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Disclaimer

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Executive Summary

This report aims to deliver fundamental information regarding the Life Cycle Analysis modelling for the NEREUS Project. One of the important goals of the decision support tool (DST) is to provide environmental assessment for the comparison of technologies and this goal can be done by using the powerful methods such as Life Cycle Analysis and C-footprinting.

University of Portsmouth (PP6) leads the Workpackage 1.4 and this deliverable is submitted as the first one of the series of deliverables on LCA within the frame of NEREUS Project. This report provides comprehensive information on the definition of the goal, scope, system boundaries, methods and inventory data which will be intended to use for modelling the life cycle analysis (LCA) in wastewater treatment and resource recovery context.

1. Goal

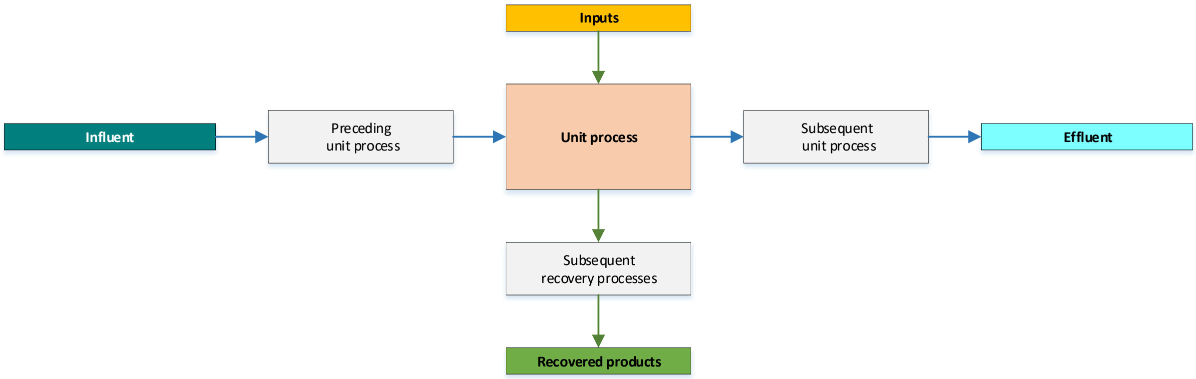
The Life-Cycle Assessment (LCA) carried out as part of the New Energy and REsources from Urban Sanitation (NEREUS) project is intended to be used as part of a wider Decision Support Tool (DST) for technology choice in urban sanitation systems. The numerical results from the LCA will be combined with a number of other quantitative indicators across 4 headings (See Table 1) to provide decision makers with wide ranging information on unit processes and process trains within a wastewater treatment system.

The assessment is intended for a professional audience to make either policy or broad design decisions and is not intended for comparative assertions intended to be disclosed to the public as defined in ISO 14040 & ISO 14044 (ISO, 2006a, 2006b).

1.1 The NEREUS DST

The structure of the DST is based on a series of “Unit processes” which may be assembled by the designer into a process train. Figure 1 shows an example of a unit process with potential preceding and subsequent processes. Each unit process changes the nature of the wastewater, consumes inputs such as energy or materials and potentially generates recovered products. A user may use the DST to investigate a treatment train made from a series of unit processes, investigate the effects of adding a process to an existing train or replacing an existing process with a new one.

Figure 1: Unit process model within the NEREUS DST



1.2 Standards

The LCA is anchored in a robust and transparent methodology derived from and compatible with recognised standards such as:

- ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework (ISO, 2006a) & ISO 14044:2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines
- PD CEN/TR 16928:2016. Guidance for the implementation of environmental aspects in product standards and system standards in the field of wastewater engineering (CEN, 2016)
- ISO 14025:2010. Environmental labels and declarations - Type III environmental declarations - Principles and procedures (ISO, 2010)
- EN 15804:2012+A1:2013. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products (CEN, 2014)

- Product category rules for Product Group: UN CPC 9411 & 9423 Waste Water Collection and Treatment Services (Del Borghi & Gallo, 2014)
- International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance (EC JRC-IES: ILCD, 2010)

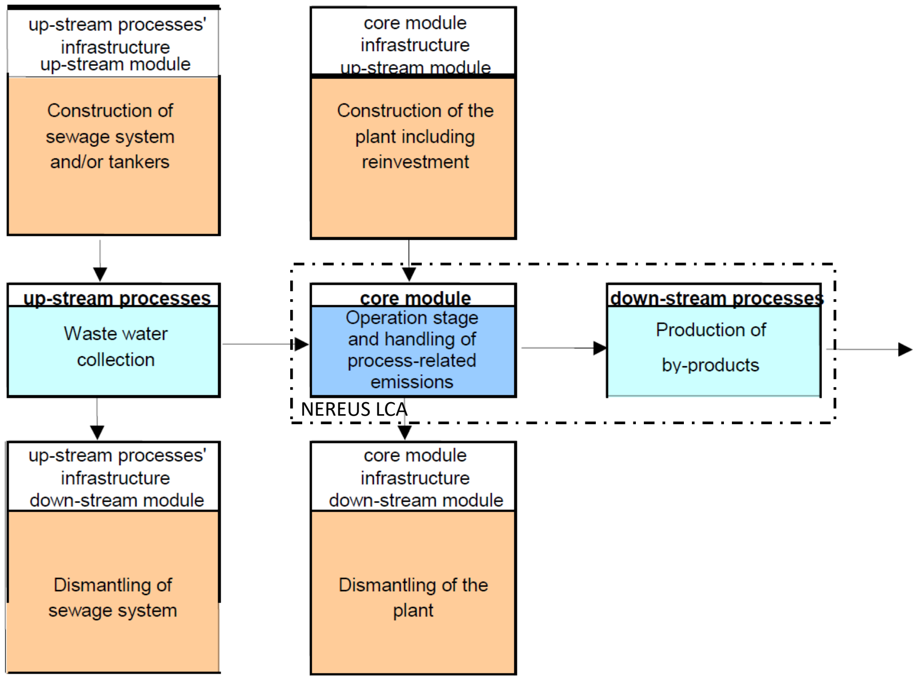
2. Scope

2.1 System Boundaries

2.1.1 Life-cycle stages

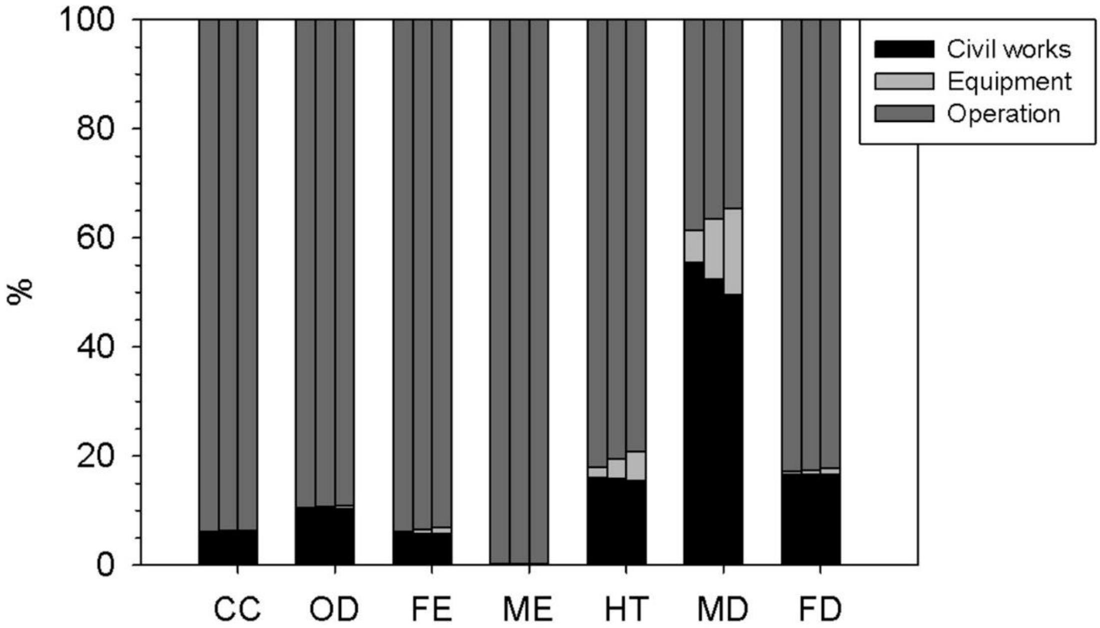
Processes within a wastewater LCA are described in the Waste Water Collection and Treatment Services Product Category Rules (Del Borghi, 2014) under ISO 14025 (ISO, 2010). A general presentation of the core modules, upstream and downstream processes are shown in Figure 22. Upstream processes are not considered in the LCA carried out as part of the NEREUS project as the treatment processes are the focus of the DST rather than the preceding infrastructure which may be considered separately. Downstream processes are, conversely, central to the NEREUS project which is concerned with the recovery of energy and resources from wastewater treatment and are therefore, included.

Figure 2: Processes defined in UN CPC 9411 & 9423 (Del Borghi, 2014) *with the system boundary used for the NEREUS LCA*



In terms of the core module, only operational inputs are considered. This is due to LCA forming only a portion of the overall decision support and a number of studies which suggest that impact related to capital works makes a very small contribution to impacts over the life-cycle of a sewage treatment asset (Sabeen et al., 2018). Of the 45 LCAs reported by Corominas et.al. (2013), only 23 considered construction and demolition and only six of these found the impact to be worthy of consideration, consisting primarily of “low-tech” processes such as constructed wetlands. In a very detailed sensitivity study, Morera et.al (2017) found the impact of civil works was < 16% for most categories including climate change (c. 5%), but up to 63% for metals depletion. It is, however notable when looking at more detailed results shown in Figure 33 that life-span makes little difference as replacement and consumables dominate. It is also noted in the paper that the inclusion of steel recycling reduces the metal depletion to negligible values.

Figure 3: Relative contribution of Civil Worlds and Operations to LCA results across 7 impact categories (Morera, 2017)



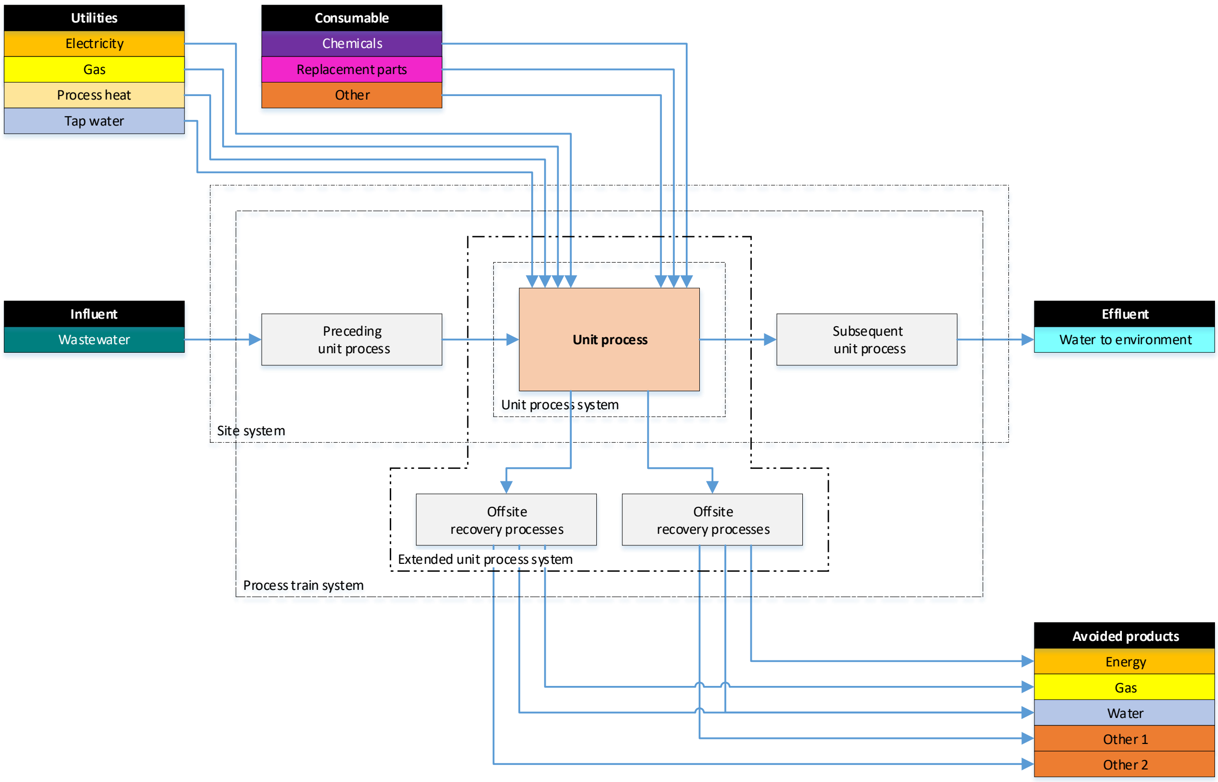
Notes: Left bar is for 10 years life-span, centre for 20 years & right for 30 years.
CC = climate change, OD = ozone depletion, FE = freshwater eutrophication, ME = marine eutrophication, HT = human toxicity, MD = metal depletion, FD = fossil depletion.

2.1.2 Process groupings & allocations

The NEREUS project has a variety of projects to which the DST & LCA model may be applied. This and the flexibility of the DST requires that a number of system boundaries be set-up to include all the scenarios which may be of interest. As described in §0, the structure of the DST is based on a series of "Unit processes" which may be assembled by the designer into a process train. A number of these potential boundaries are shown in

Figure 4. An example of how they are applied to a demo-case is shown in Figure 5.

Figure 4: Boundaries within the NEREUS LCA model



2.1.2.1 Unit process

The simplest boundary is using simple Unite processes. Inputs and outputs are summed across the unit process which form the building-block of subsequent larger boundaries. It is unlikely, but possible that a single unit process will be considered alone without further processes in a process train.

2.1.2.2 Process train

The simplest composite boundary and likely, the most useful is the entire process train. Inputs and outputs may simple be summed across all unit processes including recovery processes. In cases where there are unit processes that are not used by the process train exclusively, e.g an anaerobic digester which processes material from other treatment trains, allocations of inputs & outputs must be made between the process trains. This allocation will be based on volume of material processed in the first instance. If found to be significantly different, consideration will be given to concentrations of substances of interest.

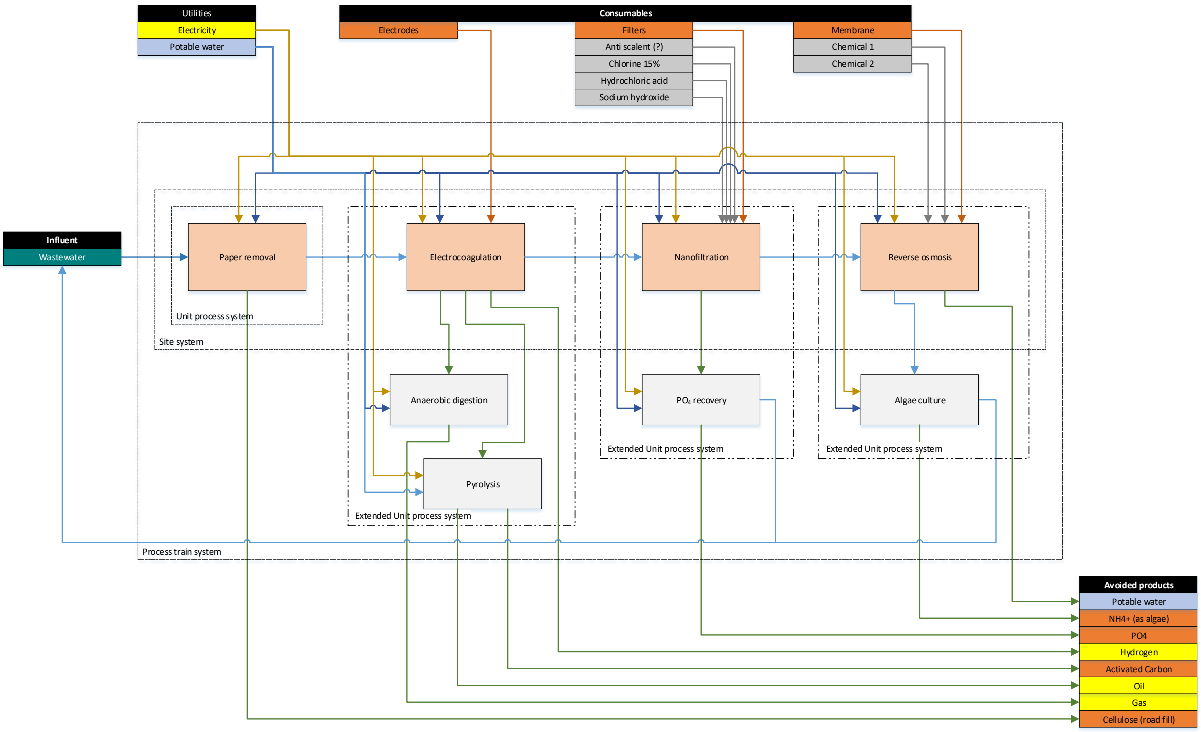
2.1.2.3 Extended unit process

If a unit process does not produce useful products and passes an intermediate flow onto another process that is either off-site or used for a number of input processes, the additional recovery process may be included within an extended unit process boundary. In cases where the additional unit process is offsite, but exclusively handles material from a single preceding unit process, it may simply be included inside the process train system. In cases where the unit process handles material from a number of sites, allocation will be made in the same manner as described in §0.

2.1.2.4 Site

For situations where the interest is in the performance of a particular site, a site boundary may be added. In this case, flows leaving the site may not be a useful/marketable product, so the avoided product much be allocated with an allowance for the impact of subsequent processing based on the mass of material as described in §0.

Figure 5: Boundaries in the Evides demo case (a larger version is in the Appendix A.1)



2.2 Functional unit

According to a wide-ranging review by Corominas et al (2013), the most used functional unit in LCAs is volume of wastewater treated, however they identify a weakness in that a simple volumetric measure fails to account for influent or effluent quality other units used include using incoming biochemical oxygen demand (BOD) (Tillman et al., 1998) and net environmental benefit in terms of influent & effluent (Rodriguez-Garcia et al., 2011). In the case of the NEREUS LCA model, it is sufficient to consider simple inlet volume as processes will be compared across the same influent expectations and effluent requirements.

The life-span of wastewater treatment plants can be in the decades, however it is expected that the NEREUS LCA will be used with emerging technologies where life spans are less certain. Moreover, the choice of operational-only boundaries in §0 makes the process less reliant on life-span choice other than consideration of the embodied impact of consumable items. To this end an analysis period of 5 years has been adopted.

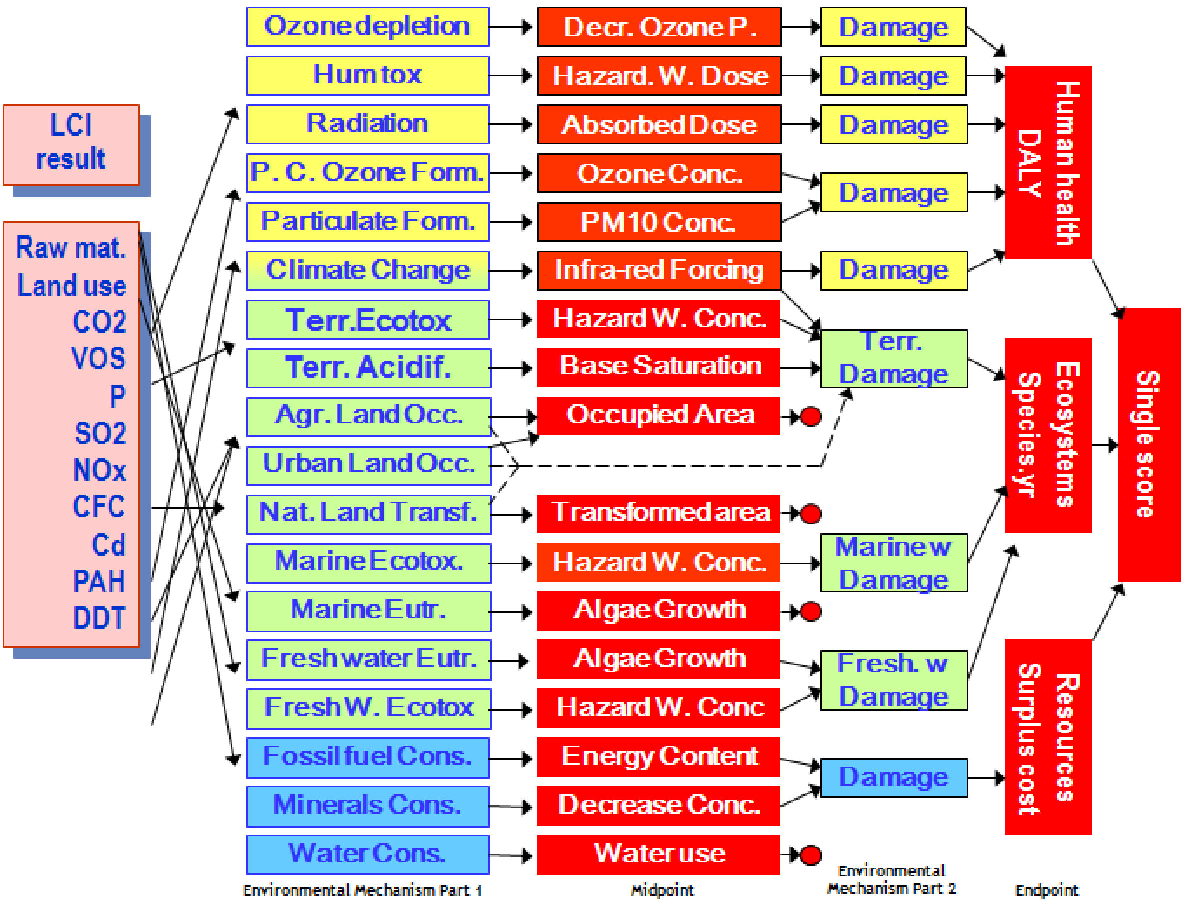
2.3 Methods used

Life Cycle Analysis will be analysed using the ReCiPe method. RéciPe is an indicator based impact assessment method, (M. A. J. Huijbregts et al., 2017) developed by collaboration of RIVM, CML, PRé Consultants, Radboud University Nijmegen and CE Delft. ReciPe can be stated as the follow up of two methodologies which are:

1. the method proposed as the baseline method for characterisation in the Handbook on LCA (Guinée, 2002) - the midpoint approach,
2. the method advanced in the Eco-indicator 99 (Goedkoop & Spriensma, 2001) - the endpoint approach.

ReciPe combines both approaches of midpoint and endpoint modelling. By this method, impact assessment of Life Cycle translates emissions and resource extractions to environmental impact scores. These scores are calculated by published characterisation factors (Mark Huijbregts et al., 2018) which are derived by two sets of impact categories such as midpoint and endpoint indicators. The overall structure of the method with the relationship between the LCI parameters, midpoint and endpoint indicators are given in Figure 6.

Figure 6: Categorisation into midpoints and endpoints under ReCiPe (Goedkoop et al, 2013).



In ReCiPe, LCIA methods are employed for the conversion of the emissions of hazardous substances and extractions of natural resources into impact category indicators at the midpoint level (such as acidification, climate change and ecotoxicity), while others employ impact category indicators at the endpoint level (such as damage to human health and damage to ecosystem quality) (M. A. J. Huijbregts, Steinmann, Elshout, Stam, Verones, Vieira, Hollander, et al., 2017). The reason behind the calculation of the endpoint indicators is the complexity of the midpoint indicator interpretation. These two sets of impact categories with associated sets of characterisation factors are provided below.

Eighteen midpoint level impact categories:

1. climate change
2. ozone depletion
3. terrestrial acidification
4. freshwater eutrophication
5. marine eutrophication
6. human toxicity
7. photochemical oxidant formation
8. particulate matter formation
9. terrestrial ecotoxicity
10. freshwater ecotoxicity
11. marine ecotoxicity
12. ionising radiation
13. agricultural land occupation
14. urban land occupation
15. natural land transformation
16. water depletion
17. mineral resource depletion
18. fossil fuel depletion

At the endpoint level, most of these midpoint impact categories are further converted and aggregated into the following three endpoint categories:

1. damage to human health
2. damage to ecosystem diversity
3. damage to resource availability

In the NEREUS LCA, the end-point indicators are uses as the midpoints have been considered too unwieldy and excessively detailed. This is further discussed in §0.

To deal with subjective factors, ReCiPe uses three perspectives – individualist, hierarchist and egalitarian – which impact what single score the LCIA produces, to the user in cases of uncertainty

These perspectives are based on assumptions of the following sorts:

- The individualist perspective is based on short term interests and technical optimism
- The hierarchist perspective is based on consensus, often preferred in scientific models
- The egalitarian perspective is based on long term interest with precautionary principle thinking

The Hierarchist perspective has been used for the NEREUS LCA as it is the most used and conforms to the majority of policies. Time horizons also match those in standards such as EN 15804

(CEN, 2014) and IPCCs Guidance on National Greenhouse Gas Inventories (Eggleston et al., 2006). Table which shows the general principles of the ReCiPe method can be found in the Appendix A.2.

2.3.1 Indicators

The indicators used form a subset of the overall indicators in the wider DST. ReCiPe has been chosen as discussed in §0. The midpoints used in ReCiPe amount to some 18 categories, which was considered too complex to include in a larger set of indicators. ReCiPe does, however provide a series of 3 endpoint categories which summarise the effects of the midpoint categories (M. A. J. Huijbregts, 2017). These have been taken forward as the indicators used in the DST. An exception to this is climate change potential which has been separated as it forms a specific part of many company's reporting requirements and is directly addressed in many environmental management systems. To avoid double counting, the effect of climate change has been removed from the damage to human health and damage to ecosystems areas of protection using the Characterisation factors published as part of ReCiPe. The 4 categories were included in a larger set of indicators decided upon at the DST workshop in December 2018.

*Table 1: Indicators for the DST (indicators in **bold** are from the LCA analysis)*

Social	Environmental	Economic	Technical
• Visual • Risk of Infection • Risk of toxic components • Health & Safety • Acceptability • Affordability	• Odour • Noise • Footprint • Reducing Local Abstractions • Effluent Quality • Risk of Accidental Emissions • **Climate Change (LCA)** • **Damage to Health (LCA)** • **Damage to Ecosystems (LCA)** • **Damage to Resource Availability (LCA)**	• CAPEX • OPEX • Willingness to pay for environment • Potential Income Generation	• Technology readiness level • Flexibility • Reliability • Risk of failure

At present, the weightings of the indicators are undecided as an exercise is planned incorporating views of the stakeholder groups identified in the NEREUS project.

2.4 Inventory data

At present two databases are under consideration:

2.4.1 Ecoinvent

Ecoinvent is an extremely comprehensive database consisting of some 4000 processes with a clear underlying methodology and the ability to customise unit processes within the inventory. The geographical scope is European, though some data is global (ecoinvent Centre, 2007). Ecoinvent has a licensing cost and this will need to be negotiated.

2.4.2 ELCD/LCDN

The European Life Cycle Database (ELCD) is a product of the European Platform on Life Cycle Assessment, a project which seeks to build a standardised database and methodology for LCA across the EU (Recchioni et al., 2013) under the umbrella of the European Commission Joint Research centre and the group who publish the International Reference Life Cycle Data System (ILCD) Handbook (EC JRC-IES: ILCD, 2010). The database itself is free of charge but much smaller than Ecoinvent with only c. 500 processes. The database itself has recently been discontinued as there has been a move to a Life Cycle Data Network (LCDN) where industry, research groups, consultants etc. may publish data with a clear format and quality assurance criteria.

For the NEREUS LCA, the ELCD database and LCDN databases will be used wherever possible. If the database proves too sparse, Ecoinvent will be explored.

2.5 Process data

The data for process inputs and outputs for the NEREUS LCA will come from the modelling underlying the DST. Data on processes within the demo-cases will be used to validate the DST model in terms of energy and martial use and in terms of yields of recovered products. Some calibration may be possible, however discussions at the DST workshop in December 2018 indicated that the DST should model “generic” unit processes resulting in a large multiplicity of possible variants, whereas the demo-cases are much fewer in number.

2.6 Cut-off

EN 15804 (CEN, 2014) specifies that the cut-off should be 1% for any single input and 5% for the total mass or energy cut. The “1% rule” is also stipulated in the product category rules (Del Borghi, 2014) The NEREUS LCA will follow the 1% rule for individual inputs/outputs and 5% for total operational inputs unless the input or output is has a recognised high environmental impact either through emissions or material depletion.

3. LCA Implementation for Pilot Plants

The LCA calculations is included in the DST and the outputs are reflected under the environmental criteria with the indicators:

- Climate Change (LCA)
- Damage to Health (LCA)
- Damage to Ecosystems (LCA)
- Damage to Resource Availability (LCA)

The LCA calculations included in the DST is reflected in the treatment train level through the cumulative impact of all the unit processes included in the train. While doing so, the two main performance indicators considered are yearly energy consumption (kwH/year) and the avoided products represented by the recovered products.

A Life Cycle Analysis full for a unit process would require full details on the inventory of materials used in construction, information on the transportation of these materials, and the chemicals used during the treatment process. However, as these components vary with each unit process as well as the supplier of those processes, this would not allow us to make generic calculations compatible with the

DST. Similarly, it would prevent the flexibility of the number of unit processes can be included in the DST. Full LCA would not be compatible with the aim of a user-friendly tool and limit its usage of it due to the requirement of complicated and a varied list of materials as well as difficulty on reaching the precise details on these required data points. Based on the information that found in the literature, energy consumption has almost 90% of the total impact on the final LCA end points. Therefore, we have implemented a more generic and applicable LCA calculation in the tool which can make a decent approximation based on the current knowledge, for the energy consumption and recovery percentages for the technology using the same values as the NEREUS DST knowledge library. We use these key performance measures for the LCA calculations and comparisons provided here.

The total energy consumption of the treatment train is based on the unit processes that take place in the train as well as the position of this unit processes in the train as the influent flow per unit process varies across the train. Additionally, whether the unit process takes place in the main or side streams has impact on the energy consumption due to the similar reason.

The avoided products are directly influenced by the influent characteristics since the number of recovered products are dependent on the mass balances. The other important factor is the recovery and removal percentages of the unit processes that affects the amount of recovered product obtained by the train.

To calculate the endpoint values explained in detail in Section 2.3, the ReCiPe method is used after the total energy consumption and recovered resources are calculated. The examples of LCA calculation used in NEREUS DST is implemented for three pilot cases of NEREUS Project. These pilot cases are selected due to their completeness as treatment train. The spreadsheet demonstrates the performed LCA is attached in this deliverable. In the spreadsheets, we have included five tabs including, (1) the diagram of treatment train of the pilot and initial influent values, (2) Calculations for LCA, (3) Calculations for LCC, (4) electricity data used in the LCA calculations based on countries, (5) recovered product used in the LCA calculations based on countries.

The tab on LCA calculations shows the unit process with their performance characteristics (recovery/removal percentages, CAPEX, OPEX, energy consumption, etc.) in addition to the mass balance and concentrations of components such as COD, TP and TN. The values used in the calculations are in line with the values used in the NEREUS DST which are mainly based on the source of Joksimović (2006) and Oertle et al (2019). For the end point calculations through Recipe method, the main data used is retrieved from Bonton et al. (2012). This tab provides all the calculations and final value on the LCA indicators considered in the DST. It is important to note that the results are all dependent on the values that we gathered from literature and in the lack of information we asked experts to generate similar numbers for similar unit processes. Regarding the values used for electricity and recovered resources for countries reflect general numbers. However, for local market, these values can vary. Therefore, the values might differ based on the assumptions we have from the real world.

For the implementation of LCA, the pilots of Evides, DuCoop and Waterlink were considered. The LCA calculations of Evides pilot can be used to show how the spreadsheet functions when there are multiple side streams and multiple product recovery and Waterlink works for treatment train with one main stream and focused on single product recovery. Based on LCA calculations for the pilots, Evides pilot gave the most environmentally friendly results across all four endpoints meaning has negative value for (1) climate change, (2) damage to health and (3) damage to ecosystems and (4) damage to resource availability. DuCoop has also positive impact for all indicators apart from ecosystems. Although, Waterlink pilot has negative impact across all four end-points. The main reason of this situation can be explained with energy intensive unit process requirements for reaching high quality drinking water legislation. Another reason could be recovering only water although both DuCoop and Evides recover multiple resources.

The tab LCC calculations provide the life cycle costing of each unit process in the train. LCC includes the capital expenditure (CAPEX), operations & maintenance (O&M), labour cost and energy expenditure. All the cost elements listed above other than CAPEX is listed as total of all the elements under operational expenditure (OPEX). In this tab, economic impact of treatment net present value (NPV) and equivalent annual cost (EAC) are calculated by taking discount rate and lifetime of the unit processes. These values provide a nice overview about the approximate costs of total treatment train over the course of 20 year planned train. The values used in these calculations are collected from the literature review.

4. Conclusions

This document outlines the process involved in the use of Life Cycle Analysis in the NEREUS project. The goals, scope and methods used have been outlined. Finally, the details of how these calculations were implemented in spreadsheet models for three pilot projects is provided. It is important to include LCA into a project with a focus on sustainable methods.

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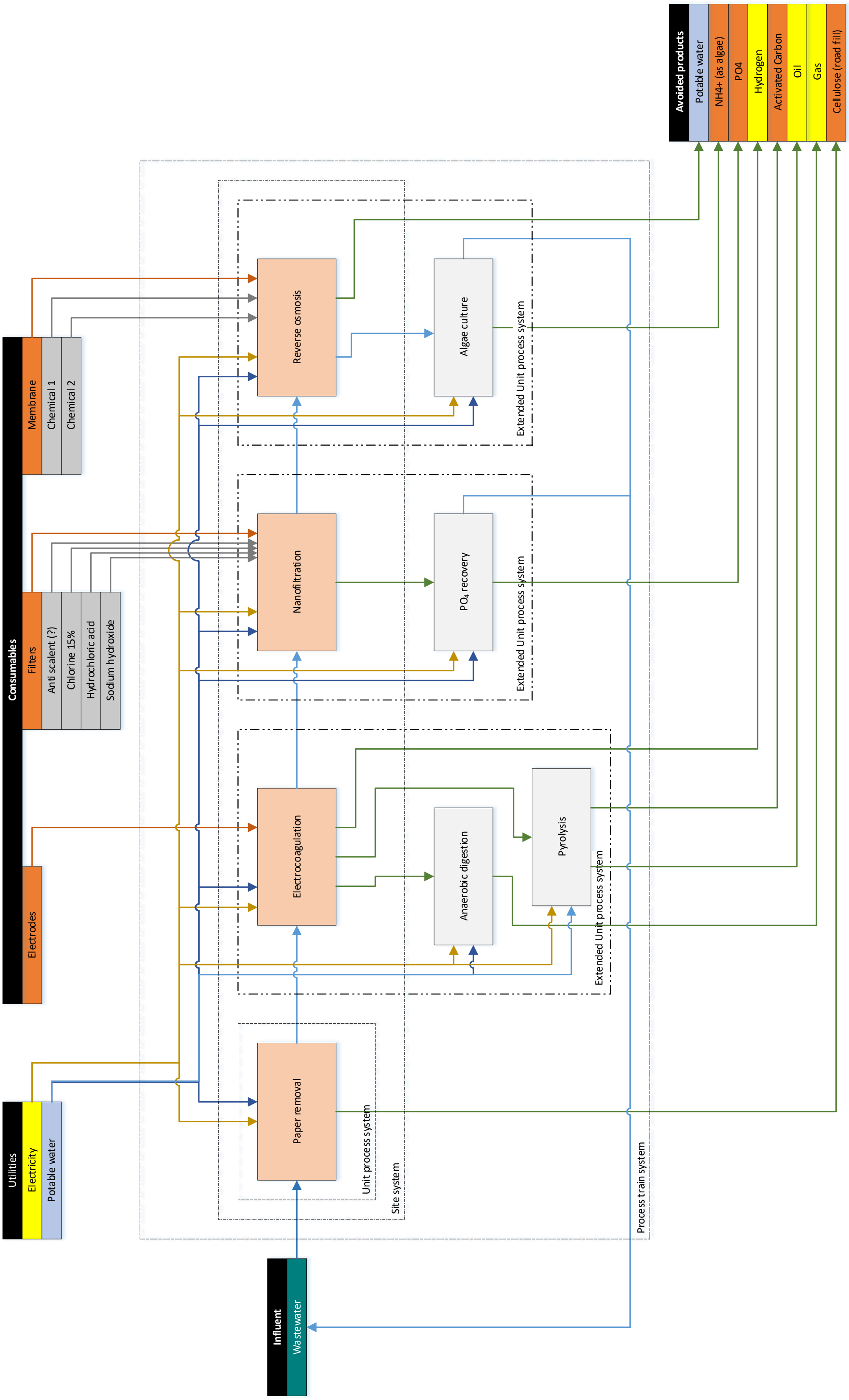
A. Appendix

A.1 Site map for Evides demo case



A.2 General Principles of ReCiPe Methodology

Principle	**Comment**
Intended purpose of the method:	Combining midpoint and endpoint methodologies in a consistent way
Midpoint/endpoint:	Midpoint and endpoint characterisation factors are calculated on the basis of a consistent environmental cause-effect chain, except for land-use and resources
Handling of choices:	Cultural perspectives are used to distinguish three different sets of subjective choices. User can choose which version to apply.
Data uncertainties:	Data uncertainties are discussed in the text but not always quantified.
Regional validity:	Europe. Global for Climate change, Ozone layer depletion and resources
Temporal validity :	Present time
Time horizon:	20 years, 100 years or indefinite, depending on the cultural perspective
How is consistency ensured in the treatment of different impacts In characterisation In normalisation and weighting?	For all emission based categories similar principles and choices are used. All impacts are marginal. All impact categories of the same area of protection have the same indicator unit. Same environmental mechanism for midpoint and endpoint calculations is used.
Midpoint impacts covered:	climate change; ozone depletion; terrestrial acidification; freshwater eutrophication; marine eutrophication; human toxicity; photochemical oxidant formation; particulate matter formation; terrestrial ecotoxicity; freshwater ecotoxicity; marine ecotoxicity; ionising radiation; agricultural land occupation; urban land occupation; natural land transformation; depletion of fossil fuel resources; depletion of mineral resources; depletion of freshwater resources
Endpoint impacts covered:	Human health (DALY); ecosystem quality (biodiversity, PDF.m^2.yr); resources (surplus cost)
Approximate number of substances covered:	Approximately 3000 substances
Other observations:	

(ILCD Handbook: Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment, 2010)