Energy Nexus 19 (2025) 100475

Contents lists available at ScienceDirect

Energy Nexus

journal homepage: www.elsevier.com/locate/nexus

Full Length Article

The water-energy-materials nexus in an industrial setting: legal and practical peripheries

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ARTICLE INFO

Keywords:
The water-energy-materials nexus
Circular economy
Regulation (EU) 2020/741
Urban wastewater treatment directive (EU) 2024/3019
Renewable energy directive EU/2023/2413
Energy efficiency directive EU/2023/179
1the iWAYS project

ABSTRACT

Due to the climate change emergency, there is an existential need to transit to a more sustainable and circular economy. Building on the European Green Deal, using quantitative and qualitative historical and doctrinal analyses, this study reviews the newest EU legislation related to water (predominantly wastewater), energy, materials and industries in search for impetuses for circular solutions and environmental sustainability. While employing the Water-Energy-Materials nexus, the paper also illustrates through a practical example, an integrated circular solution enabling to close the loop in industrial processes, aiming to significantly reduce resource waste, particularly in terms of energy and water consumption. The iWAYs project, depending on the type of industry, has demonstrated the potential to reduce waste heat and energy consumption by 10 %-80 % by recovering sensible and latent heat from challenging exhaust stream as well as the recovering up to 90 % of discarded water from condensate stream. Additionally, the proposed solutions allow the use of 30 %-60 % less freshwater.

1. Introduction

The climate change emergency calls for an urgent action to be taken by various actors, governments, societies, and businesses, including industries to transit to a more sustainable and circular economy (CE). In the EU (European Union), the European Commission launched the European Green Deal in 2019 [1], which is a roadmap for a sustainable EU economy, setting out the EU's growth strategy in the context of climatic and environmental challenges. It aims to form a 'fair and prosperous society, with a resource-efficient and competitive economy' that 'decouples' economic growth from resource use and achieves net zero emissions by 2050, made legally binding by the European Climate Law (Regulation (EU) 2021/1119). The full scope of the European Green Deal's policy ambitions and legislative proposals, which primarily are forward-looking, can only be grasped by exploring the vast plethora of communications, legislative proposals and other policy documents accompanying the European Green Deal [1]. These are based on main pillars, which, inter alia, involve energy – "supplying clean, affordable and secure energy", industry – "mobilising industry for a clean and circular economy", while also preserving "a toxic-free environment", achieving a zero-pollution action plan for air, water and soil. Access to resources is also a vital question for Europe's ambition to deliver the Green Deal. Undeniably, ensuring the supply of sustainable raw materials, especially critical raw materials is essential for clean technologies. One must also note that water, which is the basis of life, is also at the core of sustainable development and crucial for socio-economic development, energy, food production, and living eco-systems. Yet, its resource is finite [2]: approximately, only 1 % is freshwater [3]. Therefore, ensuring sustainable consumption of water is not sufficient, as there is an urgent need to improve reuse of treated wastewater (RTWW). The preservation of the environment and reducing our dependency on raw materials, energy, and water are not possible without resorting to the paradigm of circular economy. A shift towards greater circularity reconciles with sustainability. It goes beyond the correction of the often-damaging environmental implications of economic activity, encompassing a deep rethinking of the way in which businesses and societies in general, produce and consume. Undoubtedly, sustainability objectives cannot be achieved without further reinforcement of a circular economy and its principles. The circular economy model relies on a 'life-cycle thinking' approach to ensure sustainability, focusing not just on managing waste responsibly, but also on preventing its creation in the first place.

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https://doi.org/10.1016/j.nexus.2025.100475
Received 8 March 2025; Received in revised form 14 June 2025; Accepted 12 July 2025
Available online 20 July 2025

The European Commission has noted that achieving a climate neutral and circular economy entails the full mobilisation of industry, which may take 25 years to transform an industrial sector and all the value chains [1]. Therefore, together with the industrial strategy and new circular economy plan [4], the European Commission seeks to achieve the green transformation, leading to the modernisation of the EU's economy.

Given the urgency of the climate crisis, many academics have advocated for the changes in legislation [5]. Yet, one must note that the formation of the climate neutral and circular economy does not take place in a legislative vacuum: the EU's policies and laws, for instance, on renewable energy, should align with a plethora of other policies and legislative proposals regulating water, waste, materials, emission trade schemes, carbon tax reforms etc. Therefore, the paper focuses on the Water (including Wastewater)-Energy-Materials nexus in the industrial context, arguing that these areas are strongly interlinked and mutually reinforcing and therefore, should be evaluated holistically.

Specifically, aligned with the European Green Deal, the aim of the paper is twofold: i) to review the newest EU legislation (embracing binding (articles) and non-binding (recitals) provisions) related to water (predominantly wastewater), energy and industries in search of impetuses for circular solutions and environmental sustainability, as they are the main triggers for change and without appropriate rules and regulations, as well as political will, this transition is unlikely to happen; ii) while employing the Water-Energy-Materials nexus, to illustrate whether there is a technology enabler to achieve this nexus in practice in different industrial segments. The paper employs a bottom-up approach, illustrating through practical examples, an integrated circular solution, to close the loop in processes in the context of an industrial setting.

The paper is organised as follows. After this introduction (Section 1), Section 2 is devoted to review the current state of the art, namely, the circular economy contours' in different context, with further emphasis being placed on circular economy and nexus planning. While the methodology is noted in Section 3, results and discussions are formed in section 4. The final conclusion is set in Section 5.

2. Review of the state of the art

2.1. Circular economy in different contexts

The literature on a circular economy has intensified in recent years. In the context of circular economy, the eminent Ellen MacArthur Foundation, has conducted leading research, including the infamous 'butterfly' diagram, which focuses on the continuous flow of materials, contains two main cycles: i) the technical cycle; and ii) the biological cycle. While under the technical cycle, products are kept in circulation in the economy through reuse, repair, remanufacture and recycling, in the biological cycle, the nutrients from biodegradable materials are revert back to the Earth, through processes, such as composting or anaerobic digestion [6]. Furthermore, Kirchherr et al. (2017) [7] discovered 114 definitions of circular economy identified as "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes", which also functions at the micro level (i.e. products, companies, consumers), *meso* level (eco-industrial parks) and macro level (city, region, nation and beyond), aiming to accomplish sustainable development, while simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations [8].

Therefore, a circular economy approach embraces life cycle considerations; it relies on the sustainable management of natural resources, the closing of material loops, and the preservation of natural capital. Initially, recycling was a key element in circular economy thinking with the number of 'R's growing over time [9]. For instance, in 2004 the Japanese Government introduced a '3R Initiative' (i.e. Reduce; Reuse; Recycle), leading to the establishment of the "Regional 3R Forum in Asia" [10]. In 2017, Potting et al. identified nine s Rs contributing to circularity (i.e. placed in order of priority: Refuse (R0); Rethink (R1); Reduce (R2); *Re*-use (R3); Repair (R4); Refurbish (R5); Remanufacture (R6); Repurpose (R7); Recycle (R8); and Recover (R9)) [11]. Dragomir and Dumitru (2024) [12], why using the bibliometrix method, identifying 13,553 articles related to the circular economy published between 2006 and 2023, noted the predominant reliance on 3 Rs reduce-reuse-recycle. Their study distinguished five domain clusters in the literature: 1) sustainable development and life cycle assessment; 2) biomass production and waste valorisation; 3) materials and recycling; 4) wastewater treatment and environmental pollution; 5) carbon emissions reduction and energy recovery. Despite the well-defined concept of the circular economy, Yasmeen and Longsheng [13] noted that green innovation plays a key role in the development of the circular economy, and its importance is only indirectly reinforced by political support. They demonstrated that the environmental management system (EMS) plays a vital role in advancing the circular economy by guiding companies in how to fulfil and manage their environmental responsibilities. García-Quevedo et al. [14] deliberated that European SMEs that innovate in the area of circular economy experience five types of barriers: i) lack of expertise, ii) lack of human resources, iii) financial challenges, iv) administrative procedures, and the cost associated with the regulatory framework. The cost is key consideration if companies are clearly committed to CE and implement more than one activity.

The literature research reveals the importance of taking regional considerations into account when designing programmes that include waste management, plastic reduction and the promotion of circular economy solutions. This applies not only to China, India or the Philippines [15], African and Indian Ocean developing islands [16] but also to the EU. Alnafrah et al. [17] identified differences between the EU Member States (North and South) in their implementation of the CE and achievement of the Sustainable Development Goals (SDGs). In developed regions, urbanisation plays an important role in accelerating the achievement of the SDGs, while GDP growth most often correlates negatively with their accomplishment. It is, therefore, necessary to adapt policies to specific regions and their needs, recognising the differential impact of the CE initiatives at different levels of development. Education and skills development is an important component of policy support, especially in those regions where it contributes most to the SDGs. Cooperation between the EU Member States and engagement of the private sector is essential to achieve common goals. Khajuria et al. [15] also emphasise the crucial importance of cooperation between civil society, government and multi-stakeholder initiatives as well as public education in the context of regional programmes and initiatives for SDGs and the potential of a circular economy approach.

Separating core business activities from additional circular initiatives enables companies to better tailor their strategies to available resources and defined objectives [18]. Small manufacturing-related companies that often embed CE in their core business are less likely to cooperate with competitors. In terms of historical studies related to wastewater reuse and treatment, Bixioa et al. (2006) [19], already in early 2000s conducted an extensive study on wastewater reuse in Europe, identifying >200 water reuse projects across different Member States. This figure is much higher compared with the early 1990s before the Urban Wastewater Treatment Directive (91/271/EEC) was implemented, there municipal water reuse was limited to several instances, mostly incidental, (mainly pertaining to the proximity of the wastewater treatment plant to the point of use). This project mapped geographical distribution of wastewater reuse initiatives while also grouping them into different categories. The study found that in southern Europe, reclaimed wastewater was predominantly used for agricultural irrigation (44 % of the projects) and for urban or environmental applications (37 % of the projects) whereas in northern Europe, the uses were mainly for urban or environmental applications (51 % of the projects) or industrial (33 % of the projects) [19]. France was an exception, as their domestic guidance referred solely of wastewater reuse for agricultural purposes.

More recent report noted that the adoption of water reuse solutions in Europe is rather limited with vast difference across various regions in Europe. Indeed, it found that Cyprus and Malta lead with water reuse accounting for 90 % and 60 % respectively, whereas the other southern countries, such as Greece, Italy and Spain lag behind with rates between 5 % and 12 % [20].

The other theme of literature refers to the studies with an emphasis on various circular solutions related to wastewater reuse. There are publications with some fragmented aspects of wastewater management, for instance, such as risks associated with reclaimed water use [21–23], also health related risks due to chemicals in water [24], wastewater for irrigation [25], or wastewater reused in some specific regions [26]. There are also studies proposing an operational optimisation of wastewater reuse integrated energy system [27], or optimisation of a network to obtain minimum fresh water consumption or waste water discharge using mathematical programming methodology [28]

In contrast to traditional approaches to the circular economy, the Symbiotic Circular Economy Solution (SCES) focuses on the systemic linking of different sectors. SCESs aim to reclaim valuable resources, such as water, materials, energy, and nutrients, create marketable products, and deliver systemic benefits to a range of stakeholders. Collaboration and value co-creation between industry, institutions, communities and water services are key elements of the concept [29]. Bosco et al. established this novel approach to evaluate water-related sustainability and smartness, with a focus on fostering industrial symbiosis within the water sector. Implementation of the proposed SCES model in practice in six real-life use cases has shown it to be an effective tool to support decision-making among different options to increase sustainability and improve performance in environmental, social, economic, technical and organisational areas.

Furthermore, other publications focus on technology for wastewater treatment, comprising of physical, chemical, and biological methods. Different physical methods are available, such as adsorption, advanced oxidation process (AOP), separation by membranes and separation by nano-filters [30,31]. As per chemical technique, there are many chemical oxidation processes for various catalytic applications with the AOP being the fundamental method [32], which rely on active and potent oxidising agents, such as hydroxyl (OH) radicals, electrochemical oxidation, photo-electrochemical oxidation, UV-assisted Fenton oxidation and ozonation. For instance, Arzate et al. (2019) [33] conducted comparison between several scenarios of tertiary water treatment options based on ozonisation of municipal wastewater and Photo-Fenton, for the removal of micro-pollutants in wastewater, noting that the reuse of treated wastewater diminishes local water scarcity while simultaneously boosting the benefits of quality of the natural ecosystem and human health. Finally, the application of a specific biological technique, which is regarded as the most eco-friendly and efficient means for wastewater treatment, depends on the type and composition of wastewater [32].

Crovella et al. (2024) [34] conducted a systematic literature review of life cycle assessments in relation to wastewater recovery for sustainable agricultural systems in the circular economy, including sludge production analysis, as well as analysis of recovering nutrients from wastewater reuse. There have also been some limited studies in the industrial context as well [35].

2.2. Circular economy and nexus planning

Climate emergency calls for urgent actions and more integrated actions. Various nexus scenarios stressing an integrated approach are far from new. Already in the 1980s, scholars and policy makers inaugurated the need for cross-sector, cross-scale and hybrid reasoning and nexus across different sectors (Leck et al., 2015) [36]. However, the impetus and calls for a nexus approach to governance in decision making and planning have flourished drastically over the last decade [37]. The groundwork has already been undertaken. For instance, Ringler et al. (2013) [38] noted that the SDGs signal for the implementation of nexus thinking. While focusing on the water-energy-land-food nexus, they stressed the importance of understanding the linkages across these sectors, including identifying measures to shrink the costs of trade-offs and improve synergies. However, modelling the nexus framework is challenging due to complicated dynamics and interconnections, as noted by Shannak et al. [39], who highlighted that the lack of data prevents available models encapsulate interactions among nexus components. In more recent study, Verma et al. (2024) [40] further accentuated that the integration of the nexus sectors is confronted with economic, physical, and political challenges. In their comprehensive study where they aligned and quantified the nexus strategies with SDGs, they suggested to adopt a more interdisciplinary and action-oriented approach. Along similar lines, Mancini et al. (2024) [41] compared three different management scenarios in the context of a waste-wastewater-energy nexus in Southern European regions while employing a life cycle assessment. This study concluded that an integrated approach based on industrial symbiosis was the most sustainable with increased circularity [41].

However, despite various benefits, there are still several limitations (i.e. interdisciplinary integration barriers, policy implementation gaps, inclusivity and equity concerns, and measurement and evaluation aspects) that must be addressed to realise the full potential. One must not forget legal challenges as addressed by Olawuyi (2020) [37], where the author argues that ensuring the nexus (namely, Water-Energy-Food) discourse moving from purely theory to successful practical integration and adoption, any fragmented legal structures, sector specific regulations that suppress the development and application of hybrid and interlinked rules, procedures and processes across the sectors will have to be comprehensively addressed.

The linkages between provision systems in the context of implementing a circular economy are still poorly recognised, despite the fact that they can both hinder change - by creating rigidity and lock-in effects - and support it by allowing it to permeate between economic subsystems [42]. Therefore Boons et al. proposed a “nexus of circulation’ framework, which includes the expansion of solution spaces, rebound effects (money), temporal obsolescence, spatial distribution, spatial entanglement, value shifts and contestation, circulation across function, rebound effect (material); via this framework, they analyse how material and social contexts shape whether particular interconnections constrain or promote progress toward a circular economy. This understanding is intended to support the design of more comprehensive policies and strategies through a holistic perspective.

Building on the previous studies, this paper also argues that the EU legislation is too fragmented and should be more integrated embracing different domains, such as wastewater, energy, and industries. In addition, to the previous studies, practical implementation will also be addressed, noting that a ‘one-size-fits-all’ solution is not suitable to untap a truly circular system ensuring closing the loop in processes. Therefore, a more tailored integrated approach should be embedded.

3. Methodology

As far as the methodology is concerned, there were several methods employed to collect the data for this manuscript.

First of all, to have a better understanding of the EU legislative context, the study extensively reviewed the EU portal, locating the newest EU existing and forthcoming legislative instruments pertaining to the areas of wastewater, energy, materials and industries, resulting in identifying the following pieces of legislation: the Waste Framework Directive 2008/98/EC (as amended by Directive (EU) 2018/851); Regulation on minimum requirements for water reuse (EU) 2020/741 as well as the supplementary delegated Regulation 2024/1765; Urban Wastewater Treatment Directive (UWWTD) (recast) (EU) 2024/3019; Renewable Energy Directive (recast) EU/2023/2413; Energy Efficiency

Directive (recast) EU/2023/1791; the Industrial Emissions (integrated pollution prevention and control) Directive (EU) 2024/1785; the EU's Net Zero Industry Act (EU) 2024/1735. The Water Framework directive 2000/60/EC (under review) was excluded from the study, as the emphasis was placed on 'wastewater'. Doctrinal method was employed to critically analyse these laws in the context of the circular economy. While this study involved both quantitative and qualitative research, more emphasis was placed on the quantitative research. First of all, quantitative research, which also involved historical analysis, aimed to uncover trends and derive overarching insights, especially exhibiting a transition from a linear to circular economy, the extent to which regulations have embraced this change over time. Secondly, to complement the quantitative study, qualitative analysis then focused on all the identified provisions in the previous stage, addressing the notions of 'circular economy' or 'circularity' more generally, as well as encouragement for integrated solutions, to add depth to the study.

There were some limitations. Given the expansive scope of the EU legislation, to narrow down the scope, this study selected these so-called framework laws, as they set out general rules for an entire legal field with horizontal application, leaving more specific topics or subtopics to lex specialis. Furthermore, the transposition, implementation and enforcement of EU legislation at national level are not covered either, except a few examples to illustrate a specific point.

Secondly, an extensive literature review was conducted with the objective to ascertain studies related to the circular economy as well as any nexus-orientated planning embracing a holistic approach. This involved systematic review of both primary sources, such as assessment reports published by the European Commission, the European Environment Agency (EEA), JRC Science and Policy reports, as well as secondary sources, examining various published articles identified by using different keywords, such as a circular economy, water, energy, climate nexus, the EU policies on water (mainly wastewater), energy, and industries, on science direct and google scholar. Once must note higher intensity of both the EU legislation as well as scholarly articles post-2019, following the European Green Deal.

Thirdly, apart from theoretical facets, the paper has also explored a real-life example, namely, illustrating via the iWAYS project how the Water-Energy nexus can be integrated in different industries setting. The iWAYS (Innovative WAter recoverY Solutions through recycling of heat, materials and water across multiple sectors) project aims to develop a set of technologies and systems for industrial processes to recover water and heat, and in some cases materials, from exhaust streams, while reducing resource consumption, yet, increasing energy efficiency.

4. Results and discussion

4.1. The main EU legislation

As previously noted, the European Green Deal provides a much-needed roadmap in the EU for a sustainable EU economy, followed by initiatives to revise (i.e. checking whether legislation is still fit for purpose) as well as instigate new legal developments. The paper targeted the main EU legislation related to wastewater, energy and industries (solely horizontal application, rather any legislation directed at specific industrial sectors). Therefore, Table 1 illustrates all the legal instruments which were identified and analysed in this section.

4.1.1. Wastewater

4.1.1.1. Overview. While the Water Framework Directive is excluded from the scope of this study, it is important to mention the Waste Framework Directive 2008/98/EC (WFD), as amended by the directive (EU) 2018/851 (with the latest amendments being made in 2024), which set up generic measures to protect the environment and human health by preventing or reducing the generation of waste (excluding wastewater), as well as by reducing overall impacts of resource use and enhancing the efficiency of such use that are essential to a circular economy. As far as the EU regulatory frameworks are concerned related to wastewater, the study identified the following pieces of legislation: the Urban Wastewater Treatment Directive (UWWTD) (91/271/EEC) and the UWWTD (recast) (EU) 2024/3019, and the Regulation on minimum requirements for water reuse (EU) 2020/741 as well as its supplementary delegated Regulation 2024/1765. Building on the Blueprint, the European Commission in its 2020 Circular Economy Action Plan observed that it aims to introduce new regulatory tools (or policies) to facilitate water reuse and efficiency in different sectors, including agriculture and industrial processes. Therefore, a new Regulation was introduced – the Regulation 2020/741 (with its

Table 1
The main EU legislation covered the analysed areas.

Wastewater		*Energy*		*Materials*		*Industries*	
Instrument	Description	Instrument	Description	Instrument	Description	Instrument	Description
Waste Framework Directive 2008/98/EC (as amended by Directive (EU) 2018/851)	the Waste hierarchy with prevention/reduction of the generation of waste being a top priority.	Renewable Energy Directive Recast (EU/2023/2413)	the new 42.5 % renewable energy target by 2030	European Critical Raw Materials Act Regulation (EU) 2024/1252	reinforces domestic capacities and consolidate the sustainability and circularity of critical raw material supply chains	Industrial Emissions (integrated pollution prevention and control) Directive (EU) 2024/1785	sets the emission limit values; expands the scope; mandates environmental management system
Urban Wastewater Treatment Directive (recast) (EU) 2024/3019	reuse treated water 'when-ever appropriate'.	Energy Efficiency Directive Recast (EU/2023/1791)	sets an additional binding EU target of 11.7 % reduction in energy consumption by 2030			Regulation (EU) 2024/1735 establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem	aims to boost low carbon technologies Identifies 'strategic net-zero technologies'
Regulation on minimum requirements for water reuse (EU) 2020/741	the requirements for water reuse in the agricultural sector.						
Supplementary delegated Regulation 2024/1765	defines the technical specifications on the main aspects of risk management.						

supplementary delegated Regulation 2024/1765) - aimed at harmonising minimum water quality requirements at EU level ensuring that wastewater is more broadly used to lower a burden on water abstraction from surface and groundwaters.

4.1.1.2. Quantitative assessment. As far as quantitative circularity assessment is concerned, the directive 2008/98/EC did not refer to a circular economy or 'circularity' in general, yet, it encouraged to consider the whole life-cycle of products and materials (see Table 2). The concept of circular economy was introduced only by the amending directive (EU) 2018/851, with a much-improved visibility of 'circularity' and life cycle assessment (5 out of 43 Articles), also noting the adverse impacts of the generation and management of waste with the need to improve the resource use and efficiency, essential for the transition to a circular economy and guaranteeing the EU's long-term competitiveness (Article 1). Apart from articles and annexes, this study also identifies recitals, related to 'circularity' and 'life cycle assessment' which are not binding, but can indicate the legislature's intention. Disappointingly, the original UWWTD did not acknowledge any circular economy aspects; it did not have any consistency with climate and energy policies either. This was rectified by the revised UWWTD (EU) 2024/3019, which addresses other EU policies, such climate change and energy as well as notes to some limited extent circularity (1 out of 35 Articles), in the context of resource recovery (Table 2). Given that the Regulation 2020/741 was launched as a result of the Circular Economy Action Plan, 'circularity' and/or 'life cycle assessment are noted only in 1 out of 16 Articles (Table 2). This is concerning as it hinders businesses from transitioning to more sustainable practices, especially in the context of wastewater management practices, which is existential for human survival and health due to water scarcity.

4.1.1.3. Qualitative assessment. The revised WFD lays the foundation for circular solutions in waste management, by exhibiting an eminent waste hierarchy which displays five options waste management options pursuant to what is best for the environment, such as waste prevention being the top priority, preparation for reuse, recycling, recovering, and disposal being the last-resort solution to managing waste. Importantly, the amended directive expands the scope of "material recovery", embracing "any recovery operation, other than energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy", which, inter alia, includes preparing for re-use, recycling and backfilling (Article 3, point 15a). Overall, the directive stresses the need to consider the whole life cycle of products in a way that preserves resources and closes the loop, simultaneously, bringing substantial savings for businesses, public authorities and consumers, while reducing total annual greenhouse gas emissions. In addition, the directive refers the efficiency of resource use would also save the reliance of raw materials facilitating the transition to more sustainable material management and to a circular economy model. In line with the circular economy, the directive also sets some binding targets for the preparing for re-use and the recycling of waste materials, including paper, metal, plastic and glass. This framework directive covers different sectors. Yet, most recently, the proposal is to expand the scope of the directive embracing the textile industry, bringing a more circular and sustainable management of textile waste, pursuant to the vision of the EU Strategy for Sustainable and Circular Textiles [43].

Table 2
Quantitative circularity assessment: wastewater relation regulations.

Wastewater		
Instrument	Circularity/ life-cycle	Provisions
Waste Framework Directive (WFD) 2008/98/EC (as amended by Directive (EU) 2018/851)	Dir 2008/98/ EC: ➢ Circularity/ Life-cycle Dir (EU) 2018/ 851: ➢ Circularity/ Life-cycle	6 (Recitals 8, 9, 27, 40, Art 4, Annex IV) 20 (Recitals 1, 2, 3, 7, 14, 20, 38, 43, 44, 61, Arts 1, 8, 10, 11, 30)
Urban Wastewater Treatment Directive (UWWTD) 91/271/EEC and (recast) (EU) 2024/3019	Dir 91/271/ EEC: ➢ Circularity/ Life-cycle Dir (EU) 2024/ 3019: ➢ Circularity/ Life-cycle	0 3 (Recitals 18, 42, Art 1)
Regulation on minimum requirements for water reuse (EU) 2020/741 Supplementary delegated Regulation 2024/1765	Reg 2020/741: ➢ Circularity/ Life-cycle Reg 2024/ 1765 ➢ Circularity/ Life-cycle	3 (Recitals 6, 11, Art 1) 0

In terms of wastewater aspects, already in 1991, the former UWWTD (91/271/EEC), set the objective to protect the environment from the adverse effects of urban waste water discharges and discharges from certain industrial sectors. The former UWWTD also included specific requirements, such as pre-authorisation of all discharges of urban wastewater, of discharges from the food-processing industry and of industrial discharges into urban wastewater collection systems; and monitoring of the performance of treatment plants and receiving waters. It also required controls of sewage sludge disposal and re-use, and treated waste water re-use. However, this requirement applied "whenever appropriate", with "appropriateness" not legally defined. The UWWTD was successful in a significant reduction of urban wastewater emissions of organic matter, nutrients and coliforms to surface waters. However, the UWWTD did not cover some chemicals which were virtually unaffected by conventional wastewater treatment. Generally, its full potential was not utilised and it was criticised for being out-of-date. Therefore, after over 30 years, the UWWTD was finally revised with the aim to protect human health and the environment from the effects of untreated urban wastewater, which is one of the main sources of water pollution in the EU [44] Notably, the revised UWWTD expands the scope of the directive, meaning that small agglomerations of 1 000 pe. (in contrast to the current 2 000 pe.) fall under the directive's requirements (with some extended deadlines and derogations to some Member States), to provide with collecting system (Article 3). The revised directive also allows some flexibility, in case a collective system is not feasible, justifiable or cost-effective, therefore, the Member States can use individual systems to collect and treat urban wastewater. Yet, the if the Member States use individual systems to collect and/or treat >2 % of the urban wastewater load at national level from agglomerations of 2 000 pe. and above, they will have to give a justification to the Commission (Article 4). The obligation to apply secondary treatment which is the removal of biodegradable organic matter to wastewater before releasing into the environment is broadened to all agglomerations of 1 000 pe. or over, by 2035. In addition, tertiary (the removal of nitrogen and phosphorus) treatment by 2039 and additional quaternary (the elimination of a broad spectrum of micro-pollutants) treatment obligations by 2045 are placed on urban wastewater treatment plants treating urban wastewater with a load of 150 000 pe. and above.

Furthermore, the revised UWWTD also expands the scope imposing extended producer responsibility, notably, targeting producers (and importers) of pharmaceuticals and cosmetics to guarantee fair contribution of the most polluting sectors to wastewater treatment for micropollutants also pursuant to the 'polluter pays' principle. These entities will need to contribute to a minimum of 80 % of the additional costs for the quaternary treatment. The exemptions apply provided these entities place on the EU market less than one tonne of the products annually; or they can demonstrate that these products are 'rapidly biodegradable in wastewater' or do not contribute to any micropollutants in the wastewater (Article 9(2)).

In terms of energy aspects, the new provisions are imposed to reach an energy neutrality target – by 2045 where urban wastewater treatment plants (treating a load of 10 000 pe. and above) will have to generate energy from renewable sources (with purchased renewable energy being explicitly prohibited) (Article 11(2)). Building on the Energy Efficiency Directive (EU/2023/1791), energy audits will be required for all facilities above 10 000 pe.

Finally, the Regulation 2020/741 is directed at harmonising minimum water quality requirements at EU level in agriculture, ensuring that wastewater is more broadly used to lower a burden on water abstraction from surface and groundwaters. Notably, this regulation embraces the safe reuse of treated urban wastewaters solely in agricultural irrigation, while also protecting the environment and people. Drop in groundwater levels, mainly because agricultural irrigation (as well as industrial and urban development), has been recognised as one of the major threats to the EU's water environment [45]. The regulation also provides minimum monitoring requirements as well as risk management to assess any potential health and environmental risks. It also postulates permitting requirements and the provisions on transparency ensuring that main information about water reuse projects is publicly available.

Notably, the regulation 2020/741 covers reclaimed water which is obtained from wastewater that has been collected in collecting systems and has been treated in urban waste water treatment plants and which undergoes further treatment to meet the parameters set out in Annex I of the regulation (see Table 3). The Guidelines [46] that supplement the regulation further explains that the Member States after thorough consideration of the advantages and disadvantages of water reuse, may decide not to reuse water in a given area as part of integrated water management. Additionally, the regulation encompasses the multi-barrier approach, where the log reductions to obtain the required water quality class can be achieved by different treatment and non-treatment measures in combination (barriers) [46]. It requires higher standards for disinfection in comparison to the simple discharge of wastewater in surface water bodies, lower content of solids and organic matter (e.g. BOD concentration) as indicated in Table 3.

Furthermore, to supplement the regulation, the delegated Regulation No 2024/1765 was issued, noting the technical specifications related to risk management [47] This delegated regulation defines technical specifications encompassing 23 elements to be considered when drafting risk management plans in consultation to the European Commission guidelines (i.e. reclaimed water production processes, storage, distribution, irrigation techniques, intended uses, crop categories etc.). This is aimed at determining more uniform conditions for defining risk management plans necessary for the issuing of the permits essential for the production and supply of refined water intended for irrigation purposes in agriculture across the Member States.

Finally, the regulation also notes that the Member State can use treated waste water for other purposes, such as industrial assuring a high level of protection of the environment and of human and animal health. One would expect that more harmonised regulations will follow at EU level encompassing minimum reclaimed water requirements for industrial processes, as part of integrated water management and the circular economy. However, this new future EU regulation with minimum reclaimed water requirements, apart from risk assessment, should also embrace economic considerations, any incentives for industries to use reclaimed water for their processes, if it is cheaper to discharge it into the environment.

4.1.2. *Energy*

4.1.2.1. Overview. The sustainability and climate-oriented energy transition plays a significant part of the European Green Deal. This embraces the EU's previous strategies and more specifically, when in 2016 it was decided to rewrite the EU's energy policy framework to facilitate the clean and fair energy transition through the Clean Energy Package, which mainly comprises of the elements such as energy efficiency, more renewables, a better governance of the EU, more rights to consumers/prosumers, a smarter and more efficient electricity market. This package and followed by more recent initiatives, such as Fit-for-55 and the REPowerEU plan (COM/2022/230 final) postulates a modern framework for the transition towards cleaner and more sustainable energy consists of numerous communications, preparatory documents, reports and non-legislative initiatives. The main legislative files defined targets and policy and regulatory frameworks for the EU's climate and energy policies for up to 2030 and beyond. This study has focussed on two main directives: renewable energy directive (RED) and energy efficiency directive (EED).

4.1.2.2. Quantitative assessment. Historical analysis indicates that the original REDI barely had any visibility of 'circularity', which has improved with more recent directives REDII and REDIII (2 out of 39 Articles plus 2 annexes). As far as the quantitative assessment of circularity is concerned, 'circularity' appears in more recent regulatory provisions (Table 4). Similarly, any 'circularity' aspects were not visible in the EED 2012/27/EU, which was rectified by the revised EED (EU) 2023/1791 (3 out of 40 Articles) (see Table 4).

4.1.2.3. Qualitative assessment. Renewable energy is a key pillar of the clean energy transition. Specifically, to drive an acceleration of clean energy uptake in all sectors, the revised Renewable Energy Directive (RED III) (EU/2018/2001, with the latest amendments by (EU) 2023/2413) imposes a new more ambitions targets, where the Member States should collectively ensure that the share of energy from renewable sources in the Union's gross final consumption of energy in 2030 is at least 42,5 % (with an attempt to achieve 45 %, replacing the previous target of 32 %). While this is the shift to non-binding renewable energy target at the Member State level, it is accompanied by a novel instrument, the Governance Regulation ((EU) 2018/1999), which introduces numerous procedural obligations, including a specific formula for the calculation of the optimal renewable energy target for each Member State [48].

Table 3
Minimum reclaimed water requirements for agricultural (regulation 2020/741, Section 2.

Reclaimed water quality class	Indicative technology target	Quality requirements				
		Escherichia coli (number/100 ml)	BOD_5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Other
A	Secondary treatment, filtration, and disinfection	≤ 10	≤ 10	≤ 10	≤ 5	*Legionella* spp.: < 1 000 cfu/l where there is a risk of aerosolisation Intestinal nematodes (helminth eggs): ≤ 1 egg/l for irrigation of pastures or forage
B	Secondary treatment, and disinfection	≤ 100	In accordance with Directive 91/271/EEC (Annex I, Table 1)	In accordance with Directive 91/271/EEC (Annex I, Table 1)	–	
C	Secondary treatment, and disinfection	≤ 1 000			–	
D	Secondary treatment, and disinfection	≤ 10 000			–	

Table 4
Quantitative circularity assessment: energy related regulations.

Energy		
Instrument	Circularity/life-cycle	Provisions
Renewable Energy Directive Recast (EU/2023/2413)	Dir 2009/28/EC (REDI): ➢ Circularity/Life-cycle Dir (EU) 2018/2001 (REDII): ➢ Circularity/Life-cycle Dir (EU) 2023/2413 (REDIII): ➢ Circularity/Life-cycle	1 (Annex V) 6 (Recitals 21, 25, Arts 25, 28, Annex IV, Annex V) 5 (Recital 10, Arts 29a, 31a, Annex IV, Annex VI)
Energy Efficiency Directive Recast (EU/2023/1791)	Dir 2012/27/EU: ➢ Circularity/Life-cycle Dir (EU) 2023/1791: ➢ Circularity/Life-cycle	0 7 (Recitals 53, 55, 56, 92, Arts 3, 5, 7)

In addition, the Member States should also set an indicative target for innovative renewable energy technology of at least 5 % of newly installed renewable energy capacity by 2030 (Article 3). Given that industry accounts for is responsible for 25 % of the Union's energy consumption, and it is a major consumer of heating and cooling, which is currently supplied 91 % by fossil fuels, for the first time, the directive imposes renewable energy targets, specifically to the industrial sector. Article 22a provides that the Member States should attempt "to increase the share of renewable sources in the amount of energy sources used for final energy and non-energy purposes in the industry sector by an indicative increase of at least 1,6 percentage points as an annual average calculated for the periods 2021 to 2025 and 2026 to 2030″. Waste heat and cold can counted towards the average annual increases, yet, up to a limit of 0,4 % points, provided that the waste heat/cold is supplied from efficient district heating and cooling, disregarding networks which supply heat to only one building or where all thermal energy is consumed only on-site and where the thermal energy is not sold. Subject to the conditions defined in Article 22b, the Member States should ensure that the contribution of renewable fuels of non-biological origin used for final energy and non-energy purposes is at least 42 % of the hydrogen used for final energy and non-energy purposes in industry by 2030, and 60 % by 2035.

In parallel, the principle of 'putting energy efficiency first' is identified as the core element in the low-carbon energy transition in the European Green Deal. In the Energy trilemma, also known as 3Cs (Carbon, Continuity of energy supplies and Cost), energy efficiency plays the 'protagonist' role in the EU [49], in related to meeting the EU's climate change and energy objectives. Specifically, it can contribute in combat climate change, by helping to reduce GHG emissions. Energy efficiency can ensure security of energy supplies due to energy saved, provided rebound effect is avoided. Finally, energy efficiency can help to provide affordable energy. For instance, the industrial sector has huge unharnessed energy efficiency potentials and reduce their energy costs enabling to increase competitiveness of high-energy intense industries [9].

The Energy Efficiency directive (EED) (2012/27/EU with latest amendments by the directive EU/2023/1791 and accompanied 9 guidelines) sets the collective binding target for the Member States of an additional 11.7 % reduction in energy consumption by 2030, compared to the projections of the EU reference scenario 2020. In absolute terms, overall EU energy consumption by 2030 should not exceed 992.5 million tonnes of oil equivalent (Mtoe) and 763 Mtoe for primary energy and final energy, respectively. The Member States have agreed to set indicative national contributions based on a combination of objective criteria which reflect national circumstances (i.e. energy intensity, GDP per capita, energy savings potential, earlier efforts for energy efficiency etc.).

The EED sets the targets to drive energy savings in end-use sectors, such as buildings, industry and transport. Specifically, the Member States have to achieve cumulative end-use energy savings, equivalent to new annual savings of at least 0.8 % of final energy consumption in 2021–2023, 1.3 % in 2024–2025, 1.5 % in 2026–2027 and 1.9 % in 2028–2030. To elevate energy savings in the industrial sector, the directive expands the scope of energy audit obligations to embrace all companies, regardless of their size, which are consuming energy above a certain threshold. The means that even small and medium-sized enterprises (SMEs, with fewer than 250 employees and a turnover of no more than EUR 50 Million or a balance sheet of no more than EUR 43 Million) would also have to carry out an energy audit, where there is significant energy saving potential. One must note that energy management systems are a compulsory requirement for large industrial energy consumers to monitor and optimise their energy efficiency. Indeed, energy audits and energy management are identified as important instruments to explore economic energy efficiency potentials; to gain knowledge and form a strategy to improve energy efficiency in businesses.

The revised directive also progressively tightens the criteria for an 'efficient district heating and cooling system' for instance, with a system using at least 50 % renewable energy, 50 % waste heat, 75 % cogenerated heat or 50 % of a combination of such energy and heat by 2025.

In addition, the revised EED also contains measures related to efficiency in heating and cooling (Article 14 EED), requiring the Member States to carry out a comprehensive assessment of the cost-effective potential for energy efficiency in heating and cooling, mainly, through the use of cogeneration, efficient district heating and cooling and the recovery of industrial waste heat. Specifically, the Member States need to identify the technological solutions used to supply heating and cooling, while making distinctions between on-site (i.e. heat-only boilers; high-efficiency heat and power generation; heat pumps; and other on-site technologies) sources and off-site sources (i.e. high-efficiency heat and power generation; waste heat; and other off-site technologies) and between renewable and fossil energy sources [9].

To conclude, in terms of circularity, for instance, the revised REDIII, inspired by the waste hierarchy, instruct the Member States to take measures ensuring that energy from biomass is produced in a way that lessens undue distortive effects on the biomass raw material market and an adverse impact on biodiversity, the environment and the climate. In terms of technologies, heat pumps are identified as key technologies to produce renewable heating and cooling from ambient energy, including from wastewater treatment plants and geothermal energy. Yet, overall, the main focus of both renewable energy directive and energy efficiency directive is on environmental sustainability, signalling industries to invest in clean technologies.

4.1.3. Materials

4.1.3.1. Overview. Pursuant to International Energy Agency's Critical Minerals Market Review 2023 report [50], there is still the limited progress in terms of diversification of the global supply chain, for instance, the concentration levels of some CRMs (Critical Raw Materials) in specific jurisdictions have worsened in the last three years, especially for nickel and cobalt [50] In addition, there are serious environmental and social implications on local communities associated with an increase in mineral explorations. For instance, in terms of social impact, cobalt extraction from Democratic Republic of the Congo heavily relies on armed aggression and child labour [51]; as per environmental concerns, extraction of raw materials requires extensive energy and water supplies, overall, mining negatively impacts local communities deteriorating health due air, soil and water pollution [52] Significant efforts need to be made to improve sustainable development of critical raw materials value chains. Specifically, the Member States will have to adopt national programmes on circularity and measures to improve the collection of critical raw materials rich waste and ensure its recycling into secondary critical raw materials. According to the current directive 2006/21/EC (amended in 2009) on the management of waste from extractive industries, these industries have already an obligation to recover critical raw materials from extractive waste in current mining activities. However, the new Critical Raw Materials Act (CRMA) ((EU) 2024/1252) further exemplifies that the potential to recover critical raw materials should also be investigated from historical mining waste sites.

4.1.3.2. Quantitative assessment. In contrast to the previous regulations, the CRMA contains a specific chapter dedicated to 'Sustainability' (Chapter 5) and a section devoted to 'circularity' (Section 1). As illustrated in Table 5; 6 out of 49 Articles plus Annex note different aspects of 'circularity', defining national measures of circularity, recovery critical raw materials from extractive waste, recyclability and recycled content of permanent magnets etc.

4.1.3.3. Qualitative assessment. While outlining the strategic importance of critical raw materials to safeguard European sovereignty and autonomy, the Critical Raw Materials Act (CRMA (EU) 2024/1252) was proposed by the European Commission. The main objective of the CRMA is to protect the environment by improving circularity and sustainability of critical raw materials. The CRMA addresses not only environmental sustainability aspects, but also other ESG (environmental, social and governance) aspects, such as respect to human rights, labour rights, conflict-resolution etc. In terms of the specific requirements, for instance, products containing permanent magnets will have to meet circularity requirements as well as indicate information on the recyclability and recycled content. To enhance domestic capacities along the raw material supply chain, the regulation sets clear benchmarks allowing not >65 % of the EU's annual consumption of each strategic raw material at any relevant stage of processing from a single third country by 2030.

Most importantly, the CRMA also features in the EU's Green Deal Industry Plan and accompanies the Net Zero Industry Act (to be discussed in Section 4.1.4 below), to ensure sufficient access to rare materials, which are essential for manufacturing key technologies. It also professes to ensure the EU's access to 'a secure, diversified, affordable and sustainable supply of critical raw materials' for the energy transition. The rationale for CRMA is to address the backdrop of the race to Net Zero [53]

4.1.4. Industries

4.1.4.1. Overview. This section does not intend to review all the EU legislation related to industries, as there are more specialised laws, pertaining to specific industries. Instead, it notes more generic (applicable to all industries) recent developments. Therefore, two main legislative instruments were identified: Industrial Emissions Directive (IED) with its latest amendments in 2024 and the new Net-Zero Industry Act (NZIA, Regulation (EU) 2024/1735).

Table 5
Quantitative circularity assessment: materials related regulations.

Materials		
Instrument	Circularity/ life-cycle	Provisions
European Critical Raw Materials Act Regulation (EU) 2024/1252	Reg 2024/ 1252: ➢ Circularity/ Life-cycle	18 (Recitals 5, 7, 9, 10, 51, 52, 57, 60, 62, 70, 74, Arts 1, 26, 36, 37, 40, 41, Annex V)

Table 6
Quantitative circularity assessment: industries related regulations.

Industries		
Instrument	Circularity/ life-cycle	Provisions
Industrial Emissions (integrated pollution prevention and control) Directive (IED) (EU) 2024/1785	Dir 2010/75/ EU: ➢ Circularity/ Life-cycle Dir 2024/ 1785: ➢ Circularity/ Life-cycle	0 10 (Recitals 1, 2, 3, 13, 27, 30, 41, Arts 1, 27a, 27d)
Regulation (EU) 2024/1735 establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem	Reg 2024/ 1735: ➢ Circularity/ Life-cycle	7 (Recitals 18, 26, 37, 43, 65, Arts 3, 13)

4.1.4.2. Quantitative assessment. In terms of legislative instruments related to industries with horizontal application, both the revised IED and the new NZIA have some visibility of 'circularity' aspects. As exemplified in Table 6, while the initial IED did not address any circular economy related principles, 3 out of 84 Articles of the revised IED explicitly embrace circularity aspects. The new NZIA was designed to unlock the circular economy future mindset, yet, only 3 out of 49 Articles remark some aspects of circularity, predominantly calling for manufacturing net-zero technologies through practices, that implement not only improved environmental sustainability, but also circularity features.

4.1.4.3. Qualitative assessment. In line with the European Green Deal, the Industrial Emissions Directive (IED), which is the main framework regulating pollution from industrial installations and intensive livestock farms, was revised to ensure less emissions. The emission limit values under the IED are estimated on the best available techniques to restrict emissions of harmful substances to air, water and soil. The revised IED, inter alia, expands the scope of the directive, encompassing more sources of emissions, making permitting more effective, increasing transparency and most importantly, providing further support to breakthrough technologies and other innovative approaches, therefore, guiding industries towards a cleaner, more circular and competitive economy.

Most importantly, looking from a holistic point of view, the environmental management system (EMS) will have to be implemented by every operator. The EMS would embrace specific environmental data, such as environmental policy objectives for the continuous enhancement of the environmental performance and safety of the installation, for instance, measures to prevent the generation of waste, optimise resource and energy use as well as water reuse. This mandatory assessment to optimise resource efficiency, including water and energy, and hazardous substances elimination, is essential to meet the circular economy principles.

Furthermore, innovative net-zero technologies present a backbone for a clean energy transition, enabling to significantly contribute to decarbonisation as set in the European Climate Act (Regulation (EU) 2021/1119), with clear binding long-term target, achieve climate neutrality by 2050. To remain competitive and to reach their decarbonisation and zero pollution goals, the energy-intensive industries need to adopt more circular solutions, with a clear need to access to net-zero technologies, such as batteries, heat pumps, solar panels, electrolysers, fuel cells, wind turbines, carbon capture and storage etc. Likewise, net-zero technology products can contribute to the resilience and security of supply of clean energy. Therefore, the new Net-Zero Industry Act (NZIA, Regulation (EU) 2024/1735) was launched aimed to simplify regulatory environment, promote investments in the production capacity of products that are vital for meeting the EU's climate neutrality goals.

Specifically, the NZIA distinguishes two types of technologies, such as 1) net-zero technologies; and 2) strategic net-zero technologies, with the later enjoying additional benefits, such as benefiting from the resilience criterion in auctions and overall, getting the possibility to convert into Net-Zero projects with a priority status and shorter timelines. Pursuant to Article 10, net-zero strategic project can be classified based on positive impact on the Union's net-zero industry supply chain or downstream sectors, contributing to the competitiveness and quality job creation of the EU's net-zero industry supply chain, based on at least three of the following criteria: i) enhancing significant manufacturing capacity in the EU for net-zero technologies; ii) manufacturing technologies with improved sustainability and performance; iii) placing measures to attract, upskill or reskill a workforce required for net-zero technologies; (iv) adopting comprehensive low-carbon and circular manufacturing practices, including waste heat recovery. The regulation also sets a benchmark for the manufacturing capacity of strategic net-zero technologies to meet at least 40 % of the EU's annual deployment needs by 2030 (Article 1, 2(a)). However, one must note that while the proposal lists 'net-zero technologies' (Article 3), for instance, inter alia, heat pumps, there are other technologies. Heat pump technology while deployed in various geothermal application face challenges, such as fouling and corrosion. Other technologies, such as Heat Pipe Heat Exchanger and their diverse applications can provide more advanced solutions. This cherry-picking of specific technologies can be problematic, as it may exclude other more cutting-edge existing or new technologies that can contribute to reaching Europe's climate, competitiveness, resilience and sustainability goals.

While the NZIA encourages circular solutions, the emphasis on wastewater reuse is limited, except for some general connotation to adhere to EU legislation related to environmental impact assessment, emissions to air, water and soil, and also seeking to ensure high energy and resource and water efficiency. There are some further provisions related to organising auctions to deploy renewable energy sources without prejudice to the RED III. Innovative technologies are key enablers for sustainability, contributing to the European Green Deal objectives, therefore, it is not clear why smart holistic circular solutions are undermined.

To conclude, the above analysed legislation contains some positive developments in terms of circularity and sustainability more generally. Yet, these fragmented examples are insufficient to achieve the Green Deal objectives. One must note that under the Corporate Sustainability Reporting Directive (CSRD, (EU) 2022/2464), which is in line with the European Green Deal commitments, all large companies (including industries) and listed SMEs (small and medium enterprises) while using common mandatory standards, require to report on their various sustainability commitments, including on environmental protection, social responsibility, respect for human rights, and governance. They need to set targets, select a baseline, and report progress towards these targets. Furthermore, the information required entails both forward-looking and retrospective information, with reference to the whole value chain. This legislation also envisages the adoption of sector-specific requirements.

4.2. Circularity in an industrial setting with the water-energy-materials nexus

4.2.1. 5Rs principles

The EU waste hierarchy displays five options waste management options pursuant to what is best for the environment, therefore, noting waste prevention as its top priority and disposal being the last-resort solution to managing waste. This study focuses on the 'preferred' options of this hierarchy, such as rethink, reduce, remove, reuse and reclaim - 5Rs as illustrated in Fig. 1. The paper argues that rethink is a key strategy that should be embedded in business models, essential to build a sustainable economy.

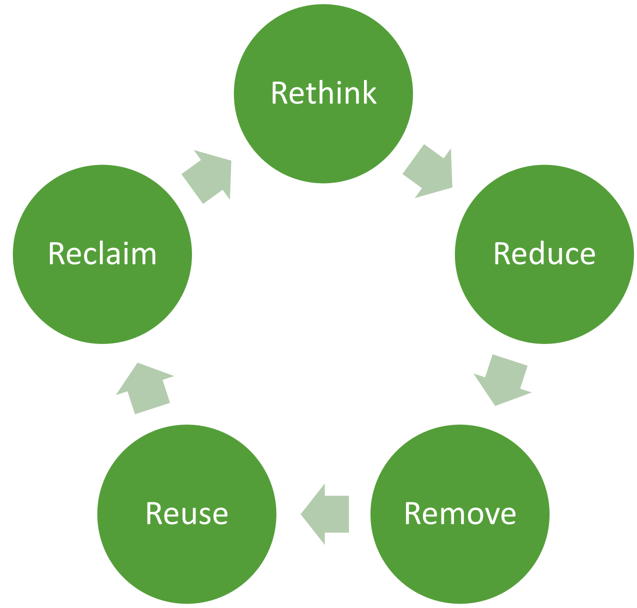

Fig. 1. 5Rs.

4.2.2. Practical illustration of the water-energy-materials nexus

4.2.2.1. Overview. The iWAYS project seems like an innovative and comprehensive approach to addressing energy, water efficiency and materials in industrial processes. By integrating the state-of-the-art technologies, such as Heat Pipe Condensing Economiser (HPCE), advanced water treatment systems and a decision support system, iWAYS aims to recover significant amounts of energy, water, and materials from industrial exhaust streams.

The HPCE, based on Heat Pipe technology, appears to be a key component in recovering waste heat from industrial processes. Its ability to efficiently transfer heat while mitigating fouling and corrosion challenges makes it a promising solution [54]. Additionally, the water treatment system, employing techniques such as membrane distillation [55] and photocatalytic nanofiltration [56], targets the purification of reclaimed water for reuse in industrial processes, thereby reducing overall water consumption.

Moreover, the decision support system based on real-time monitoring promises to enhance operational effectiveness by providing insights for optimization and decision-making. This holistic approach not only improves resource efficiency but also contributes to reducing operational risks and costs for industries.

Independently from the industrial processes that generate flue gas, the condensed water recovered from these streams (among other contaminants) contain organic matter, metals and acidic gas that are difficult to treat with conventional systems. The main objective of the iWAYS project is the recovery of condensed water by pushing on near-zero discharge processes with recovery of materials and resources. The iWAYS technology will be tested in three different industrial processes: ceramic, chemical and steel.

4.2.2.2. iWAYS technology. Heat Pipe Condensing Economiser. The heat pipe condensing economiser operates on the principle of Heat Pipe technology, which involves a hermetically sealed tube containing a small amount of working fluid at saturation. Within the tube, the liquid phase resides at the bottom while the vapor occupies the remaining space. Heat is applied to the lower section, causing vapor generation on the internal volume. This vapor then ascends to the condenser section, where heat is released to the heat sink (air, water, or another fluid), leading to vapor condensation on the heat pipe surface. The condensate gravitates back to the evaporator section, establishing a constant two-phase process for heat transfer between the exhaust flow and the heat sink without any moving parts. This uniform temperature distribution minimizes management requirements and reduces the risk of cold spots forming.

In a Heat Pipe Heat Exchanger (HPHE, Fig. 2), Heat Pipes are arranged in a staggered configuration, with both flow streams separated by a separation plate. Each Heat Pipe functions as an independent heat exchanger, sealed individually to prevent cross contamination due to a single damaged pipe. The versatility of HPHE technology enables its application across a wide range of exhaust compositions and temperatures, with bespoke designed heat sink options including air, water, pressurized water, oil, or other fluids to suit end-user needs.

Similarly, the Heat Pipe Condensing Economiser (HPCE) utilises heat pipes to transfer heat from a flue gas to the heat sink. By maintaining Heat Pipe surface temperature below the dew point, corrosive moisture condenses on specific rows, facilitating an effective separation of organic material in the stream. Typically divided into three sections, the HPCE recovers sensible energy in the first section while keeping heat pipe surfaces temperature above the dew point. The second section focuses on condensing acid-based moisture from the flue gas, while the final section addresses any remaining exhaust water content before the environmental discharge. Additional sections can be incorporated as needed based on flue gas characteristics, with each section tailored to specific compounds extraction requirements identified during the iWAYS project.

Water treatment system. The overarching goal of iWAYS is to lead industries towards achieving near-zero discharge processes. To achieve this, the water treatment system will be tailored to the specific needs of end-users. A combination of innovative technologies will be employed. Initial treatment involves sand and hollow fibre ultrafiltration to remove particulates and prevent fouling. Subsequently, reverse osmosis will be employed to achieve an exceptional water recovery rate of up to 95 %, producing a high-quality, low electrical conductivity stream (around 150–200 micro-S/cm) suitable for direct recirculation into industrial processes.

For targeted removal of metals and pollutants, the iWAYS solution incorporates a photocatalytic nanofiltration reactor (PNFR). This system utilizes advanced photocatalytic monoliths and porous polymeric fibres embedded with TiO2-based photocatalysts. These components efficiently eliminate metals and organic contaminants from the wastewater, ensuring the treated water meets stringent quality standards.

4.2.2.3. iWAYS' circular solution. The iWAYS project aims at upgrading industrial processes through the development of a dynamic process monitoring, control, and optimisation dashboard. This cutting-edge dashboard will seamlessly integrate data collection, harmonisation, processing, and visualisation, empowering stakeholders to make informed decisions based on evidence.

Through continuous data acquisition, the monitoring system will enable predictive analysis of the iWAYS system's behaviour, offering

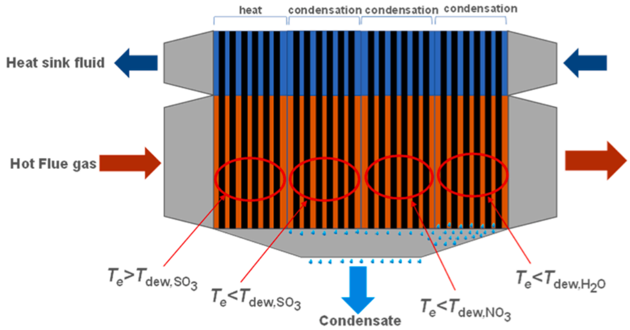

Fig. 2. Heat pipe head exchanger.

actionable insights for optimal water reuse and recycling strategies. The platform's capabilities extend to real-time monitoring, management, and maintenance of interconnected machinery and devices, facilitating remote access and automated data collection and analysis.

These advancements provide invaluable benefits to the industry, enhancing operational effectiveness across multiple fronts. By increasing productivity, improving plant efficiency, uptime, and asset quality, and mitigating operational risks and costs, the iWAYS project drives substantial improvements in overall performance and efficiency, ultimately fostering sustainable practices and reducing changeover times.

The iWAYS project expects a significant reduction in resource waste, particularly in terms of energy and water consumption. Within the ceramic industry, iWAYS reclaims substantial amounts of water, including 500 litres per hour discharged from spray dryers and an additional 1500 litres per hour from the water treatment plant, totalling a potential recovery of 2000 litres per hour. The HPCE, that cools the spray dryer exhaust below the dewpoint temperature, aims to recover 1.3 MW of thermal power from spray dryer exhaust, determining an annual energy recovery of 6 GWh.

In the chemical sector, a dual-stage HPCE unit is designed to recover 600 kW of thermal power, yielding an estimated 5 GWh of recovered thermal energy annually. The first stage will decrease the temperature below the acid dewpoint, determining the hydrofluoric acid recovery; the second stage will determine the water recovery.

The iWAYS water treatment system complements this by managing condensate from the HPCE, as well as recycled water previously destined for discharge, addressing the recovery and reuse of up to 10 m3/h of water.

Innovating further, the steel industry implementation involves a cutting-edge radiative HPCE concept, with the goal to recuperate heat and condense vapor produced during hot rod cooling. Designed to capture 80 kW of thermal power, this setup anticipates a water recovery rate of around 450 liters per hour.

Table 7 summarises the circular solution of the iWAYS project in the context of the Water-Energy-Materials nexus.

5. Conclusion

The study reviewed the main most recent EU legislation related to wastewater, energy, materials and industries in the context of circularity and environmental sustainability. While the paper has identified some positive 'pockets' of legislative developments, overall, the EU legislation is still rather complex and disjointed. These fragmented 'positive' examples in relation to environmental sustainability and/or circularity are insufficient to achieve the Green Deal objectives. Stress on the visibility of 'circularity' from a quantitative point of view is rather limited in the all analysed EU legislative instruments, save the CRMA. There is clearly a more emphasis on environmental sustainability, yet, as the paper argues this cannot be achieved without embracing circular solutions, especially in terms of industrial settings. Therefore, the paper also calls for further policy instruments specifically designed for industrial processes to untap the water reuse solutions, as part of integrated water management while simultaneously achieving energy efficiency as well as recovering valuable resources in line with the circular economy principles, as illustrated by the iWAYS project. As presented in Section 4.2.2.3, in this project, there is an annual thermal energy recovery of 6 GWh and 5 GWh in the ceramic industry and chemical sector respectively, and recovery of significant amounts of water. While embracing the Water-Energy-Materials nexus, this project provides an integrated circular solution closing the loop in industrial processes, expecting to significantly reduce resource waste, particularly in terms of energy and water consumption. This real-life example can serve as a bottom-up instrument to influence future EU legislation. Potentially, this can be achieved via the newly launched Clean Industrial Deal, aimed at the decarbonisation of energy-intensive industries.

Table 7
Water-energy-materials nexus in the iWAYS context.

Principle	Water	Energy	Materials
RETHINK	Holistically analyse the process embracing an integrated approach to close the loop in industrial processes		
Reduce	30 %–60 % less freshwater used	10 %–80 % reduction in waste heat and energy consumption by recovering sensible and latent heat from challenging exhaust stream.	N/A
Remove	Removal of pollutants from wastewater	Remove the CO2 emission by reusing the waste thermal energy recovered in the industrial process. Decrease of >25 % CO2eq.	Concurrent removal of elements in the exhaust gases (particulate matter, boron, VOCs, acidic gases – HF, SOx, NOx, HCl). Decrease of >60 % of final gaseous pollutants.
Reuse	Use wastewater as an alternative source of water supply. Water reuse from 3500 to 10,000 m^3 per year.	Reuse of the recovered heat in the industrial process. Annual energy reduction from 0.3 to 6 GWh per year depending on the industrial process.	Reuse of the HF pollutants in the chemical process. 50 t per year.
Reclaim	Up to 90 % of discarded water will be recovered from condensate stream	Recovery of heat from waste sources (challenging exhaust gases). Thermal power recovered from 80 to 1100 kW_{th}.	N/A
RETHINK	Reduced water costs Meeting environmental requirements	Reduced energy costs, further investment potentials; Meeting environmental requirements	New business opportunities: sale of different acids

CRediT authorship contribution statement

J. Malinauskaite: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **B. Delpech:** Project administration, Investigation. **H. Jouhara:** Validation, Supervision, Project administration, Investigation, Funding acquisition.

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.

Acknowledgement

The paper was supported by the European Union's Horizon 2020 funded project iWAYS (the grant agreement No 958274). Additional information about the project is available at: iWays - Water closed loop in industrial processes - iWays

Data availability

No data was used for the research described in the article.

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