recycled materials divided by the value for produced materials. The method, can support decision making when complemented with LCA-based environmental indicators. A non-monetary value oriented approach was published by Franklin-Johnson et al. [52]; a longevity indicator was developed as a measure of the duration of a resource in a production system considering i) initial lifetime, ii) lifetime after refurbishment, iii) lifetime earned after recycling.

The Material Circularity Indicator (MCI) is one of the most widely applied circular indicator. It was developed by Ellen MacArthur Foundation [53] and mainly focuses on the assessment of material flows, guiding during products' design considering reporting and investment opportunities [7]. However, this method does not consider materials flowing in the biological cycle and from renewable sources (i.e. food) [53]. The majority of the aforementioned indicators have been mainly designed to evaluate products and businesses circularity strategies and therefore, are not directly applicable to the water sector. Additionally, dimensional circular economy indicators neglect significant aspects for the circular economy concept (i.e. energy, materials or water flows) [50].

China's circular economy indicator system on a macro level consists of a number of metrics to quantify water use, consumption, irrigation efficiency, re-use and wastewater discharge and reclamation [50]. However, a recent report of IWA [54] highlights the complexity of assessing the transition of the water industry into circular economy. Three major routes are identified; the water, materials and energy pathway. Circular economy indicators standalone or complemented with environmental assessments for the water sector, accounting for material, energy and water flows are essential to enable the sector to investigate and overcome regulatory barriers and identify market opportunities.

A recent approach developed within the circular economy concept discusses the barriers created by "contaminated interaction" and is strongly linked with the water industry [55]. Three types of contamination that can hinder circular economy concept are identified, i) the technical contamination describing challenges imposed by the contamination of products in a processing system, ii) the systemic contamination describing contamination of materials flowing within a system and iii) contaminated interaction which deals with perceived impurities due to previous use. Specifically, regarding resources recovered from wastewater and wastewater re-use, contaminated interaction (i.e. public perception) must be investigated and understood in-depth in order to enhance market value of water and materials recovery in the biorefineries of the future.

Additionally, Cullen et al. [56], emphasize that circular economy is interlinked with sustainability; therefore innovative circular economy strategies should assessed on the basis of energy flows and environmental efficiency of recycling solutions. An in depth analysis and understanding of resources and energy flows is needed in both linear and circular systems. Consequently, the progress to circular economy will be assessed based on the theoretical circular economy ideal. In a holistic approach trade-offs, synergies and conflicting areas of water, material and energy flows should also be accounted.

3.2. Eco-efficiency vs Eco-effectiveness and relation to the Circular economy

Eco-efficiency is a concept integrates practises for increasing the economic value of a product or service while decreasing its environmental impact [57]. Thus, it can be used for the increase of the sustainability of a system providing a quantitative assessment of two of the pillars of sustainable development. However, the eco-efficiency concept has been developed under the assumption of a linear flow of materials through a product system [58]. In a wider ontext, the urban water systems follow the linear (cradle to grave) system approach: water is abstracted from nature, purified, delivered to the users and treated in its "end of life" in WWTPs. Hence, the application of the eco-efficiency approach in the water sector has been focused mainly on techniques aiming to minimize the material and energy inputs and environmental footprint while maintaining the same quality of the water services [59]–[62]. However, the increase of the eco-efficiency considering only the minimization of the environmental and economic impact would flatten the examination of other solutions in the holistic context of the circular economy. In contrast to the eco-efficiency approach, the eco-effectiveness concept does not strive to the reduction of the environmental impact but rather stimulate and improve the positive footprint of the system [58]. In this context, the eco-effectiveness is closer to the circular economy principles focusing on the maximisation of the recovery of valuable resources and energy among the entire water supply chain.

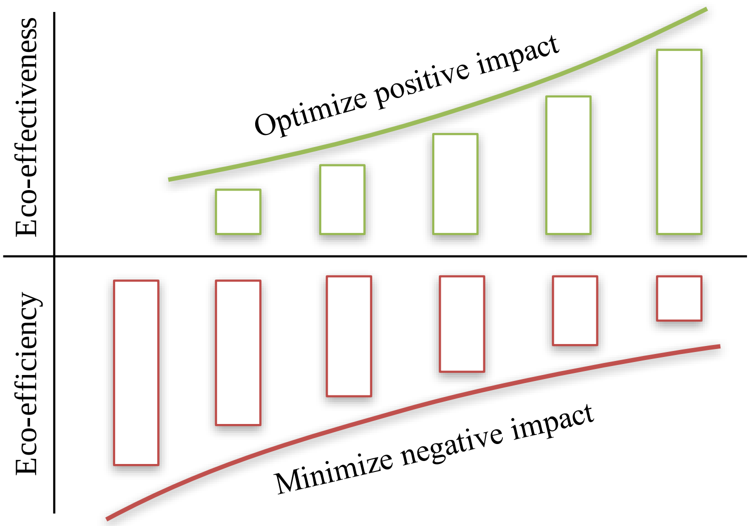

Figure 2 Eco-efficiency and eco-effectiveness and relation to the circular economy approach *(Adapted from* [63]*)*

3.3. Circularity and environmental performance

In recent studies assessing the circular economy potential in water sector, the main focus has been on the reuse and recycle as measures to increase the circularity of the system [64], [65]. However, in some cases the straightforward application of reuse and recycle principles might result in a net negative environmental impact and even worsen the overall sustainability performance of the system. For instance, energy intensive recycling technologies, such as RO for water reuse, driven by the current energy mix, where fossil fuels are still playing a major part, would only shift the environment impact to another impact category. Nair et al. [66] analyses the water-energy nexus of technologies reclaiming water from alternative water sources and the link between water scarcity and climate change impacts.

From a historical point of view, the WWTPs present an "end-of-pipe" solution primarily designed to treat the wastewater and limit the pollution load discharged to the environment. In this regard, the CE approaches for urban WWTPs are driven by the assumption that the urban water systems will continue to follow the linear model of water use, transportation, and treatment of wastewater in the future. However, since the primary principle of circular economy is to reduce the environmental impact on its source, other regenerative thinking approaches consider decentralised sanitation, reuse models and ecological sanitation closing the CE loops at community level. Closing the CE loops to the source has higher recovering potential by avoiding the high material and energy losses in the sewerage networks [67], [68].

4. Barriers and drivers to the circular economy transition in water sector

Currently, there are several research or innovation actions that address different aspects of the circular economy concept in the water sector. However, most of these projects are limited to specific segments of the water cycle and/or do not address regulatory barriers. Additionally, the full-scale implementation of innovative recovery technologies is still limited. According to Puyol et al. [36] the impacts of emerging technologies for bioproducts recovery have not yet been completely assessed in terms of sustainability and economics whereas in many cases, the technology readiness level (TRL) is still below 5. Widespread full-scale implementation of circular solutions for wastewater requires a standardized approach to evaluate fit-for-purpose developing technologies addressing environmental, cost, social (i.e. contaminated interaction), market and political aspects (i.e. policy favouring GHG reduction over resource recovery), while addressing legislative barriers. In fact, absence of integrated policies [69] and existing legislative barriers can impair significantly the development of wastewater biorefineries. Financial instruments and the adequate regulatory mechanisms are needed to support public and private engagement in circular pathways at various local settings.

Competitiveness of wastewater reuse can be also boosted when freshwater costs are comparable with wastewater treatment costs, while industrial symbiosis enhancing wastewater reuse and recycling of materials present significant economic opportunities [21]. However, the circular economy-based synergies within urban water systems are still unclear. To overcome these shortcomings, an integrated and systematic approach towards circular economy implementation in urban water systems that impacts at micro (single stages and process), meso (water system value chain) and macro (basin, region) level is needed. The application of systems thinking perspective on city, basin and regional level can identify and link all possible relationships between the physical elements of the systems. This will bring together all relevant stakeholders and facilitate the overcoming of current social, regulatory/governance and market barriers in the transition to circular economy. Expanding the boundaries of the WWTPs and developing co-operation mechanisms within the whole value chain will enable the identification of suitable Water Public Innovation Procurement Policies or public-private governance alternatives.

5. Conclusions

Sustainable water management practices and energy, materials and water recovery strategies from wastewater are fundamental for the transition to circular economy models. However, the fragments of circular approaches on water resources management have yet to be translated into systematic methods and standardized metrics to evaluate different circular models. Existing circular indicators focus on industrial products, ignoring the biological cycles or provide an oversimplified approach without considering the water and energy flows. A methodological framework needs to be developed considering all three pathways to water circularity (energy, materials, water), while addressing market opportunities, environmental and social dimensions.

Acknowledgments

This paper is supported by the Horizon 2020 research and innovation programme, SMART-Plant under grant agreement No 690323. The authors would like to acknowledge the Royal Society for the funding of the current research: Ad-Bio, Advanced Fellowship-2015/R2.

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