

Reference values for sustainability assessment

Incorporating monetary terms for enhanced decision-support

Master's thesis in Architecture and Civil Engineering

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Cover: Results during workshops for different assessment groups, comparing valuations derived from conventional percentage weighting and the willingness to pay for the reduction of one tonne carbon dioxide equivalent.

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Abstract

Large-scale infrastructure projects involve substantial investment and have far-reaching environmental consequences. As regulatory standards grow increasingly stringent, for example in the wastewater sector where treatment requirements are continuously updated, developers are often required to upgrade or construct new facilities to satisfy regulatory demands. Decision-making in such settings must account for multiple, sometimes conflicting, criteria, and multi-criteria analysis (MCA) offers a structured means of comparing alternatives across selected criteria. However, the weighting step within MCA remains susceptible to subjectivity and a lack of transparency and objectivity. This study investigated whether integrating reference values, derived from governmental guidelines and accepted industry norms, could support more objective and consistent weighting. The analysis focused on the environmental sustainability criteria: climate impact, energy use as a resource, and nutrient discharge (nitrogen, phosphorus, and organic matter) to receiving waters. It further examined the potential of basing weights on decision-makers' willingness to pay (WTP) for improvements in specific criteria. The conventional MCA weighting-methodology was refined for WTP input and cost weighting. Workshops were conducted to compare conventional percentage weighting with WTP-based weighting, and participants reported greater confidence when relying on reference values rather than subjective estimations. When comparing previous assessments, conventional weighting exhibited wide variations both within and between groups. Weighted score ratios calculated from conventional weightings were compared to collected reference values, revealing noticeable inconsistencies. These findings indicate that conventional methods risk inconsistency and bias, while WTP anchored in reference data contributes to improved transparency and reliability. Incorporating such reference values into MCA thus offers valuable decision-support, enabling more robust, evidence-based choices in the planning of high-cost, environmentally significant infrastructure projects.

Keywords: Sustainable assessment, multi-criteria analysis (MCA), weighted score ratios (WSR), willingness to pay (WTP), decision-support, weighting methods, environmental criteria, reference values

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Rebecca Loman, Gothenburg, April 2025

List of Acronyms

Displayed below is a list of acronyms that are being used throughout this report, in alphabetical order:

ASEK	Analysis Method and Socioeconomic Calculation Values for the Transport Sector ("Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn")
BOD	Biochemical Oxygen Demand
BSAP	Baltic Sea Action Plan
C	Carbon
CHP	Combined Heat and Power
CO ₂ e	Carbon Dioxide Equivalents
DICE	Dynamic Integrated Climate-Economy
DKK	Danish Krone (Currency of Denmark)
ETS	Emissions Trading System
EU	European Union
EUR	Euro (Currency of the Eurozone)
GAC	Granular Activated Carbon
GIVE	Greenhouse Gas Impact Value Estimator
HELCOM	Helsinki Commission
IAM	Integrated Assessment Model
KPI	Key Performance Indicator
LCOE	Levelised Cost Of Energy
MCA	Multi-Criteria Analysis
MKN	Environmental Quality Standards ("Miljökvalitetsnormer")
MSW	Municipal Solid Waste
N	Nitrogen
P	Phosphorus
PAC	Powdered Activated Carbon
PEI	Prince Edward Island (in Canada)
PLN	Polish Złoty (Currency of Poland)
SEK	Swedish Krona (Currency of Sweden)
SC	Social Cost
USD	United States Dollar (Currency of the United States)
WSR	Weighted Score Ratio
WTP	Willingness To Pay
WW	Wastewater
WWT	Wastewater Treatment
WWTP	Wastewater Treatment Plant

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1

Introduction

The future of urban water management faces many challenges. Climate change is contributing to increased and more intense rainfall, leading to higher pressure on existing water infrastructure. At the same time, regulations for wastewater treatment plants (WWTPs) are becoming stricter, with updated directives that impose higher treatment standards and require improved resource efficiency. The European Parliament and Council Directive of the European Union (EU) 2024/3019 (The European Parliament and the Council of the European Union, 2024) sets new legal requirements for wastewater treatment (WWT) across its member states, including stricter treatment requirements, increased energy efficiency measures, and a gradual reduction of greenhouse gas emissions, measured in carbon dioxide equivalents (CO₂e), contributing to the EU 2050 climate neutrality goal.

A significant portion of Sweden's municipal water and wastewater (WW) infrastructure was developed between the 1950s and 1970s (NCC, n.d.). As these systems approach the end of their lifespan, many require substantial reinvestments to maintain operational efficiency. The increasing demands on the WWTPs are revealing capacity limitations, particularly in older facilities. Without the required investments, both treatment efficiency and water quality are at risk of deterioration. With ongoing urbanisation and population growth, municipalities face increasing pressure to expand and modernise their WW infrastructure. However, financial and technical constraints, particularly in smaller municipalities, present significant challenges to the necessary reinvestments. To meet these challenges, large-scale investments in WW infrastructure are essential in the coming decades. Expanding and modernising these facilities must be done in a sustainable manner, balancing environmental, economic, and social considerations. A valuable tool for assessing sustainability in decision-making is multi-criteria analysis (MCA) (Neth et al., 2023). MCA provides a structured approach for comparing different alternatives by integrating environmental, economic, and social criteria into the decision-making process.

MCA conventionally involves scoring by a scoring-group of alternatives under weighted criteria, weighted by an assessment group (Neth et al., 2023). The weighting approach, however, can in conventional MCAs lack transparency and objectivity, as it often obscures the factors that contribute to the final weight distribution among the criteria. To address this issue, Neth et al. (2023) suggest a method using WSRs to enhance transparency and objectivity where conventional weighting falls short. By applying WSRs, decision-makers can better understand how weight distributions influence the valuation of different criteria, thereby improving comparability across assessments and enabling alignment with societal valuations.

This master’s thesis explores the application of WSRs in MCA to improve transparency and objectivity in sustainability assessments for WWTP expansion and modernisation. Reference values sourced from authorities and scientific studies will be incorporated to establish a comparative basis, enabling a more informed decision-making process when conducting an MCA.

1.1 Problem analysis

MCA is a widely used decision-support tool that evaluates alternatives based on sustainability criteria such as climate impact, energy use, and economic costs. The process conventionally involves assigning percentage-based weights to each criterion, determining how much influence it should have on the final result. These weights are decided by an assessment group, relying on expert judgment or stakeholder preferences. While this provides structure, it introduces several challenges.

One issue is the lack of transparency and objectivity in the weighting process. Since percentage weights are often assigned subjectively, it becomes difficult to trace how total sustainability scores are derived. Additionally, environmental criteria, particularly climate impact, tend to receive high weights, sometimes resulting in excessively high WSRs compared to other criteria. While this reflects their importance, the weighting is rarely grounded in a clear economic logic. In most cases, there is no explicit link to how much society, stakeholders, or decision-makers are actually willing to pay for improvements in these areas. Without such a basis, the weighting process becomes arbitrary, and it remains unclear what cost-level is considered reasonable for specific sustainability outcomes.

To address these issues, this study proposes a monetary-based weighting approach, where reference values serve as decision-support for the willingness to pay (WTP) for quantifiable criteria and used as input in MCA weighting rather than being determined subjectively. Instead of relying solely on expert judgment, monetary values from real-world data provide a structured foundation for decision-making. This approach offers a database for determining the WTP, where the reference data could include the reduction’s worth of one tonne of CO₂e on the European market, how much Sweden applies in carbon (C) taxation or emission trading, or what has historically been paid for reductions in nitrogen (N) or phosphorus (P) discharge into recipients. Using reference values as foundation in the weighting process ensures that sustainability criteria are assigned weights based on real-world economic considerations rather than subjective estimations. Additionally, WSRs can be derived from previous assessments to analyse implicit valuations or used directly as input for MCA weighting.

A long-term objective of this methodology is to establish a reference value database, allowing decision-makers to select appropriate WTP values when conducting sustainability assessments. By bridging the gap between MCA and economic valuation, this study builds upon the WSR approach developed by Neth et al. (2023), but extends it by addressing how reference values can be systematically incorporated as input data in the weighting process. This provides a more structured and transparent approach to sustainability assessments, ensuring that sustainability valuations align with economic realities and existing policy frameworks.

1.2 Aim

The primary objective of this project is to improve transparency and objectivity in MCA-based sustainability assessments by integrating monetary-based weighting using reference values as basis for the WTP. The transparency issue will be addressed by replacing conventional weighting with monetary terms, expressing values in 2024 Swedish Krona (SEK). The project will be structured in three steps:

1. Identify reference values for the sustainability criteria: climate impact, energy use, and WWTP discharge of N, P, and organic matter measured as biochemical oxygen demand (BOD) to receiving waters.
2. Calculate WSRs for these sustainability criteria in previous assessments, to show how they have been valued previously.
3. Conduct workshops to:
 - Compare conventional weighting methods with weighting using the WSR approach with reference values systematically incorporated as decision-support for the WTP.
 - Explore how different assessment groups evaluate and apply reference values when conducting a sustainability assessment.

1.3 Limitations

All reference values will be expressed in monetary terms (2024 SEK) per unit of environmental impact. The following units are used throughout this thesis:

- Tonnes (t) for climate impact, expressed as CO₂e.
- Kilowatt-hours (kWh) for energy use.
- Kilogrammes (kg) for nutrient discharge to receiving waters.

The project will only evaluate quantitative criteria and it was decided that the reference values of focus for the thesis would be:

- Climate impact, SEK/tCO₂e.
- Energy use, SEK/kWh.
- Emission values for:
 - Nitrogen, SEK/kgN.
 - Phosphorus, SEK/kgP.
 - Organic material, SEK/kgBOD.

2

Theory

This chapter provides a brief overview of the MCA methodology and introduces WSRs along with their potential applications. It also outlines the environmental goals and policy context for the investigated sustainability criteria: climate impact, energy use, and nutrient discharge.

2.1 Multi-criteria analysis

An MCA generates a valuable foundation for decision-making. The analysis ensures that various sustainability aspects; environmental, economical, and social, are systemically considered when comparing different alternatives (Neth et al., 2023). The criteria involve both quantifiable and qualitative criteria that can be valued in the same assessment. Based on the result of the sustainability assessment, the alternatives can be ranked and the least sustainable can be identified and removed from further investigations.

The analysis requires background data, which typically comes from a project that provides data acquisition as basis for the scoring. Backeström and Ceder (2022) display a general criteria list in their master thesis' report, which can be used as a template for choosing what criteria to include in the assessment. Each assessment is unique, thus requiring individual criteria selection.

Once the criteria list has been set and background data has been prepared, a scoring group can score each alternative for each criterion. There are multiple scoring-scales to use, but an example used by Neth et al. (2023) is presented in Table 2.1.

Table 2.1: Example of a scoring scale used for MCA.

Score	Interpretation
1	Considerably worse than future acceptable level
2	Worse than future acceptable level
3	Future acceptable level
4	Better than future acceptable level
5	Considerably better than future acceptable level

Weighting of each criterion by an assessment group can be conducted either before or after the scoring, although it is generally recommended to perform the weighting before

the scoring. The weights can be set on a scale of 1–20 as suggested by Neth et al. (2023) and Ernst et al. (2020) to allow the participants to focus on assigning a low or high priority to a criterion. The weights are then calculated into percentage weights where the sum of the weights for all criteria should equal 100%. Percentage weights can also be set directly, for example by distributing 100 points between the criteria (Malmqvist et al., 2015).

Lastly, the scores and weights are grouped by multiplying each score with the weights for each criterion and then summarising the weighted scores for each alternative, resulting in the total sustainability score per alternative (Ernst et al., 2020), see Equation 2.1 used by Neth et al. (2023).

$$S_j = \sum_{i=1}^m W'_i \cdot s_{i_j} \quad (2.1)$$

Where S_j is the total sustainability score of alternative j , m is the number of criteria included in the analysis, W'_i is the percentage weight for criterion i , and s_{i_j} is the score for alternative j on criterion i .

2.2 Weighted score ratios

WSRs serve as a tool to make sustainability assessments more objective and transparent (Neth et al., 2023). By iteratively calculating WSRs throughout the weighting process, it becomes possible to visualise how different decisions and assigned weights influence the final valuations. WSRs can be expressed in various units, such as EUR/tCO₂e, EUR/kWh, or kWh/kgCO₂e, which can then be compared to reference values or standard values. The WSR is calculated using Equation 2.2, where A and B represent two different criteria, depending on which unit is desired for the WSR.

$$WSR [\textit{unit A}/\textit{unit B}] = \frac{V_A}{V_B} \cdot \frac{W_B}{W_A} \quad (2.2)$$

In Equation 2.2, V_A and V_B is the value per score step for criteria A and B, which can be calculated by dividing the range in values with the range in the corresponding scores (see an example in Section 3.2). W_A and W_B are the weights assigned to the criteria A and B.

2.3 Policy context of evaluated criteria

This section presents an overview of the environmental challenges associated with each of the three evaluated criteria: climate impact, energy use, and nutrient discharge. It also outlines relevant policy frameworks that address these challenges and clarifies the role and responsibilities of the WW sector in relation to each.

2.3.1 Climate impact

Today, the global average temperature is approximately 1 °C above pre-industrial levels and continues to rise (Naturvårdsverket, 2022). Sweden has adopted a national goal of limiting the global temperature increase to well below 2 °C in line with the Paris Agreement, with an even more ambitious aim of restricting the rise to 1.5 °C and actively supporting international efforts to align with this target. According to the Paris Agreement, global carbon dioxide emissions must reach net zero by 2050, and greenhouse gas emissions should be halved by 2030. Despite growing awareness of climate change and its impacts, temperatures continue to rise, and current policy instruments and measures remain insufficient to meet these targets. However, as highlighted in Naturvårdsverket (2022), a report from the UN’s Intergovernmental Panel on Climate Change (IPCC), offers a reassuring perspective: these goals are still attainable across all sectors, provided that essential structural changes are implemented. There are considerable opportunities for emission reductions in every sector, and although some measures involve higher investment costs, they may also yield greater reduction potential.

The WWT sector plays an important role in emission reduction efforts, as WWTPs are significant sources of CO₂e emissions (Lorick & Videbris, 2024; The European Parliament and the Council of the European Union, 2024). These arise primarily from high energy consumption, methane emissions from sludge treatment, nitrous oxide release during biological nitrogen removal, and CO₂ emissions related to fossil carbon use. Climate impact is included as a criterion in all of the studied MCAs (see Section 4.2), highlighting the priority of reducing CO₂e emissions from WWTPs. The latest directive on urban wastewater treatment, Directive (EU) 2024/3019 (The European Parliament and the Council of the European Union, 2024), outlines measures to mitigate these emissions and sets a clear target for net zero emissions by 2045. In particular, the reduction of methane and nitrous oxide emissions (Ekspertgruppen for en Grøn Skattereform, 2024) is receiving increased attention, as both gases have significantly higher global warming potential than CO₂. Methane, primarily released during sludge digestion and storage, and nitrous oxide, generated during nitrogen removal processes, are now recognised as key contributors to climate impact from WWTPs. Reducing these emissions is therefore a central objective in current and future climate strategies within the WWT sector.

2.3.2 Energy use

Energy is a finite resource, and to achieve the goal of reducing climate impact by transitioning from fossil fuels to renewable energy sources, the need for energy efficiency is increasing. One of the main EU targets is to reduce energy consumption by at least 11.7% by 2030 compared to projected levels (European Commission, n.d.). The overall objective is to enhance energy efficiency and reduce the EU’s dependence on imported energy sources. In Sweden, national targets align with these goals (Sveriges Riksdag, 2024). Sweden aims to expand its electricity demand to 300 TWh by 2045, while ensuring that energy efficiency measures are implemented to not overburden the system. As industries increasingly electrify to lower their carbon footprint, the importance of optimising energy use continues to grow.

At the municipal level, WWTPs are significant energy consumers (Ghimire et al., 2021). Approximately 80% of municipal WWTPs use the activated sludge process, which relies

on aeration, which can account for over 60% of a WWTP's total energy demand. In smaller communities, WWTPs can represent 25–40% of local electricity budgets. Given these considerations, and in alignment with Sweden's (Sveriges Riksdag, 2024) and the EU's energy efficiency targets (European Commission, n.d.), WWTPs must integrate low-energy treatment alternatives and energy recovery strategies.

In MCAs, energy use is a frequently included criterion. For example, energy use was considered in seven out of eight MCAs examined in this thesis (see Section 4.2). In this context, energy is assessed as a resource, where lower energy consumption is preferred. Given that sewerage systems and water services are among the largest energy consumers in urban areas (Hamawand, 2023), incorporating energy use into MCAs serves as an effective strategy to support energy efficiency goals and promote sustainable decision-making.

2.3.3 Nutrient discharge

Nutrient discharge, particularly of P and N, is one of the main drivers of eutrophication in both inland and coastal waters. In freshwater systems, P is typically the limiting nutrient and therefore the principal target of reduction measures for inland waters (Söderqvist and Wallström, 2017). In Sweden, nutrient management is governed through environmental quality standards (MKN), which are legally binding thresholds aimed at achieving good water status (Boverket, 2024), as required under the EU Water Framework Directive (Directive 2000/60/EC) (The European Parliament and the Council of the European Union, 2000). These standards are integrated into physical planning and infrastructure development processes. Complementing this, the recently revised Urban Wastewater Treatment Directive (Directive (EU) 2024/3019) introduces stricter emission thresholds and expand monitoring requirements of WW systems (The European Parliament and the Council of the European Union, 2024).

The Baltic Sea is especially sensitive to nutrient pollution and receives discharges from many WWTPs within the Baltic Sea catchment area, including from Sweden. Addressing eutrophication in this context requires coordinated efforts from all countries bordering the Baltic, reflecting a shared responsibility. This regional cooperation is formalised through the Baltic Sea Action Plan (BSAP), adopted by the Helsinki Commission (HELCOM) in 2007 and updated in 2021 (HELCOM, 2021), which aims to achieve good environmental status in the Baltic Sea. A central objective of the BSAP is to reduce eutrophication by decreasing inputs of total N and total P. Scientifically based thresholds define the allowable nutrient load for each marine sub-basin.

WWTPs represent one of the largest point sources of nutrient discharges to both inland and marine environments. Directive (EU) 2024/3019 addresses this by introducing enhanced treatment requirements in areas sensitive to eutrophication (The European Parliament and the Council of the European Union, 2024). These include more ambitious discharge limits for total N and total P, along with binding timelines for implementation, monitoring, and reporting. The updated framework reinforces the importance of limiting nutrient discharges from WWTPs as a necessary step towards achieving environmental policy targets such as MKN and BSAP. These evolving requirements also underline the need for systematic evaluation tools, such as MCA, to support decision-making in prioritising investments and identifying effective treatment strategies.

3

Methodology

To achieve the aim of this thesis, a literature review was conducted to identify relevant reference values. Previous MCA studies related to WWTPs were also reviewed, with WSRs calculated to reveal how the sustainability criteria had been valued in earlier assessments. Additionally, a worksheet was developed to systematically organise and present the findings. Workshops were conducted to evaluate the practical application of reference values as a decision-support tool for determining WTP within MCA processes.

3.1 Literature review

A literature review was conducted to collect reference values intended for use as monetary-based inputs to evaluate the weighting of the sustainability criteria: climate impact, energy use, and the discharge of N, P, and BOD to recipients. The objective was to establish a reliable and representative set of values to inform decision-makers when conducting a WTP-based weighting within MCA.

The review included a range of sources, including scientific publications, governmental reports, and industry guidelines, to ensure a comprehensive and well-founded basis. In addition to academic literature, particular emphasis was placed on governmental and institutional sources commonly used in policy and practice. These included documents from the Swedish government, the EU, Trafikverket, and environmental agencies such as the Swedish Environmental Protection Agency (Naturvårdsverket). By systematically reviewing these sources, the literature review produced a reference value database to support the determination of WTP in monetary weighting within MCA. These collected values were also compared with WSRs derived from previous MCA studies.

3.2 Calculating WSRs from previous MCA studies

Part of the aim of this thesis is to calculate how the sustainability criteria: climate impact, energy use, and WWTP discharge of N, P, and BOD to receiving waters have been valued in previous assessments. To achieve this, the methodology proposed by Neth et al. (2023) will be applied to calculate WSRs.

For this project, WSRs were calculated using Equation 3.1, which is a slightly modified version of Equation 2.2 presented by Neth et al. (2023).

$$WSR = \frac{V_c}{V_i} \cdot \frac{W_i}{W_c} \quad (3.1)$$

The main difference in Equation 3.1 compared to the method used by Neth et al. (2023) is that here, the WSRs are always expressed in monetary units. This means that V_c represents the value of annual cost per score step, and W_c is the weight assigned to the criterion 'annual cost'. The other parameters are defined as follows: V_i represents the value per score step for criterion i , and W_i is the weight of criterion i . Maintaining this format allows for direct comparison with the reference values identified in the literature review, which are also expressed on a monetary basis, and enables exploration of how well they align.

The value per score step (V_i) for criterion i , can be calculated with Equation 3.2, or by using the gradient of the linear relationship between data acquisition and the corresponding scores. One example of such a relationship is displayed in Figure 3.1, where the data on the y-axis is the operational cost for different alternatives and the x-axis shows the corresponding scores. Here, the gradient is -1.2, meaning that the value per score step is 1.2 MSEK/score (or 1 200 000 SEK/score).

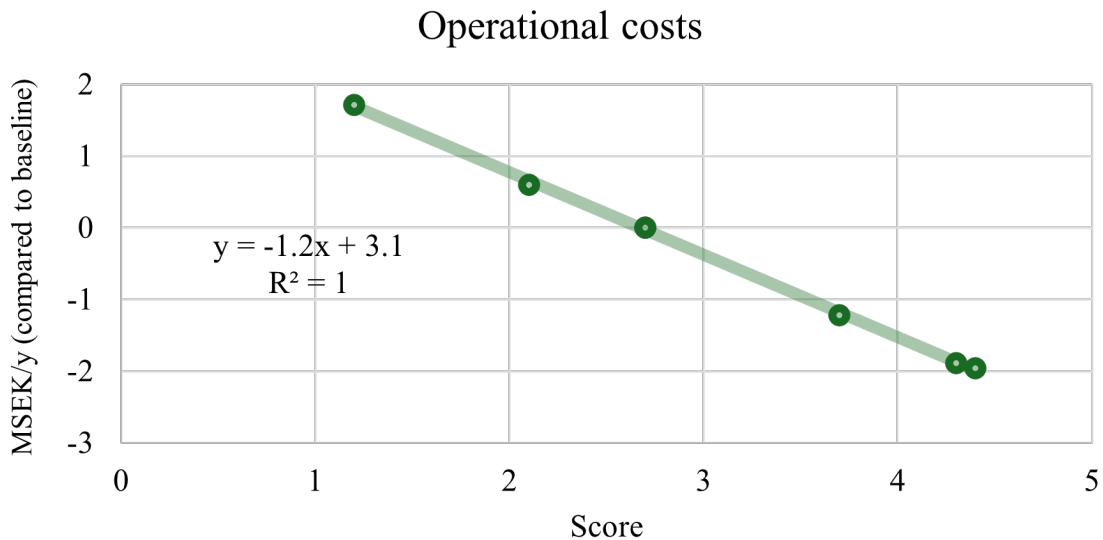


Figure 3.1: Example of a plot showing the linear relationship between the data acquisition for annual operational costs for different alternatives and the corresponding scores to this data, from Backeström and Ceder (2022) master's thesis.

Figure 3.1 shows a perfect linear relationship between the data acquisition for operational cost and the scoring, with $R^2 = 1$. According to Neth et al. (2023), for a relationship to be considered linear, then R^2 should be ≥ 0.95 . The linearity becomes an important parameter to ensure that each score step corresponds to the same value change.

$$V_i = \frac{\Delta v_{ij}}{\Delta s_{ij}} \quad (3.2)$$

For Equation 3.2, Δv_{ij} is the range of the data acquisition for criterion i under alternative j and Δs_{ij} is the corresponding range in scores. Table 3.1 exemplifies the data acquisition and scores, and how it connects to the criteria and alternatives.

Table 3.1: Illustration of data acquisition and scores for different criteria (A and B) under different alternatives (1, 2, and 3) in an MCA.

	Alternative 1	Alternative 2	Alternative 3	Alternative 1	Alternative 2	Alternative 3
	<i>Data acquisition</i>			<i>Scores</i>		
Criteria A	v_{A_1}	v_{A_2}	v_{A_3}	s_{A_1}	s_{A_2}	s_{A_3}
Criteria B	v_{B_1}	v_{B_2}	v_{B_3}	s_{B_1}	s_{B_2}	s_{B_3}

Below is an example on how to calculate WSR. This example is based on data provided by Backeström and Ceder (2022).

Example of WSR calculation

Value per score step for annual operational costs: 1.2 MSEK/score

Value per score step for annual climate impact: 750 tCO₂e/score

Weight assigned to operational costs: 2.1%

Weight assigned to climate change: 3.6%

$$\implies WSR = \frac{1.2 \cdot 10^6}{750} \cdot \frac{3.6\%}{2.1\%} = 2\,700 \text{ SEK/tCO}_2\text{e}$$

3.3 Data collection

During the project, the collected reference values and the calculated WSRs were recorded in an Excel worksheet. The recorded data included the source, a brief notation, the original value, and the conversion into 2024 SEK. Each value was initially documented in its original currency and year, such as 2020 United States Dollars (USD). These values were then converted to SEK using exchange rates from Exchange Rates UK (n.d.). To ensure comparability, inflation adjustments were applied using SCB's Price Calculator "Prisomräknaren" (Statistics Sweden (SCB), n.d.), expressing all values in 2024 SEK. The conversion tables, containing data from Exchange Rates UK (Table C.1) and SCB's Price Calculator (Table C.2), are provided in Appendix C.

3.4 Monetary-based weighting approach in MCA

To refine the conventional MCA method (Neth et al., 2023), this thesis implements reference values as decision-support for determining WTP for sustainability criteria, serving as input to the weighting process in place of conventional approaches. The following presents the full step-by-step methodology for conducting an MCA, with the conventional weighting step replaced by this approach, based on WTP and cost evaluation:

1. Formulation of the aim of the assessment.
2. The different alternatives are clearly specified and all assumptions and conditions are declared.
3. A scoring scale is implemented.
4. The sustainability criteria set is decided upon in relation to the specific aim of the assessment.
5. Background material is prepared through data acquisition so that all alternatives can be scored for all criteria.
6. Given background data, a scoring group scores (s) the different criteria, according to the scoring scale.
7. After scoring, the value per score step (V_i) will be calculated for the different criteria, see Equation 3.2.
8. An assessment group will decide on the weight of the criteria annual cost (W_c), which is determined based on a scale of $1-\lambda$, where λ is the scaling factor, which could, for instance, be 20 or 100.
9. The monetised value (WTP_i) for each sustainability criteria (i_1, i_2, i_3, \dots) is chosen for criteria that can be monetised. Reference values can serve as basis for the decision on WTP.

10. Based on the WTP, the weights for the sustainability criteria can be calculated by using Equation 3.3.

$$W_i = WTP_i \cdot W_c \cdot \frac{V_i}{V_c} \quad (3.3)$$

Here, WTP_i is the WTP for criterion i , W_c is the weight assigned to the cost criteria (in step 8), V_i is the value per score step for criterion i , and V_c is the value per score step for the criteria annual cost.

- (a) For criteria that cannot be monetised, for instance *flexibility* that is a common criterion in sustainability assessments for WWTPs (Backeström and Ceder, 2022), the weights are decided based on a scale of $1-\lambda$, where λ must be the same as the λ -value decided in step 8.
11. The weights for all sustainability criteria are normalised using Equation 3.4, to ensure that their sum equal 100%.

$$W'_i = \frac{W_i}{\sum_{i=1}^m W_i} \times 100 \quad (3.4)$$

Here, W'_i represents the normalised weight in percentage, W_i is the weight of each individual criterion i , m is the number of criteria included in the analysis, and the multiplication by 100 ensures that the weights are expressed as percentages.

12. The total sustainability score (S) is calculated by multiplying the normalised weight of each criterion (W'_i) with the score of each alternative under that criterion (s_{ij}) and summarising the weighted scores for each alternative, ultimately resulting in a total sustainability score for each alternative. See Equation 3.5.

$$S_j = \sum_{i=1}^m W'_i \cdot s_{ij} \quad (3.5)$$

Where S_j is the total sustainability score of alternative j , m is the number of criteria included in the analysis, W'_i is the normalised weight for criterion i , and s_{ij} is the score for alternative j on criterion i .

13. The total sustainability score for each alternative can be illustrated using a stacked bar chart, where each coloured segment represents the contribution of an individual criterion to the overall total sustainability score. This visualisation allows for a detailed comparison of how different criteria influence the final total sustainability score of each alternative. The alternative with the lowest total sustainability score is considered the least sustainable, while the one with the highest score is regarded as the most sustainable.

3.5 Workshops

The workshops were conducted to address the third objective: Explore how different assessment groups evaluate and apply reference values when conducting a sustainability assessment. The workshops were held with three different assessment groups: one utility group with employees at Gryaab, one consultancy group at Envidan, and one academic group with researchers at Chalmers.

The workshops were structured around two real-world sustainability assessments, selected for their differing objectives, independent authorship, geographic spread, and varied environmental criteria:

- **Case 1:** A pre-study of pharmaceutical removal at the Rya WWTP in Gothenburg in Sweden, assessment conducted in 2020 by Ernst et al. (2020).
- **Case 2:** A case study of resource recovery in the Baltic Sea region (Uppsala, Fyriså river catchment, in Sweden), conducted by Johannsdottir et al. (2021).

Case 1 focused on climate impact and energy use, while case 2 addressed climate impact and eutrophication potential, further divided into P and N discharge to water.

The assessment groups were assigned two tasks. The first was to conduct a conventional weighting of the selected criteria, assessing their relative importance in relation to other criteria with fixed weights from the original assessments. Participants used a weighting scale without restrictions on specific values. An Excel-based script was used to facilitate the weighting process, ensuring a structured approach while allowing participants to freely determine their weights. The formulas within the Excel sheet were hidden to ensure that decisions were based solely on participants' judgment rather than influenced by the underlying calculations.

In the second task, participants repeated the weighting process, this time incorporating reference values as decision-support for their WTP. The methodology followed the approach outlined in Section 3.4. The Excel-based script remained hidden from participants in this step as well. The assessment groups' function was to decide on their WTP for the criteria: climate impact, energy use, and P & N discharge to water, while BOD discharge was excluded as it was not part of the baseline assessments. To support decision-making, participants were provided with lists of reference values and WSRs derived from previous assessments, along with descriptions and values adjusted to 2024 SEK. Additionally, a historical timeline illustrating how values varied over time was displayed, helping participants understand potential trends and uncertainties in valuation.

4

Results

In the results chapter, a summary of all collected reference values from the literature review is first presented. This is followed by the calculated WSRs from previous sustainability assessments, and lastly, the results and main discussions from the workshops.

4.1 Reference values

The complete list of reference values is provided in Appendix A, where all figures have been adjusted to 2024 SEK to ensure consistency and comparability. Original values are presented as found, preserving the number of significant figures used in their respective sources to facilitate traceability. Converted values, including adjustments to 2024 SEK, are rounded to two significant figures. The following sections provide a more detailed explanation of these values, their interpretations, and the underlying factors influencing the estimates.

4.1.1 Climate impact

The reference values for climate impact include carbon taxes set, the social cost of carbon (SC-C), which reflects the monetary valuation of damage associated with CO₂e emissions, and other indicators such as the market price in EU's emissions trading system (ETS) and key performance indicator (KPI) values used by Gryaab. All values are presented in Figure 4.1 (expressed in 2024 SEK). For a detailed list, see Table A.1.

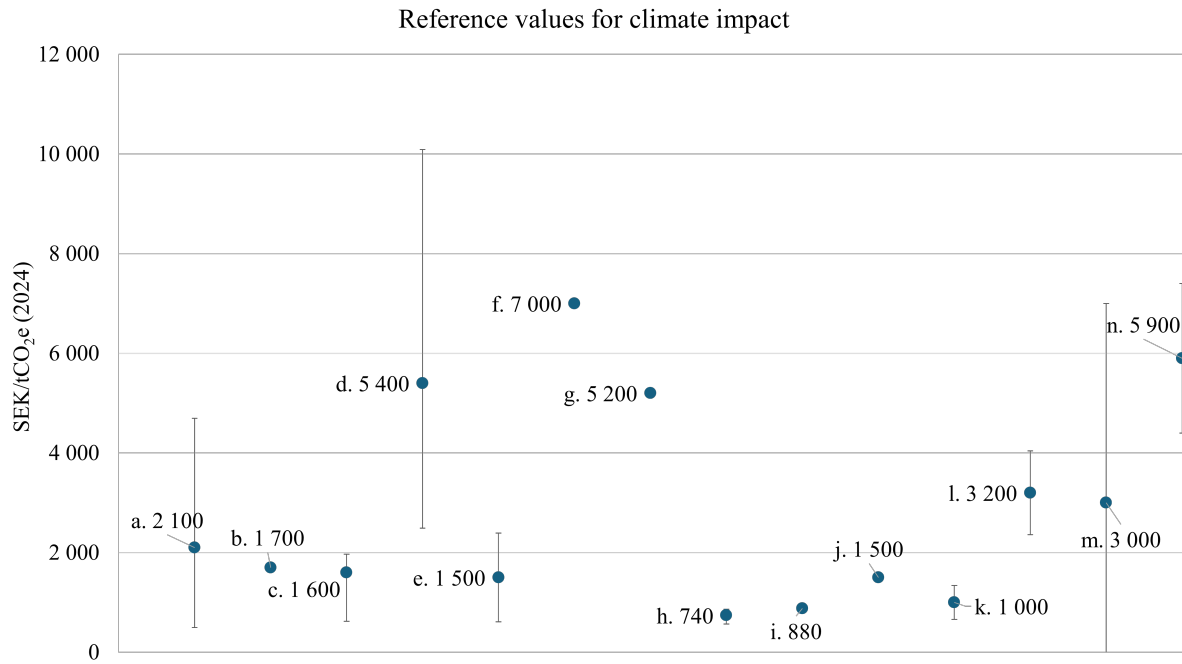


Figure 4.1: Collected reference values for the sustainability criteria climate impact (SEK/tCO₂e) in 2024 values.

The values presented in Figure 4.1 are specified in greater detail in Table 4.1, which also includes the corresponding notation letters for improved readability and contextual relevance. Expressed in 2024 SEK, the median value is 2 600 SEK, with a minimum of 740 SEK and a maximum of 7 000 SEK, yielding an average of approximately 3 300 SEK.

Table 4.1: Reference values for the sustainability criteria climate impact, values converted to 2024 SEK and original values.

Letter	Source	Value in 2024 SEK (SEK/tCO ₂ e)	Original value
a	SC-C (Rennert et al., 2022)	2 100 (500–4 700)	185 (44–413) USD/tCO ₂ e
b	W. Nordhaus (Gustafsson, 2021)	1 700	1 400 SEK/tCO ₂ e
c	CE Delft short-term projection (de Vries et al., 2024)	1 600 (610–2 000)	130 (50–160) EUR/tCO ₂ e
d	CE Delft long-term projection (de Vries et al., 2024)	5 400 (2 500–10 000)	437 (200–819) EUR/tCO ₂ e
e	Suggested carbon tax based on SC-C (Sterner et al., 2023)	1 500 (590–2 400)	125 (50–200) EUR/tCO ₂ e
f	Trafikverket ASEK 7.1 (Trafikverket, 2023)	7 000	7 SEK/kgCO ₂ e
g	Trafikverket ASEK 8.0 projection after 2065 (Trafikverket, 2024)	5 200	5.22 SEK/kgCO ₂ e
h	EU's ETS 2024 (European Energy Exchange, 2024)	740 (570–860)	65 (50–75) EUR/tCO ₂ e
i	<i>Klimatklivet</i> initiative (Naturvårdsverket, 2025)	880	1.14 kgCO ₂ e/SEK
j	Carbon taxes in Sweden 2024 (Regeringen, 2024)	1 500	1.45 SEK/kgCO ₂ e
k	Target for the Paris Agreement of 2 °C (World Bank, 2024)	1 000 (670–1 300)	95 (63–127) USD/tCO ₂ e
l	Target for the Paris Agreement of 1.5 °C (World Bank, 2024)	3 200 (2 400–4 100)	(226–385) USD/tCO ₂ e
m	Gryaab's KPI values (Lorick and Videbris, 2024)	3 000 (0–7 000)	3 000 (0–7 000) SEK/tCO ₂ e
n	City of Gothenburg (Göteborgs Stad, n.d.)	5 900 (4 400–7 400)	5.9 (4.4–7.4) SEK/kgCO ₂ e

4.1.1.1 Social cost of carbon

Various sources provide estimates of the SC-C, which represents the monetised cost of damage associated with CO₂e emissions. One of these, Rennert et al. (2022), recalculated the SC-C, concluding that previous estimates did not fully reflect recent scientific advancements. Using an updated approach based on integrated assessment models (IAMs) they developed the greenhouse gas impact value estimator (GIVE) model, which integrates improved socioeconomic projections, climate modelling, damage assessments, and discounting methods. Their findings yielded a central estimate of 185 USD/tCO₂ and a 5% to 95% confidence range of 44–413 USD/tCO₂, expressed in 2020 value. The estimate

was significantly higher compared to the previously used US government estimate of 51 USD per tonne.

In 2018, the Nobel Prize in economics was awarded to William Nordhaus, alongside Paul Romer, for integrating climate change into long-term economic analysis (International Institute for Sustainable Development, 2018). Nordhaus is best known for developing the dynamic integrated climate-economy (DICE) model, an IAM that quantifies the economic impact of climate change, based on the concept of SC-C, and determines the optimal carbon tax to mitigate its effects on society and climate (Nordhaus, 2018). According to Nordhaus' model, a carbon tax of 1 400 SEK/tCO₂, expressed in 2020 value, is required to limit global warming to 2.5 °C over a 100-year period (Gustafsson, 2021).

For CE Delft, a Dutch organisation specialising in environmental pricing since 1997, environmental prices represent the loss of economic welfare caused by a pollutant entering the environment. In *The Environmental Prices Handbook 2024: EU27 version*, CE Delft presents their latest update to environmental prices, including carbon (de Vries et al., 2024). The handbook shows a price on carbon of 130 euro (EUR) per tonne of CO₂, with a lower bound of 50 EUR and an upper bound of 160 EUR. These values, expressed in 2021 value, reflect the SC-C, incorporating economic damage estimates from climate change, health impacts, and environmental degradation. For long-term projections, until 2050, CE Delft estimates an increase of the carbon price to 437 EUR/tCO₂, with a lower bound of 200 EUR and an upper bound of 819 EUR. The rise until 2050 reflects the expected escalation of climate-related damages, the growing economic risks of inaction, and the increased mitigation costs associated with achieving net-zero emissions.

4.1.1.2 Taxing carbon

Carbon taxation varies significantly across countries, with multiple frameworks guiding its implementation, many of which are based on SC-C estimates. Sweden has one of the highest carbon dioxide taxes in the world, at 1.45 SEK/kgCO₂ (Regeringen, 2024), with only Switzerland, Liechtenstein, and Uruguay imposing higher taxes, according to the World Bank (2024). The World Bank (2024) also states that to effectively meet the Paris Agreement targets, carbon price levels should be at least within the range of 63–127 USD/tCO₂ to limit global temperature rise to 2 °C above pre-industrial levels. However, to achieve the more ambitious target of limiting warming to 1.5 °C, a higher price range of 226–385 USD/tCO₂ is recommended. Only seven countries currently meet the lower Paris Agreement's target required to limit warming to 2 °C above pre-industrial levels, with Sweden among them. For the more ambitious 1.5 °C target, no country has yet set carbon prices within the recommended range.

Since carbon dioxide emissions are the main cause for climate change, according to Sterner et al. (2023), a global tax on carbon could be an appropriate and efficient instrument to reduce the emission levels. In their article they refer to estimates of the SC-C, and concludes that the appropriate tax level should be in the range of 50-200 EUR/tCO₂. Within this range, lower values suggest a lower perceived future risk, while higher values indicate significant anticipated economic damages due to climate impacts. For simplicity, it is assumed that these values are expressed in 2022 value, as the range includes economic and climate model updates up to 2022.

4.1.1.3 Other estimates

The EU’s market for carbon dioxide, the ETS, is an emissions trading scheme that sets a price on carbon, where companies receive or buy emission allowances, which they can trade with one another as needed (Clean Energy Wire, 2024). In Figure 4.2 the market price between 2012–2024 is displayed (European Energy Exchange, 2024) where the values have been adjusted to 2024 SEK. The maximum value these years has been 1 200 SEK/tCO₂ and the minimum value 30 SEK/tCO₂, in 2024 value. As highlighted in Section 4.1.1.2, according to the World Bank (2024), a range of 63 to 127 USD/tCO₂ (670–1 300 SEK/tCO₂ in 2024 value) is necessary to meet the Paris Agreement target to limit temperature rise to 2 °C above pre-industrial levels. The EU ETS reach this, but is far from the more ambitious target of limiting warming to 1.5 °C.

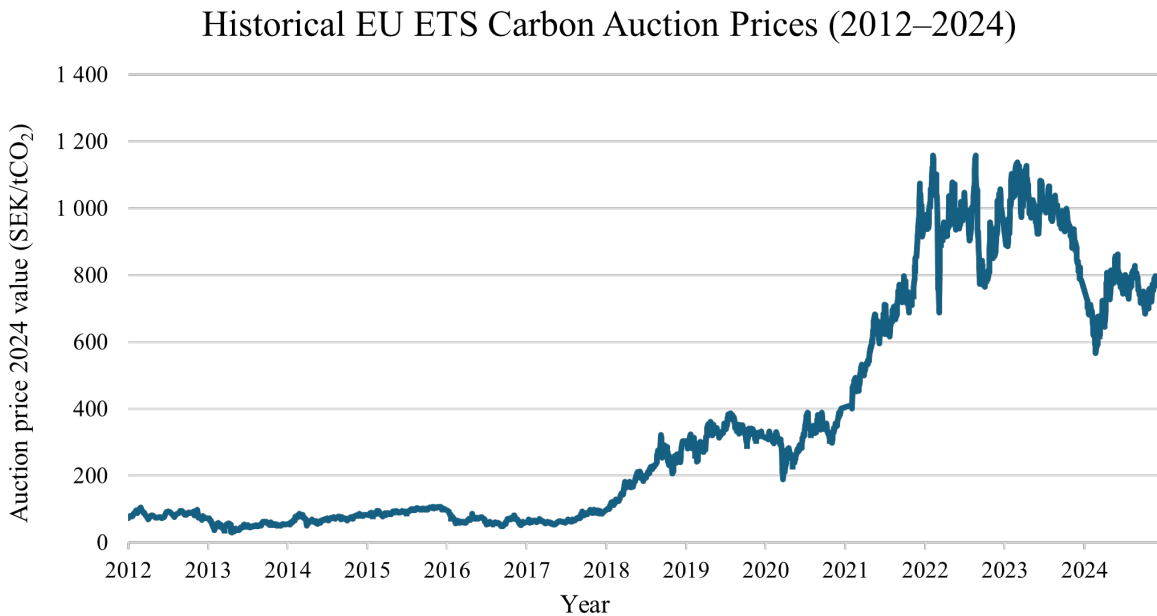


Figure 4.2: EU ETS, the historical auction price data on carbon between 2012–2024, expressed in 2024 SEK (European Energy Exchange, 2024).

Another estimate, by Trafikverket (2024) in their prognosis ASEK 8.0, is a calculated carbon valuation based on Sweden’s climate policy, aiming for a fossil-free transport sector by 2045. The valuation follows the marginal cost principle, meaning that the price of CO₂ emissions should reflect the cost of phasing out fossil fuels. In 2019, the carbon price was set at 1.38 SEK/kgCO₂, increasing gradually to 5.04 SEK/kgCO₂ by 2045, and eventually stabilising at 5.22 SEK/kgCO₂ from 2065 onward. The stabilisation occurs because, according to ASEK 8.0, future valuation updates follow a real annual growth of 1.15% per year until 2065, after which no further adjustments are made. In practical applications, Trafikverket includes this valuation in infrastructure planning, such as road, rail, and public transport projects. It is also considered when evaluating measures to reduce emissions, such as electrification of transport or sustainable construction methods. In another prognosis, ASEK 7.1, also conducted by Trafikverket, the valuation is instead 7 SEK/kgCO₂ (Trafikverket, 2023) which is higher than the latest suggested value in ASEK 8.0. The lower value in ASEK 8.0 reflects updated climate policies, a shift in

valuation methodology, and better alignment with EU's ETS.

In Sweden, there is an initiative called *Klimatklivet* (Naturvårdsverket, 2025), administered by the Swedish Environmental Protection Agency (Naturvårdsverket) on behalf of the Swedish government. Its purpose is to reduce CO₂e emissions by providing grants to organisations implementing emission reduction measures. As of December 31, 2024, the programme has achieved an overall average reduction of 1.14 kgCO₂e per SEK invested since its inception.

At Gryaab, a climate action plan (Lorick and Videbris, 2024) has been implemented to improve the management of CO₂e emissions, particularly carbon dioxide, methane, and nitrous oxide. A key component of this initiative is the use of KPI values for CO₂e, ensuring alignment with the city of Gothenburg's Environmental and Climate Programme. Gryaab's set KPI values for CO₂e ranges up to 7 000 SEK/tCO₂e. Measures with a cost of up to 3 000 SEK per tonne are considered acceptable and viable for implementation. Actions costing between 3 000 and 7 000 SEK per tonnes require further assessment. However, mitigation measures exceeding 7 000 SEK per tonne are generally not considered justifiable from a cost-effectiveness standpoint within this framework.

The City of Gothenburg's Environmental Department provides a set of monetary values intended to support socio-economic analyses of municipal interventions and projects. These are published on the webpage *Economic valuation of socio-economic benefits* (Göteborgs Stad, n.d.). The recommended price range for carbon dioxide, according to the City of Gothenburg, is between 4.4–7.4 SEK/kgCO₂, reflecting the societal cost of emissions to be used when evaluating the environmental impact of planned measures. These values are based on a report by Söderqvist and Wallström (2017) and have been adjusted for inflation using SCB's price calculator. An assumption that the values were adjusted to 2024 values was made.

4.1.2 Energy use

For the sustainability criterion energy use, the aim was to identify reference values that reflect the value of energy as a resource, rather than specific market prices. Nonetheless, two of the reference values represent actual energy prices: the national average electricity price in Sweden for 2024, which was 0.4 SEK/kWh (Elbruk, 2024), and the average energy price at the Rya WWTP in 2024, which was 0.6 SEK/kWh (M. Neth, personal communication, 26 March 2025). In addition, the total energy cost at Rya in 2024, 1.4 SEK/kWh, is also included, reflecting not only the energy price but also taxes and grid fees (M. Neth, personal communication, 24 January 2025). Other collected reference values include the cost of expanding electricity generation capacity and the levelised cost of energy (LCOE). These values are presented in Figure 4.3.

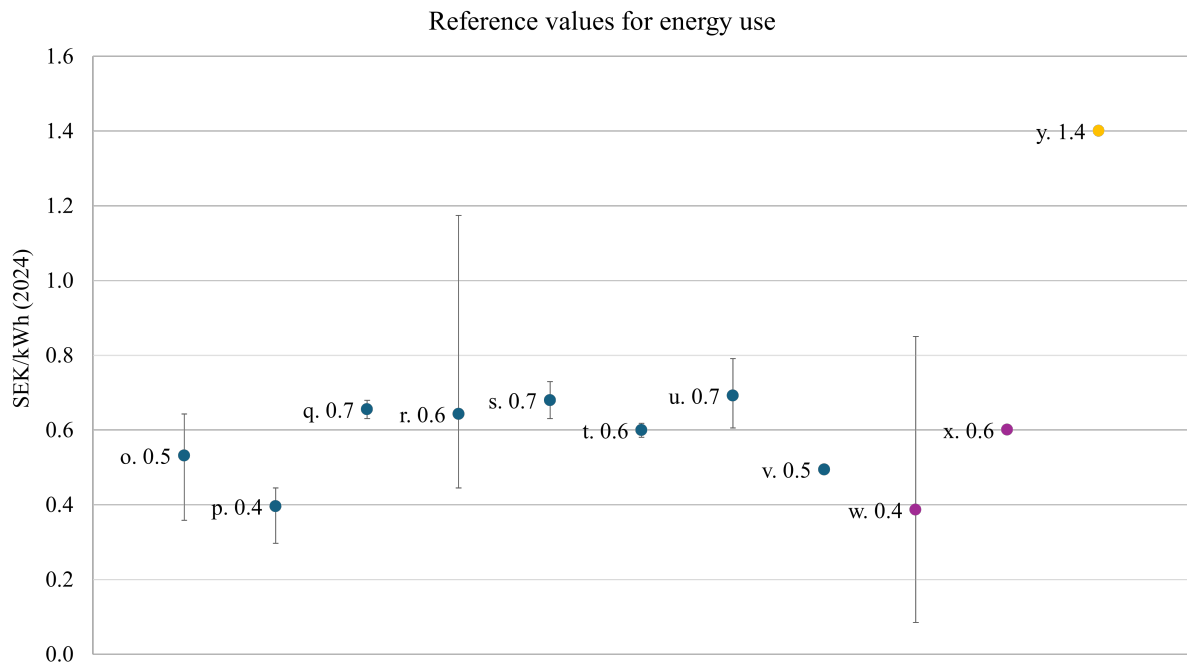


Figure 4.3: Collected reference values for the sustainability criteria energy use (SEK/kWh), expressed in 2024 value. Including real energy prices (purple), and total energy price (yellow).

The values discussed in this section are summarised in Table 4.2, Table A.2 shows the list in full detail.

Table 4.2: Reference values for the sustainability criteria energy use, values converted to 2024 SEK and original values. The last row (y) is separated from the others as the total electricity price (including taxes and grid fees) is not comparable with the other values.

Letter	Source	Value in 2024 SEK (SEK/kWh)	Original value (SEK/kWh)
o	LCOE solar parks (Energiforsk, 2021)	0.5 (0.4–0.6)	0.43 (0.29–0.52)
p	LCOE onshore wind power (Energiforsk, 2021)	0.4 (0.3–0.4)	0.32 (0.24–0.36)
q	LCOE offshore wind power (Energiforsk, 2021)	0.7 (0.6–0.7)	0.53 (0.51–0.55)
r	LCOE hydropower (Energiforsk, 2021)	0.6 (0.4–1.2)	0.52 (0.36–0.95)
s	LCOE biomass CHP (Energiforsk, 2021)	0.7 (0.6–0.7)	0.55 (0.51–0.59)
t	LCOE MSW CHP (Energiforsk, 2021)	0.6	0.485 (0.47–0.5)
u	LCOE nuclear power (Energiforsk, 2021)	0.7 (0.6–0.8)	0.56 (0.49–0.64)
v	City of Gothenburg/NEPP (Göteborgs Stad, n.d.)	0.5	0.4
w	Annual average electricity prices in Sweden 2024 (Elbruk, 2024)	0.4 (0–1.0)	0.386 (0.085–0.85)
x	Average electricity price at Rya WWTP 2024 (M. Neth, personal communication, 26 March 2025)	0.6	0.6
y	Average total electricity price at Rya WWTP 2024 (M. Neth, personal communication, 24 January 2025)	1.4	1.4

In a report produced by Energiforsk (2021), the LCOE is presented for various power generation technologies. The LCOE reflects all expected lifecycle costs associated with a power plant, including construction, operation & maintenance, and decommissioning, distributed over the estimated electricity production. The LCOEs included in the report are based on solar parks (0.29–0.52 SEK/kWh), onshore wind power (0.24–0.36 SEK/kWh), offshore wind power (0.51–0.55 SEK/kWh), hydropower (0.36–0.95 SEK/kWh), combined heat and power (CHP) based on forest biomass (0.51–0.59 SEK/kWh) and municipal solid waste (MSW) (0.47–0.50 SEK/kWh), as well as nuclear power (0.49–0.64 SEK/kWh). The values are considered to be expressed in 2020 value, as the data acquisition took place between 2019–2021.

The City of Gothenburg recommends a value of 0.4 SEK/kWh on its webpage *Economic valuation of socio-economic benefits* (Göteborgs Stad, n.d.). This figure is derived from Gråd et al. (2023) and represents the estimated cost of expanding Sweden’s electricity production capacity. To meet an additional production target of 50 TWh per year, the North European Energy Perspective Project (NEPP) estimated in 2020 that the required investment would be between 560 and 640 billion SEK. This corresponds to a fixed cost of approximately 0.4 SEK/kWh per year.

4.1.3 Nitrogen discharge to water

The collected reference values for N discharge to water are presented in Figure 4.4. These values represent the SC of N (SC-N) associated with environmental damages in aquatic ecosystems, N taxation on WWTP effluent discharge, mitigation costs required to meet the BSAP target, and the WTP for reducing N discharge.

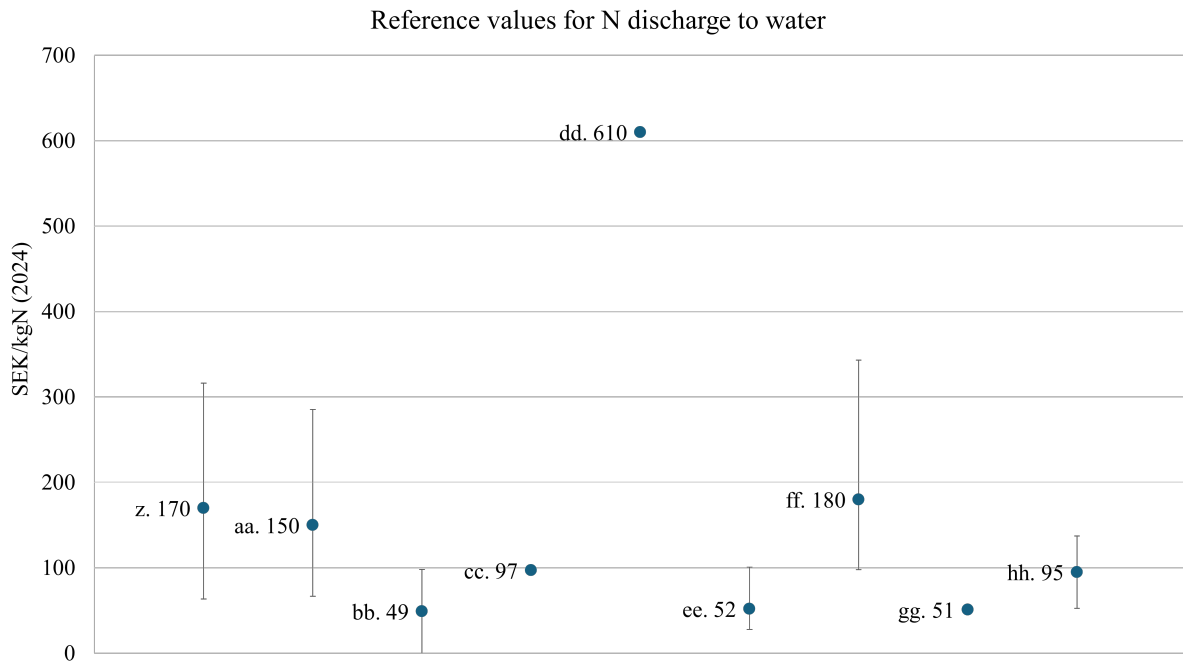


Figure 4.4: Collected reference values for the sustainability criteria N discharge to water (SEK/kgN) expressed in 2024 value.

The collected values are detailed in Table 4.3. For the full detailed list, see Table A.3. The median value is 97 SEK/kgN, with a minimum value of 49 SEK/kgN and a maximum value of 610 SEK/kgN, resulting in an average value of 160 SEK/kgN.

Table 4.3: Reference values for the sustainability criteria N discharge to water, values converted to 2024 SEK and original values.

Letter	Source	Value in 2024 SEK (SEK/kgN)	Original value
z	SC-N from N-runoff (Brink et al., 2011)	170 (66–320)	13 (5–24) EUR/kgN
aa	BSAP mitigation costs at WWTPs (Naturvårdsverket, 2012)	150 (68–290)	111 (50–210) SEK/kgN
bb	SC-N from N leachate (Keeler et al., 2016)	49 (0–99)	(0.001–10) USD/kgN
cc	WTP for Swedish residents to meet BSAP (Söderqvist and Wallström, 2017)	97	73 SEK/kgN
dd	Total WTP for Baltic-connected countries to meet BSAP (Söderqvist and Wallström, 2017)	610	460 SEK/kgN
ee	CE Delft freshwater (de Vries et al., 2024)	52 (28–100)	4.23 (2.27–8.19) EUR/kgN
ff	CE Delft saltwater (de Vries et al., 2024)	180 (93–340)	14.3 (7.6–27.6) EUR/kgN
gg	Danish emission taxes (Skatteministeriet, 2022)	51	33.39 DKK/kgN
hh	WTP amongst residents on PEI (Withey et al., 2024)	95 (53–140)	(5–13) USD/kgN

4.1.3.1 Social cost of nitrogen discharge

Similar to the SC-C, there is also a SC-N, which aims to reflect the environmental damage costs associated with N discharge. According to Brink et al. (2011), the SC-N from N discharge to water is estimated to be in the range of 5–24 EUR per kg of N, with 13 EUR/kgN used as a central estimate, expressed in 2008 value. This valuation accounts for health effects (0–4 EUR/kgN) and ecosystem impacts (5–20 EUR/kgN). The estimated valuation incorporates several factors, including ecosystem degradation, reduction of water quality, and loss of biodiversity. The variation in range depends on the investigated region, as certain ecosystems, for example, coastal areas, are more sensitive than others, thus leading to a higher SC-N.

Like for carbon prices, CE Delft also presents values for N discharge to water in their handbook for environmental prices: *The Environmental Prices Handbook 2024: EU27 version* (de Vries et al., 2024). The presented values are divided into N discharge to freshwater and saltwater and expressed in 2021 value. For freshwater, the valuation is 4.23 EUR/kgN, with a lower bound of 2.27, and an upper bound of 8.19. For saltwater, the value is instead 14.3 EUR/kgN, with a lower bound of 7.6 and an upper bound of 27.6, indicating that saltwater compartments are more sensitive to eutrophication caused by N discharge than freshwater bodies.

Proposed by Keeler et al. (2016) is an comprehensive approach to estimate the SC-N, which quantifies the monetary damages associated with an increase of N to aquatic environments. Their framework tracks N as it moves through water systems, primarily in the form of nitrate, and assesses the resulting economic costs linked to drinking water contamination and ecosystem degradation. Based on N leachate from fertiliser applications, they estimated SC-N by modelling N transport through groundwater and surface water and assigning monetary values to the costs of treating contaminated drinking water. Their results indicate that the SC-N varies significantly depending on location, hydrological conditions, and population exposure, with estimates ranging from less than 0.001 USD/kgN to more than 10 USD/kgN, expressed in 2010 values.

4.1.3.2 Other estimates

A policy instrument called CEASAR was proposed by Naturvårdsverket (2012) to support Sweden's N reduction commitments under the BSAP. CEASAR was designed to cover three marine basins, the Baltic Sea, Öresund, and Kattegat, which are directly linked to the BSAP. The system aimed at introducing a tradable N certificate scheme, allowing WWTPs to trade N reduction obligations through a market-based approach. Although the CEASAR certificate trading system was never implemented, it was designed to align with the BSAP, which set an overall N reduction target of 20 900 tonnes per year for Sweden by 2021, of which WWTPs were allocated a reduction target of 3 000 tonnes per year. Estimated mitigation costs varied depending on site-specific factors and treatment efficiency, ranging from 50 to 210 SEK per kg of N. However, when assessed as a weighted average, the cost was 111 SEK/kgN, reflecting that the majority of reductions were expected to take place at lower-cost facilities rather than at those with higher treatment costs. These estimates, produced by IVL in 2011 under commission from Naturvårdsverket, are assumed to be based on 2010 price levels.

The Danish emission tax *Spildevandsafgiftsloven* applies to N, P, and BOD in WW effluents. For N discharge, the tax covers total N and is set at 33.39 DKK/kgN in 2024 (Skatteministeriet, 2022).

In a report by Söderqvist and Wallström (2017), the WTP for a mitigation package to reduce N discharge into the Baltic Sea was estimated for all countries surrounding the Baltic. The WTP was divided by the reduction targets set by the Helsinki commission (HELCOM) in the BSAP for 2021, which required a total N load reduction of 70 988 tonnes annually. For Swedish residents, the WTP is estimated at 5 173 million SEK per year, which, when divided by the reduction target, corresponds to a WTP of 73 SEK/kgN reduced. However, the total WTP for residents in all Baltic-connected countries is significantly higher, estimated at 32 548 million SEK per year, reflecting a WTP of 460 SEK/kgN. Since these WTP values originates from a study conducted in 2014, it is assumed that the values are expressed in 2014 SEK.

Another WTP study for N reduction was conducted on Prince Edward Island (PEI) in Canada (Withey et al., 2024), and aimed to evaluate the WTP amongst PEI residents to reduce N leaching into the ground and surface waters. The findings showed that the PEI residents were willing to pay about 5–13 USD per kg of N reduced.

4.1.4 Phosphorus discharge to water

The collected reference values for P discharge to water are summarised in this section. Figure 4.5 presents these values converted to 2024 SEK. The dataset includes mitigation costs at WWTPs for P reduction measures, the SC of P (SC-P), WTP estimates based on mitigation costs for P reduction in inland waters (lakes and rivers), WTP estimates linked to the reduction targets for the Baltic Sea under the BSAP, and the taxation of P discharge from WWTP effluents.

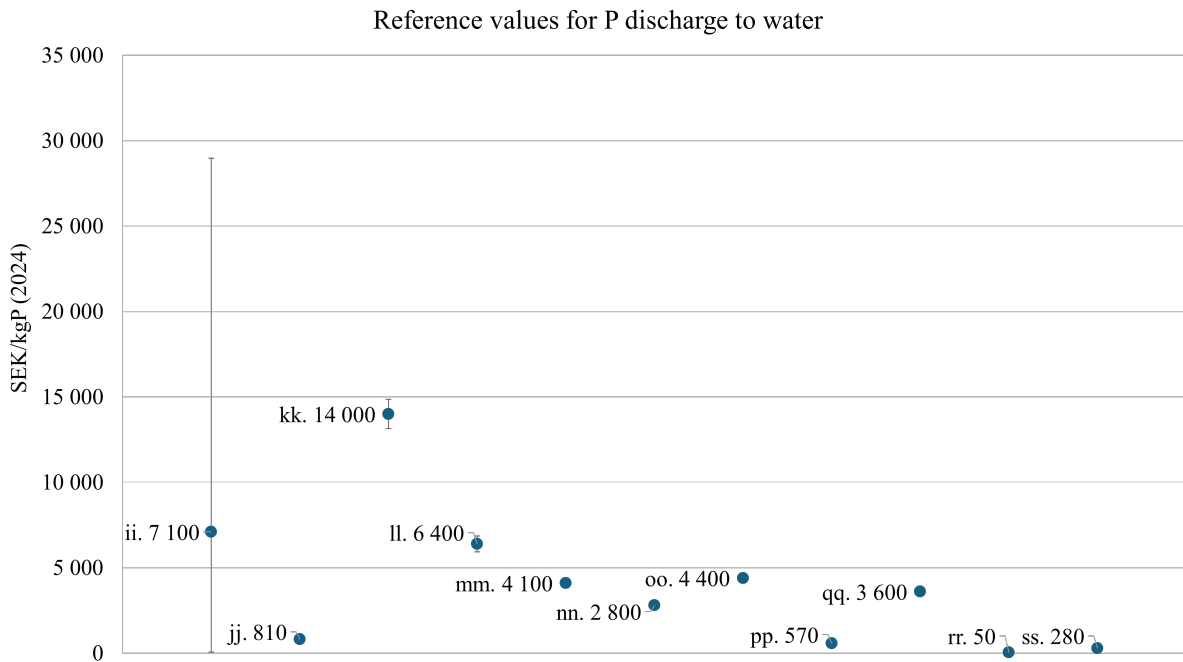


Figure 4.5: Collected reference values for the sustainability criteria P discharge to water (SEK/kgP), expressed in 2024 value.

The median value is 3 600 SEK/kgP, with a minimum value of 46 and a maximum value of 14 000 SEK, resulting in an average value of 4 000 SEK/kgP.

Further in this section is a summary of all the collected reference values, including short descriptions. In Table 4.4 are these listed along with conversion of the values to 2024 SEK, excluding the values jj–oo which are displayed in Table 4.5. For the full detailed list, see Table A.4.

Table 4.4: Reference values for the sustainability criteria P discharge to water, values converted to 2024 SEK and original values.

Letter	Source	Value in 2024 SEK (SEK/kgP)	Original value
ii	Mitigation costs for P reduction measures at WWTPs (Naturvårdsverket, 2012)	7 100 (51–29 000)	5 177 (37–21 169) SEK/kgP
pp	WTP for Swedish residents to meet BSAP (Söderqvist and Wallström, 2017)	570	430 SEK/kgP
qq	Total WTP for Baltic-connected countries to meet BSAP (Söderqvist and Wallström, 2017)	3 600	2 700 SEK/kgP
rr	CE Delft freshwater (de Vries et al., 2024)	46 (31–120)	3.74 (2.56–10.13) EUR/kgP
ss	Danish emission taxes (Skatteministeriet, 2022)	280	183.64 DKK/kgP

Naturvårdsverket (2012) presents descriptive statistics on the mitigation costs at WWTPs for implementing P reduction measures. The average estimated cost is 5 177 SEK/kgP, with a minimum of 37 SEK/kgP and a maximum of 21 169 SEK/kgP. The broad cost range reflects the fact that major modifications to the treatment process can be highly expensive, whereas reductions of up to 20 tonnes of P per year can typically be achieved through process optimisations. Since these values are derived from mitigation cost estimates published by IVL in 2011, it is assumed that they are expressed in 2010 price levels.

Naturvårdsverket (2012) also discusses a possible certificate trading system for P, similar to CEASAR, which was proposed for N. This system, referred to as CEASAR-E, is intended to support the target of reducing 15 tonnes of P annually, in line with MKN goals. While no specific mitigation cost can be directly linked to CEASAR-E, it is likely that the certificate system would be influenced by cost estimates such as those presented above.

In the report by Söderqvist and Wallström (2017), a study measuring the WTP to reduce P discharge to inland waters among Swedish residents is described. The WTP is divided by the targeted P reduction, where 151 areas are studied, but only for 139 of these a reduction target for P exists. Regionally, there are significant variations in WTP, from 102 to 487 252 SEK/kgP. Behind the large variations is the fact that areas that have a larger population but a smaller reduction target tend to have a higher WTP per kg of P, whereas areas with smaller populations and larger reduction targets have smaller WTP per kg of P. Therefore, the authors have summarised the WTP across Sweden's five water districts, see Figure 4.6, providing more generalised values that are less dependent on specific population sizes and reduction targets. Detailed values for each district are presented in Table 4.5, which also shows the national average WTP.

Table 4.5: WTP in different water districts for reducing P discharge into inland waters, originally expressed in 2012 value with conversions to 2024 value (Söderqvist and Wallström, 2017).

Letter	District	Original value (SEK/kgP)	2024 value (SEK/kgP)
jj	Bottenviken	560-670	740-890
kk	Bottenhavet	9 700-11 000	13 000-15 000
ll	Norra Östersjön	4 500-5 200	5 900-6 900
mm	Södra Östersjön	2 900-3 300	3 800-4 400
nn	Västerhavet	2 000-2 300	2 600-3 000
oo	National	3 100-3 500	4 100-4 600



Figure 4.6: Map of Sweden’s five water districts. Adapted map generated with ChatGPT-4 using the prompt: “Generate a picture showing the outline of the Swedish map, just the land-borders, and fill the map with this colour: 1C6A91”. The district sectioning is inspired by Vattenmyndigheterna (n.d.).

In the article by Söderqvist and Wallström (2017) the authors also refer to another study where the WTP among Baltic-connected countries have been measured to meet the BSAP target for reducing P discharge into the Baltic Sea. Here, the Swedish population accounts for a WTP of 5 173 million SEK annually, reflecting a WTP of 430 SEK/kgP. For Baltic-connected countries in total, the WTP is instead 32 548 million SEK annually, reflecting a WTP of 2 700 SEK/kgP. The values can be assumed to be expressed in 2014 prices, as this is the year of which the referred to study was conducted.

CE Delft, as for N discharge to water, also provides environmental price estimates for total P discharge to freshwater systems (de Vries et al., 2024). In their handbook: *The Environmental Prices Handbook 2024: EU27 version*, the central estimate is 3.74 EUR/kgP, with a lower bound of 2.56 EUR/kgP, and an upper bound of 10.13 EUR/kgP, all expressed in 2021 value. These values represent the estimated SC-P in the environment, primarily accounting for its role in water pollution and eutrophication.

The Danish emission tax, which includes charges for N discharge, also applies to P discharge from WWTP effluents under the *Spildevandsafgiftsloven* regulation. For total P, the tax rate is set at 183.64 DKK/kgP in 2024 (Skatteministeriet, 2022).

4.1.5 BOD discharge to water

Finding reference values for the monetised value of BOD discharge to water proved to be challenging. The research was discontinued after identifying only one value, which was the Danish emission tax *Spildevandsafgiftsloven*, which sets the tax rate for BOD₅ at 18.36 DKK/kgBOD₅ for 2024, or 28 SEK/kgBOD₅ in 2024 (Skatteministeriet, 2022). The value is displayed in detail in Table A.5.

4.2 Weighted score ratios

From eight previous sustainability assessments (A-H), WSRs were calculated (Equation 3.1) for the sustainability criteria: climate impact, energy use, and nutrient discharge (N, P, and BOD) to receiving waters, with cost as the comparable factor. The WSRs reflect the valuations made in these assessments and will be used for comparison with the reference values. Not all assessments included every sustainability criterion of interest, but WSR calculations were performed for the criteria that were included.

The sustainability assessments studied were the following:

- A. Resource recovery in the Baltic Sea region, two case studies (Johannesdottir et al., 2021).
 - WSRs: Climate impact, and discharge of N & P).
- B. Water reuse at the Rya WWTP - a master's thesis (Backeström and Ceder, 2022).
 - WSRs: Climate impact, energy use, and discharge of N, P & BOD.
- C. "Nya Rya" Process investigation of the Rya WWTP (Lorick et al., 2023).
 - WSRs: Climate impact, energy use, and discharge of P & BOD.
- D. Pre-study of pharmaceutical removal at the Rya WWTP (Ernst et al., 2020).
 - WSRs: Climate impact and energy use.
- E. Pharmaceutical removal at the Rya WWTP (second edition) (Neth et al., 2023).
 - WSRs: Climate impact and energy use.
- F. System analysis of the WW management in Kalmar (Arnell et al., 2011).
 - WSR: Energy use.
- G. System study for WW and bio-waste management in the Gothenburg-region (Andersson et al., 2007).
 - WSRs: Climate impact and energy use.
- H. Leachate management to the Rya WWTP (Malmqvist et al., 2015).
 - WSRs: Climate impact, energy use, and discharge of N & P.

All calculated WSRs are presented in detail in Appendix B. Table B.1 presents the values converted to 2024 SEK, while Table B.2 shows the WSRs based on the original data. The following subsections provide brief summaries of the calculated WSRs for each criterion. Converted values are rounded to two significant figures, while original values are retained in their initial format for consistency and traceability.

4.2.1 Climate impact

The WSRs for climate impact ranged from 2 140 to 55 720 SEK/tCO₂e or, when adjusted to 2024 values, from 2 400 to 69 000 SEK/tCO₂e. Figure 4.7 illustrates the values in 2024 SEK, and Table 4.6 presents the median, minimum, and maximum values.

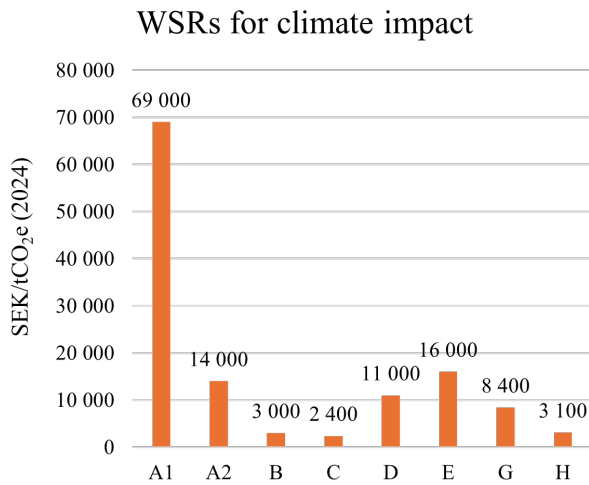


Table 4.6: Median, minimum, and maximum values of the WSRs for climate impact.

	Value	Unit
Median	9 600	SEK/tCO ₂ e
Minimum	2 400	SEK/tCO ₂ e
Maximum	69 000	SEK/tCO ₂ e

Figure 4.7: Calculated WSRs for climate impact (SEK/tCO₂e), in 2024 SEK.

There is one value in the range that stands out significantly from the other WSRs. This comes from the assessment conducted by Johannesdottir et al. (2021), where the investigated project had a very high cost for different alternatives, leading to a high cost value per score step (363 SEK/score and person) for the annual cost criterion. In contrast, the value per score step for climate impact was relatively low (3.96 kgCO₂e/score and person). Given the assigned weights for climate impact (10.4%) and annual cost (17.1%), the resulting WSR calculation amounted to 55 720 SEK/tCO₂e before conversion to 69 000 SEK/tCO₂e in 2024 value.

4.2.2 Energy use

For energy use, the WSRs ranged from 0.2 to 8.2 SEK/kWh originally in the assessments, and after conversion into 2024 SEK, from 0.2 to 11 SEK/kWh. Figure 4.8 illustrates the values in 2024 SEK, while the median, minimum, and maximum values are presented in Table 4.7.

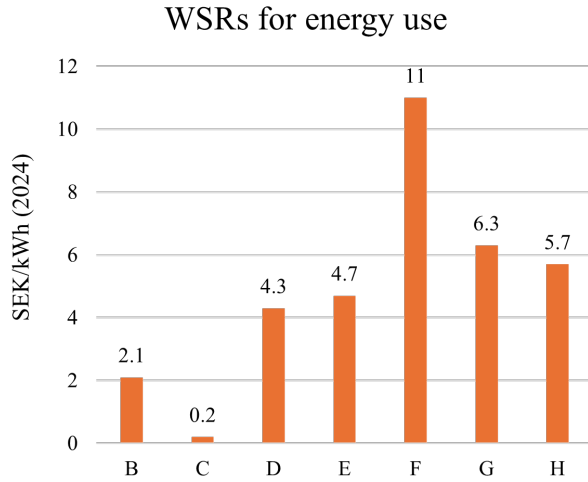


Figure 4.8: Calculated WSRs for energy use (SEK/kWh), in 2024 SEK.

Table 4.7: Median, minimum, and maximum values of the WSRs for energy use.

	Value	Unit
Median	4.7	SEK/kWh
Minimum	0.2	SEK/kWh
Maximum	11	SEK/kWh

4.2.3 Nitrogen discharge

Regarding the WSRs for N discharge, the assessment values ranged originally from 32 to 3 762 SEK per kg of N, while after conversion to 2024 SEK, from 36 to 5 000 SEK/kgN. Figure 4.9 illustrates the values in 2024 SEK, and Table 4.8 presents the median, minimum, and maximum values.

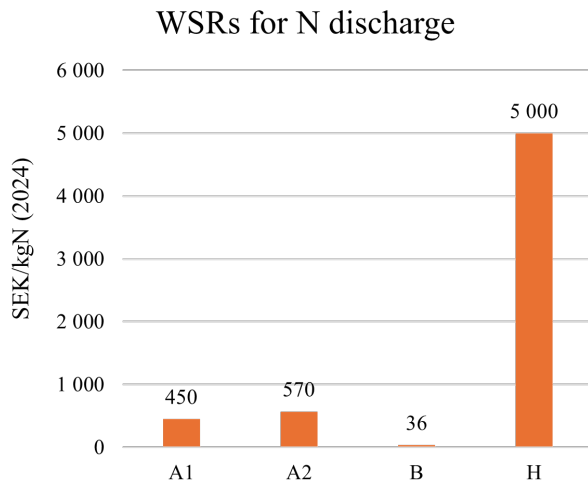


Figure 4.9: Calculated WSRs for N discharge (SEK/kgN), in 2024 SEK.

Table 4.8: Median, minimum, and maximum values of the WSRs for N discharge.

	Value	Unit
Median	510	SEK/kgN
Minimum	36	SEK/kgN
Maximum	5 000	SEK/kgN

Particularly one value is rather high compared to the rest of the WSRs, pushing the average value (1 500 SEK/kgN) up much higher than the median. The reason for this is the rather small value per score step for N in the assessment conducted by Malmqvist et al. (2015) (1 050 kg N/score), compared to the value per score step for annual cost (39 500 000 SEK/score). Given the assigned weights for eutrophication caused by N (3%) and annual cost (30%), the calculated WSR becomes 3 762 SEK/kgN.

4.2.4 Phosphorus discharge

The WSRs for P discharge originally ranged from 8 to 91 860 SEK per kg of P, and after conversion to 2024 SEK, from 9 to 120 000 SEK/kgP. These values are displayed in Figure 4.10, while Table 4.9 presents the median, minimum, and maximum values.

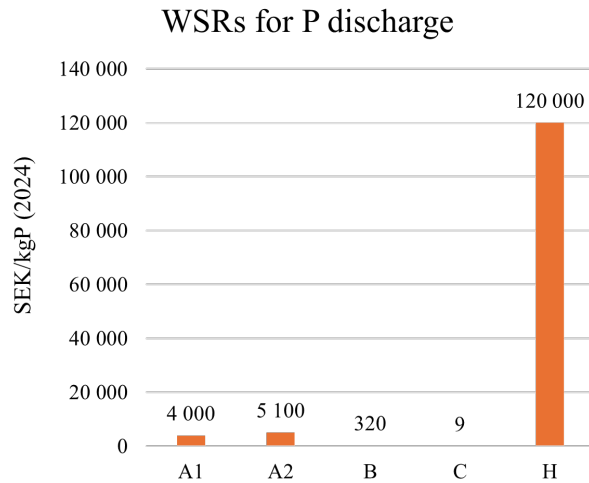


Table 4.9: Median, minimum, and maximum values of the WSRs for P discharge.

	Value	Unit
Median	4 000	SEK/kg P
Minimum	9	SEK/kg P
Maximum	120 000	SEK/kg P

Figure 4.10: Calculated WSRs for P discharge to water (SEK/kg P), in 2024 SEK.

The median value is low compared to the average (26 000 SEK/kgP) and maximum values in the range. The primary reason for this is the high WSR in one of the assessments, conducted by Malmqvist et al. (2015). Same as for N, is the criteria eutrophication (regarding P discharge) assigned the weight 3% in the assessment. At the same time, the value of one score step for P is quite low (43 kg P/score) compared to the value of one score step for annual cost (39 500 000 SEK/score). As already mentioned, the assigned weight for the criterion for annual cost was 30%, leading to a WSR of 91 860 SEK/kgP.

4.2.5 BOD discharge

Only two assessments included BOD discharge as a criterion (B & C), and the WSRs calculated from these resulted in values of 0.2 and 7 SEK per kg of BOD. After conversion to 2024 SEK, the values were 0.2 and 7.8 SEK per kg of BOD.

4.3 Workshop results

A total of three workshops were conducted with different assessment groups, following the methodology outlined in Section 3.5. Two real-world cases formed the basis for applying the two different weighting approaches. The assessment groups were the following:

- **Utility group (U):** This group consisted of six employees at Gryaab that together had a deep knowledge about WWT and were experienced with sustainability assessments.
- **Academic group (A1 & A2):** This group comprised professors, post-doctoral researchers, PhD students, and master's students from Chalmers University of Technology, affiliated with the Water Environment Technology (WET) group. Given the group's size of twelve participants, they were divided into two subgroups of six. However, some professors had to leave before the second weighting exercise based on reference values was carried out, which may have introduced some bias into the results.
- **Consultant group (C):** This group consisted of five consultants at the company Envidan who had their expertise in different parts of the urban water cycle. They all had a deep understanding of sustainability issues.

The following sections present the workshop results for each case, along with the assessment groups' reasoning behind the selected weights and reference values.

4.3.1 Case 1: Pre-study of pharmaceutical removal at the Rya WWTP

The first case was built on the assessment conducted by Ernst et al. (2020), where a pre-study for pharmaceutical removal at the Rya WWTP in Gothenburg was assessed through an MCA. The assessment covered three different system alternatives: ozonation, powdered activated carbon (PAC), and granular activated carbon (GAC). The involved criteria comprised of quantitative and qualitative criteria covering all of the three sustainability dimensions: *environmental, social, and economical*. For instance did the assessment involve the criteria "usable heat production", "public perception", and "annual cost". The criteria of focus for weighting during the workshops were: climate impact and energy use. These criteria were weighted in relation to the other criteria with fixed weights ranging from 5–25.

Table 4.10 displays the normalised weights (%) for each criteria, from the two different weighting approaches, per group. Further in this section follows the individual discussions for case 1 per group when performing the two weightings.

Table 4.10: Results from the weighting of climate impact and energy use in case 1 by the four assessment groups (U, A1, A2, C), including the initially assigned weights in the conventional weighting approach and the selected WTP values in the second weighting approach. For both methods, the resulting normalised weights (in percent) are also presented.

Criterion	Group	Conventional weighting		WTP-weighting	
		Weight	Norm. Weight	WTP	Norm. Weight
Climate impact	U	20	12%	2 800 SEK/tCO ₂ e	7%
	A1	25	15%	2 500 SEK/tCO ₂ e	6%
	A2	17	9%	3 500 SEK/tCO ₂ e	9%
	C	30	17%	4 500 SEK/tCO ₂ e	11%
Energy use	U	5	3%	0.25 SEK/kWh	1%
	A1	5	3%	2.0 SEK/kWh	6%
	A2	23	13%	1.4 SEK/kWh	4%
	C	10	6%	0.7 SEK/kWh	2%

U=Utility, A1=Academic 1, A2=Academic 2, C=Consultant

The utility group discussed various perspectives regarding energy use, with particular attention to the vulnerability associated with high energy consumption. It was argued that relying heavily on energy makes systems more susceptible to disruptions, such as power shortages or outages, which could require backup power and limit functionality. Additionally, the broader societal implications were considered, including the potential need to expand the electricity grid to support high consumption. It was also noted that energy efficiency aligns with organisational goals for Gryaab, highlighting its relevance. Despite some initial disagreement on the level of importance, the group concluded that, relative to other criteria, a weight of 5 was appropriate. For the criterion climate impact, there was unanimous agreement that it is of very high importance. The group therefore assigned it a weight of 20.

Regarding the WTP for climate impact, the utility group was unanimous in viewing the Nordhaus reference value of 1 700 SEK/tCO₂e (Gustafsson, 2021) as a minimum threshold. The group considered the WSR from the assessment *Nya Rya* by Lorick et al. (2023) to be a reliable benchmark, given the extensive work behind it and the fact that some in the group had authored the report. While some proposed using Gryaab's KPI value of 3 000 SEK/tCO₂e, this was considered slightly too high and ultimately voted down. As a compromise, the group settled on a WTP of 2 800 SEK/tCO₂e. For energy use, the group agreed that the valuation should not exceed the cost of expanding new

energy production. The cost of new nuclear power was acknowledged as high, so the group preferred a lower valuation to provide a more reasonable and proportionate reference. It was also noted that high energy consumption increases vulnerability, which should be reflected in the valuation. The group considered the reference value of 0.2 SEK/kWh used in *Nya Rya* (Lorick et al., 2023) as a useful starting point, but slightly too low. In the end, the group reached consensus on a WTP of 0.25 SEK/kWh.

The weighting of the criteria climate impact and energy use varied notably between the two academic groups (A1 & A2), reflecting different priorities and perspectives. In A1, climate impact was given high importance during the conventional weighting step, with the group ultimately assigning it a weight of 25. There was strong consensus that climate impact should be prioritised in light of its increasing relevance in societal and political decision-making. Some members initially suggested a lower weight, around 15, comparable to other criteria, but the group agreed that its importance warranted a higher valuation. In contrast, energy use was considered less critical. While its relevance as a limited resource and source of potential vulnerability was acknowledged, a dominant view in the group held that these concerns did not justify a high weighting. Consequently, energy use was assigned a weight of 5. A2 also recognised the significance of climate impact but evaluated it slightly differently. While the criterion was considered important, it was not prioritised over other criteria such as cost, safety, and work environment. As a result, the group assigned climate impact a weight of 17. In contrast to A1, energy use was viewed as a highly important criterion in A2, largely due to anticipated future constraints in energy distribution. The group stressed the importance of favouring alternatives with lower energy consumption and ultimately assigned energy use a weight of 23.

The WTP also differed between the two academic groups. In A1, there was no full agreement within the group. Some participants considered William Nordhaus's estimate of 1 700 SEK/tCO₂ (Gustafsson, 2021) a well-founded baseline for climate impact, while others favoured aligning with the EU ETS value of 740 SEK/tCO₂ (European Energy Exchange, 2024), as it reflects the established market price for carbon dioxide. One member argued in favour of using the ETS value, noting that emission permits could be purchased from actors able to reduce emissions more cost-effectively. However, the majority disagreed, reasoning that a municipality with both the resources and responsibility to act should not rely on purchasing permits. Other suggestions included taking the average of several values, while some maintained that Nordhaus's estimate remained the most credible reference point, although a slightly higher value was justified given the proximity of 2030 climate targets. The group ultimately agreed on a WTP of 2 500 SEK/tCO₂e. In A2, the group chose a higher WTP for climate impact, settling on 3 500 SEK/tCO₂e. Although the recommended value by the City of Gothenburg of 5 900 SEK/tCO₂ (Göteborgs Stad, n.d.) was considered, the group opted for a lower figure, considering other available estimates. For energy use, the discussion progressed slowly in the A1 group, as they found the valuation challenging. Eventually, a consensus emerged around selecting a value slightly above the total average electricity price at Rya WWTP in 2024 equalling 1.4 SEK/kWh (M. Neth, personal communication, 24 January 2025), and the group settled on 2.0 SEK/kWh. In A2, the group did not remain consistent with their conventional weighting, where energy use had been given a high weight. Instead, they opted for a medium valuation of 1.4 SEK/kWh, in line with the total average electricity price at Rya WWTP in 2024 (M. Neth, personal communication, 24 January 2025).

The consultant group assigned a weight of 30 to climate impact, reflecting its strong relevance in political and societal goals. They agreed that such priorities should be clearly visible in the decision-making process, thus giving climate impact a higher weight than annual cost (fixed at 25). Energy use was given a lower weight of 10. While still considered important, its impact on climate was not directly included in the criterion. However, as a limited resource in society, the group found it appropriate to assign it a moderate weight.

When determining the WTP for climate impact, the consultant group agreed on a reference value of 4 500 SEK/tCO_{2e}. This level was considered consistent with the climate ambitions of the City of Gothenburg ranging between 4 400–7 400 SEK/tCO₂ (Göteborgs Stad, n.d.). It was argued that the cost of climate measures should be adapted to local context, with higher valuations being appropriate in Sweden due to its economic capacity and environmental commitments. The chosen value exceeds both the Swedish carbon tax of 1 500 SEK/tCO₂ (Regeringen, 2024) and the estimate proposed by Nordhaus of 1 700 SEK/tCO₂ (Gustafsson, 2021), which was regarded as a minimum threshold. Gryaab's internal KPI value of 3 000 SEK/tCO_{2e} (Lorick & Videbris, 2024), reflecting the customer's valuation, was also taken into account. However, the group found it difficult to justify setting the level below this and ultimately agreed that 4 500 SEK/tCO_{2e} represented a reasonable and contextually appropriate reference. For the criterion energy use, the group discussed whether the WTP should reflect the added value of reduced energy consumption beyond the actual electricity price, which was confirmed. Based on recent and relevant reference values, the group agreed that a range of 0.5–0.7 SEK/kWh was reasonable. Ultimately, the consultant group settled on 0.7 SEK/kWh as an appropriate value.

The total sustainability scores for each alternative, based on the weighting method applied, are presented in Figure 4.11, which shows the combined results from all assessment groups. The error bars in the diagram illustrate the variation in outcomes between the groups. For reference, the original results from the assessment conducted by Ernst et al. (2020) are also included.

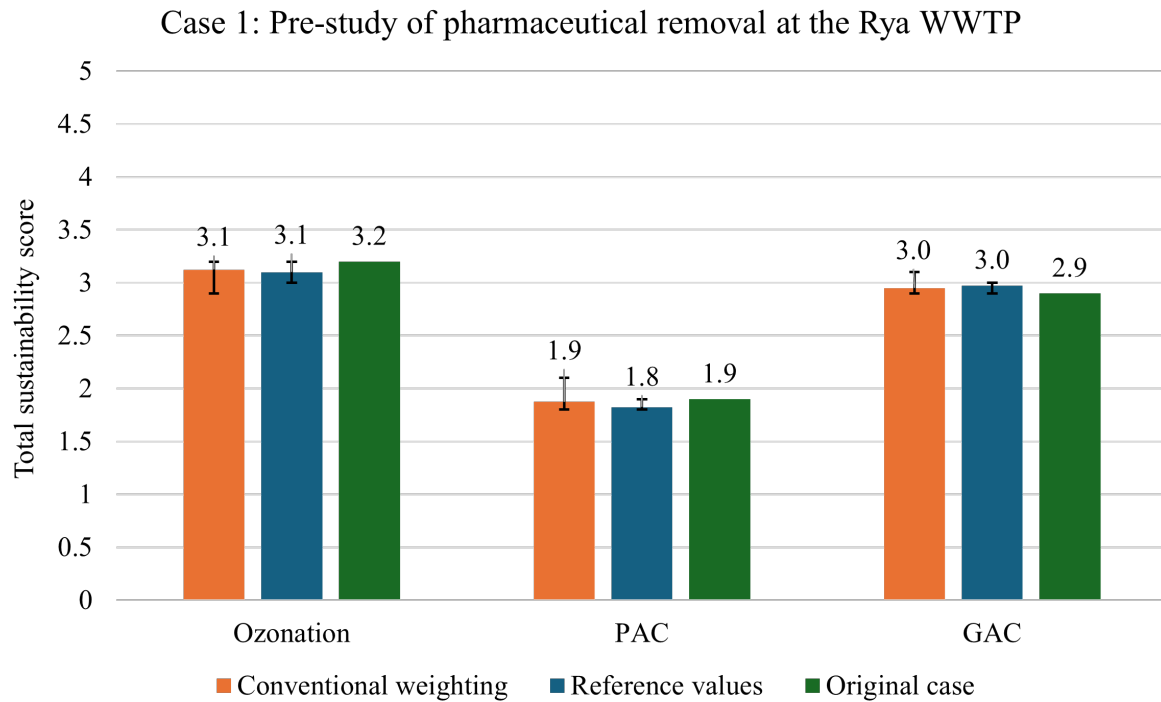


Figure 4.11: Workshop results for case 1 present the total sustainability score for each treatment alternative (ozonation, PAC, and GAC), combined for the assessment groups. The bars represent outcomes using two different weighting approaches: the conventional weighting method (orange) and weighting based on reference values (blue). Next to these are the total sustainability scores from the original assessment conducted by Ernst et al. (2020) (green).

To illustrate the actual variation between groups, the total sustainability scores for each assessment group are presented in Table 4.11.

Table 4.11: Total sustainability scores per alternative and assessment group, case 1.

	Total sustainability score with conventional weighting				Total sustainability score with WTP-weighting			
	U	A1	A2	C	U	A1	A2	C
Ozonation	3.2	3.2	2.9	3.2	3.1	3.0	3.1	3.2
PAC	1.8	1.8	2.1	1.8	1.8	1.9	1.8	1.8
GAC	2.9	2.9	3.1	2.9	3.0	3.0	3.0	2.9

U=Utility, A1=Academic 1, A2=Academic 2, C=Consultant

4.3.2 Case 2: Resource recovery in the Baltic Sea region (Fyris, Sweden)

The second case was based on the assessment by Johannesdottir et al. (2021), which investigated resource recovery measures of N, P, and C at a WWTP in the Fyriså catchment in Uppsala, Sweden, where the recipient "Fyriså river" discharges into the Baltic Sea. The three different system alternatives were the following: incineration, nutrient extraction, and source-separation. The criteria involved in the assessment were divided into qualitative and quantitative criteria, for instance "nutrient recovery", "total costs", and "acceptance". For the workshop the criteria of focus in the two weightings were: climate impact and eutrophication potential, which for the reference values weighting was divided into N and P discharge to water (weight distribution: 80% for N and 20% for P). For the conventional weighting, the weights were set in relation to the other criteria with fixed weights ranging between 7–19.

Table 4.12 presents the selected weights and WTP values per assessment group and criterion, along with the corresponding normalised weights. The criteria eutrophication potential is divided into N & P discharge, although this distinction was not made in the first weighting step (conventional weighting). The weight distribution for N and P is the following: 80% of the weight for N and 20% for P. The remainder of this section summarises the individual discussions that took place during the workshops and the reasoning behind the estimates.

Table 4.12: Results from the weighting of climate impact and N & P discharge to water in case 2 by the four assessment groups (U, A1, A2, C), including the initially assigned weights in the conventional weighting approach and the selected WTP values in the second weighting approach. For both methods, the resulting normalised weights (in percent) are also presented.

Criterion	Group	Conventional weighting		WTP-weighting	
		Weight	Norm. Weight	WTP	Norm. Weight
Climate impact	U	12	13%	2 800 SEK/tCO ₂ e	1%
	A1	13	13%	2 500 SEK/tCO ₂ e	1%
	A2	13	13%	3 500 SEK/tCO ₂ e	1%
	C	15	16%	4 500 SEK/tCO ₂ e	1%
N discharge to water	U	8	9%	150 SEK/kgN	2%
	A1	15	15%	150 SEK/kgN	2%
	A2	15	15%	53 SEK/kgN	1%
	C	8	9%	160 SEK/kgN	2%
P discharge to water	U	2	2%	7 000 SEK/kgP	3%
	A1	4	4%	10 000 SEK/kgP	4%
	A2	4	4%	4 500 SEK/kgP	2%
	C	2	2%	4 500 SEK/kgP	2%

U=Utility, A1=Academic 1, A2=Academic 2, C=Consultant

The utility group found it challenging to assign a weight to the eutrophication potential criterion, as it was not separated into N and P, which would have felt more relevant. It was also difficult to evaluate the criterion without knowing the sensitivity of the recipient, along with how the criterion relates to established requirements or permit conditions. The group ultimately agreed on a weight of 10. For climate impact, the group considered it important and decided to relate the weighting to that used in case 1, meaning it should have a high priority. While suggestions ranged from 10 to 15, there was concern that 15 would be too high in relation to the other criteria. The group reached consensus on a weight of 12 but noted the difficulty of deciding without being able to calculate the WSRs iteratively alongside the weighting.

For the WTP for the criterion climate impact, the utility group considered it reasonable to use the same basis as in case 1 and remained consistent with their previously established value of 2 800 SEK/tCO₂e. For N and P discharge, the group considered mitigation costs

associated with the BSAP target, 150 SEK/kgN and 7 100 SEK/kgP (Naturvårdsverket, 2012), to be relevant and decided on values of 150 SEK/kgN and 7 000 SEK/kgP.

Both academic groups A1 and A2 assigned identical weights for climate impact and eutrophication potential, with 13 for climate impact and 19 for eutrophication potential. These weightings reflect a shared judgement that, in the context of the case and the sensitivity of the recipient, eutrophication potential should be prioritised over climate impact.

The academic groups took different directions when deciding on the WTP. For climate impact, both A1 and A2 decided to keep their valuations from case 1, as they found it applicable to this case as well. The WTP for climate impact was decided on 2 500 SEK/tCO₂e for group A1, and 3 500 SEK/tCO₂e for A2. For P discharge to water, A1 opted for a value of 10 000 SEK/kgP, reflecting the WTP in the water district *Bottenhavet* (see Table 4.5) and recognising P as more critical than N for this recipient. At the same time, they chose 150 SEK/kgN, aligning with both the mitigation cost to meet BSAP target of 150 SEK/kgN (Naturvårdsverket, 2012) and the SC-N of 170 SEK/kgN (Brink et al., 2011). For A2, the WTP for P discharge was 4 500 SEK/kgP. Regarding N discharge, A2 chose a value of 53 SEK/kgN, aligning with both the SC-N set by Keeler et al. (2016) to 49 SEK/kgN and the Danish emission tax of 51 SEK/kgN (Skatteministeriet, 2022).

The consultant group noted that if a technique performs well in nutrient recovery, it may also contribute positively to reducing eutrophication potential. While the two criteria reflect different aspects, their interrelation was acknowledged. The group discussed the relevance of recipient sensitivity, given that the local recipients are particularly vulnerable to eutrophication. However, it was argued that environmental permits should already account for such sensitivity. The group initially considered assigning a weight of 20 to eutrophication, but after further deliberation agreed on a weight of 10, aligning it with the weight for the criteria nutrient recovery (fixed at weight 10). Regarding climate impact, there was discussion on whether it should carry the same weight as the acceptance criterion (fixed at weight 19). While some argued for equal weighting, others maintained that acceptance should be weighted higher. The group ultimately agreed to assign climate impact a weight of 15.

When deciding the WTP, the consultant group agreed that the valuation of climate impact should remain consistent across different contexts. It was considered important to establish a national benchmark for the level of investment deemed acceptable for climate-related measures, regardless of local circumstances. The group therefore retained the value previously determined in case 1, which was 4 500 SEK/tCO₂e. For the criteria eutrophication, the group acknowledged the variability in both sources and impacts. It was suggested that a reference value, such as the cost of precipitation per kg P, would have been useful. Questions were raised concerning the nature of the measures and how the allocated funds would be applied. The group ultimately agreed on a WTP value of 4 500 SEK/kgP, based on BSAP mitigation cost estimates (7 100 SEK/kgP) presented by Naturvårdsverket (2012) and the variation in WTP across Sweden's water districts (see Table 4.5). As P was considered the more critical nutrient due to its greater sensitivity in local recipients, N was assigned a considerably lower valuation. It was suggested that achieving good water status in the River Fyris could be relevant, though reference values were difficult to identify. The group ultimately settled on a value of 160 SEK/kgN, in

line with BSAP mitigation costs (150 SEK/kgN) (Naturvårdsverket, 2012) and the SC-N of 170 SEK/kgN presented by Brink et al. (2011).

The total sustainability scores from the different weighting approaches are displayed in Figure 4.12, combined for all the assessment groups with error bars displaying the variation in results.

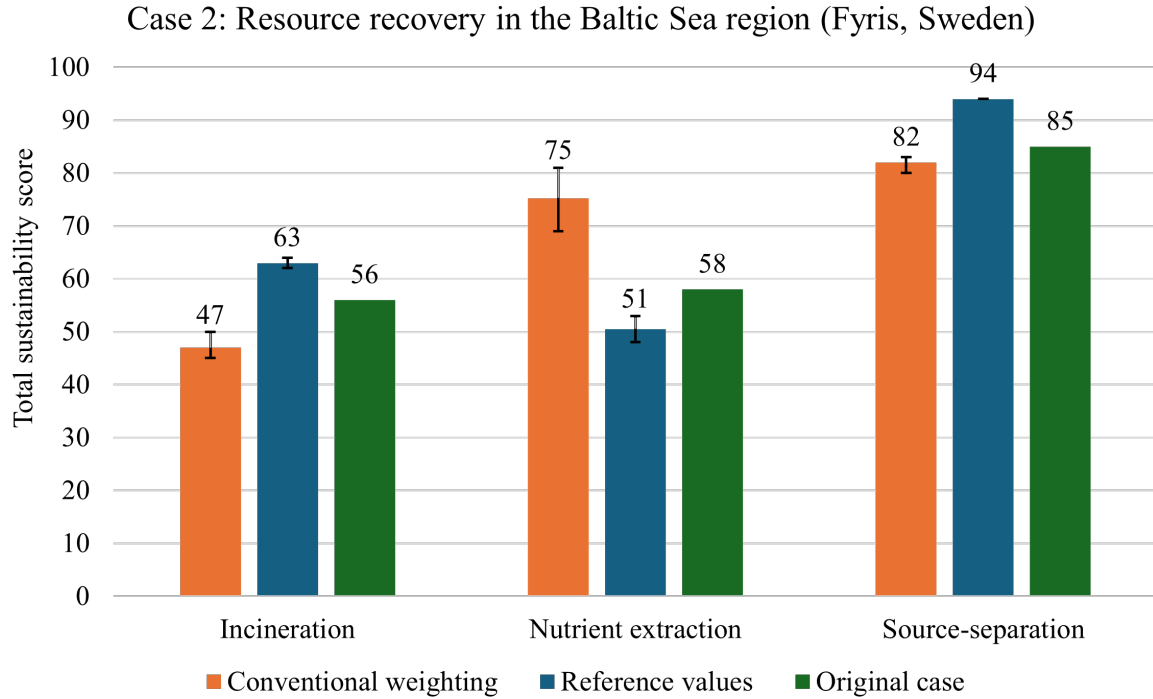


Figure 4.12: Workshop results for case 2 present the total sustainability score for each alternative (incineration, nutrient extraction, and source-separation), combined for the assessment groups. The bars represent outcomes using two different weighting approaches: the conventional weighting method (orange) and weighting based on reference values (blue). Next to these are the total sustainability scores from the original assessment conducted by Johannesdottir et al. (2021) (green).

The total sustainability scores per assessment group and weighting approach are detailed in Table 4.13.

Table 4.13: Total sustainability scores per alternative and assessment group, case 2.

	Total sustainability score with conventional weighting				Total sustainability score with WTP-weighting			
	U	A1	A2	C	U	A1	A2	C
Incineration	50	45	45	48	63	62	64	63
Nutrient extraction	69	81	81	70	51	53	48	50
Source-separation	82	83	83	80	94	94	94	94

U=Utility, A1=Academic 1, A2=Academic 2, C=Consultant

5

Results analysis

This chapter presents an analysis of the collected reference values and calculated WSRs (Equation 3.1) from conventional MCAs, both from previous assessments and workshop exercises. The aim is to explore how sustainability criteria have been valued across different contexts and to assess how the use of reference values influences the consistency, transparency, and objectivity of these evaluations.

5.1 Reference values and previous valuations

A comparison between the collected reference values and WSRs derived from previous assessments provide valuable insight into how sustainability criteria have been valued in previous assessments, and how these valuations differ from those used by industry, governmental bodies, and other external sources. The comparison between these values for the sustainability criteria climate impact is shown in Figure 5.1.

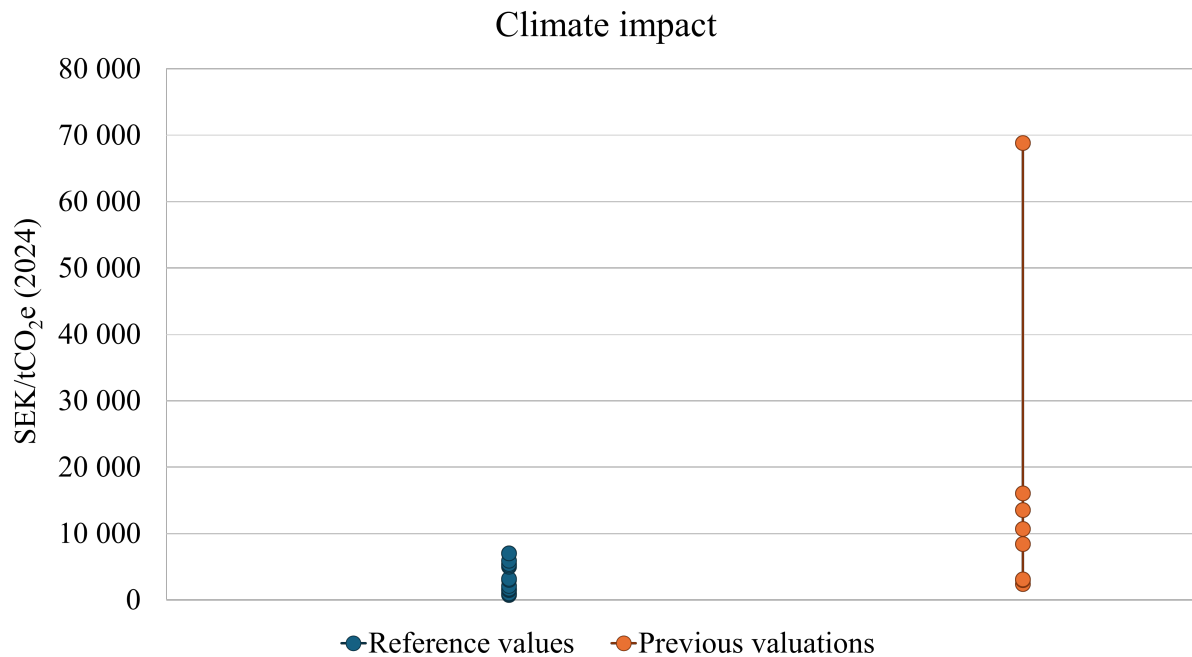


Figure 5.1: Comparison of the valuation made in previous sustainability assessments (orange) and the collected reference values (blue) for the sustainability criteria climate impact (SEK/tCO₂e), expressed in 2024 value.

As illustrated in Figure 5.1, the variation in valuations from previous assessments is substantial, reaching up to 66 000 SEK/tCO_{2e}, compared to a much narrower range of 6 300 SEK/tCO_{2e} among the collected reference values. This pronounced difference indicates inconsistency in how climate impact has been valued historically. While the reference values present a more centralised and policy-aligned benchmark, the wide spread in previous valuations suggests subjectivity, likely influenced by differing interpretations, organisational priorities, stakeholder interests, or perceived environmental urgency. The fact that many of the valuations exceed those used by industry and public authorities implies that decision-makers in earlier assessments have assigned more weight to the climate impact criterion than what is economically justified by established reference values. However, a few of the valuations fall within the reference value range, some of which originate from assessments where WSRs were calculated iteratively during the weighting process. In these cases, decision-makers were made aware of the monetary implications of their weightings, which likely contributed to more balanced and informed outcomes.

A comparison between valuations from previous assessments and collected reference values for the sustainability criteria energy use is displayed in Figure 5.2.

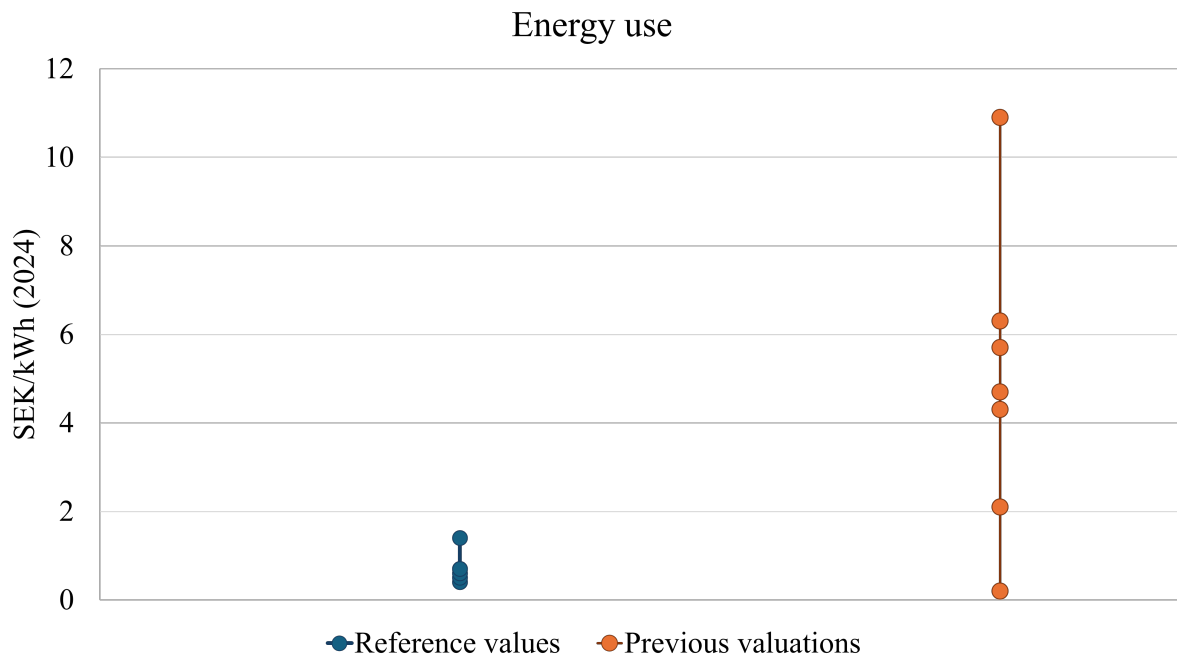


Figure 5.2: Comparison of the valuation made in previous sustainability assessments (orange), and the collected reference values (blue) for the sustainability criteria energy use (SEK/kWh), expressed in 2024 value.

The difference between calculated previous valuations and reference values for energy use follows a similar pattern as for climate impact. The valuations from previous assessments show a broader spread, reaching up to 11 SEK/kWh, while the reference values span a narrower range of 1.0 SEK/kWh. This variation suggests that the valuation of energy as a resource has not been consistent across assessments. Most of the collected reference values are based on LCOE, which represent the life cycle cost of energy generation, but do not include the market price of energy, or reflect its value as a scarce resource. Since actual

energy prices are already accounted for in the cost criterion, the energy use criterion is intended to capture energy use from a broader sustainability perspective. Whether the narrower range of reference values offers a more appropriate valuation, or if the wider spread in previous assessments better reflects context-specific priorities, remains to be discussed. However, the comparison highlights a need to clarify what is being valued, whether it is the efficiency, vulnerability, or strategic significance of energy, and to ensure that the basis for weighting is transparent and well understood.

Figure 5.3 shows the comparison of valuations from previous assessments and collected reference values for the sustainability criteria N discharge to water.

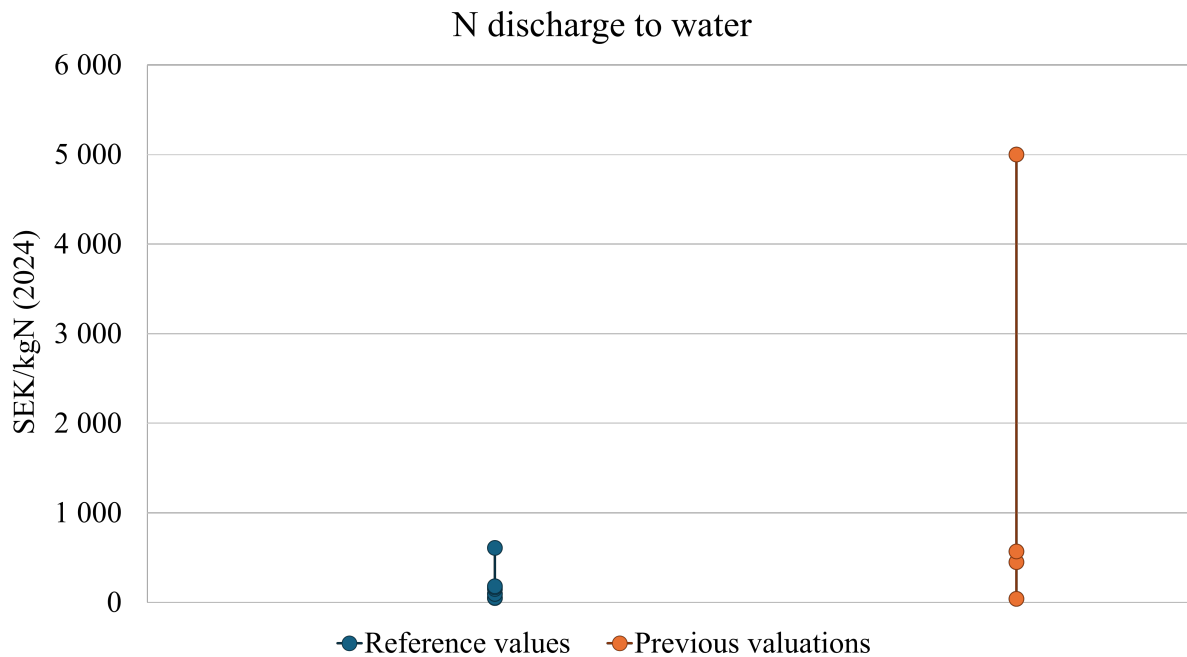


Figure 5.3: Comparison of the valuation made in previous sustainability assessments (orange), and the collected reference values (blue) for the sustainability criteria N discharge to water (SEK/kgN), expressed in 2024 value.

As with climate impact and energy use, the valuations from previous assessments for N discharge show a significantly wider variation, reaching 5 000 SEK/kgN, compared to a span of 560 SEK/kgN among the collected reference values. However, this difference appears to be largely driven by one extreme value of 5 000 SEK/kgN. When this outlier is excluded, the variation in previous valuations narrows to 530 SEK/kgN, which is slightly below the reference value range. The reference values also contain one high estimate of 610 SEK/kgN, and if this is removed, the variation decreases to 130 SEK/kgN. Despite these adjustments, the pattern suggests that N discharge has, in some cases, been assigned a higher weight than what might be economically justifiable. That said, the difference between previous valuations and the collected reference values is not as pronounced as for climate impact and energy use. In the end, the valuation of N discharge should be informed by local conditions, including the vulnerability of the recipient. New regulations (The European Parliament and the Council of the European Union, 2024) may also influence the cost of N discharge, further reinforcing the importance of site-specific and well-informed decision-making.

Figure 5.4 shows the comparison of valuations from previous assessments and collected reference values for the sustainability criteria P discharge to water.

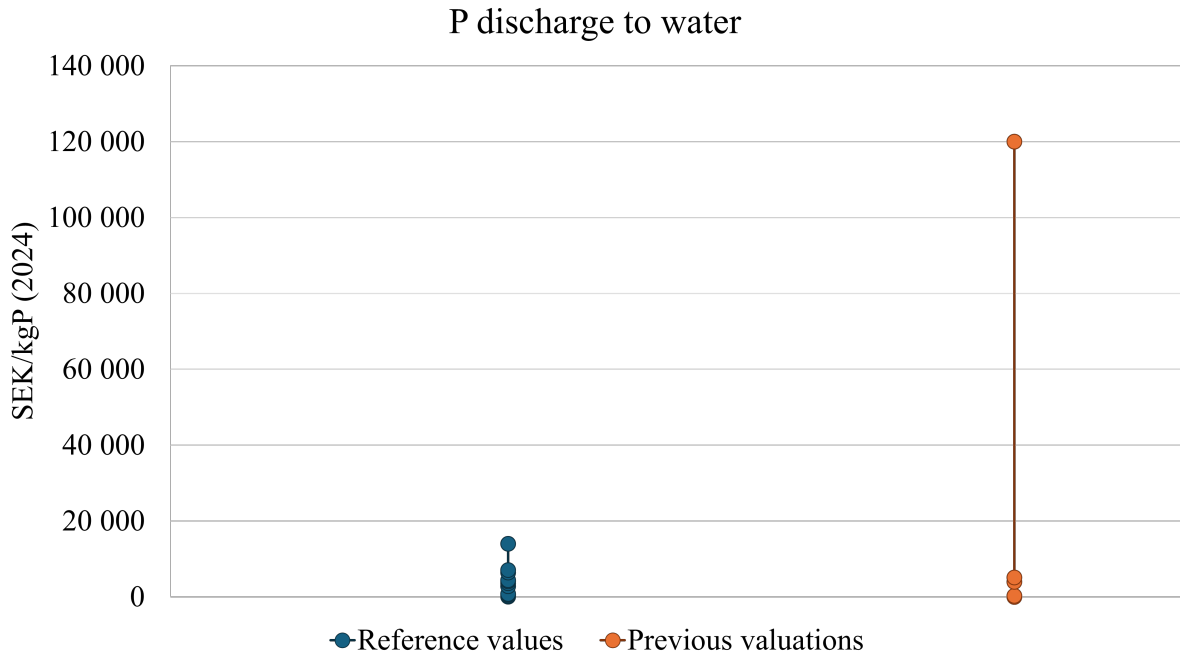


Figure 5.4: Comparison of WSRs (orange), that illustrate the valuation made in previous sustainability assessments, and the collected reference values (blue) for the sustainability criteria P discharge to water (SEK/kgP), expressed in 2024 value.

Again, there is a large variation in valuations from previous assessments also for P discharge, with a range of 120 000 SEK/kgP compared to 14 000 SEK/kgP among the collected reference values. However, one outlier strongly influences this result, and if excluded, the variation in previous valuations narrows to 5 000 SEK/kgP. The reference values also include one extreme value, and removing it reduces the variation to 7 000 SEK/kgP, which is larger than the adjusted span of the previous valuations. This could suggest that P discharge has been under-valued in previous assessments and that more weight may be warranted for this criterion. As with N discharge, decision-makers need to consider local conditions and the vulnerability of the recipient. Future costs may also need to be adjusted in response to new regulations (The European Parliament and the Council of the European Union, 2024), as stricter nutrient regulations could drive the need for more costly mitigation measures at WWTPs. In this context, the upper end of the reference range, as reflected in the estimate by Naturvårdsverket (2012), where mitigation costs could reach up to 29 000 SEK/kgP (2024 value), may become increasingly relevant.

In Figure 5.5 the comparison of valuations from previous assessments and the collected reference value for BOD discharge to water is displayed.

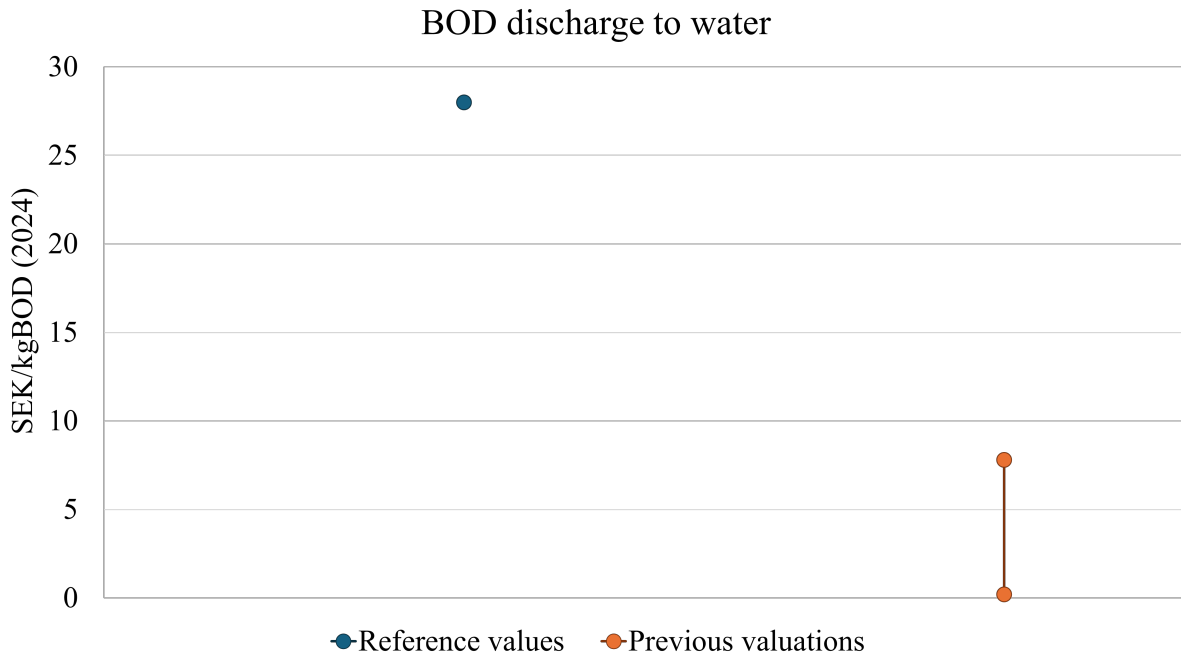


Figure 5.5: Comparison of the valuation made in previous sustainability assessments (orange), and the collected reference value (blue) for the sustainability criteria BOD discharge to water (SEK/kgBOD), expressed in 2024 value.

Only one reference value was collected for BOD, 28 SEK/kgBOD, based on the Danish emission taxation for BOD discharge in WWTP effluent, as set by Skatteministeriet, 2022. For previous valuations, two values were identified from the assessed studies, amounting to 0.2 and 7.8 SEK/kgBOD. With only one reference value available, it is difficult to draw firm conclusions, but the deviation suggests that BOD discharge may have been under-valued in previous assessments.

5.2 Workshop results

To further analyse the workshop results, box-and-whisker plots are presented in Figures 5.6 and 5.7. These figures show the combined outcomes from all assessment groups, comparing the results from conventional weighting and weighting based on reference values to determine the WTP. The two approaches are displayed side by side for each alternative, where the height of the boxes represents the variation in total sustainability scores between groups. The plots highlight how the results differ between the two methods, allowing for a direct comparison of outcomes depending on the weighting approach used. To enable deeper reflection, the total sustainability score from the original assessments is also included in the plots.

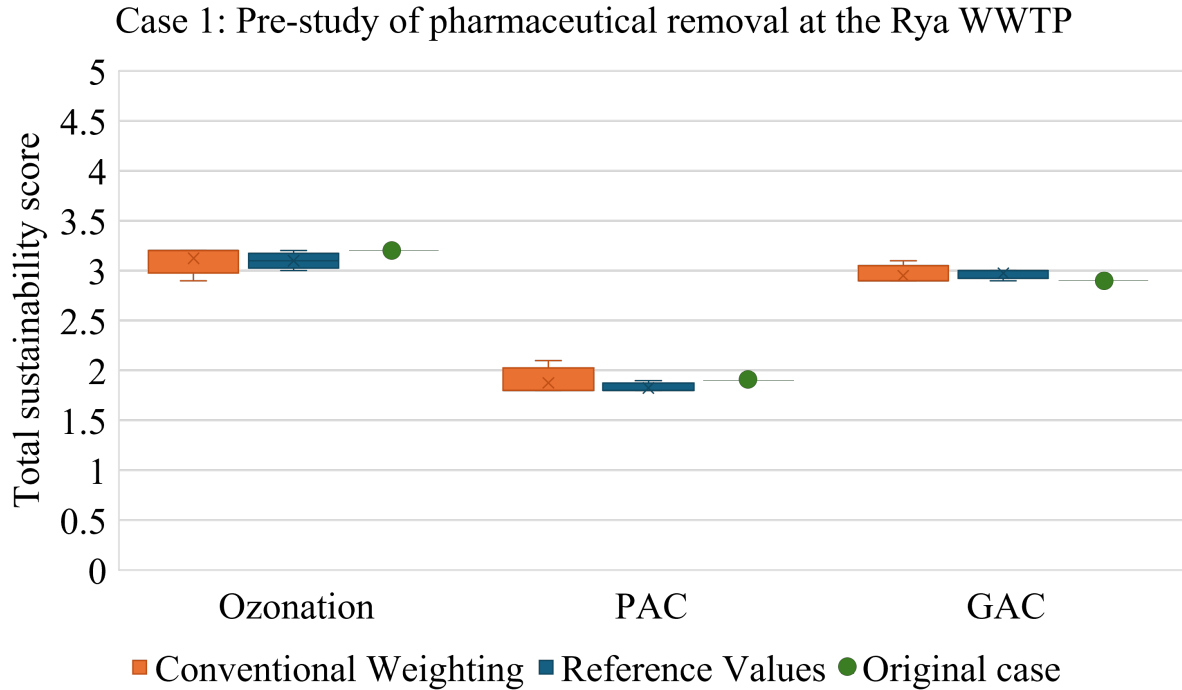


Figure 5.6: Workshop results for case 1, combined for all assessment groups, illustrating the range of total sustainability scores between the alternatives when weighting conventionally (orange) or with WTP (blue). Additionally, the results are compared with the weighting applied in the original case (green).

In case 1, PAC appears to be the least favourable alternative across all weightings, including the original weighting. However, the preference between ozonation and GAC is less clear. Especially for the workshop groups. Further analysis of both alternatives is likely beneficial before reaching a final decision. Regarding the variation in results, the distribution of total sustainability scores between the alternatives follows a similar pattern for both conventional weighting and weighting using reference values. However, the variation between assessment groups is significantly smaller when using reference values, indicating a more consistent evaluation process.

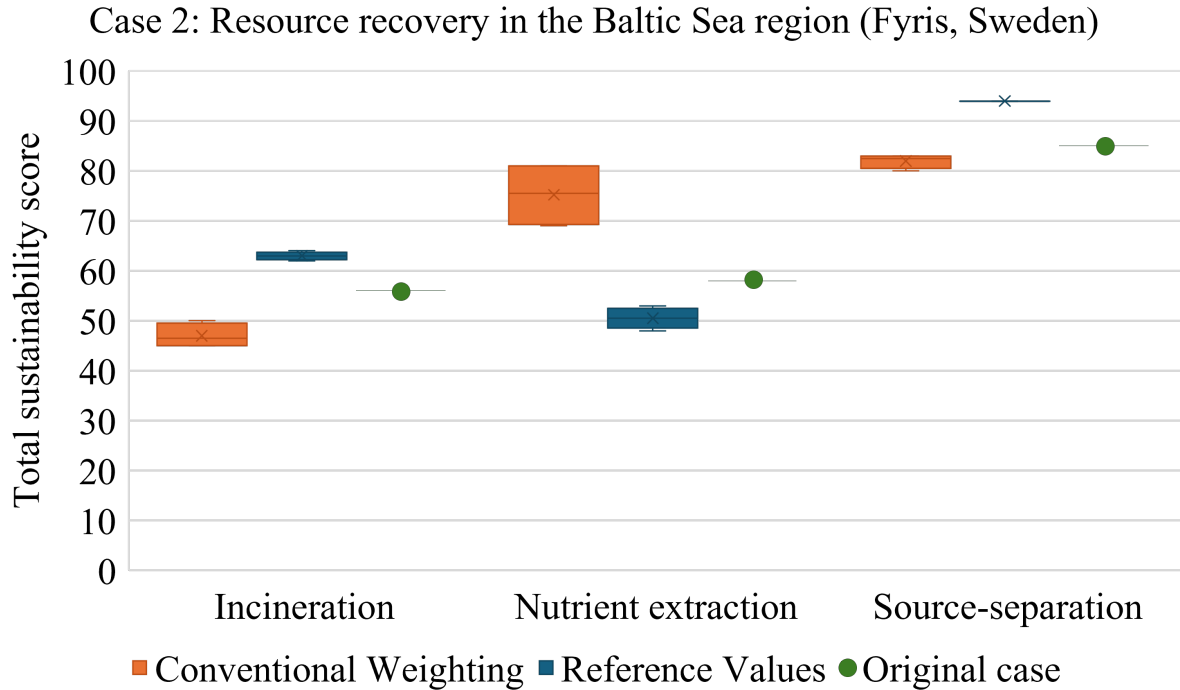


Figure 5.7: Workshop results for case 2, combined for all assessment groups, illustrating the range of total sustainability scores between the alternatives when weighting conventionally (orange) or with WTP (blue). Additionally, the results are compared to the weighting applied in the original case (green).

For case 2, source separation is clearly the most favourable alternative when using reference values in the weighting process, whereas this distinction is less pronounced with the conventional weighting method. The rankings of the other two alternatives, incineration and nutrient extraction, shift depending on the weighting approach. Another observation is that the variation in results between the assessment groups is smaller when using reference values compared to conventional weighting (as it was also in case 1). The key insight from observing the two cases and comparing the weighting methods is that weighting using reference values results in a smaller variation in the total sustainability scores between assessment groups. In contrast, the conventional weighting method led to greater variability in the results, indicating a higher degree of inconsistency across assessments.

From the conventional weightings, WSRs were calculated (Equation 3.1) to enable comparison with the WTP. The aim is to analyse the differences that emerge when both weighting methods are applied by the same assessment group. Specifically, the analysis seeks to determine whether these differences align with those discussed in Section 5.1, where WSRs derived from previous assessments were generally found to be higher than the reference values. The figures 5.8, 5.9, 5.10, and 5.11 illustrates the WSRs derived from the conventional weighting exercises conducted during the workshops, alongside the WTP by the same groups in the second weighting approach.

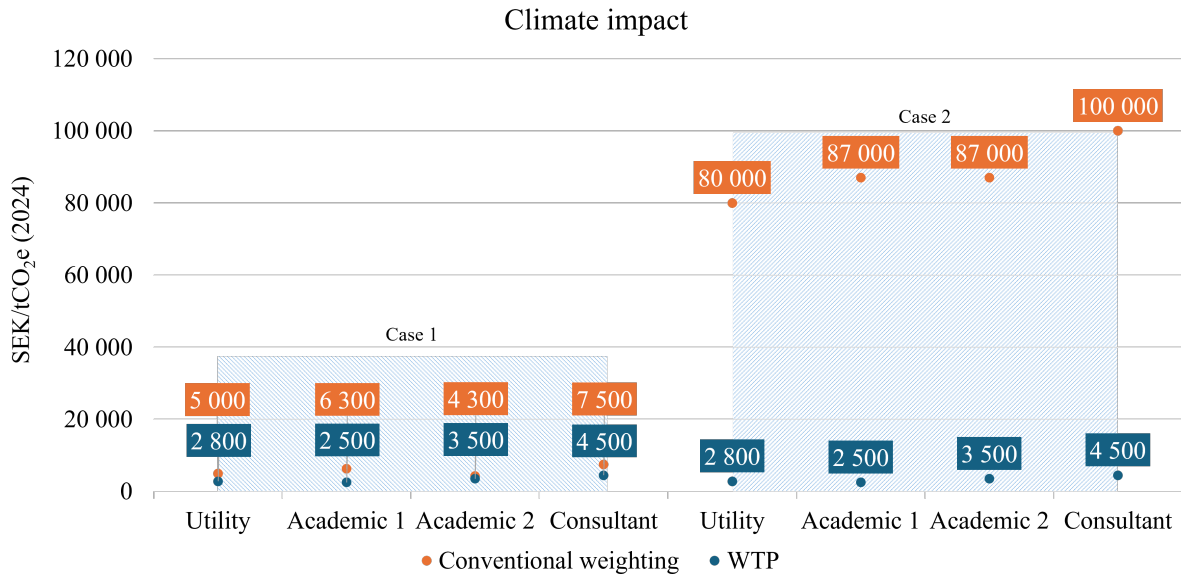


Figure 5.8: Workshop results illustrating the calculated WSRs (orange) based on the conventional weighting made by the assessment groups, and the WTP (blue) that the groups decided for the sustainability criteria climate impact (SEK/tCO_{2e}), expressed in 2024 value.

In Figure 5.8, the comparison between the WSRs derived from the conventional weighting approach and the groups' WTP is shown for both case 1 and case 2, as climate impact was included as a criterion in both assessments. What can especially be noted is the large differences between WSRs and WTP in case 2. There is also a notable difference between the WSRs and the WTP in case 1, but not as extreme as in case 2. These differences highlight how hidden valuations, when not made visible to decision-makers during the weighting process (e.g. through iterative WSR calculations), can significantly influence the outcome. The ambiguity surrounding these implicit valuations may skew results and reduce the transparency of the assessment.

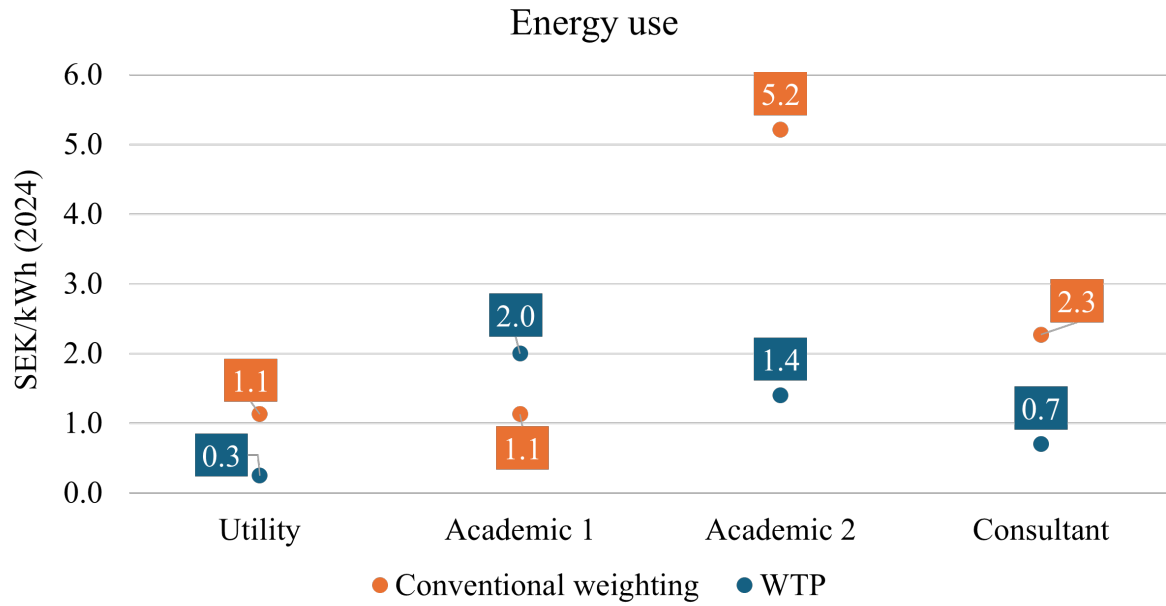


Figure 5.9: Workshop results illustrating the calculated WSRs (orange) based on the conventional weighting made by the assessment groups, and the WTP (blue) that the groups decided for the sustainability criteria energy use (SEK/kWh), expressed in 2024 value.

The differences between the derived WSRs from the conventional weighting approach and the groups' WTP for the criterion energy use in case 1 are shown in Figure 5.9. While the differences are not particularly pronounced, the results indicate greater consistency between groups when using WTP, whereas the conventional approach shows more variation.

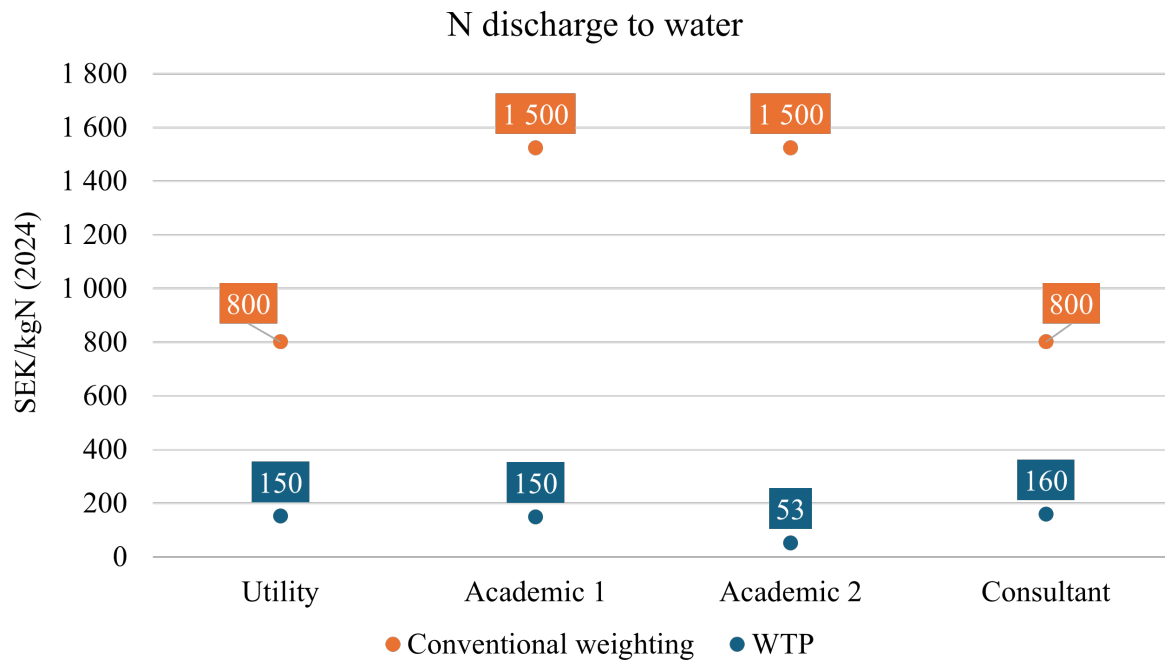


Figure 5.10: Workshop results illustrating the calculated WSRs (orange) based on the conventional weighting made by the assessment groups, and the WTP (blue) that the groups decided for the sustainability criteria N discharge to water (SEK/kgN), expressed in 2024 value.

For N discharge, the groups' WTP values were relatively similar, as shown in Figure 5.10. In the conventional weighting approach, the two academic groups arrived at the same WSR, and the utility group and the consultant group also produced identical WSRs. However, there was a notable difference between these two clusters, indicating a greater variation in perspectives when relying on conventional weighting.

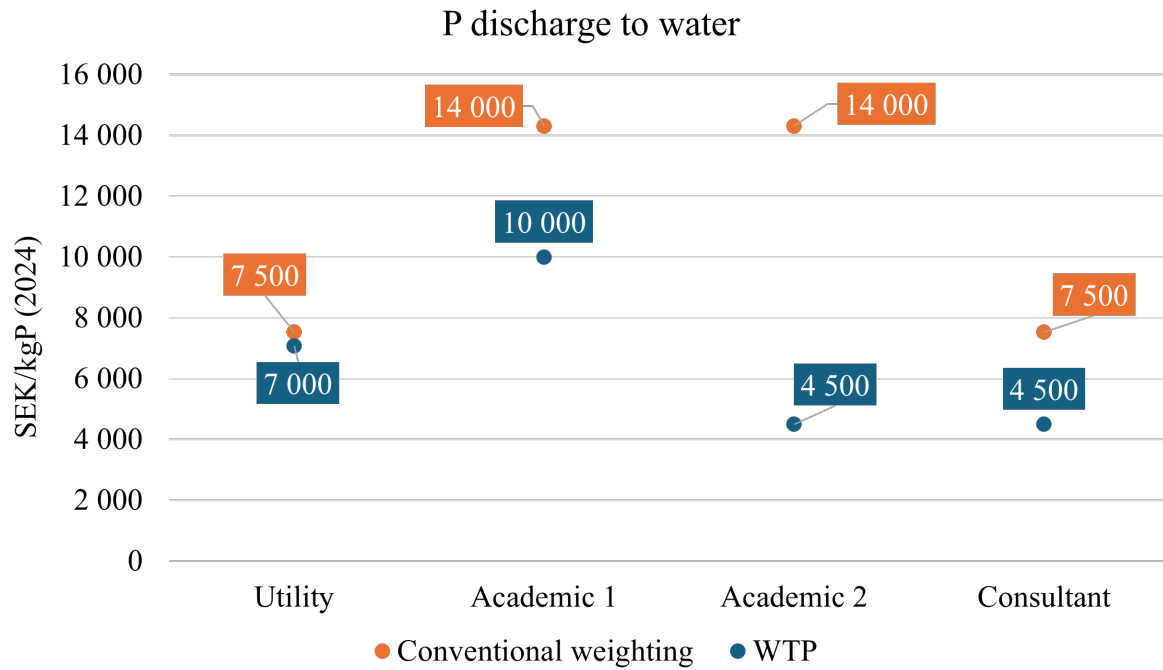


Figure 5.11: Workshop results illustrating the calculated WSRs (orange) based on the conventional weighting made by the assessment groups, and the WTP (blue) that the groups decided for the sustainability criteria P discharge to water (SEK/kgP), expressed in 2024 value.

The variation between groups for the criterion P discharge was similar across both weighting approaches, as shown in Figure 5.11. However, the groups' WTP values were generally lower than the WSRs derived from the conventional weighting approach, consistent with the pattern observed for the other criteria.

6

Discussion and conclusion

One of the primary objectives of this thesis was to identify reference values that could support more objective, transparent, and data-driven weighting in MCA. This objective was successfully achieved. For the climate impact criterion, reference values were readily available, although the main challenge lay in selecting the most relevant ones from a wide range of sources. In contrast, identifying suitable values for energy use proved more challenging, not due to a lack of data, but due to uncertainty about which type of valuation most accurately reflects energy as a sustainability resource. Ultimately, values related to the cost of building new energy capacity, such as LCOE, were considered the most appropriate. For N and P discharge, relevant reference values were available, although fewer in number. From the author's perspective, CE Delft provided particularly valuable and well-structured data. However, mitigation costs for WWTPs to reduce effluent discharge varied considerably, highlighting the importance of context-specific knowledge and placing responsibility on decision-makers to understand the unique characteristics and policy goals of each case. For BOD discharge, reference values were virtually absent, with only one identified during the course of this study.

The second objective was to calculate WSRs from previous assessments, to explore how sustainability criteria have been valued in practice. This objective was also achieved. The results demonstrated considerable variation across assessments. In some cases, individual criteria were assigned disproportionately high weights, resulting in WSRs that did not reflect realistic WTP levels. Notably, assessments that applied WSRs iteratively during the weighting process and that did a "plausibility check" such as those conducted by Lorick et al. (2023) and Ernst et al. (2020), generally resulted in lower WSRs, suggesting that assessment outcomes can shift significantly when a different perspective is adopted.

The third objective was to conduct workshops comparing a conventional weighting approach with one based on reference values to support WTP estimations. This objective was fulfilled, and the workshops yielded valuable insights into how different assessment groups interpret and apply reference values. As highlighted during the discussions, the main challenge encountered in the conventional weighting approach was the limited understanding of the embedded values within the criteria. Participants from the utility group, who were experienced in using WSRs, particularly noted the difficulty of assigning weights without knowing how those decisions would influence the final result. Another recurring issue was the valuation of energy use. Unlike climate impact or nutrient discharge, energy use was a more ambiguous criterion to value. It was unclear what the valuation should be based upon, energy as a cost, as a climate proxy, or as a resource. Some participants suggested that WSRs for energy should perhaps be expressed in terms

of kgCO₂e/kWh. The workshops also raised concerns about potential overlap between criteria. For instance, energy use is sometimes included in the criteria climate impact, as some reference values for the social cost of carbon (SC-C) incorporate increased energy use as part of the estimate. Similarly, if energy price is used to represent WTP, it may risk being double-counted under both the energy use and cost criteria. Questions were also raised if energy use should remain as a stand-alone criteria, or if it should be, or already is, integrated into other criteria. The workshops emphasised the importance of understanding what each reference value actually represents when applying it in an assessment.

Another significant observation was the discrepancy between WSRs derived from conventional weighting and the WTP levels expressed by participants in the workshops. These inconsistencies point to a risk of unintentional overvaluation or undervaluation when relying on subjective judgements alone. For instance, in case 2, the groups assigned particularly high weight to the climate impact criterion, leading to WSRs that diverged notably from their actual WTP. This indicates that embedded valuations, if not made transparent, can have a substantial and possibly unintended influence on assessment outcomes.

Although this thesis does not recommend any specific reference values, some guidance is unavoidable. For example, given Sweden's climate neutrality target and its commitment to limiting global warming to 1.5 °C, it would be reasonable to apply a carbon valuation aligned with this level of ambition. If sustainability assessments are to reflect the urgency of climate action, more ambitious valuations may be required. A reasonable approach might involve adopting the range proposed by the World Bank: 2 400–4 100 SEK/tCO₂ (World Bank, 2024), to meet the target of limiting global warming to 1.5 °C.

It is important to emphasise that there is no absolute right or wrong in this methodology. Rather, the goal is to improve transparency and to help decision-makers understand how outcomes may change depending on the perspective and assumptions applied.

6.1 Conclusion

To summarise the findings:

- For the sustainability criteria of climate impact, energy use, and nutrient discharge, several relevant reference values were identified. These provided a valuable basis for supporting WTP-based weighting in MCA. However, for the criterion of BOD discharge, reference values were scarce and difficult to identify.
- The calculation of WSRs from previous studies where percentage-based weighting was applied revealed considerable variation. In some cases, criteria were assigned disproportionately high weights, particularly climate impact, resulting in WSRs that did not correspond to realistic WTP levels. These findings suggest that not seeing the actual economic consequences of the weighting in some cases can sometimes lead to very high weighting.
- The workshop results indicated that different assessment groups tended to weight criteria more evenly when using reference values. Participants expressed greater

confidence in relying on structured, external data sources rather than assigning subjective weights without a clear rationale.

Overall, this thesis demonstrates that incorporating reference values into sustainability assessments enhances transparency, reduces variability between assessment groups, and grounds decision-making in evidence-based data. Future research could further refine these methods and explore standardisation of reference values across broader applications.

6.2 Future work

Future research could expand the use of reference values to include additional sustainability criteria beyond those considered in this study, such as land use, chemical use, or other environmental and social aspects. It would also be valuable to explore whether certain criteria, particularly energy use, are better represented using alternative units rather than monetary terms. For instance, future research could investigate whether reference values in units such as kWh/kgCO₂e can be identified. Linked to this is the need to further develop the MCA methodology to accommodate other forms of WTP, not limited to monetary-based valuations. This could affect the step-by-step process and lead to a more flexible and robust method that accommodates a broader range of valuation approaches.

Another promising area is the development of a reference-value database. Such a resource could evolve into a decision-support tool for practitioners, offering both suggested values and guidance on their use within specific decision-making contexts.

Finally, future work could examine how the integration of reference values influences actual investment decisions and whether it leads to more cost-effective or environmentally beneficial outcomes. It would also be valuable to explore whether assessments using reference values lead to different prioritisation of alternatives compared to those using conventional weighting methods.

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A

Appendix A: Reference values

Table A.1: Collected reference values for climate impact (SEK/tCO₂e), displaying the original value, its source and the year the original value is based on, including a conversion to 2024 SEK.

Letter	Notation	Value in 2024 SEK (SEK/tCO ₂ e)	Original value	Unit	Year the original value is based on	Source
a	Social cost of carbon from the GIVE model	2 100 (500-4 700)	185 (44-413)	USD/tCO ₂ e	2020	Rennert et al. (2022)
b	William Nordhaus	1 700	1 400	SEK/tCO ₂ e	2020	Gustafsson (2021)
c	CE Delft	1 600 (610-2 000)	130 (50-160)	EUR/tCO ₂ e	2021	de Vries et al. (2024)
d	CE Delft long-term projection until 2050	5 400 (2 500-10 000)	437 (200-819)	EUR/tCO ₂ e	2021	de Vries et al. (2024)
e	Taxing carbon in accordance with the social cost of carbon	1 500 (590-2 400)	125 (50-200)	EUR/tCO ₂ e	2022	Sterner et al. (2023)
f	Trafikverket ASEK 7.1	7 000	7	SEK/kgCO ₂ e	2024	Trafikverket (2023)
g	Long-term projection (after 2065) from Trafikverket ASEK 8.0	5 200	5.22	SEK/kgCO ₂ e	2024	Trafikverket (2024)
h	EU:s Emission Trading System (ETS)	740 (570-860)	65 (50-75)	EUR/tCO ₂ e	2024	European Energy Exchange (EEX) (2024)
i	Naturvårdsverket's initiative "Klimatklivet"	880	1.14	kgCO ₂ e/SEK	2024	Naturvårdsverket (2025)
j	Carbon taxes in Sweden 2024	1 500	1.45	SEK/kgCO ₂ e	2024	Regeringen (2024)
k	Target for the Paris Agreement of 2 °C	1 000 (670-1 300)	95 (63-127)	USD/tCO ₂ e	2024	World Bank (2024)
l	Target for the Paris Agreement of 1.5 °C	3 200 (2 400-4 100)	(226-385)	USD/tCO ₂ e	2024	World Bank (2024)
m	Gryaab's KPI values	3 000 (0-7 000)	3000 (0- 7 000)	SEK/tCO ₂ e	2024	Lorick and Videbris (2024)
n	City of Gothenburg	5 900 (4 400-7 400)	5.9 (4.4-7.4)	SEK/kgCO ₂ e	2024	Göteborgs Stad (n.d.)

Table A.2: Collected reference values for energy use (SEK/kWh), displaying the original value, its source and the year the original value is based on, including a conversion to 2024 SEK.

Letter	Notation	Value in 2024 SEK (SEK/kWh)	Original value	Unit	Year the original value is based on	Source
o	LCOE solar parks	0.5 (0.4-0.6)	0.43 (0.29-0.52)	SEK/kWh	2020	Energiforsk (2021)
p	LCOE onshore windpower	0.4 (0.3-0.4)	0.32 (0.24-0.36)	SEK/kWh	2020	Energiforsk (2021)
q	LCOE offshore wind power	0.7 (0.6-0.7)	0.53 (0.51-0.55)	SEK/kWh	2020	Energiforsk (2021)
r	LCOE hydropower	0.6 (0.4-1.2)	0.52 (0.36-0.95)	SEK/kWh	2020	Energiforsk (2021)
s	LCOE biomass CHP	0.7 (0.6-0.7)	0.55 (0.51-0.59)	SEK/kWh	2020	Energiforsk (2021)
t	LCOE MSW CHP	0.6	0.485 (0.47-0.5)	SEK/kWh	2020	Energiforsk (2021)
u	LCOE nuclear power	0.7 (0.6-0.8)	0.56 (0.49-0.64)	SEK/kWh	2020	Energiforsk (2021)
v	City of Gothenburg/NEPP	0.5	0.4	SEK/kWh	2020	Gråd et al. (2023)
w	Annual average electricity prices in Sweden in 2024	0.4 (0-1.0)	0.386 (0.085-0.85)	SEK/kWh	2022	Elbruk (2024)
x	Average electricity at Rya WWTP 2024	0.6	0.6	SEK/kWh	2024	M. Neth (personal communication, 26 March 2025)
y	Average total electricity price at Rya WWTP 2024	1.4	1.4	SEK/kWh	2024	M. Neth (personal communication, 24 January 2025)

Table A.3: Collected reference values for N emissions to water (SEK/kgN), displaying the original value, its source and the year the original value is based on, including a conversion to 2024 SEK.

Letter	Notation	Value in 2024 SEK (SEK/kgN)	Original value	Unit	Year the original value is based on	Source
z	Social cost of nitrogen (N runoff)	170 (66-320)	13 (5-24)	EUR/kgN	2008	Brink et al. (2011)
aa	BSAP mitigation costs	150 (68-290)	111 (50-210)	SEK/kgN	2010	Naturvårdsverket (2012)
bb	Social cost of nitrogen (from N fertiliser leachate)	49 (0-99)	(0.001-10)	USD/kgN	2010	Keeler et al. (2016)
cc	WTP for Swedish residents to meet BSAP	97	73	SEK/kgN	2014	Söderqvist and Wallström (2017)
dd	Total WTP for Baltic-connected countries to meet BSAP	610	460	SEK/kgN	2014	Söderqvist and Wallström (2017)
ee	CE Delft freshwater	52 (28-100)	4.23 (2.27-8.19)	EUR/kgN	2021	de Vries et al. (2024)
ff	CE Delft saltwater	180 (93-340)	14.3 (7.6-27.6)	EUR/kgN	2021	de Vries et al. (2024)
gg	Danish emission taxes	51	33.39	DKK/kgN	2024	Skatteministeriet (2022)
hh	WTP amongst residents on PEI	95 (53-140)	(5-13)	USD/kgN	2024	Withey et al. (2024)

Table A.4: Collected reference values for P emissions to water (SEK/kgP), displaying the original value, its source and the year the original value is based on, including a conversion to 2024 SEK.

Letter	Notation	Value in 2024 SEK (SEK/kgP)	Original value	Unit	Year the original value is based on	Source
ii	Naturvårdsverket mitigation costs	7 100 (51-29 000)	5 177 (37-21 169)	SEK/kgP	2010	Naturvårdsverket (2012)
jj	WTP (Bottenviken)	810 (740-890)	615 (560-670)	SEK/kgP	2012	Söderqvist and Wallström (2017)
kk	WTP (Bottenhavet)	14 000 (13 000-15 000)	10 350 (9 700-11 000)	SEK/kgP	2012	Söderqvist and Wallström (2017)
ll	WTP (Norra Östersjön)	6 400 (5 900-6 900)	4 850 (4 500-5 200)	SEK/kgP	2012	Söderqvist and Wallström (2017)
mm	WTP (Södra Östersjön)	4 100 (3 800-4 400)	3 100 (2 900-3 300)	SEK/kgP	2012	Söderqvist and Wallström (2017)
nn	WTP (Västerhavet)	2 800 (2 600-3 000)	2 150 (2 000-2 300)	SEK/kgP	2012	Söderqvist and Wallström (2017)
oo	WTP (National)	4 400 (4 100-4 600)	3 300 (3 100-3 500)	SEK/kgP	2012	Söderqvist and Wallström (2017)
pp	WTP for Swedish residents to meet BSAP	570	430	SEK/kgP	2014	Söderqvist and Wallström (2017)
qq	Total WTP for Baltic-connected countries to meet BSAP	3 600	2 700	SEK/kgP	2014	Söderqvist and Wallström (2017)
rr	CE Delft (freshwater)	46 (31-120)	3.74 (2.56-10.13)	EUR/kgP	2021	de Vries et al. (2024)
ss	Danish emission taxes	280	183.64	DKK/kgP	2024	Skatteministeriet (2022)

Table A.5: Collected reference values for BOD emissions to water (SEK/kgBOD), displaying the original value, its source and the year the original value is based on, including a conversion to 2024 SEK.

Notation	Value in 2024 SEK (SEK/kgBOD)	Original value	Unit	Year the original value is based on	Source
Danish emission taxes	28	18.36	DKK/kg BOD	2024	Skatteministeriet (2022)

B

Appendix B: Weighted score ratios

Table B.1: Calculated WSRs from previous sustainability assessments, converted into 2024 SEK value.

	WSR (converted to 2024 SEK)					Year	Source	
	Notation	CO ₂ e (SEK/tCO ₂ e)	Energy (SEK/kWh)	Nitrogen (SEK/kgN)	Phosphorus (SEK/kgP)			BOD (SEK/kgBOD)
A1	Resource recovery in the Baltic Sea region (Fyris, Sweden)	69 000		450	4 000		2020	Johannesdottir et al. (2021)
A2	Resource recovery in the Baltic Sea region (Slupia, Poland)	14 000		570	5 100		2020	Johannesdottir et al. (2021)
B	Water reuse at Rya WWTP	3 000	2.1	36	320	7.8	2022	Backeström and Ceder (2022)
C	"Nya Rya" Process investigation	2 400	0.2		9	0.2	2022	Lorick et al. (2023)
D	Pharmaceutical removal at Rya WWTP	11 000	4.3				2020	Ernst et al. (2020)
E	Pharmaceutical removal at Rya WWTP (2:nd edition)	16 000	4.7				2023	Neth et al. (2023)
F	Wastewater management in Kalmar (system analysis)		11				2011	Arnell et al. (2011)
G	System study for wastewater and bio-waste management in the Gothenburg-region	8 400	6.3				2007	Andersson et al. (2007)
H	Leachate management to Rya WWTP	3 100	5.7	5 000	120 000		2015	Malmqvist et al. (2015)

Table B.2: Calculated WSRs from previous sustainability assessments, values based on original data without conversion.

	Notation	WSR (from original assessment)				Year	Source	
		CO ₂ e (SEK/tCO ₂ e)	Energy (SEK/kWh)	Nitrogen (SEK/kgN)	Phosphorus (SEK/kgP)			BOD (SEK/kgBOD)
A1	Resource recovery in the Baltic Sea region (Fyris, Sweden)	55 720		360	3 209		2020	Johannesdottir et al. (2021)
A2	Resource recovery in the Baltic Sea region (Slupia, Poland)	10 957		464	4 096		2020	Johannesdottir et al. (2021)
B	Water reuse at Rya WWTP	2 650	1.9	32	285	7	2022	Backeström and Ceder (2022)
C	"Nya Rya" Process investigation	2 141	0.2		8	0.2	2022	Lorick et al. (2023)
D	Pharmaceutical removal at Rya WWTP	8 658	3.5				2020	Ernst et al. (2020)
E	Pharmaceutical removal at Rya WWTP (2:nd edition)	15 618	4.6				2023	Neth et al. (2023)
F	Wastewater management in Kalmar (system analysis)		8.2				2011	Arnell et al. (2011)
G	System study for wastewater and bio-waste management in the Gothenburg-region	5 895	4.4				2007	Andersson et al. (2007)
H	Leachate management to Rya WWTP	2 336	4.3	3 762	91 860		2015	Malmqvist et al. (2015)

C

Appendix C: Conversion tables

Table C.1: Exchange rates to SEK from 2008 to 2024, based on historical exchange rate data from Exchange Rates UK (n.d.), expressed as the yearly average exchange rate. The number of significant figures are inconsistent with those in this report, as a higher level of detail was required to ensure accurate conversions, and the values shown here reflect those actually used in the calculations.

Year	EUR	USD	DKK	PLN
2008	9.625 SEK	-	-	-
2009	-	-	-	-
2010	-	7.203 SEK	-	-
2011	-	-	-	-
2012	8.706 SEK	-	-	-
2013	8.654 SEK	-	-	-
2014	9.102 SEK	-	-	-
2015	9.359 SEK	-	-	-
2016	9.469 SEK	-	-	-
2017	9.637 SEK	-	-	-
2018	10.263 SEK	-	-	-
2019	10.587 SEK	9.456 SEK	-	-
2020	10.491 SEK	9.207 SEK	-	2.362 SEK
2021	10.149 SEK	-	-	-
2022	10.635 SEK	-	-	-
2023	11.484 SEK	-	-	-
2024	11.441 SEK	10.575 SEK	1.533 SEK	-

Table C.2: Inflation rates and corresponding multipliers for the years 2007—2023, used to adjust SEK values to 2024 prices, were derived from SCB’s price calculator ”Prisomräknaren” (Statistics Sweden (SCB), n.d.). The number of significant figures is inconsistent with those in this report, as a higher level of detail was required to ensure accurate conversions, and the values shown here reflect those actually used in the calculations.

Year	Inflation (%) (yearly average 2024)	Multiplier
2007	42.91%	1.4291
2008	38.15%	1.3815
2009	38.53%	1.3853
2010	36.78%	1.3678
2011	33.30%	1.3330
2012	32.14%	1.3214
2013	32.19%	1.3219
2014	32.42%	1.3242
2015	32.48%	1.3248
2016	31.19%	1.3119
2017	28.88%	1.2888
2018	26.41%	1.2641
2019	24.18%	1.2418
2020	23.57%	1.2357
2021	20.96%	1.2096
2022	11.61%	1.1161
2023	2.83%	1.0283

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
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