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Research article

Method selection for sustainability assessments: The case of recovery of resources from waste water

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A B S T R A C T

Sustainability assessments provide scientific support in decision procedures towards sustainable solutions. However, in order to contribute in identifying and choosing sustainable solutions, the sustainability assessment has to fit the decision context. Two complicating factors exist. First, different stakeholders tend to have different views on what a sustainability assessment should encompass. Second, a plethora of sustainability assessment methods exist, due to the multi-dimensional characteristic of the concept. Different methods provide other representations of sustainability. Based on a literature review, we present a protocol to facilitate method selection together with stakeholders. The protocol guides the exploration of i) the decision context, ii) the different views of stakeholders and iii) the selection of pertinent assessment methods. In addition, we present an online tool for method selection. This tool identifies assessment methods that meet the specifications obtained with the protocol, and currently contains characteristics of 30 sustainability assessment methods. The utility of the protocol and the tool are tested in a case study on the recovery of resources from domestic waste water. In several iterations, a combination of methods was selected, followed by execution of the selected sustainability assessment methods. The assessment results can be used in the first phase of the decision procedure that leads to a strategic choice for sustainable resource recovery from waste water in the Netherlands.

1. Introduction

Transition towards a circular economy has been proposed as one of the solutions for a future that supports the growing world population and welfare per capita within the environmental and social boundaries of our planet (Ellen MacArthur Foundation, 2013). Initiatives towards realizing a circular economy can be found from global to local levels (Bocken et al., 2016; European Commission, 2016; Geng et al., 2013; Linder and Williander, 2015; Ministerie van Infrastructuur en Milieu, 2016; Municipality Utrecht, 2015; UN, 2015). The transition process needs be supported by insights from different disciplines with respect to the economic, environmental and social costs and benefits, amongst which trade-offs may occur. In addition, decision makers have to deal with uncertainties and unknowns that are characteristic of investing in new business models (Linder and Williander, 2015), and with different stakeholders views on the current situation, the desired solution and on what sustainable choices should encompass (Zijp et al., 2015). The selection of sustainable solutions for a resource-efficient economy is a wicked problem *sensu* Rittel and Webber (1973).

An example of the need for such strategic choices in the realms of circularity is the recovery of resources from domestic waste water. We selected this as a case study to design and test an approach to support decision making with a sustainability assessment. We applied a solution focused sustainability assessment

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framework (Zijp et al., 2016), with specific focus on the translation of the sustainability question and its context into sustainability analysis methods selection (Zijp et al., 2015).

Currently, the use of waste water flows as a potentially valuable resource are evaluated in various pilot projects in the Netherlands and elsewhere. In order to invest in full-scale operations, water system managers need to make strategic choices. The choices involve technical issues (e.g. different solutions for resource recovery from waste streams are possible but can be mutually exclusive), political issues (e.g. the focus on climate change draws organizations towards low-energy cost solutions without considering the biomass value pyramid (Gavrilescu, 2014)), many unknowns (e.g. what will be the future quality of waste water) and many stakeholders.

A sustainability assessment (SA) provides scientific support in the decision making for selecting amongst competing sustainability-enhancing technologies. Its outcomes can be utilized in a decision-making process that is solution focused, participative, iterative and transparent in its definition of sustainability (Zijp et al., 2016). However, many SA methods can be utilized and the question arises: which (set of) SA methods is most suitable for the evaluation of a specific situation? In practice, assessment methods are often selected by an expert, with poor question articulation and with limited inclusion of stakeholders' views on sustainability (Zijp et al., 2015). This approach can lead results that are incomplete in their coverage of the sustainability metrics of relevance, and may furthermore not be supported by the stakeholders and decision makers, so that they are consequently of limited practical influence in the decision context.

In order to support the consistency and utility of SA, Zijp et al. (2015) proposed the idea of a sustainability assessment identification key, to identify case-specific requirements for a SA and use these requirements to make selections amongst the available SA methods. The key supports a transparent and well-considered choice for an SA method or combination of methods. Furthermore, it specifies what can and cannot be expected from the assessment. Since its publication, the proposed SA-methods identification key has been applied to studies that report transparently on method selection (e.g., Moreira et al. (2015)), but not yet in its inverse application: to first determine the specifications of a transition plan, and then select a method. This process, of setting the requirements for an SA, is further referred to as 'question articulation'. Ideally, question articulation is performed together with the stakeholders (Harder, 2015). Firstly, because every stakeholder can

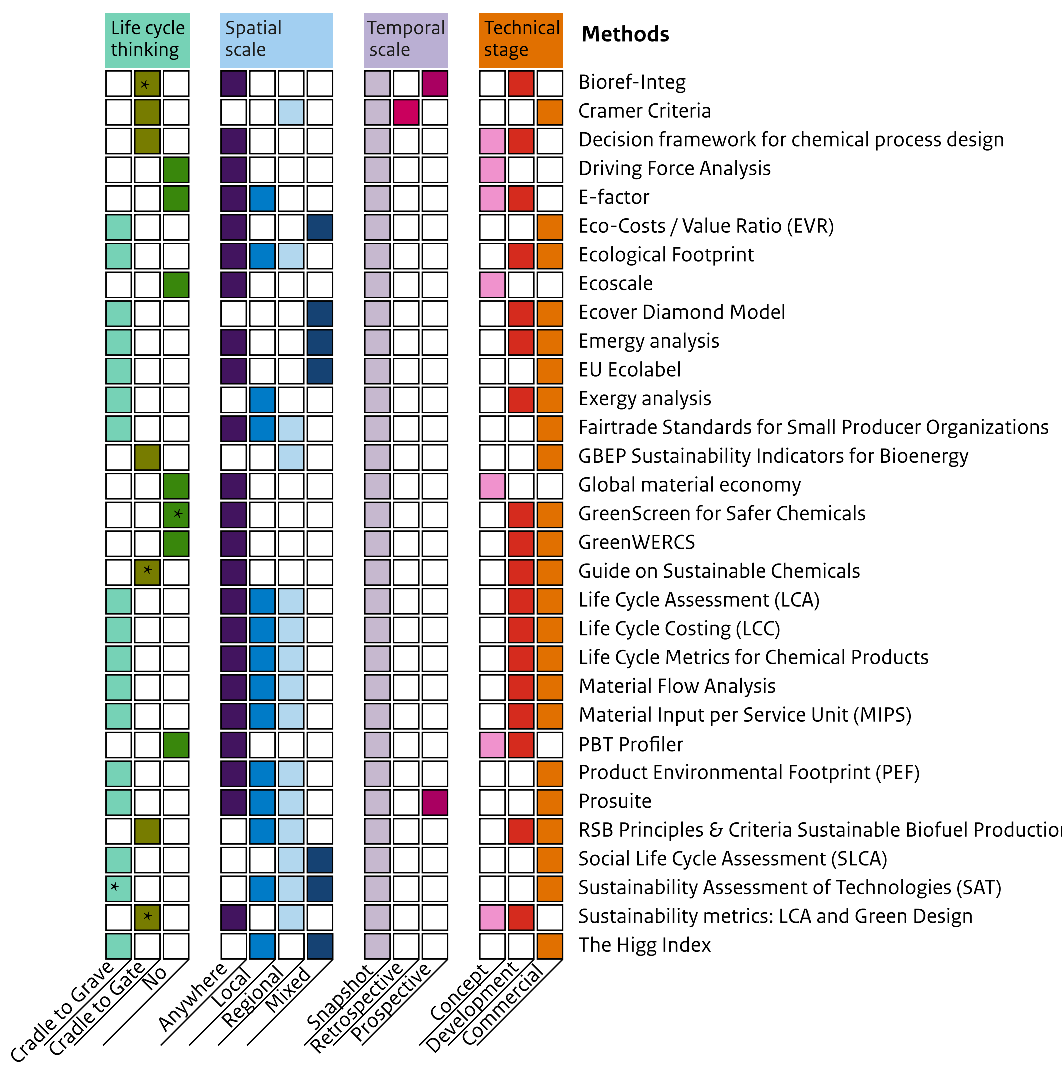

Fig. 1. Overview of the system boundaries of the methods collated in the review of this study; for references of the methods see SI, Table S5. The asterisk (*) shows that for this method life cycle perspective is taken into account for part of the themes (Bioref-Integ and Guide on Sustainable Chemicals only qualitative; Greenscreen only for the theme "Biodegradation"; SAT only for the themes "Climate Change" and "Economic Performance"; Sustainability metrics only for the theme "Energy efficiency").

contribute to the question articulation with knowledge on potential problems and solutions from a diversity of points of view (Zijp et al., 2016); and secondly, because transparent and participative processes enhance the trust in the outcomes and in the choices based on the outcomes (Lind et al., 1990; Lind and Tyler, 1988; Tyler and Lind, 1992).

In practice, operating the SA identification key for use in a process of finding solutions for wicked problems requires insight in what is required (the demand), knowledge on which methods are available to choose from (the supply) and a procedure to select the most suitable (combination of) available methods based on the question articulation and the inventory of available methods. This paper reviews a non-limitative set of existing SA-methods, and thereupon provides a transparent way to select a method for sustainability assessment from those, based on participative question articulation, in the context of its case-specific decision process.

In detail, the aims are to:

1) Provide a protocol for sustainability question articulation (the demand-side of method selection);
2) Review available sustainability assessment methods for products (the supply-side of method selection)
3) Provide a tool that matches the demand- and supply side of method selection; and
4) Evaluate and illustrate the applicability of the protocol and the tool to the early strategic decision stage of a wicked problem case study: the recovery of resources from waste water in the Netherlands.

Focus is mainly on environmental aspects of sustainable development.

This paper is structured as follows: in section 2 the approach to draft the protocol (§2.1), perform the review and design the tool (§2.2) are explained, and the case study is introduced (§2.3). Then, in section 3, the results are described: first the protocol (§3.1), then the results of the review of SA methods and the tool in which the review results are translated (§3.2) and finally the results of applying the protocol and the tool on the case study (§3.3), including the actual sustainability assessment. The discussion on the approach, the case study results and the meaning of the results for application of the protocol and tool in other studies are presented in section 4. Finally, main conclusions are summarized in section 5.

2. Research approach

A protocol (§2.1) and a tool (§2.2) for question articulation and method selection were developed, based on a review of currently available SA methods and participation approaches. The applicability of the protocol and tool was tested in a case study (§2.3). The Supporting Information defines the terms used in this paper, acknowledging that different literature sources use different terminologies for similar matters.

2.1. Protocol for question articulation

The goal of the protocol is to help specifying the sustainability question(s) and the(ir) context such that the transition problem can be translated into sustainability metrics that should be part of the SA. The protocol supports the systematic exploration of the problem definition and its solution scenarios, and merges the possible diversity of inputs from different stakeholders into requirements

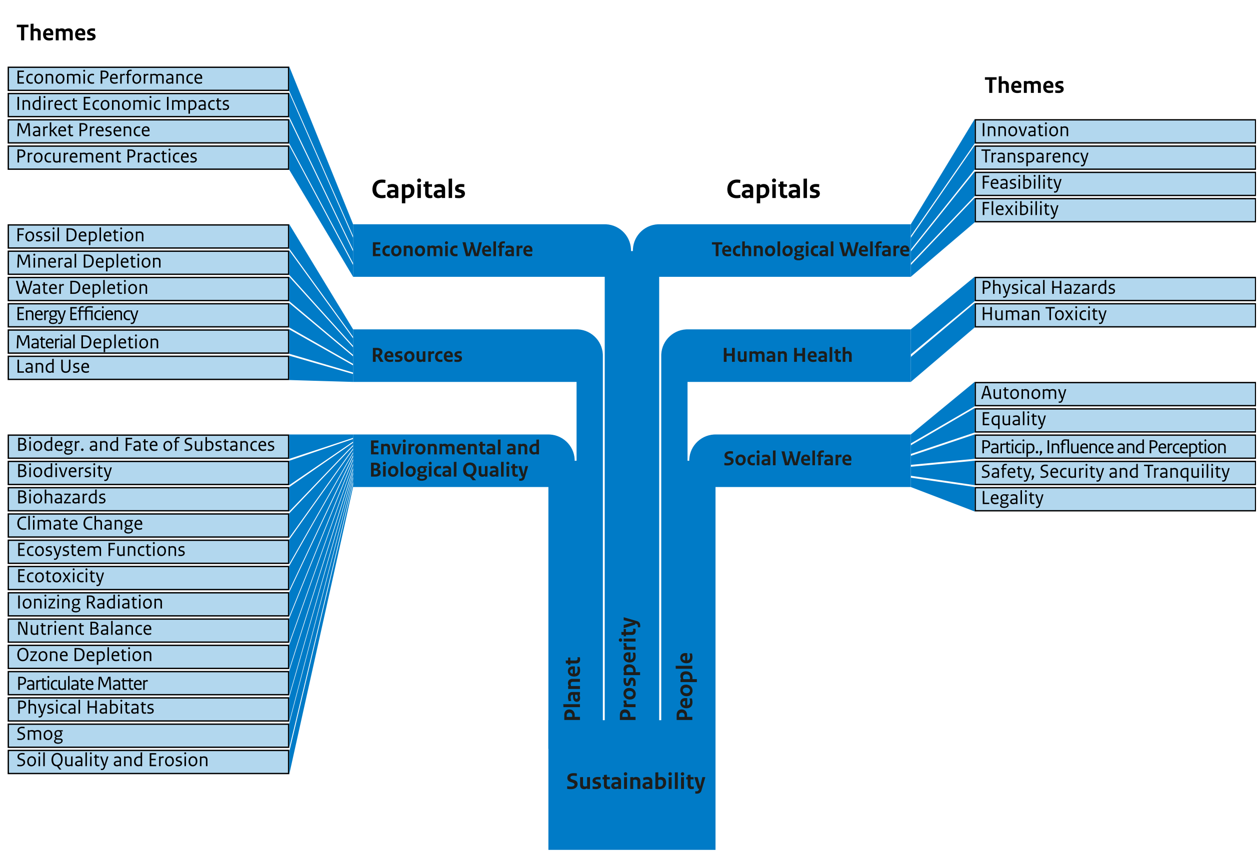

Fig. 2. Overview of the capitals (areas of protection) and themes distinguished by the different methods.

for the method selection. For example, the protocol helps to sub-select pertinent themes (such as climate change, economic performance and social equality, Fig. 2), as sustainability assessments do not have to include all themes of sustainability (Laniak et al., 2013). In complex situations this may be an iterative process, involving different groups of stakeholders, e.g. first with the internal stakeholders that are involved in the design of solution scenarios and then with external stakeholders. The protocol was aligned with approaches described in the literature on stakeholder participation, such as https://www.irgc.org/stakeholder (visited 02-11-2016), and expertise of the authors on transparent decision making.

2.2. Tool with available sustainability assessment methods

The goal of the SA-method selection tool is to transparently translate the question articulation provided by the protocol into a selection of methods pertinent to the question.

The tool was designed by making a database of existing SA methods. An inventory of available sustainability assessment methods was drafted based on expertise within the consortium, an iterative search in google scholar using the keywords: "Sustainability assessment" AND "Products" AND/OR "Tool", AND/OR "Method", AND/OR "Methodology", AND/OR "Approach" and input from a group of experts in the field of sustainability assessments. Methods were selected that:

- assess either products or feedstock (thus excluding methods that assess the sustainability of organizations, such as the Dow Jones Sustainability Index); or
- are applied at least once; and
- are transparently described in accessible sources.

This approach was meant to result in a non-limitative overview of methods that are available for practical application. Hence, this overview (and the tool) can be expanded.

The selected methods were analyzed and categorized using the sustainability assessment method selection criteria found in literature and reported in Zijp et al. (2015). It was scored, for example, which themes are covered by one or more of the indicators of a method, and what spatial and temporal scales covered by the method are? The list of criteria and their definitions are reported in the supporting information, Table S1.

The tool was designed such that it links the specifications of the question articulation (protocol) with the criteria of the reviewed methods. The protocol and tool can be combined or used standalone, depending on the expertise and problem at hand.

There may not always be a particular method available to fit the question. Therefore, like the protocol, the tool supports an iterative working process, changing the method requirements until a 'best method available selection' can be made. Although presentation of the SA-results, e.g. by aggregation of various indicators in an overall score of each solutions, is an important aspect of method selection (Brewer and Stern, 2005; Laniak et al., 2013; Özdemir et al., 2011; Zijp et al., 2015), it was not made part of the protocol and tool.

2.3. The case study

A case study was performed to evaluate and illustrate the utility of the protocol and tool for assessing sustainability in an early stage decision context. The case concerns the opportunities for recovery of resources from waste water, evaluated by the Energy and Resource Factory (ERF). ERF is a consortium of Dutch water boards' innovation and sustainable development strategists. It explores solutions to treat domestic waste water as a resource instead of a waste-stream.

Presently, various solutions to extract resources from waste water are operational at different water boards in the Netherlands (STOWA, 2016). Only the recovery of energy has reached a matured implementation stage and has full-scale applications. Upscaling of pilot installations for the recovery of other resources to full-scale operations requires significant investments. Also, different solutions for resource recovery can be mutually exclusive. Alternative options imply different types and magnitudes of impacts across different SA themes. Therefore, strategic choices have to be made on the combination of recovered resources that yield the best sustainability performance. This case study is an early-stage exploration of the potential sustainability aspects of different strategies to recover resources from domestic waste water. That is, the assessment should support the first iteration of the decision procedure towards strategic choices for large investments: how to interpret and obtain sustainable development and what are the differences between the resource recovery and utilization pathways from a sustainable development point of view?

The following five waste water resource recovery and utilization options are considered in this study and are presently under investigation and/or in operation by ERF water boards:

- Alginate is a substance that is available in algae and seaweeds, but can also be produced by bacteria. Alginate is used by various industries for its adhesive qualities.
- Biogas is currently produced from sludge in waste water treatment processes as an energy resource. It is included in this study as comparison to the new resource recovery solutions.
- Cellulose are fibers, mainly from toilet paper, that can be recovered from the waste water and reused in several applications, of which we include fermentation (biogas), pellets for incineration to produce bioenergy, replacement of cellulose in construction (asphalt, concrete, isolation) and application in the production of carton and paper.
- Polyhydroxyalkanoate (PHA) is a polymer that can serve as basis for bioplastic products. It can be produced by feeding sludge biomass fatty acids that can be extracted from waste water.
- Phosphorus is a nutrient that can be recovered from waste water as struvite (at the waste water treatment plant, WWTP, which is further referred to as decentral) or as phosphor (after incineration of the sludge, which we will refer to as central) and used as fertilizer.

A general flowchart of a waste water treatment plant (WWTP) detailing process steps at which the above resources can potentially be recovered is provided in Fig. S2.

3. Results

3.1. Protocol for question articulation

The protocol developed for question articulation (SI Table S3) consists of three parts.

The first part explores the context in which the participants of the SA-process operate and whether (and how) sustainable development can be related to this context. For example: what are the major challenges the company faces. Different internal and external stakeholders are requested to provide their views on what the challenges are and these views are then clustered by the participants (and with that discussed). The resulting overview of challenges is then discussed in the light of sustainable development goals. This first step is important because i) it provides the context of the SA from different perspectives; ii) it reveals the relation of the SA with the actual working process of the whole system of participants; iii) it provides insight for all participants in each of the stakeholders' view on sustainable development, which, in return, leads to improved understanding of each other's input in the process; and iv) it creates insight in what is expected of the SA, in the format of eventual decision-support information. The process was developed such that interaction between the participants is stimulated, while securing individual input from every participant.

The second part of the protocol is the question articulation and consists of a series of questions to specify the sustainability question such that method selection can be transparent and based on the stakeholder preferences (SI Table S4). During this phase participants discuss what they think is important and motivate why it is important.

The third part of the protocol is the discussion of the question-articulation based steps towards method selection and the design of the further process. The resulting action plan documents the actions required to start the sustainability assessment. This can be for example a flow chart of the data that needs to be gathered, an iteration of the question articulation with other stakeholders, or a more detailed exploration of a selection of methods.

3.2. Tool for method selection

The review search for available SA methods resulted in 30 methods (Fig. 1) that fitted the search profile (§2.2). Although non-limitative, the list provides an overview on the diversity in methods that are available. The results of reshaping the method analysis results into the design of an operational SA-methods selection tool are summarized below. It should be noted that the results below are observations and not assessments. For example, the fact that method A covers more themes than method B does not make method A better than B. The final goal of the tool is to match SA-questions to available (combinations of) method(s), and not to rank or validate methods. Evidently, identified methods should be scrutinized for quality aspects and validity.

3.2.1. System boundaries covered by the methods

The methods differ in their system boundaries (Fig. 1). Of the 30 methods, 18 methods apply life cycle thinking on all themes covered by the method, either cradle to gate or cradle to grave. Five methods hold a combination of themes that are, or are not assessed with life cycle thinking. The other seven methods do not take life cycle thinking into account. The spatial focus of the methods ranges from anywhere (generic metrics and data are used) to local (assessment of a site-specific situation). Again, within methods the spatial focus can differ between themes. Furthermore, methods that include life cycle thinking often use a combination of site-specific data (foreground data) and regional-average and/or generic data (background data). This is common practice in life cycle assessments (EC-JRC, 2010). With regard to the temporal focus, we observed that although most methods could be suitable for a retrospective or prospective analysis, the default settings and primary use are snapshots. That is: the assessment is based on data and knowledge from a recent time-lock (Harder, 2015). Two methods are explicitly designed to look forward (prospective). Finally, methods are available for all technical development- and implementation stages, with relatively the lowest coverage for the development stage.

3.2.2. Themes covered by the methods

Methods differ in their coverage of sustainability themes. Furthermore, different methods use different names for comparable themes. In order to provide an overview of theme coverage and to make this applicable for the method selection tool, we harmonized and structured the themes. The themes covered by the methods were arranged under six 'areas of protection', so called capitals: economic welfare, environmental and biological quality, human health, social welfare, resources and technological welfare. The choice for these capitals was based on existing frameworks (Blok et al., 2013; UN, 2015) and expert judgment (see for definitions Table S2 in the SI). Several qualifications (e.g. transparency of the assessed techniques) were encountered in SA methods that could not be linked to the capitals, yet such meta-information can be valuable to judge. These themes were grouped under the capital Technological Welfare. Based on the literature, we distinguish the following themes within Technological welfare: innovation (the potential of an innovation to open up new markets and product applications can in some situations be an argument to accept uncertainties in its long term environmental benefits, economic gain and human health improvements); transparency (is the solution and its assessment transparent, are participants willing to share information about the technology under investigation); feasibility (what happens when a solution is introduced at large scale: are enough feedstocks available); and flexibility (can the solution be adapted, e.g. replacement of resources). The themes covered per Capital are visualized in Fig. 2.

The capitals Environmental and Biological quality, Resources and Human Health are represented in most of the methods (~75%), whereas the other capitals are less covered, with the lowest coverage for the capital Technical Welfare (3 of the 30 methods, Fig. S1 in the SI). Two of the methods cover all capitals, while five methods focus on only one capital. An overview of the themes covered per method can be found at www.sustainabilitymethod.com (last visited at 21-02-2017).

3.2.3. Online version of tool

A tool for supporting utilization of the collated knowledge on method characteristics was designed in the format of a decision tree, based on the protocol steps, and implemented on a website (www.sustainabilitymethod.com). The tool works with filters for the system boundaries and scores for the theme coverage. That is, the required system boundaries and themes can be chosen in the tool as selection-relevant criteria. The use of the tool results in an overview of the possible (set of) method(s) that fit the selected requisites of a case. The selected method(s) need to be checked prior to utilization in the SA, to ascertain that methodological details are fit to address the problem. If not, the identified method is a 'most-similar' methodological approach, on the basis of which a tailored SA can be designed.

3.3. Process aspects of the case study

The case study has been executed with focus on the process steps (the context exploration and the method selection as part of the solution focused SA framework) and on a judgement of the outcomes for the resource recovery scenarios. The protocol was applied in two workshops with members of the water boards. Part one and two (the context and question articulation) were covered in the first workshop, and part three (the method selection and action plan) in the second workshop.

3.4. Context exploration

Evaluation of the context revealed that ERF members are intrinsically motivated to work on recovery of resources from wastewater, because the majority of the members expressed the believe that a circular economy is more sustainable than a linear economy. As an organisation, ERF expressed the hope that an organized sustainability assessment process and analysis can support the process towards a shared vision on the role of the water boards for a circular economy, and in preparing the strategic choices for one or a combination of resources and techniques to focus on. ERF stated that they want sustainable development as leading principle for technical innovations in the future, both in an environmental and in a socio-economic way. That is, environmental in the sense that environmental impacts are reduced compared to the present situation and socio-economic in the sense that the resulting products/techniques have a healthy economic performance in which, further, innovations are stimulated.

3.4.1. Question articulation

The context exploration (SI Table S3) was followed by the question articulation (SI Table S4) and resulted in the following specification of the sustainability question, and thus in requirements for the sustainability assessment (method selection):

- The question focuses on products as object. The focus of the ERF is on products that are based on recovered resources from wastewater and are more sustainable than their alternatives. The goal is not recovery of resources from waste water per se, but a net more sustainable practice.
- The chosen life cycle perspective is from the waste water flow (cradle) to the use (including disposal) of the products that are based on the recovered resource (grave).
- The spatial focus of the SA is national. Thus, the potential of all WWTPs in the Netherlands should be taken into account. The assessment has thus to result in conclusions on the macro level: taking into account actual flows of resources. The life cycle of the products that are based on the recovered resources can contain activities that are outside the Netherlands, such as the production of chemicals that are required for an extraction procedure. These activities are taken into account.
- The temporal focus of the SA is the present. Strategic choices must be taken the coming five years.
- The technical stage of the techniques under consideration range from development to commercial stage, i.e., technology readiness level 3–9 (EC, 2014).
- Finally, the themes that the participants mentioned to be important were: climate change; economic performance; energy efficiency; feasibility; fossil depletion; human toxicity; innovation; land use; legality; material efficiency; mineral depletion; nutrient balance (eutrophication); perception; physical habitat; physical hazards; safety, security and tranquility; salinization; water depletion. The theme perception covers the interests of and barriers for different stakeholders to support and use resources recovered from waste waters (Liang and Van Dijk, 2016). The themes physical hazards, safety and perception are to be understood in relation to the perception on potential microbiological hazards of resources recovered from waste water.

3.4.2. Method selection

Of the 30 existing SA-methods, 10 appeared to fit the system boundaries chosen at the workshops. Of those 10 methods, Prosuite (Blok et al., 2013) covers most of the themes mentioned (12 of the 16 themes, Table 1). One theme mentioned during the workshop, salinization, is not yet part of the overview of themes that was created based on the review (Fig. 2). Although salinization relates to the themes climate change and water depletion, which are the main causes of salinization, the impact of salinization due to emissions, e.g. from WWTPs, is not covered in any of the reviewed methods. Other themes fully overlap. For example: material efficiency is not an explicit theme or, in LCA terms, impact category, but is implicitly taken into account in the assessment: higher material efficiency results in less mineral depletion, fossil resources depletion and emissions (e.g. climate change). This type of indirect coverage of themes by methods is indicated with an 'i' in Table 1.

Prosuite covered most of the selected themes (12 of the 16). However, data for micro-economic analysis as described in Prosuite was not available for most of the solutions for reasons of absence of data and data confidentiality. Furthermore, the weighing applied in Prosuite to aggregate results was not required for this case study.

The resulting set of potentially selected SA methods was evaluated in interaction with the ERF. As a result a combination of methods was chosen for the final SA that was selected: a life cycle assessment approach (LCA, for the themes under Resources, Environmental quality and Human health), a literature review and expert elicitation (for Economic welfare and Social welfare) and an evaluation of the technical readiness level (EC, 2014) (TRL, for Technical welfare). This combination of methods was applied to summarize the sustainability differences between the current practice of WWTPs, including retrieval of biogas, and the alternatives described in section 2.3.

3.5. Sustainability assessment outcomes of the case study

The first goal of the assessment was to gain a general overview

Table 1
The ten methods that fit the system boundary specification of the case study, and their theme coverage chosen by the ERF in the workshop. An x indicates direct coverage; an i indicates that the theme is covered indirectly via an indicator used for another theme in the method.

Method		a	b	c	d	e	f	g	h	j	k
Economic welfare	Economic performance	x			x	x					x
Resources	Energy efficiency	i	i	i	i						
	Fossil depletion	x	x	x	x		x		x		
	Land use	x	x	x	x					x	
	Material efficiency	i	i	i	i		x		x		
	Mineral depletion	x	x	x	x		x				
	Water depletion	x	x	x	x		x				
Environmental and biological quality	Climate change	x	x	x	x	x				x	
	Nutrient balance	x	x	x	x						
	Physical habitat	i	i	i						i	
	Salinization										
Technical welfare	Feasibility										
	Innovation										
Human Health	Human toxicity	x	x	x	x						
Social welfare	Legality					x		x			
	Perception of biological safety	x				x		x			

a = Prosuite; b = Life cycle metrics for chemical products; c = Product environmental footprint; d = Eco-cost value ratio; e = Sustainability assessment of technologies; f = Material input per unit service; g = Social LCA; h = Emergy analysis; j = Ecological footprint; k = Life cycle costing.

Table 2
Results of the sustainability assessment. The economic welfare and social welfare themes are expressed in categories. The higher the score the better the performance of the solution. Market values lower than the range of production costs indicated a negative economic performance (implementation not likely, category 0), market values above the range of production costs indicated a positive performance (most likely, category 3) and overlapping ranges of costs and market values were an indication of possible (category 1) or likely positive economic performance (category 2). The resources, environmental and biological quality and human health themes are expressed in their LCA units and in comparison with the current situation (waste water treatment with biogas production). Hence, a negative value indicates a benefit compared to the reference situation and positive values and vice versa.

Capital	Theme	Struvite Central	Struvite Decentral	PHA	Cellulose Biogas	Cellulose Bioenergy	Cellulose Paper	Cellulose Construction	Alginate
Economic welfare	Economic performance	1	1	1.5	3	3	1	3	3
Resources	Fossil depletion (kg Oil eq.)	$-1.1\cdot10^4$	$-8.2\cdot10^4$	$1.0\cdot10^4$	$-1.7\cdot10^5$	$-1.4\cdot10^5$	$6.3\cdot10^4$	$2.2\cdot10^4$	$-1.5\cdot10^5$
	Land use (m^2)	$-9.0\cdot10^2$	$-1.1\cdot10^4$	$-2.4\cdot10^5$	$-2.5\cdot10^4$	$-1.9\cdot10^4$	$-1.3\cdot10^6$	$-1.3\cdot10^6$	$-1.1\cdot10^4$
	Mineral depletion (kg Fe eq.)	$-8.5\cdot10^2$	$-3.2\cdot10^4$	$2.4\cdot10^3$	$-6.1\cdot10^3$	$-5.6\cdot10^3$	$-1.1\cdot10^4$	$-1.2\cdot10^4$	$-6.0\cdot10^4$
	Water depletion (m^3)	$2.3\cdot10^2$	$-8.5\cdot10^3$	$-1.4\cdot10^4$	$-1.8\cdot10^3$	$-1.6\cdot10^3$	$-6.2\cdot10^3$	$-6.4\cdot10^3$	$-6.2\cdot10^3$
Environmental and biological quality	Climate change (kg CO_2 eq.)	$-3.8\cdot10^4$	$-2.6\cdot10^5$	$-1.2\cdot10^5$	$-5.2\cdot10^5$	$-4.1\cdot10^5$	$9.6\cdot10^4$	$-2.9\cdot10^4$	$-4.5\cdot10^5$
	Nutrient balance (kg P eq.)	$-1.0\cdot10^1$	$-2.1\cdot10^2$	$-1.8\cdot10^2$	$-1.2\cdot10^2$	$-9.3\cdot10^1$	$-3.9\cdot10^2$	$-4.0\cdot10^2$	$-1.4\cdot10^2$
Human Health	Human toxicity (kg 1.4-DB eq.)	$-7.9\cdot10^3$	$-1.8\cdot10^5$	$8.8\cdot10^4$	$-9.7\cdot10^4$	$-7.8\cdot10^4$	$-3.0\cdot10^5$	$-3.2\cdot10^5$	$-2.5\cdot10^5$
Social welfare	Legality	1.1	1.1	0.7	1.0	2.7	0.3	0.7	1.0
	Perception -relevance	1.8	1.8	1.0	1.8	2.8	0.3	2.8	1.5
	Perception -influence on market	2.2	2.2	1.9	2.0	2.8	1.1	2.6	1.7

on how the five potential resource recovery solutions differ in their impact on the selected themes compared to the present situation: are the solutions for a more circular business model more sustainable the present business model? The second goal was to compare the solutions among each other. Which solutions should be considered by the ERF for large scale investments? The results are summarized in Table 2 and discussed below.

3.5.1. Economic welfare

The economic performance was assessed using existing market exploration studies complemented with expert judgment. The exploration of existing studies (references in SI) resulted in insights in expected production costs and market values for the different solutions.

As shown in Table 2, all solutions are potentially economically feasible (scores ≥ 1). Economic performance appeared to depend on the WWTP-specific features. Furthermore, it depends on the temporal scope of the assessment. For example, struvite production is not competitive (the production costs are higher than the market value) on the short term, but when taking into account that its recovery would imply reduction of maintenance of the WWTP in the long term it was expected to be economically neutral. The business case with respect to the economical welfare seemed promising for alginate and most of the cellulose applications. The application of cellulose as source for carton or paper seemed, however, less beneficial due to the costs of an extra hygiene step, which was discussed as a need for this application. For PHA, just like struvite, the business case depends on location-specific aspects, but it appeared promising enough for further investigation.

3.5.2. Resource depletion

The themes fossil depletion, mineral depletion, land use and water depletion were quantified using life cycle assessment (LCA) (Van Nieuwenhuijzen et al., 2016). The life cycle that was studied included the retrieval of resources from waste water, the production of products from those resources and the use and disposal of these products. In order to be able to compare the different solutions, the functional unit for the LCA was set at 100.000 population equivalents of inflow of a medium-consistency type of domestic waste water. The functional unit is consistent with the function of WWTPs: treating domestic waste water. The assessment is aimed to quantify the difference in impacts when implementing the solutions compared to normal operations, i.e. it covers the additional interventions and operational changes. Furthermore, the impacts are calculated compared to the present situation at the WWTPs, including biogas production. Thus, when a solution for recovery of a resource results in less biogas retrieval compared to the present situation this was accounted for in the results. Finally, when a product replaces another product this is accounted for in the LCA, e.g. using struvite instead of another fertilizer. Further details of the LCA were reported in Van Nieuwenhuijzen et al. (2016) and STOWA (2016).

The results show that the novel resource management pathways often resulted in a reduction in the depletion of resources (fossils, minerals, land, water). In more detail, decentral phosphorous recovery results in more reduction of resource depletion than central recovery. PHA production resulted in a slight increase in mineral and fossil depletion, but in less land use and water depletion effects. Cellulose recovery and application in construction and paper industry resulted in extra fossil depletion compared to the current situation, due to an extra preparation step prior to this use in the paper and construction industry. On the other hand, these solutions result in high reductions of mineral depletion, land use and water depletion. Use of cellulose for biogas and bioenergy are solutions at the bottom of the biomass value pyramid (Gavrilescu, 2014). However, they do result in reduced use of fossil fuels. Finally, alginate production shows beneficial results for all resource themes.

3.5.3. Environmental and biological quality

The themes climate change and nutrient balance were assessed using LCA, as described above for Resource depletion. Again, decentral struvite production scores better than central production. The only solution that has higher impacts on environmental quality than the reference situation is the use of recovered cellulose for paper production. This is a result of the energy use for the extra hygiene step that is thought to be required for use in the paper industry. This hygiene step is not required for use of gained cellulose in constructions, which is why that solution scores positive (less impact) compared to the reference situation.

3.5.4. Technical welfare

Feasibility and innovation were assessed using the TRL method, which provides a score to technologies based on expert elicitation. The scores range from 1 (basic principles observed) to 9 (actual system proven in operational environment) (EC, 2014). Details of the assessment can be found in STOWA (2016). At the time of the SA, the solutions were characterized by differences in the technical stage. Recovery of biogas is more or less the standard in present-day waste water treatment, while products from alginate or cellulose are still in a pre-mature stage. Of all solutions, struvite and the use of cellulose for biogas showed the highest technological readiness level, i.e. successful mission operation, and alginate production from waste water the lowest: validation in lab. PHA and cellulose for paper and for construction scored a TRL of 5 (technology validated in relevant environment) and cellulose for bioenergy a TRL of 7 (system prototype demonstration in operational environment). This score is reported separately from the other themes (not in Table 2), because a low technical readiness level is not necessarily a negative feature.

3.5.5. Human health

Human toxicity was assessed using LCA, as described above under Resource depletion. Only PHA production results in emissions of toxic substances to the environment that may cause higher impacts on human health than the emissions in the reference situation.

3.5.6. Social welfare

The impacts of regulation (legality) and risk perception of stakeholders on the safety of resources from waste water on the market chances of the solutions were assessed using expert elicitation, following the guidelines provided by Gaasbeek and Meijer (2013) (for detailed information see SI). Next to market influence, the relevance of risk perception was assessed compared to perception of the market on the supply security, on the costs and on the sustainability of the solution. According to the experts, risk perception is less important than the other issues for struvite and application of cellulose for biogas, bioenergy and in construction. For the other solutions, risk perception was equally important (PHA and Alginate) or more important (application of cellulose in paper and carton industry) than the perception of the market on the supply security, on the costs and on the sustainability of the solution. In general, risk perception is seen by the experts as a problem that can be solved on the short term. One product can pave the way for other products, as long as there are no large incidents or calamities. It was further noted that not everybody has to feel comfortable with the products to be successful. A relatively small group of customers might be enough for a successful circular solution. There is an exception for the paper industry using waste water resources. This relates to a negative risk perception (hygienic aspects) and because experts estimate the volume of this route to be too low for practical large-scale application. Legality is interpreted as the legally attributed status of the resources, that is: whether it is formally assigned to be either a waste or a product. This assignment is considered to present a serious challenge for the success of resource use, which needs to be solved in order to become successful. Legality scores more or less alike for all solutions, except for bioenergy from cellulose. The other solutions require a change in status from waste to resource, which was remarked to be preferably accepted at an international level (e.g., the EU) in order to support a successful implementation. More details on the expert elicitation and its results can be found in the supporting information.

3.5.7. Overall results

All analyses steps resulted in the classified outcome scales, but were also characterized by uncertainty (not shown). This is partly a result of the intrinsic uncertainty in the applied methods, but merely due to the premature development and application phase for most of the solutions which inhibits an accurate estimation (Van Nieuwenhuijzen et al., 2016). This is typical for a SA in an early stage of scenario definition and evaluation. Nonetheless, the SA outcomes were considered by the ERF to be useful in the decision making procedure as follows. First, the recovery of resources from waste water indeed appeared to lead to a reductions in environmental impacts and resource depletion. Secondly, it was shown that there is not one solution that scores best on all selected themes. Hence, choices will require evaluation of trade-offs and weighing of the results. Thirdly, based on the results, one of the solutions, paper or carton from cellulose, could be decided to be left out of further assessments and technological development, because implementation would be prohibited in relation to negative safety perceptions of the paper industry towards the product (safety and volume). Finally, continuing the decision procedure for an investment in one or a combination of resources requires a new iteration with the protocol, including stakeholders in the method selection process. The SA can then be broadened by analyzing WWTP-specific possible combinations of resource recovery (De Fooij, 2015; Van Nieuwenhuijzen et al., 2016) and take into account actual yield estimates at the different WWTP in the Netherlands (Van Nieuwenhuijzen et al., 2016).

4. Discussion

Wicked problems – complex societal problems with multiple types of impacts to be considered, multiple perceptions on the problem and its optional solutions (Rittel and Webber, 1973) – ask for assessment approaches that transcend the classical risk assessment approaches. The latter often focuses on a single aspect of a problem, the reduction of which is used as target, while the transition towards a circular economy requires multi-metric sustainability assessments. Although sustainability is not a new concept and many sustainability assessment methods exist, there is room for improving the contribution of these assessments to decision making (Benson, 2003; Kates et al., 2001; Little et al., 2016; Sala et al., 2013).

The protocol and the tool discussed in this manuscript facilitate a process that increases the value, transparency and reproducibility of sustainability assessments in decisions aimed at improved sustainability of alternative management strategies. Although there are often unknowns and the assessment can only provide the knowledge available to serve as one of the ingredients in decision making (Harder, 2015), its contribution to the decision making can be optimized with a process that is characterized by four elements:

1) Participation: the protocol makes it possible to select methods based on what is defined to be important by the different stakeholders, based on their expertise in disparate and often widely varying disciplines. This participation of stakeholders supports the scientific analyses of sustainability-relevant metrics by gathering all ideas of possible relevance and supports the decision process by gaining support for the assessment results.
2) Decision support: the method selection is discussed with the decisions that have to be made in mind, and with the stakeholders that play a role in these decisions.
3) Iteration: finding and deciding on solutions for wicked problems is characterized by adaptive management; the protocol (and the tool as well) can easily be used in an iterative way, transparently adjusting method selection and design based on new insights, e.g. from new stakeholders or knowledge.
4) Transparency: the protocol provides transparency in both the process of method selection as well as in what can be expected from an assessment (and what not).

The protocol and tool are flexible in design, which enables broader use. For example, aggregation across themes is not part of the protocol and the tool yet. If needed, aggregation of results from different sustainability metrics can be made by implementing value choices, which should in such cases be made transparent and explored in dialogue as well (Gasparatos and Scolobig, 2012; Özdemir et al., 2011).

The approaches that were proposed here have been applied in an example case study. The case study described a first iteration of the protocol with members of the ERF. The participants mentioned that the context evaluation provided a broad view on the situation, while the second phase, the question articulation, was structured such that it narrowed down to choices for themes and system boundaries, which were deemed necessary for method selection. The case study did not include participation of other stakeholders than the ERF members. However, the context evaluation resulted in the participants recognizing the importance to involve stakeholders in the process towards the SA and the interpretation of its results. This sequence, first with the internal organization, then an iteration with stakeholders, might be an effective working order in other case studies as well. Either for reasons of effort (as try-out) or to determine the point of view of the own organization before a discussion with external stakeholders is organized. External stakeholders identified during the context evaluation were the customers for the resources to be extracted, the government that decides on the juridical approval of the resource re-use and their use in new products and citizens, in order to check and act on citizen's perceptions of new products based on resources extracted from wastewater. The application of the protocol in the waste water case study revealed that the systematic approach towards context analysis and question articulation improved the quality and relevance of the items discussed on- and specified for the SA. As a result, next to the method selection, application of the protocol provided insight in the purpose of the assessments and in who are expected to act on the SA results in decision-making.

The tool, which was based on the review of existing SA methods, resulted in the identification of 30 currently available methods. This set can easily be supplemented with other methods. The scopes of the methods appeared to be unequal, which corroborates that method selection is a step that matters, i.e. it influences the assessment outcomes and thus decisions based on the outcome (Zijp et al., 2015). On the other hand, some of the methods have a comparable basis or overlap. For example, the Ecocost Value Ratio is in fact a combination of LCA, monetization methods and product costs. Some methods combine indicators with different scopes. For example, environmental impacts are covered at the whole life cycle of a product and social impacts only at the production stage. This is not necessarily wrong, but it should be transparently communicated when choosing to apply such methods. In the tool, this was operationalized with notifications during method selection. Regarding the sustainability themes, next to the well-known themes that fit within the areas of protection people, planet and prosperity, we found that technical issues are important to be additionally taken into consideration when deciding on alternative sustainable solution options and thus should be considered when designing a SA that supports these decisions. The review and the selection of methods in the tool was not extensive, but revealed the variability within the field of sustainability assessment methods for products. The tool was designed such that other methods can easily be added in the future, for example assessment methods that focus on other objects such as organizations. Also other system boundaries and themes may be added.

The case study showed that the protocol and the tool supported a thorough, transparent, case specific question articulation and method selection, which required iterations between ‘demand’ (the question) and ‘supply’ (the method and data availability). The selected methods were applied as first iteration in the process towards a strategic decision on which resources to focus on. The SA revealed, amongst others, that there is not one solution that scores best on all aspects that were defined to be important. Also, the solutions differed in their technical readiness level and thus in the information availability and with that the certainty of the derived scores. Hence, the decision for one or more of the solutions will have to involve weighing of different themes. The SA results showed that all solutions appeared to be beneficial for environmental quality and reduced resource depletion, compared to the business as usual scenario (Van Nieuwenhuijzen et al., 2016). Furthermore, one of the solutions seems unrealistic, given its chances in- and the identified perception of the market, and for this reason can be decided to be left out of further decision steps. In a next iteration, the stakeholders that were distinguished during the process can be invited to participate in the discussions on how to assess the different solutions. Also, the SA could be broadened by analyzing possible combinations of resource recovery (De Fooij, 2015; Van Nieuwenhuijzen et al., 2016) and taking into account actual yield estimates at the different WWTP's in the Netherlands (Van Nieuwenhuijzen et al., 2016).

The application resulted in three general lessons for method selection. First, there was not one existing method that fitted all the requirements that were made explicit by the ERF. Hence, a combination of methods was required for the assessment. This will often be the case. Secondly, method selection appeared to require an iterative process. In the case study, the method selected was not fully applicable due to limited data availability and therefore, after consideration between the SA experts that performed the assessment and the ERF, that part of the method was replaced by another approach. Thus, after a method is selected that fits the question articulation, other elements of method selection, e.g. data availability, software availability and costs of the assessment, need be explored in order to check if the method can be applied. This can lead to adjustment of the method (this case study) or the selection of another method. Finally, the application of the protocol and tool presented in this manuscript revealed the important role of scientists and sustainability experts. Their role is larger than the technical role of performing the sustainability assessment. Firstly, based on knowledge and experience in the field of sustainable development they can contribute in the discussion on what is important to include, as one of the stakeholders. They have to guard that the method selection is not arbitrary, but aligned with the state of the art knowledge with regard to sustainable development. Secondly, the specification can lead to a list of selected sustainability themes that partly overlap. The expert can propose a coherent set of themes based on the input of the question articulation. Thirdly, when the list of possible (combinations of) methods are derived the expert can propose which combination suits best, given the organizational restrictions such as data availability. Finally, experts can take the initiative at every opportunity by questioning the question and apply, evaluate and improve the approaches provided in this manuscript.

5. Conclusions

Existing efforts towards designing and implementing circular economy principles demonstrate the urgent needs to expand mono-univariate risk prevention approaches aimed at risk prevention and reduction to multi-metric sustainable-development approaches aimed at swift sustainability improvements, both in science as well as in (decision-support) practice (Zijp et al., 2016). This need is not exclusive for the transition towards a circular economy, but extends to all sustainability development goals (UN, 2015) and to all the wicked environmental problem definitions decision makers at every policy level are confronted with. The field of sustainability science is developing swiftly, but requires improvement on the assessment process and its contents: i.e. question articulation, linking metrics to the question at hand, facilitating stakeholder participation and finally providing decision support under (multi-metric) outcomes and associated uncertainty. The protocol and tool presented here provide a practical way to manage and execute the process of selecting a SA method with input from stakeholders. Based on the case study, we conclude that the proposed approaches can support users in managing the processes of question articulation and method selection. They are an operationalization of the recently proposed SA identification key (Zijp et al., 2015). Both the protocol and tool have a flexible design, which enables broader use and further development based on growing experience and new insights. Using them increases the chance that SA outcomes are used in the decision making context and indeed contribute to reaching goals for sustainable development at all levels.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.04.006.

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