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Strategic routes for wastewater treatment plant upgrades to reduce micropollutants in European surface water bodies

Morgan Abily [a,b,*], Vicenç Acuña [a,b], Lluís Corominas [a,b], Ignasi Rodríguez-Roda [a,c], Wolfgang Gernjak [a,d]

[a] Catalan Institute for Water Research (ICRA), Carrer Emili Grahit 101, 17003, Girona, Spain
[b] University of Girona, Plaça de Sant Domènec 3, 17004, Girona, Spain
[c] Laboratory of Chemical and Environmental Engineering (LEQUiA), Institute of the Environment, University of Girona, 17071, Girona, Spain
[d] Catalan Institution for Research and Advanced Studies (ICREA), Passeig Lluís Companys 23, 08010, Barcelona, Spain

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ABSTRACT

The European Union is determined to address the problem of contaminants of emerging concern (CEC) occurrence in natural water bodies. However, if a broad range of possible advanced treatment technological solutions exists as well as a variety of possible future conditions, then emission and consequently strategies for wastewater treatment plan (WWTP) upgrade and operation are not easy to anticipate. Here, a strategic foresight exercise was carried out to support decision-making matching anticipated future conditions toward the goal of finding suitable treatment upgrades to control CECs release in the environment. As a result, a roadmap and strategic routes were developed based on the interpretation of drivers for the EU region in the context of Shared Socioeconomic Pathways (SSPs) global change narratives. Screening and ranking of WWTP tertiary and advanced treatment technology upgrades were performed. Analysis of the resulting envisioned strategic routes allowed identifying and confronting core challenges such as the CEC removal agenda, technologies' performance, requirements for CEC removal and water scarcity. The results also underline opportunities to shape WWTP technological upgrade planning such as: enhancing circular economy solutions in WWTP, water reclamation, and accelerated increase of the technology readiness level of hybrid and nature-based solutions.

1. Introduction

Chemical pollution of surface water bodies (SWB) impacts their ecological status and their potential use as a water resource. In the EU, the Water Framework Directive (WFD) instructs member states to strive for water bodies having a so-called "good chemical status" (EU, 2000). The concern for protecting water resources and ecosystems led the EU Commission to issue the first list of priority substances (Decision 2455/2001/EC) and a Directive on Environmental Quality Standards (Directive 2008/1005/EC), both later revised in Directive 2013/39/EU, and issued guidance on reaching these ambitious objectives (European Commission, 2015a & 2015b). However, the current situation regarding contaminants of emerging concern (CEC) threatens the achievement of these targets. Indeed, during the recently concluded River Basin Management Plan (RBMP) reporting period (2015–2021), the number of riverine SWB failing to reach a good chemical status would rise from 3% to 34% if CEC were to be considered in the chemical status assessment (EEA, 2018). The chemical status being part of the assessment of the ecological status or potential of SWB, CEC impose decisive limitations on the ecological status of EU SWB. Though postponed to the end of the following RBMP cycle (2021–2027), the EU Commission's target to attain good ecological status in all SWB already now appears challenging (Posthuma et al., 2020); and the situation will be even worse due to climate change (Abily et al., 2021).

Urban wastewater treatment plants (UWWTP) are the main qualitative and quantitative point sources of pollutants, notably for CEC, released to SWB (Rizzo et al., 2019). The management of the quality of the released wastewater is a trade-off between investment in wastewater treatment operation and infrastructure, and acceptable released pollutant concentration which complies with established contaminant threshold values. Besides source-control solutions (Corominas et al., 2020), investment in the upgrade of the UWWTP treatment processes is therefore a key management necessity for member states. WWTP upgrades can imply significant financial investment with long-term

* Corresponding author. Catalan Institute for Water Research (ICRA), Carrer Emili Grahit 101, 17003, Girona, Spain.
E-mail address: mabily@icra.cat (M. Abily).

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impacts (Gimeno et al., 2018). While a broad range of possible tertiary and advanced treatment technological solutions upgrades exists (CTO, 2021), envisioning the future of wastewater treatment to specifically target and control CEC release remains challenging. This is due to the complexity and variation in CEC behaviour, to the demanding assessment of the maturity and evolution of technologies toward this specific removal purpose and lastly, due to dependency upon political, environmental, and social forces. These driving forces produce changes (i) in water resource availability and (ii) in CEC levels of production and excretion. Changes in (i) and (ii) are driven by climate change impacts, policy, social behaviour, demographic changes such as urbanisation, population growth and evolution of demographic pyramids in member states and, for example, associated changing pharmaceutical use patterns. Models of these drivers' status and evolution exist and are often used to predict their current and future trends. Such types of model results are however often asserted with a high degree of uncertainty and not easily used to support decisions without an information integration strategy for decision support making (Ratcliffe, 2021). Nevertheless, the possible changes in driving forces and events which impact the efficiency of investment measures in wastewater treatment technologies shall be considered.

In an uncertain context regarding the future of this century in the mid to long term, several approaches exist to consider potential future realisations as part of strategic foresight approaches (Durst et al., 2015; EU, 2020; Mehmood et al., 2020), such as scenario planning (Dellink et al., 2017; Elsawah et al., 2020) or strategic road-mapping (Barker and Smith, 1995; Phaal et al., 2004; Weinberger et al., 2012). Scenario planning elaborates flexible plans and is prepared by evaluating alternative future scenarios. A strategic technological roadmap is a future mapping approach often based on scenario planning to cover a range of uncertain futures. At a practical level, scenario planning and strategic road-mapping approaches have been implemented in a broad range of fields to draw several projected sets of future conditions (Reardon et al., 2013; Li et al., 2019; Rulleau et al., 2020), or to test the viability of strategies under variable circumstances, aiming to foresee and analyse *a priori* their success and failure potentials. As an example, climate change Shared Socioeconomic Pathways (SSP) narratives are a widely known framework developed via scenario planning. SSPs linking the CO_2 concentration target, socioeconomic development pathways, and shared policy assumptions for scenario building have been used since the 5th IPCC assessment report (IPCC, 2007b; O'Neill et al., 2014; Riahi et al., 2017). SSPs are used as narratives to support the building of so-called storylines. Anthropogenic forcing of the climate system -Representative Concentration Pathways (RCPs)- and SSPs narratives jointly establish climate change baseline scenarios. Furthermore, this RCPs/SSPs bi-dimensional matrix is often joined with shared policy assumptions to consider policy-driven mitigation scenarios (Kriegler et al., 2014; O'Neill et al., 2017).

In general, scenario planning and roadmap-building approaches do not aim to predict the future but allow the development of an understanding of the trends and their relationships that could shape future conditions. This can ultimately help to draw goal-oriented strategic routes. Moreover, road mapping allows a connection between challenges and specific actions to be made and measures to meet them, supporting technological upgrade planning for instance (Tugrul and Terry, 2008; STOWA, 2010; Reardon et al., 2013). As a part of a strategic foresight process, these approaches permit proactive selection for a preferred future by (i) recognizing the implications of the forecast, and (ii) organizing to achieve the envisioned future defining strategy and plans.

Here, the objective is to produce (i) roadmap, and (ii) strategic routes for CEC removal-oriented WWTP technology upgrade in the context of the European WFD goals. The first aim is to chart and rank technologies' characteristics and merits to address the CEC removal goals. By aggregating these characteristics into a set of dimensions (performance, scalability, energy, sustainability, and economy), technologies and SSP narratives can be matched in the roadmap to be created in the next step. Following this, by combining the roadmap, technologies and SSP narratives, strategic routes are built for each SSP narrative. The goal of each route is to frame the strategic potential for technological upgrades, implementing policy-driven objectives of environmental water quality concerning CEC removal.

Building SSP-dependent strategic routes will allow transversal key opportunities and threats for efficient technology upgrade implementation to be identified. The analysis of strategic routes across different SSPs shall permit transversal gap identification and enhance the perspective for overcoming them. Moreover, the development of such strategic routes will provide an opportunity to produce a common and reusable perspective framing of an applied scenario of a technological upgrade for modelling water quality in future work.

2. Process design and method

The process to establish a roadmap as a background for strategic routes building has been conducted in three main steps (Fig. 1): (i) framing of roadmap structure; (ii) technology screening to characterise technologies and their performance and provide foresight of their future development trends; (iii) building the roadmap and assessing strategic routes in a collaborative iterative process.

2.1. Framing of roadmap structure

The roadmap information layers (Fig. 2) are bi-dimensional structures, where the horizontal axis is the timeline and the vertical axis are information layers which are graphical representations linking the questions why (here objectives and drivers), what (here the WWTP technological upgrades) and how (here function/capability). The layers defined and described hereafter were aligned to cross their information, structuring the roadmap with a common framework, but filled differently, according to the SSP narrative they refer to (SSP1, SSP2 or SSP5). The roadmap structure is arranged in four high-level classes of information layers:

- Policy objectives for CEC removal. This layer encompasses the elements of awareness and policy set framework and targets for CEC removal in WWTP. The rising awareness about CEC concerns, the UN SDG goals, and the EU WFD structure this layer.
- Trends and drivers. This layer is directly framed by the EU regional interpretation of the SSP of interest. The SSP storylines are in that case interpreted specifically for the EU region as in (Strokal et al., 2021), where the whole EU is considered a homogeneous region with a Human Development Index > 0.785 (Kummu et al., 2018; UNDP, 2017). The layer is composed of five sub-components.
  a. The source control sub-component reflects the EU region's SSP-driven assumptions regarding urbanisation, population growth and ageing, and assumed social and political commitment toward emission reduction.
  b. Climate change impacts on the water resources, which qualitatively reflects the induced stress on water resource quantity, seasonal variability, and extreme events (flood and drought) occurrence frequency.
  c. Availability of resources such as energy and financial capability, as determined by GDP levels.
  d. Policies application for CEC removal at the EU member state level in the narratives, driven by the expected level of investments and commitments towards the water resource and environmental protection.
  e. The science and technology sub-component is composed of qualitative assessment of: (i) the level of investment in science in the field of water technologies, thus allowing the technologies which still have margin for improvement to reach their maximal

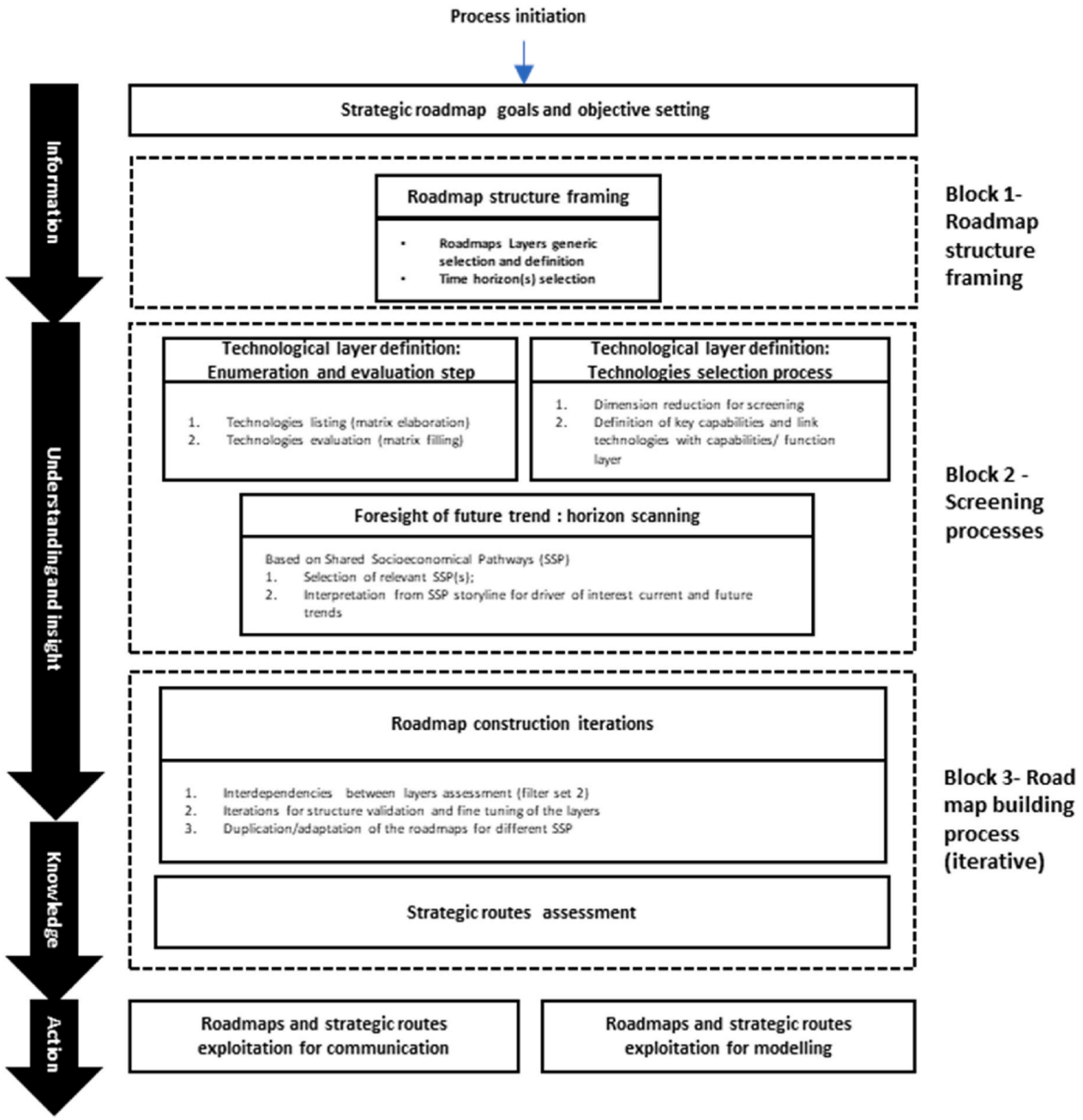

Fig. 1. Staging of the processes used to build the roadmap and the strategic routes to envision WWTP technology upgrade for CEC removal in EU.

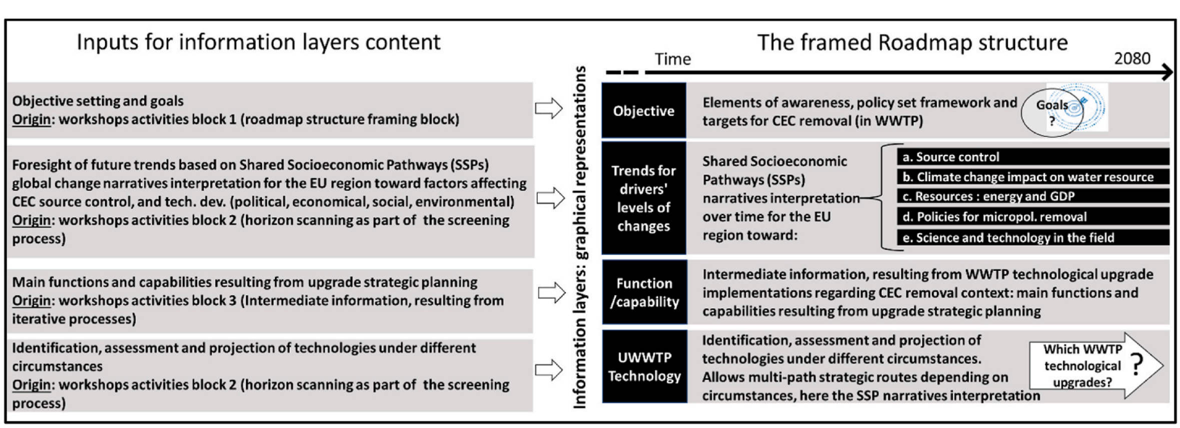

Fig. 2. Graphical representation of the information layers to frame the roadmap for WWTP technology upgrade strategic road building.

potential, and (ii) the propensity of techniques and practices for monitoring CECs, to become prevalent.

- Function/capability layer. This layer reflects key functions and capabilities in the wastewater treatment utilities/services, potentially developed as a result of technological upgrades. Components of this layer are the key perspectives offered by WWTP technological upgrade implementations regarding CECs removal resulting from upgrade strategic planning.
- WWTP upgrade technologies. This technological layer of the roadmap combines the selected technological upgrades with the appropriate SSP narratives. The criteria used are aggregated dimensions such as: overall CEC removal performance, economy, sustainability, energy, and scalability. The list of categories of technologies considered and the list of criteria are shown in Fig. 3. The list is composed of twenty fields and the grading of the technology for the different criteria is based on the expert opinion collected from a series of workshops detailed in next sub-section.

The time horizon considered for the roadmap ranges from the early 1900s to 2080. The rationale behind this timespan selection was to reflect in the roadmap past trends and swiftness of technological upgrades (up to 2010s), the current trends (2010–2025), the near future (2025–2040) and future vision (up to 2080s). This 2080 future horizon limit is what authors consider as the infrastructure asset lifespan of technological upgrades that would be implemented as of today.

2.2. Technology screening

A plethora of different advanced treatment technologies for upgrading wastewater treatment has been considered (see Fig. 3). These unit processes involve different decontamination mechanisms based mostly on physicochemical separation (e.g., different membrane processes, sand filtration, adsorption), chemical conversion through redox reactions (e.g., ozonation, electrochemical treatment, advanced oxidation) or biologically and microbiologically mediated metabolic processes (e.g., nature-based solutions). Each process has unique features regarding their resource needs for establishing and operating them (Gu et al., 2017). They each also provide specific water quality and potentially other benefits. Both aspects have been evaluated in this manuscript for the present and expected future state-of-the-art of the technology. However, describing the gamut of these technologies and their respective performances in detail goes beyond the scope of the present manuscript and, if interested in more detail about a specific technology, the reader is kindly referred to scholarly reviews (e.g., Castellar et al., 2022; Morera et al., 2020; Morera et al., 2016; Radjenovic and Sedlak, 2015; Rizzo et al., 2019), textbooks, and other literature.

The technologies layer definition was designed through an enumeration and an evaluation of mature and incipient tertiary treatment technologies. These steps were performed through six workshops conducted during 2021/2022 with project collaborators. The panel of experts was composed of members of two different institutions (University

	Microfiltration	Nanofiltration / Reverse osmosis	Membrane Biological Reactors	Sand Filtration	Powdered Activated Carbon	Granulated Activated Carbon	Ozonation	UV based Oxidation	Plasma Based Oxidation	ELOX	UV disinfection	Chlorine-based disinfection	NBS: Treatment wetland	NBS: Ponds/lagoon	NBS: Soil Infiltration
Micropollutant removal efficiency: towards organic compounds	1.5	8.5	6.0	3.0	5.0	6.0	7.0	6.0	3.0	5.0	2.0	3.0	5.3	5.0	5.7
Micropollutant removal efficiency: toward particles compounds	8.0	9.5	8.0	5.0	2.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	4.3	3.0	5.0
Micropollutant removal efficiency: toward microroganisms	7.0	8.5	7.0	2.0	2.0	2.0	8.0	9.0	5.0	6.0	9.0	7.0	4.3	5.3	6.3
Nutrients removal efficiency	2.5	8.0	7.5	3.0	1.0	4.0	2.0	2.0	2.0	2.0	1.0	3.0	6.0	6.5	5.5
Cost: CAPEX performance	4.0	8.0	6.5	8.0	3.0	8.0	6.0	4.0	10.0	9.0	2.0	2.0	5.0	4.0	4.0
Cost: OPEX performance	4.0	9.0	6.5	2.0	6.0	3.0	4.0	7.0	10.0	8.0	3.0	3.0	4.5	3.0	2.5
Cost: Economy of scale	3.0	6.5	7.0	5.0	3.0	5.0	6.0	4.0	4.0	5.0	3.0	3.0	4.5	4.5	3.5
Robustness of technology performance	7.5	5.0	7.0	6.0	6.0	5.0	5.0	3.0	5.0	5.0	8.0	3.0	7.0	9.0	7.0
Energy efficiency	7.0	2.5	4.5	9.0	9.0	9.0	5.0	4.0	1.0	2.0	9.0	10.0	9.0	9.0	10.0
Direct greenhouse gases emission performance	9.0	9.0	4.5	8.0	9.0	8.0	9.0	9.0	9.0	9.0	9.0	9.0	5.0	3.5	7.0
Space occupation	8.5	7.5	6.0	6.0	8.0	6.0	7.0	9.0	9.0	9.0	9.0	8.0	1.5	2.5	1.5
A priori social acceptance potential	6.5	5.0	5.0	6.0	6.0	6.0	6.0	6.0	4.0	7.0	10.0	9.0	8.5	8.0	8.0
Green chemistry	5.0	3.0	6.0	10.0	7.0	7.0	8.0	5.0	7.0	7.0	7.0	3.0	6.5	7.0	7.5
Undesierable waste production	3.5	6.0	5.0	2.0	7.0	3.0	4.0	2.0	8.0	7.0	1.0	6.0	5.0	4.0	1.5
Safety aspects of the technology	2.5	4.5	3.0	1.0	2.0	1.0	4.0	3.0	8.0	6.0	2.0	4.0	1.5	2.0	2.0
Other benefits: N recovery	2.0	4.5	3.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.5	2.5	0.5
Other benefits: P recovery	2.5	5.0	4.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.5	2.5	0.5
Other benefits: Carbon Recovery	2.5	2.5	5.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	7.5	2.5	0.5
Other benefits: Biodiversity, aesthetic value, air purification	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	8.0	7.0	4.5
Other benefits: High Value Products	1.0	4.0	2.5	1.0	1.0	1.0	1.0	1.0	1.0	3.0	1.0	1.0	2.0	2.5	0.5

Fig. 3. Heatmap of the twenty criteria used for relative comparison of WWTP tertiary and advanced treatment technology upgrade.

of Girona, Catalan Institute for Water Research) and members from across four different departments with expertise broadly ranging from treatment technology to water quality and ecology. The members were selected based on: (i) their high profile and ample experience in interdisciplinary thinking, (ii) their availability for recurrent workshops, and (iii) their involvement in previous projects on decision support systems for treatment upgrades using grey and blue-green infrastructures (SANNAT; SUGGEREIX), each of these projects counting with the contribution of multiple agents.

Under the support of one facilitator, the workshops meetings focused on: (i) scanning tertiary and advanced treatment technologies commonly applied to upgrade WWTPs and also incipient non-mature alternatives; (ii) establishing a list of criteria to compare the technologies; (iii) rating the relative evaluation of the technologies against these criteria, whereby relative means that each technology was graded from 1 (worst performance) to 10 (best performance). This outcome is summarised in Fig. 3.

The foresight of future trends was performed for horizon scanning using the existing SSP framework. In other words, for each SSP considered, the future trend for each technology and criterion was assessed. Assessments were carried out in individual criteria that were agglomerated in the following dimensions: pollution elimination performance, economy, sustainability, energy requirement and scalability. The outcome of this evaluation is illustrated in Fig. 4.

Among the five SSP scenarios, this study focuses on "SSP1 – Sustainability (Taking the Green Road)", "SSP2 – Middle of the Road", and "SSP5 – Fossil-fuelled development (Taking the Highway)" as it was reasonably expected that these three SSPs would yield the most contrasting results on a European level. In turn, this study disregardSSP3 and SSP4 which are narratives impacting inter-regional socioeconomic pathways as opposed to the EU region as a whole. Possible variations in RCPs in the building process for the roadmap were not included in this study since it was not the intention to analyse the impacts of greenhouse gas emissions.

2.3. Building the roadmap and strategic routes

The creation of roadmap, based on the SSP narrative, which frames the context of the WWTP technological upgrade for microcontaminants removal, represents a combination of projection and problem-oriented exploration of the potential futures. The approach then, by developing goal-oriented strategic routes, elaborates on how a specific future targeting EU sets CEC removal objectives, could be shaped. It should be emphasized that the overall approach aims to identify gaps and opportunities revealed throughout the exploration of these strategic routes.

The information layers defined and described in section 4 were aligned to cross their information, structuring the roadmap with a common framework, but filled differently, according to the SSP narrative they refer to (SSP1; SSP2 or SSP5). This reflects in both, the *trends and drivers* and in the *technology* layer of the roadmap. The *trends and drivers* layer is a direct interpretation of the narrative. The *technology* layer displays the selection of the potentially relevant technologies based on the following dimensions: performance, economy, sustainability, energy, and scalability by grading the importance of these dimensions for the given SSPs. Thus, in this stage of the process, a technology selection was performed in the technology layer. A filter was applied for dimension reduction. All the criteria in the matrix from Fig. 3 were classified into five categories for dimension reduction: performance, economy, sustainability, energy requirement and scalability of the technology potential (Fig. 5).

Strategic routes were developed on the roadmap and illustrate how a certain goal could be reached based on current circumstances, setting objectives, and showing a reasoned path to reach the goal. The alignment of the reasoning behind selecting the goals was based on the breakdown of the high-level society goals to a more tangible objective. The goals were here defined differently in terms of performance and timing for the strategic routes as an interpretation of the SSPs narratives.

However, before moving to the strategic roads and the roadmap results in next sections, the panorama of technology upgrades displayed in Fig. 5 allows key messages to be drawn from the dimension reduction on the actual status and positioning of these technologies.

1. The dimension coverage is very different in the various technological upgrade categories.
2. The highest performing technology upgrades are nanofiltration and reverse osmosis, as well as membrane biological reactors. These technologies' performance for CEC removal is very good for the different types of micropollutants (Fig. 3). On the other hand, technologies with the least coverage of the radar chart dimensions are recent technologies such as Electrochemical (ELOX) and Plasma-based oxidation which are not mature enough at the current stage of their development.
3. NBS are not well-performant for CEC removal, but they are covering the other four dimensions at very high levels. A targeted

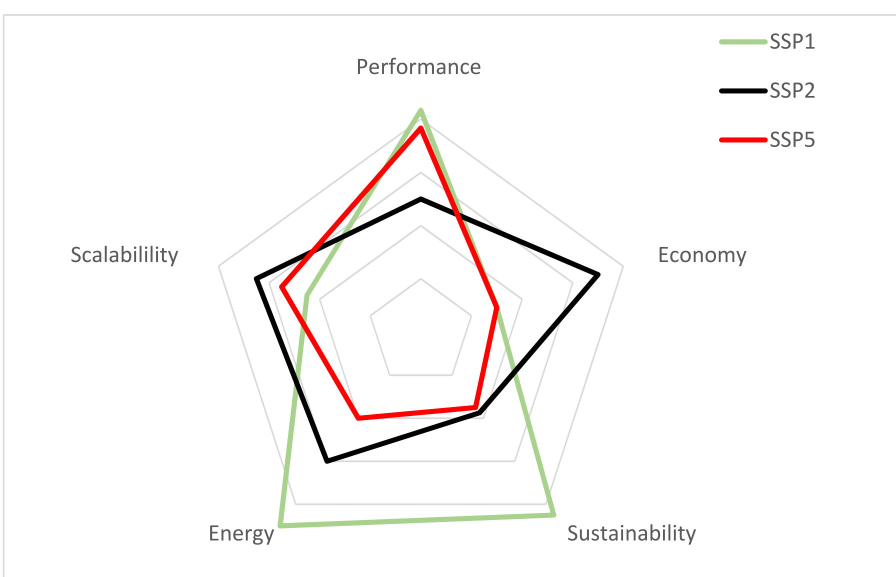

Fig. 4. Dimension to be prioritised in the three SSP considered.

Fig. 5. Dimension reduction ranking of the WWTP tertiary and advanced treatment technologies.

development to improve their CEC removal performance would provide technological solutions that are “ideal".

3. Results

The roadmap structure, filled for SSP1, SSP2 and SSP5 is shown in Fig. 6. This roadmap is the background framework to develop the strategic routes targeting, via technology upgrade, a shift from current conditions toward the goals specified for CEC removal. The time frames for the envisioned changes is determined for the near future (2025–2040) and for the distant future (2040–2080) horizons.

3.1. SSP1 (‘Taking the green road’): drivers, goals, roadmap, and strategic routes

In this SSP narrative, EU regional interpretation of the drivers is here envisioned up to the end of the near future period (2040), whereas policies for CEC removal are expected to come into force and translate into actions, a relatively high level of CEC emission is still expected. Moreover, despite inherent inertia for such profound changes in infrastructure, as a consequence of the short time frame, actions for a greener society are not necessarily impacting at a high level yet. Meanwhile, climate change impacts will further exacerbate pressure on water resources available, impacting the dilution capacity of the surface water bodies, especially for Mediterranean regions of the EU. To compensate for the dilution capacity reduction of the surface water bodies, higher level of CEC removal performance would be required to categorize a surface water body as having a “good” chemical status (Abily et al., 2021). In parallel, financial resources (for investments in WWTPs upgrades CAPEX and OPEX) and decarbonised energy are expected to become more available due to socio-political awareness and greener orientation in this SSP. Still, independently from the energy source’s carbon footprint, parsimonious energy consuming solution are favoured by this SSP.. Science and technology are expected to advance as well. In the second phase (2040–2080) driving forces will continue to exert pressure in a green direction, although climate change impacts on water resources shall still be expected to deteriorate by the mid to end of the century (IPCC 6th).

Thus, the goal in the SSP1-driven scenario is to match as realistically as possible with the 2027 EU WFD ecological status objective: all the surface water bodies shall have a good ecological status (implying that all the surface water bodies shall have a good chemical status from

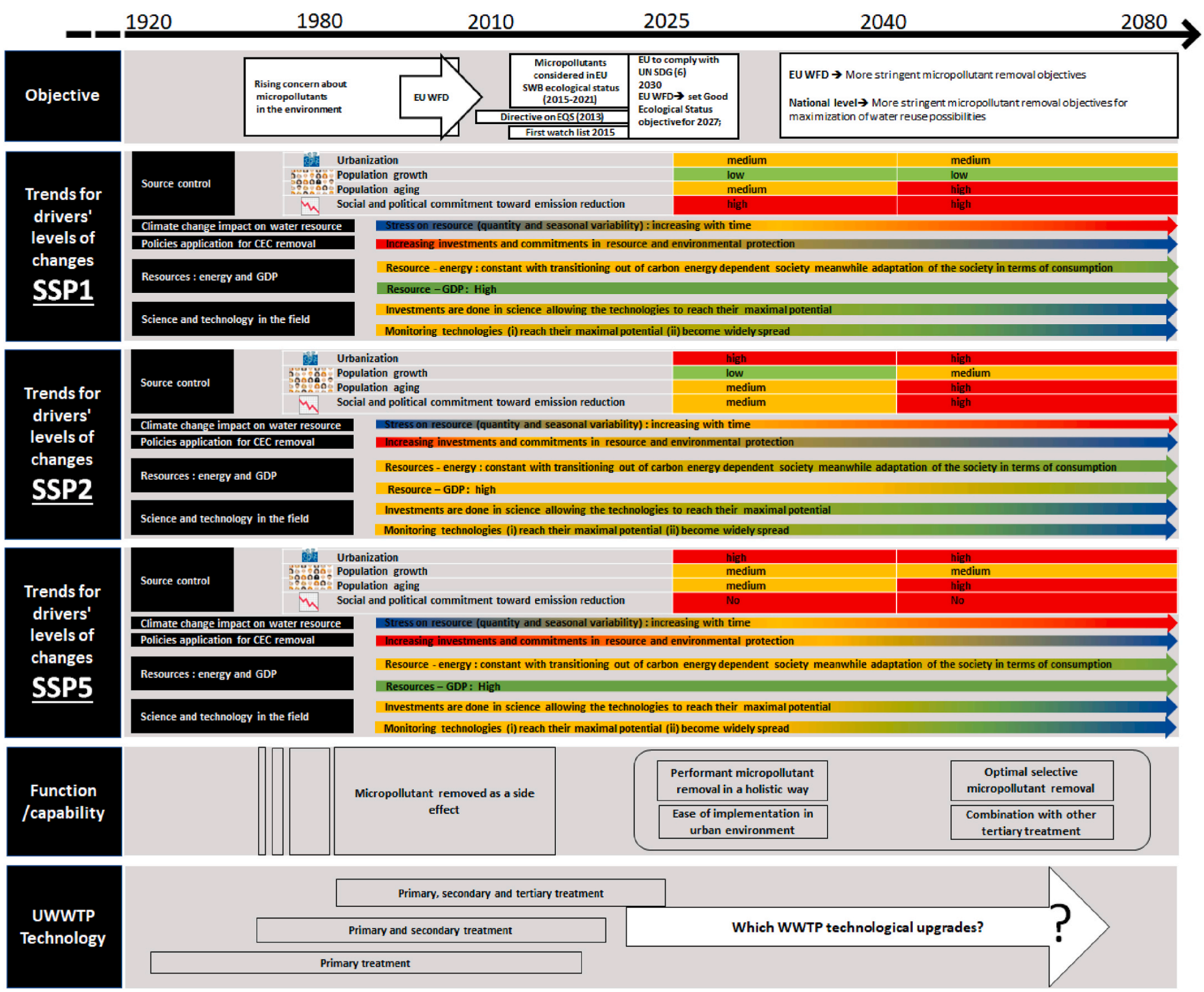

Fig. 6. Roadmap structure, filled for SSP1, SSP2 and SSP5 narrative context where hot/cold colours reflect the drivers’ condition evolution. A warmer criteria/component colour means that the criterion/component condition is expected to act more stringently upon the driver.

which ecological status of surface water bodies depends on (European Commission, 2015a & 2015b). The need to do so would be at least an 85–90% CEC removal for 85–90% of the total wastewater volume released in the environment by EU WWTPs. These objectives (applied in a similar form in Switzerland already) coupled with the dilution factor of WWTP effluent within the rivers shall permit that the WWTP points source discharge does not hamper the surface waterbodies chemical and thus ecological status classification as requested by the EU WFD. Even more so, if a part of the treated wastewater is derived to be reused for other purposes.. This ambition translates to a rapid implementation of high and holistically performant CEC removal technology. From the technology listing (Fig. 3), and the SSP narrative interpretation (Fig. 4), the technologies selected for this SSP are those maximizing the performance dimension first, then the energy and sustainability dimensions.

For the strategic route elaboration (Fig. 7), the technologies selected to implement such a scenario shall emphasise the following capabilities: (i) holistic CEC removal performance and, (ii) ease of implementation in the urban environment to reach the set treatment goal, which includes improvements. Applying such a selection process in terms of capabilities and dimensions prioritisation, led to the selection of microfiltration, nanofiltration and reverse osmosis, as well as membrane biological reactors as the most appropriate technologies for WWTP upgrades. Nature-based solutions (NBS) suffer from lower removal CEC efficiency (Fig. 5). Although they shall be prioritised when possible as they are considered to be energy-efficient and with a high level of sustainability. A drawback of NBS at their current level of maturity is that they are more complicated to implement in dense urban areas.

In the longer term (2040–2080 period), the goal will be to further increase the removal efficiency and the treated volume. Thus, the strategic route shall target even higher CEC removal efficiency technological upgrades and shall aim for the possibility to integrate/combine with tertiary and advanced treatments previously installed to reach the desired higher CEC removal levels (Fig. 7). Indeed, although the CEC emission might reduce in this later period, the monitoring and detection levels of the existing and persistent CEC will be improved as an investment in monitoring technologies and campaigns shall be prioritised. NBS are expected to make significant improvement in different performance aspects over the next thirty years in the SSP1 context. Hence, they will increase in prominence as a suitable technology to further upgrade previously installed advanced treatment.

3.2. SSP2 ('Taking the middle road'): drivers, goals, roadmap, and strategic routes

The SSP2 narrative extrapolates the current situation regarding societal priorities and its interpretation is comparable to a 'business-as-usual' scenario. Thus, even though the stringency of the EU directives increases toward the water resource environmental protection measures, the likelihood of seeing a drastic change in CEC source emission level at national scales is seen as low. This is notable up to the end of the 2025–2040 phase, as a consequence of EU societies' inertia in lifestyle and collective behaviour shift. Fewer resources (GDP and green energy) will be available compared to a green economy-based development (SSP1), or, in regard to GDP, even to a fully carbon-fuelled development (SSP5). "Science and technology development" will likely not be especially the favoured investment prioritisation sector by the government and businesses, likely prone to conservative budget repetition in the context of SSP2. Therefore, the evolution of technology maturity is not expected to reach its full potential quite as quickly as in SSP1. Neither shall trends of this first period (2025–2040) be expected to drastically shift or accelerate in the second period (2040–2080).

The goals in SSP2 are to match as realistically as possible with the 2027 EU WFD ecological status objective as a part and solution-focused strategy building. The need to do so would require at least an 85–90% CEC removal for 85–90% of the WWTP volume. However, the realistic achievement date for this objective would be one or two RBMP cycles after the 2027 deadline set by the EU commission with thus, at best, six to twelve years delay.

In comparison to SSP1, the dimensions for technological upgrade selection are more balanced in this SSP (Fig. 4). The economic dimension of the technology upgrade solutions is given the same level of importance as performance in this socioeconomic context (Fig. 8). As a result, based on Fig. 5, microfiltration and membrane biological reactors emerged as the most balanced solutions foreseen to be favoured, along with oxidation processes (ozonation, UV and chlorination). Even though these oxidation processes only tackle a part of the CEC spectrum and thus have a more limited range of performance (except for ozonation), they are the solutions that are envisioned to continue to be selected for

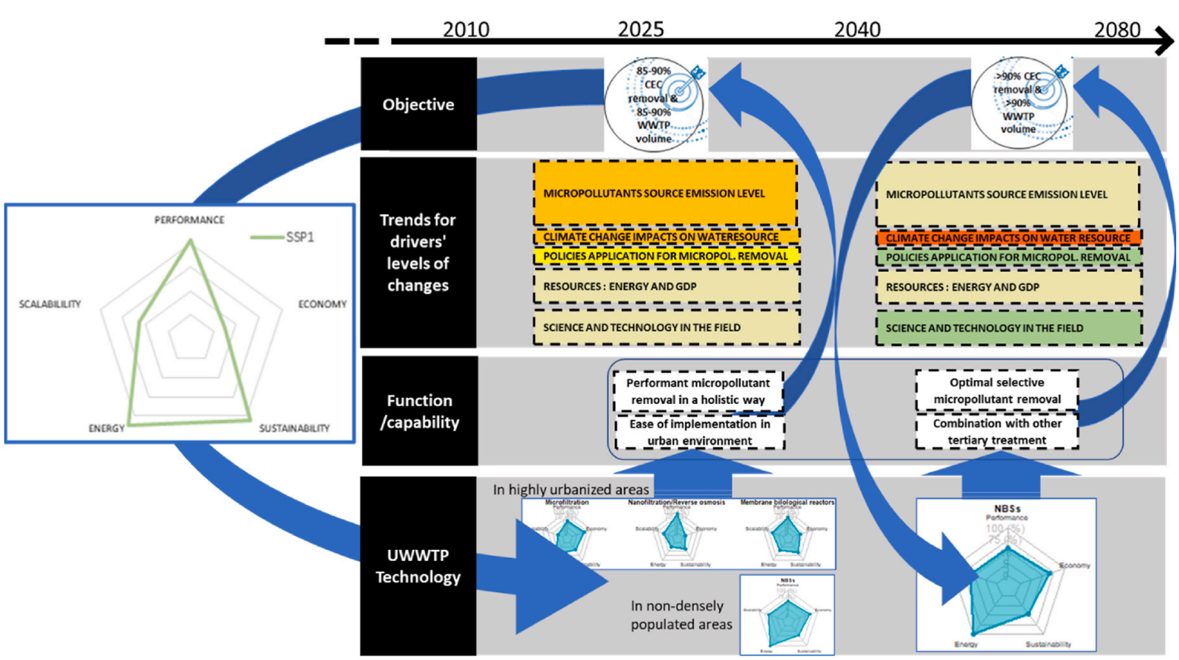

Fig. 7. Strategic routes based on SSP1 derived scenario where the trends and driver are represented by colours palette scaling from green (good) to red(bad) to reflect the given drivers' condition.

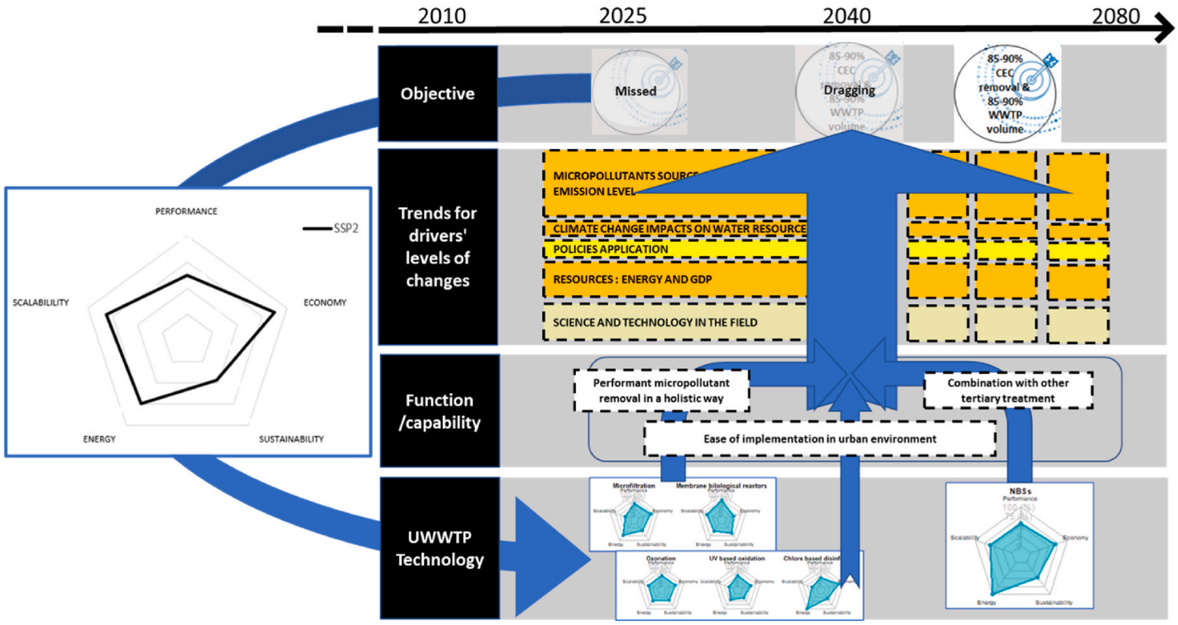

Fig. 8. Strategic routes based on SSP2 derived scenario where the trends and driver are represented by colours palette scaling from green (good) to red(bad) to reflect the given drivers' condition.

implementation due to their economic performance, at least in the near future. The same *status quo* remarks apply to NBS for non-urban areas. Compared to SSP1, broad implementation of ultrafiltration and reverse osmosis technologies is discarded due to an economic dimension which would burden the ease of implementation in this socioeconomic context. The functions and capabilities of the distribution of the technological upgrade implementation are seen as a blend of mixed technologies mirroring current tendency, whereby the speed of implementation is essentially driven by willingness-to-pay.

This broader, more economic but less effective blend of solutions is envisioned to gradually treat the CEC pollution problem, but in a manner which may not be sufficient to cope with the magnitude of the required urgency to match with EU imposed agenda (2027).

3.3. SSP5 ('Taking the highway'): drivers, goals, roadmap, and strategic routes

The driver pathways resulting from this carbon development-oriented society narrative puts the emphasis on the intensive use of resources -economical, energy and technological-for an environmental problem-solving oriented approach. Thus, in this rapid economic and population growth narrative, CEC source emissions levels are expected to increase as the societal markers are expected to follow that direction (population ageing, growth, and urbanisation). Climate change impacts on water resources are also expected to increase over the course of the century due to global greenhouse gases emission levels. The policy for CEC removal is expected to be inadequately applied in the near future period as it potentially requires significant economic investment. Conversely, in a more distant future phase (2040–2080), high investments might be made in WWTP upgrades due to the expected critical condition of and stress on the water resources. The critical water resource condition leading to considerable direct and indirect economic impact that investment in treatment technologies would have to tentatively counter-balance.

The goal in the SSP5 driven roadmap is to match as realistically as possible with the 2027 EU WFD ecological status objective. The need to do so would be at least an 85–90% CEC removal for 85–90% of the WWTP volume. However, the temporality of the reach of these objectives will be more economically driven, and the clear intent to achieve these goals will not likely start until the economic penalties and the environmental impacts become concerning. This ambition would translate into the late implementation of high and holistically performant CEC removal technology, accompanied by specific upgrades directly targeting selective CEC removal as a reactive remediation process (Fig. 9).

In terms of a technological upgrade selection (from Fig. 5), the performance dimension of the technologies and the scalability of the processes are envisioned to be highly favoured in this scenario, due to the increased urbanisation projections. The capabilities preferred are (i) holistic CEC removal, (ii) ease of implementation in an urban environment and, (iii) capability of the upgrade to combine with other tertiary and advanced treatments already in place. Microfiltration, nanofiltration, reverse osmosis and membrane biological reactors are seen as the most applicable for WWTP technological upgrades for this narrative.

4. Discussions

The set of diverse future exploring scenarios are synthesised in this section. The analysis relies on the envisioned strategic routes built to reach goals appropriate to the narrative-derived scenarios. This cross-analysis of the developed-strategic routes firstly highlights common core challenges to be addressed independently from the SSP narrative. Then, key opportunities to strengthen the shaping of WWTP technological upgrade investments targeting CEC removal are also identified, as well as future exploitation of the roadmap and strategic routes prospects.

4.1. Core challenges

- *Aligning with the EU proposed timelines for the CEC removal agenda.* Based on the current SSP narrative-derived scenarios, only the SSP1-derived strategic route would include the appropriate technological upgrade and political, economic and social contexts to achieve good chemical and ecological status of freshwater systems by the end of the next RBMP (2027) as proposed by the EU. This remains an optimistic pathway, where, in addition to the necessary essential and rapid technological investment, key political, economic, and societal changes would be required in the next four to five years to potentially

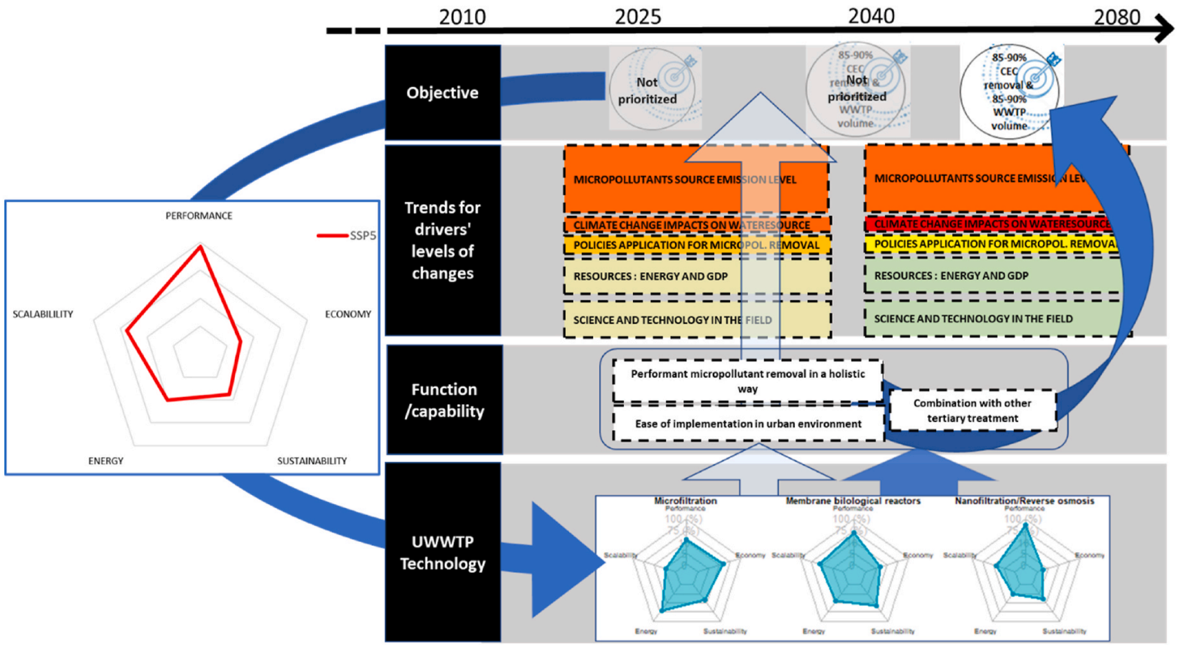

Fig. 9. Strategic routes based on SSP5 derived scenario where the trends and driver are represented by colours palette scaling from green (good) to red(bad) to reflect the given drivers' condition.

see effects by 2027. Currently, the required radical changes in these multiple drivers seem unlikely to occur swiftly. In the other SSP-derived strategic routes, reaching the EU commission-defined targets for good chemical and ecological status would require two or more RBMP cycles. Then, the EU agenda aiming for CEC removal appears as a compromised realistic objective before the 2040 horizon without any breakthrough event (either a technological or societal crisis event instigating drastic changes).

- *Technological performance of CEC removal.* Even though microfiltration and membrane biological reactors (MBR) are technological upgrades transversally selected in all presented strategic routes, they are not the most efficient in terms of CEC removal. Indeed, the microfiltration category, englobing micro- and ultrafiltration here, is inefficient toward organic micropollutants CEC, though it reduces well CEC belonging to highly relevant contaminant categories such as microorganisms (such as antibiotic-resistant bacteria) or suspended solids (e.g. microplastics). The MBR performs overall equally well for the different types of CEC categories (organic, particle and microorganism compounds), but is not the most efficient removal technology in any of the single categories (Fig. 3). However, microfiltration and MBR were selected over technologies that remove micropollutants better (nanofiltration/reverse osmosis, activated carbon, or ozonation) for being more balanced with other dimensions (with respect to scenario constraints and offering appropriate scaling capacity). At present, no existing technological upgrade offers an ideal solution for the different drivers shaping investment decision-making. Moreover, the efficiency of CEC removal is not optimal in terms of energy consumption or cost due to the need for space (at this stage of their maturity levels) for existing technological tertiary and advanced treatment upgrades. This stresses the need for improved WWTP technologies toward these critical dimensions.
- *Stress on water resource quantity.* A common challenge for any of the scenarios, regardless of the social aspect, is the quantitative aspect of the water resource, which, due to climate change impact projections, will become further at risk in the near future in addition to present-day water scarcity. The stress on the volume of water resources directly impacts the dilution capacity of the river surface water bodies (Abily et al., 2021). Thus, to categorize a surface water body as having a "good" chemical status, an even higher level of CEC removal performance in highly affected EU regions would be required, in order to compensate for the dilution capacity reduction of the surface water bodies and to comply with the acceptable CEC concentration threshold.

4.2. From obstacles to key opportunities

- *Combining several tertiary and advanced technology upgrade solutions in treatment trains.* Treatment trains can provide a higher level of performance for CEC removal, addressing a more diverse set of contaminants and with cumulative removal rates. This well-known approach is also suitable to provide solutions for addressing multiple contamination issues with diverse characteristics where individual technologies fail. The investment costs, though higher, would potentially provide a return value in terms of treatment performance and energetic synergies with processes optimisation. This stresses the need to further study and plan multi-barrier upgrades and investment and adaptation pathway enterprises (Mendoza et al., 2018). Furthermore, current R&D trend is investigating upgrades options under the form of hybrid treatment systems, which merges technologies aiming to build up synergies effects that enhance efficient micropollutants removal (e.g., MBR combination with advanced oxidation, electrochemical, or activated carbon filtration processes) (Keller et al., 2021; Liu et al., 2022). Hybridisation or a combination of the technologies could accelerate the achievement of CEC removal goals. They would provide an effective technical solution, more balanced toward the different dimensions, independently of the SSP. Uptake of combined or hybrid solutions require a SSP that favour innovation.
- *Closing the loop inside the wastewater treatment plant.* Industrial processes' current and future development and optimisation will help to improve the overall sustainability dimension of the wastewater treatment industry, notably by developing internal recovery solutions in terms of energy, water, and sludges (Neczaj and Grosser, 2018). In such a context, the upgrades in WWTP treatment trains tackling the CEC removal problem can be favoured by the circular economy concept implementation. Indeed, the significance of the energy, economy and sustainability dimensions of the upgrades

would become minor in such a scenario, independently from the SSP. As such, the strategic routes would be shifted, favouring the CEC removal performance dimension for a sustainable pathway. This stresses the urgent need for the wastewater utility industrial sector to target net-zero in terms of GHG emissions, as well as water and energy footprints.

- *Water reuse in urban environments.* The EU has recently pushed forward the legal framework for water reuse in agricultural irrigation via the "Regulation EU-2020/741 Minimum Requirements for Water Reuse" (European Commission, 2020). Barriers and opportunities for implementation remain Members State-dependent based on the local context and perceptions of water reuse (Mesa-Pérez and Berbel, 2020). However, with respect to WWTP upgrade economic and sustainable dimensions addressing, the need to strengthen further water reuse in the EU is key. The legal framework and societal acceptance in the EU for potable water reuse already developed in other regions (Angelakis and Gikas, 2014. Singapore Public Utilities Board, 2002) shall be swiftly developed. Indeed, the CEC removal, as well as the water scarcity in the future scenario, shall be seen as an opportunity for evolution: even though technological upgrades are costly in terms of energy and economical investment, the overall cost for society is reduced if WWTP and drinking water supply are part of the same processes. When advanced technologies are applied to remediate CEC from wastewater, some could raise toxicity levels due to intermediate or by-products. The sustainable dimension (which encompasses among others the use of green chemistry, the limitation of undesirable waste production including by-products) becomes even more key for the reuse context.
- *Technological development of NBS.* These green technologies were identified as the most sustainable treatment solutions. However, their current technology readiness level hinders their effective deployment to date. Hence, if these promising technologies were to be used at a large-scale and in a timeframe that matches the European Union's expectations, swift and extensive efforts would be required to increase their efficiency. Existing research works aims to improve both space occupation and performance in cold climate, focusing on optimal design and operation of wetland treatment systems for performance intensification, such as the presence of plant, operational mode, effluent recirculation, artificial aeration and in-series design (Wang et al., 2017). On top of that, investment in research and development, via biotech development in these technologies, could allow for better performance to specifically tackle CEC elimination.

5. Conclusions

Through a strategic foresight exercise, this study conducted a screening and ranking of technological upgrades for WWTPs, specifically focusing on advanced treatment of contaminants of emerging concern (CECs) within the context of the Shared Socioeconomic Pathways (SSPs) narratives. The analysis primarily revolved around interpreting the SSPs narratives within the EU region, subsequently developing roadmaps and strategic approaches to guide WWTP upgrades aimed at meeting CEC removal objectives aligned with the European Commission's agenda.

The strategic routes identified through this exercise were instrumental in identifying and addressing key challenges associated with the CEC removal agenda, technology performance, and requirements. In light of the interpreted strategic roadmaps, the following insights emerged, irrespective of the specific SSP-derived scenarios considered:

1. Achieving EU water quality goals related to CECs is unlikely to occur before 2040.
2. To mitigate the potential negative impacts of WWTP upgrades on economic, energy, sustainability, and scalability aspects, circular economy solutions should be strengthened.
3. Enhancing the technology readiness level of nature-based solutions in terms of performance and reducing the side effects of more advanced technologies on other dimensions will be crucial.
4. Combining multiple tertiary and advanced technology upgrade solutions in treatment trains will be essential for maximizing CEC removal performance while addressing potential flaws in the selected technological solutions related to economy, energy, sustainability, and scalability.

In summary, the strategic interpretation of the SSP scenarios promotes innovation and can potentially expedite the achievement of CEC removal goals.

CRediT authorship contribution statement

Morgan Abily: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Vicenç Acuña:** Conceptualization, Formal analysis. **Lluís Corominas:** Conceptualization, Formal analysis, Supervision. **Ignasi Rodríguez-Roda:** Conceptualization, Formal analysis. **Wolfgang Gernjak:** Conceptualization, Validation, Supervision, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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