GIS

Feedstock Transition Study

IDENTIFYING OPPORTUNITIES TO IMPLEMENT MEASURES FOR SUSTAINABLE FEEDSTOCK ALTERNATIVES, EFFICIENCY AND WASTE VALORIZATION

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List of abbreviations and acronyms

CO_2	Carbon dioxide, a greenhouse gas
CO_{2eq}	Carbon dioxide equivalent
GHG	Greenhouse Gas
GIS	Grondstoffen Innovatie Studie – Feedstock Transition Study
GWP	Global Warming Potential
MCA	Multi-Criteria Analysis
TRL	Technical Readiness Level

1. Introduction

The transition from a linear economy based on fossil resources to a circular economy must be accelerated. As part of the Deltalinqs Climate Program, and in line with the policy of the Province of South Holland to promote circularity and sustainable industry – ultimately to achieve the national target of a 50% reduction in primary abiotic raw materials by 2030 – The Province of South-Holland and Deltalinqs have submitted the request of developing the Grondstoffen Innovatie Studie (GIS) to Tekkoo and TransitionHERO.

The methodology has been developed based on the combined expertise of Tekkoo and TransitionHERO and an analysis of best practices and interviews with key stakeholders in the field of the feedstock transition and the region of the Port Industrial Complex of Rotterdam.

2. Goal and Scope of the GIS Study

2.1. Goal of the study

The **Feedstock Transition Study (Grondstoffen Innovatie Studie - GIS)** was initiated jointly by the Provincie Zuid-Holland and Deltalinqs Climate Program to support companies in the industrial cluster in the port of Rotterdam in the transition toward circular and sustainable use of resources.

The goal of GIS study is threefold:

1. To provide insight into the potential transition from fossil-based raw materials to non-fossil-based or circular raw materials (**alternative feedstocks**),
2. To optimize internal raw material flows at companies to improve raw material efficiency (**feedstock efficiency**),
3. To identify high-quality destinations for residual flows (**waste valorization**).

To carry out this study, TransitionHERO and Tekkoo developed a first of a kind methodology to support companies in implementing a more circular approach and to assess the resulting benefits for business economics. This methodology was subsequently applied in a real-world case at a pilot company. Between June 2025 and January 2026, the methodology was tested and validated during this proof-of-concept phase.

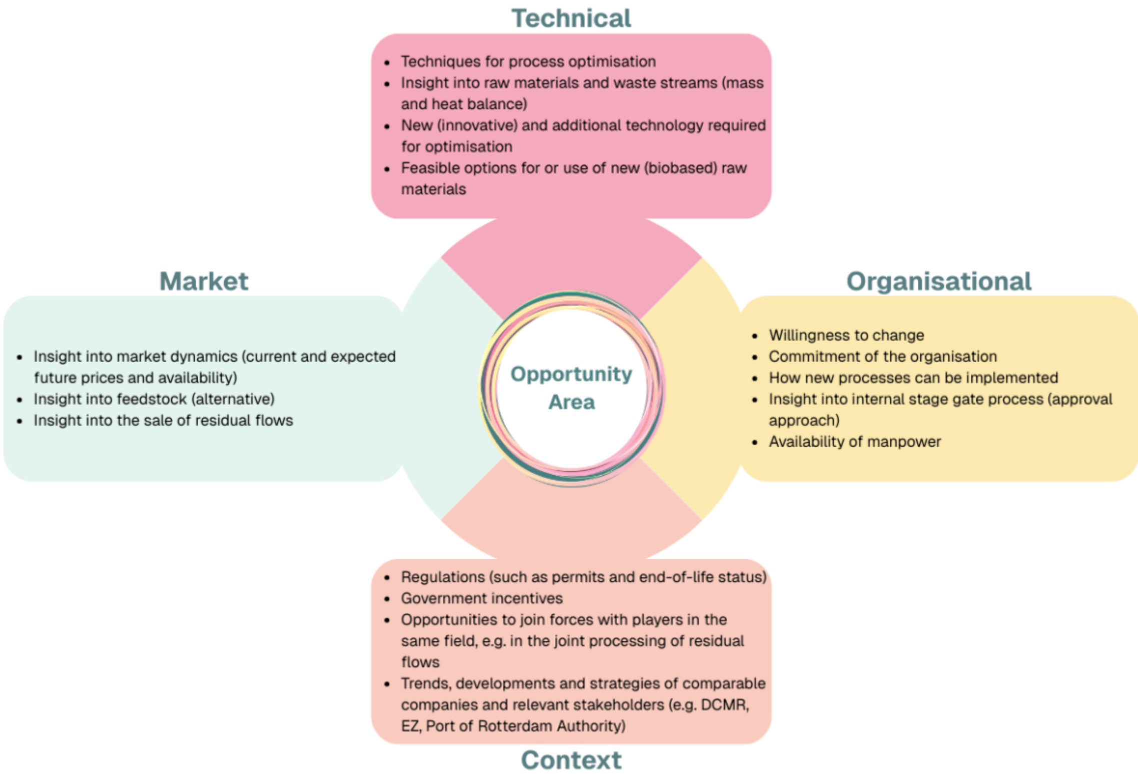
The developed methodology consists of the following phases:

- Preparation phase,
- Phase 1: Analysis & Longlist,
- Phase 2: Deep Dive & Selection,
- Phase 3: Feasibility & Shortlist,
- Phase 4: Roadmap.

These four phases are described in this document in detail.

2.1. Scope of the study

This methodology was designed to provide an integral approach: combining technical, market & financial, organisational and contextual factors with a strong focus on implementation of suggested measures.



The methodology was designed based on principles found in the holistic 'Sociotechnical Systems Theory (STS), the Open-systems Theory and the PESTEL framework. These models view organizations as systems in which technology, people, structure and the external environment influence each other. They provide a holistic perspective especially fit for analysing companies in industrial clusters where interdependencies play a major role.

3. Description of the methodology

The GIS methodology starts with generating a broad set of circular measures and then applies a structured funnel approach to identify solutions with high implementation potential (considering contextual factors and organisational factors) that are both economically and technically feasible. In this section, the way of working and all phases of the methodology are described.

3.1. Approach and way of working

The approach covers the beforementioned 4 factors and can be divided into a preparation phase and 4 different phases stretching analysis and delivery of results. In total, the execution of the methodology will take about 4 months including preparations and final delivery.

Applying this methodology requires close collaboration between ‘the advisor’ and ‘the company’. Each of the phases in evaluated with the entire project team consisting of both representatives of the advisor and the company. This evaluation focuses on going through the result of the previous phase, reflecting on the collaboration and a preview of the coming phase. Project check-in/stand-up meetings are held once a week to once every two weeks to access progress on different task and identify and solve possible bottlenecks. These meetings are attended by at least the project lead from the side of the advisor and from the side of the company.

3.2. Preparation phase: System understanding and boundary definition

Before initiating the generation and evaluation of measures, it is essential to develop a clear understanding of the current industrial process, the material streams within it, organizational factors like company culture and strategy and contextual factors like societal dynamics and regulations. Furthermore, it is essential to establish a good common ground for collaboration with the company. This step must be carried out in close collaboration with the site or organization where the general methodology is being implemented.

Key activities in this phase include:

- **Project kick-off:** An event aimed at introducing people working together in the project to each other, establishing a good understanding of roles and responsibilities (RACI) withing the project and determining team agreements on how to collaborate within the project effectively. The methodology is explained to the project team in detail, and a project planning and way of working is established.
- **Site-visit:** A physical inspection of the company site helps examine and understand the specific installations and operations.
- **Process mapping**: A simplified overview of the current process should be provided by the company to highlight major operations, material and energy flows. This includes main unit operations, flows of feedstocks, consumables, by-products, and waste streams.

- **Scope definition**: If the industrial process is extensive, it is important to define which process sections will be included in the study. The selection can be guided by criteria such as the most CO_2- or energy-intensive unit operations, the largest volumes of feedstocks or by-products involved, or process areas where the internal team has not yet identified effective improvement measures.
- **Constraint identification**: The company should also inform the team about known constraints that could significantly affect potential measures, such as limited site layout, permitting conditions, safety requirements, and existing utility capacities (e.g., limitations in the electrical grid). Sharing this information helps prevent the development of solutions that would be unfeasible within the site's operational context.
- **Prioritising**: The company should provide the team executing the methodology with a prioritized list of feedstocks, processes, and waste streams for analysis. This is particularly relevant when the facility handles a wide range of products and feedstocks. In most cases, companies have already conducted sustainability or energy efficiency assessments; therefore, effective knowledge transfer is essential to accelerate the study and build upon existing insights.
- **Data availability review**: Before starting the study, the availability of required information and data must be confirmed. It should also be assessed if the gaps in information can be filled in during the timeline of the project, or if assumptions should be used. Assumptions will be defined with the team on site.
- **Analysis of strategic and organizational factors:** A session to identify government incentive measures, company culture, company decision making governance, trends in the sector and relevant company strategy. These internal and external conditions are discussed to predict their potential influence on successful implementation of measures. Outcomes of this session will help assess the complexity of implementing a measure in phase 1, 2 and 3.

This foundational step is not about generating solutions yet, but rather about equipping the team with the right contextual understanding to ensure that ideation and evaluation are realistic, focused, and aligned with the company context.

3.3. Phase 1 – Analysis & Longlist

The first phase focuses on developing a broad list of potential measures, which are assessed against high-level criteria. The purpose of this phase is to quickly eliminate options that are not strategically, technically or economically feasible, regardless of site-specific circumstances.

3.3.1. Criteria used in phase 1

In Table 1, the criteria used in the first selection funnel is shown. The measures are scored against 5 criteria: technical feasibility, maturity of the market, GHG reduction potential, relevance to the Dutch market and economic potential. Each of the above-mentioned criterion is be scored using a general 1 to 5 qualitative scale (from very poor = 1 to very good = 5). The criteria were used in the order of importance from top to bottom.

Table 1. Criteria used in the first selection funnel

Criteria	Very good (5)	Good (4)	Moderate (3)	Poor (2)	Very poor (1)
Technical feasibility	TRL 9: Proven, commercial-ready technology.	TRL 8: Demonstrated in pilot or relevant environment.	TRL 7: Validated at lab or prototype Phase.	TRL 6: Early concept, theoretical or limited experiments.	TRL <6: Basic principle only; unvalidated technology.
Maturity of the market	Mature market: widely deployed, standardized products; strong demand and supply chains.	Growing market: multiple plants in operation; supply chains developing, adoption expanding.	Early commercial: first plants in operation/ construction; supply chains immature.	Demo/early trials: small demo plants or test batches; limited volumes, high costs.	Research/ pilot: concept stage; no commercial products; very low TRL.
GHG reduction Potential*	Very high CO_2 savings (>xx kta)	High CO_2 savings (>xx and ≤xx kt CO_2/year)	Moderate CO_2 savings (>xx and ≤xx kt CO_2/year)	Low CO_2 savings (>xx and ≤xx kt CO_2/year)	Negligible CO_2 savings (< x kta year)
Relevance to Dutch market (future)	Strategic importance; large-scale volumes; policy/ infrastructure support.	High relevance: expected to play an important role; import routes developing; multiple off takers.	Emerging presence; pilots/demos or small but growing imports.	Limited role: small volumes, niche uses; no large-scale infrastructure.	No foreseeable role in Dutch industry or markets
Complexity of integration	Direct drop-in replacement with existing processes; minimal effort required.	Minor modifications to existing processes or equipment; relatively straightforward.	Requires technical adaptations, but solutions are known and manageable.	Significant modifications and investments are needed; integration is challenging.	Requires fundamental process changes; very high cost and risk.
Economic potential (ROM)	Strong indications of large savings or revenues; attractive even conservatively.	Clear cost savings or avoided costs; attractive in most cases.	Savings possible but uncertain; depends on scale or market conditions.	Limited savings; only viable with subsidies or favorable circumstances.	Negative economics: costs exceed benefits.

*GHG reduction potential ranges are defined based on the size of the company and potential emissions associated with the operations.

3.3.1.1. Technical feasibility

Technical feasibility is assessed using Technology Readiness Levels (TRL). This criterion reflects the maturity and reliability of the technology. In the pilot study, this criterion was used as **knocked-out criteria**. Technologies which TRL lower than 8 (scoring "Good") were discarded. The reason was to prioritise technologies with lower technical risk and greater readiness for implementation.

It should be noted that companies differ in their willingness and capability to invest in and implement innovative technologies that are not yet widely adopted. Therefore, this knock-out criterion can be adjusted depending on the company to which the methodology is applied.

3.3.1.2. Maturity of the market

Market maturity for alternative feedstocks, feedstock efficiency measures, and waste-stream valorisation can be assessed in a structured manner by combining market analysis with a review of available standard products and commercial technologies.

For **alternative feedstocks,** the assessment focuses on whether the feedstock is commercially available at sufficient scale and whether a reliable local or regional supply is in place. It is also assessed if alternative feedstocks can be produced on site. In this case, required technologies and their TRL are included.

For **feedstock efficiency** measures, the assessment examines opportunities to improve the efficiency with which feedstocks are converted and used. This may include, for example, deploying improved catalysts, new reactors, or other process enhancements to optimise conversion and reduce losses. The analysis then considers the technology readiness and market availability of the required solutions – specifically whether they have been demonstrated at industrial scale and whether the necessary equipment can be procured from established suppliers.

For **waste valorisation** measures, the assessment evaluates whether end markets for valorised products already exist and the scale of current and expected demand. It also considers the geographic distribution of demand – i.e., whether customers can be secured in the Netherlands or in neighbouring countries.

In the pilot study, this criterion was also used as **knocked-out criteria**. Solutions which scored lower than Good (4) were discarded. The reason for it is to focus on alternative materials that have at least growing markets and technological solutions which their adoption is expanding.

3.3.1.3. GHG reduction potential

The estimation of the GHG reduction potential is different for feedstocks, efficiency and waste valorisation.

Approach for calculating specific emissions for feedstocks:

The estimation of the carbon footprint was carried out using SimaPro software, applying the IPCC 100-year Global Warming Potential (GWP) method. For compounds available in the databases (e.g., Ecoinvent), established emission factors were directly applied.

For substances not represented in these databases, the Research, Reaction, and Energy (RRE) methodology was used. This complementary approach derives emission factors from the underlying reactants and the associated energy requirements, with data also sourced from SimaPro.

Approach for calculating specific emissions for efficiency measures:

Improving material efficiency in context of this methodology is defined in two ways:

- Improving the efficiency with which the material is converted and utilized. In this way, less feedstock is required for a specific process. The reduction in CO_2 emissions is then calculated as the avoided emissions from reduced mass of the feedstock. The CO_2 emissions of the feedstocks are calculated as described in the paragraph above.

- Recovering value which was not used efficiently in the process and cannot be processed further, but energy can be generated from it, instead of disposing the material.

Approach for calculating specific emissions for waste valorisation:

In the context of this study, valorising feedstocks was defined in the following ways:

- By valorising waste streams into products which can be used as green alternatives to fossil feedstocks. The reduction in CO_2 emissions is then calculated as the CO_2 emissions which would be associated with using the same volume fossil-based feedstocks or material.
- By valorising waste streams into fuels. For example, waste hydrocarbons can be converted into biogas, which will replace natural gas for heat or electricity production. The CO_2 emissions are calculated as equivalent CO_2 emissions of the volume of natural gas that can be substituted with biogas.

3.3.1.4. Relevance to Dutch (future) market

The relevance to the Dutch (future) market, is assessed as follows:

For **alternative feedstocks** it is evaluated whether the alternative feedstock is available through Dutch domestic production or import routes, and whether it connects to established or emerging Dutch industrial clusters.

For **waste valorization** measures it is assessed whether Dutch industries or value chains exists that can use the valorised products, and whether markets extend beyond niche/high-value applications.

For **efficiency measures**, this criterion is not used.

3.3.1.5. Complexity of integration

Complexity of integration is assessed qualitatively. It is evaluated whether the new feedstock, waste valorization, or efficiency gain requires process modifications. In some cases, for example for certain feedstocks, the integration is straightforward as fossil molecules will be replaced by green molecules. In other instances, when the measure requires additional processing steps, the integration may be more complex and will most likely result in significant CAPEX. In some cases, there can be a physical barrier (e.g. very long distance), so that the measure cannot be implemented. The company for which the study is conducted should be well positioned to determine whether a given measure is feasible to implement, or whether its complexity will outweigh the potential benefits.

3.3.1.6. Economic potential (ROM)

At this stage the economic potential is assessed as Rough Order of Magnitude (ROM) estimate of cost savings, based on qualitative judgment, quick calculations, or available data.

For **alternative feedstocks** the economic potential is estimated as cost savings from replacing feedstock.

For **efficiency measures** the economic potential is calculated as cost savings from improved efficiency, i.e. by using less material or generating energy.

For **waste valorisation** measures, the economic potential is estimated as cost savings from reducing disposal costs and potential revenue from converting waste into marketable products (e.g., by-products, recycling, or energy recovery). In case waste streams are turned into fuels, the economic potential is calculated as cost savings from reducing disposal costs and reduction in purchase of natural gas or electricity.

3.3.2. Step by step approach for generating and funnelling longlist

In this section, a step-by-step approach is for generating and funnelling the longlist is described. The generation and selection process for the 3 main study area slightly differ.

3.3.2.1. Analysis of alternative feedstock measures

The following steps are taken when analysing feedstocks:

Step 1: Understand the feedstock flows in the facility

When analysing feedstocks, one should start from generating a list of materials used in the facility including annual volumes used. It should be noted that all materials, not only feedstocks which then are converted into products, should be looked at. Other auxiliary materials, which support the process but are not part of the final product, should be considered. Examples of those materials are catalysts, solvents, cleaning agents, process chemicals, additive, nitrogen for inerting and consumables.

Step 2: Understand the CO_2 emissions associated with these materials

When the list of materials and their volumes are known, one can calculate the emissions associated with the materials. It is important that if the facility uses, for example, hundreds of different feedstocks, it can be considered to prioritise the materials which are used in highest volumes or the ones with highest price per ton. Then choose max. 10 or 20 feedstocks for which the next step will be performed.

Step 3: Assess whether those feedstocks can be produced in a green way and what is the TRL level of this route

Theoretically, almost all feedstocks can be produced using green feedstocks, nevertheless many of those routes are still at a very low TRL level or the economics of the green paths are not attractive. As an example, 3 very common feedstocks used in the (chemical) industry are presented in the table below:

Table 2. Examples of feedstocks, their green production methods and corresponding TRL

Feedstock name	Conventional production method	Example green production method	TRL green route
Hydrogen	Steam Methane Reforming (SMR), coal gasification.	One of the methods is water electrolysis is powered by green electricity.	TRL 9 – Electrolysis is a proven technology, with some commercial plants operating worldwide.
Phosphoric acid	The production of PA, H_3PO_4, from PR (mining) is typically carried out by wet chemical digestion with sulfuric acid.	One of the methods is phosphorus recovery from residual material from thermal sewage sludge utilization.	TRL 8 – Remondis' TetraPhos® full-scale plant in Hamburg already operates, proving industrial scale.
Bleaching earth	Mine Ca-bentonite, treat with mineral acid (68% acid activated, 32% natural/other bleaching earths)	Natural bleaching earth without mineral-acid activation (lower acidity) or regenerating the spent bleaching earth (SBE)	TRL 6/7: only a few occasions that have demonstrated the technology for SBE at a commercial level but proven on a smaller scale.

Because TRL is a knocked-out criterion in this study, bleaching earth would not be further investigated for relevance to the Dutch market, because of the technical unfeasibility.

Step 4: Assess which feedstocks are relevant to the Dutch market and if synergies can be found in the local context

Taking the 2 remaining feedstocks from table above, the following can be concluded:

- Hydrogen would be scored as very good (5 points) on this criterion as The Netherlands wants to position itself as a European hydrogen hub (Port of Rotterdam, import terminals, offshore wind integration). There is strong relevance for local industry (refineries, chemicals, steel) and for exports to Germany. It is expected that green hydrogen will be produced or imported to the Rotterdam harbour, therefore there is a high potential that this feedstock will be available locally for companies in the complex.
- Phosphoric acid would be scored good (4 points) as the Netherlands has strong demand (fertilizer, food industry, technical chemicals) and strategic interest in reducing import dependence on phosphate rock (almost entirely imported from Morocco and Russia). EU and Dutch circular economy policies make phosphorus recovery highly relevant. This feedstock is not scored as very good in terms of relevance, as it is currently not expected that in the coming year a significant volume of green phosphoric acid will be produced in The Netherlands or imported.

In this case, both feedstocks would be evaluated and included in the following criteria maturity of the market.

Step 5: Assess the maturity of the market for those products

In the following table a qualitative assessment of the hydrogen and phosphoric acid markets is shown.

Table 3. Examples of market assessment for hydrogen and phosphoric acid

Feedstock name	Market assessment
Hydrogen	Green hydrogen can be assessed as growing market (Good – 4 points) because its transition from early commercial to scaling phase is already underway. Multiple large-scale electrolysis projects are under construction or starting operation in the Netherlands and wider Europe, supported by strong EU and national policies. Supply chains are beginning to take shape, with certification systems for renewable hydrogen (e.g., RFNBO rules) being implemented and offtake agreements signed with refineries, fertilizer producers, and emerging e-fuels markets.
Phosphoric acid	The market for renewable phosphoric acid is at an early commercial stage (Moderate - 3 points). Remondis already markets recovered phosphoric acid under the RePacid® brand. Expected that renewable phosphoric acid is not yet available at high quantities.

The market for green phosphoric acid is at early commercial stage, and this feedstock is not yet available in high volumes. For this reason, phosphoric acid would be discarded from further analysis.

Step 6: Assess the economic potential

In most cases, the economic potential of purchasing green feedstocks vs fossil feedstocks is negative as green chemicals are oftentimes more expensive than their fossil alternatives. For example, the price of grey hydrogen is currently about 3 €/kg, while green hydrogen prices are expected to be more than 13 €/kg (TNO, 2024). These prices rise even further when transportation is required.

Nevertheless, there are examples where green/ circular alternatives can lead to a positive business case:

- Production of biomethane from organic components to replace natural gas,
- Recycled aluminium (scrap) used to make secondary aluminium is cheaper than virgin aluminium,
- Utilising used cooking oil (UCO) instead as crude oil/naphtha replacement.

At this stage of the analysis, it is only looked at the price difference between green and fossil feedstocks. In the following phase of the analysis, it is checked which of the feedstocks can be potentially produced on site and if the business case can be competitive with fossil materials. For example, green hydrogen could be potentially produced on site if the site footprint is sufficient, there is access to green electricity (via de grid or directly connecting to the green assets) and permits allow it.

Step 7: Fill in the MCA for the longlist feedstocks and select measures for the next phase

When all the steps are followed, then each of the feedstocks can be scored according to the criteria mentioned in 3.3.1. Based on the scoring, the measures with positive economic potential and highest scores should be chosen for the next phase.

After that it is checked which of the materials can be potentially produced on site:

- The green alternatives which show positive economic potential and can be produced on site will be assessed in the 2nd phase as a specific measure.

- Feedstocks which can only be purchased and will be used as direct replacement for old feedstocks without technical modifications, should be investigated by the company where the study is done and do not have to be assessed further in this study, as the methodology is focused on evaluating technical solutions.

3.3.2.2. Analysis of efficiency measures

The following steps are taken to generate efficiency measures:

Step 1: Identify material inefficiencies

To identify potential material inefficiencies, one should make inventory of the following:

- Determine materials including the annual volumes which are lost (and unused) in the process, for example:
  - Emissions to atmosphere,
  - Emissions to wastewater,
  - Loss of material due to leaks,
  - Loss of material due to unwanted evaporation,
  - Loss of material due to poor material handling.
- Determine materials which for which the reaction yield should be higher than the theoretical yields.
- Determine materials for which the processing parameters could be optimised (e.g. increasing material efficiency by increasing the pressure of the reaction).

Step 2: List potential measures to deal with material inefficiency

The next step is to list any potential technical solutions to address the material inefficiencies. For a specific material, several technical solutions can be identified.

Some examples of technical solutions for typical material inefficiencies in industry:

- Vapor recovery units, these systems capture fugitive VOC (Volatile Organic Compound) vapours from storage tanks or loading stations. The gases are compressed and cooled back into a liquid state to be pumped back into the process instead of being vented,
- Changing catalyst of process conditions to achieve better reaction yields,
- Using flammable vapours in thermal oxidizer for energy production.

Step 3: Understand the reduction of CO_2 emissions caused by increased efficiency

Calculate the CO_2 emissions associated with improving material efficiency as described in 3.3.1.3.

Step 4: Assess the complexity of implementing the measure

At this stage one should qualitatively assess the complexity of implementing the measure. To do so, one should evaluate at least the following aspects:

- Is this an end of pipe solution, add on to the process?
- Do the process conditions have to be modified?
- Does any additional equipment have to added to the process?
    - If yes, what is the approximate footprint of the equipment?
    - Does this equipment need connection to utilities?

After answering those questions, one should look at the criteria table for "Complexity" and score the measure according to the definitions.

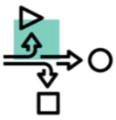
Step 5: Assess the economic potential

Assess the economic potential as described in 3.3.1.6.

Step 6: Fill in the MCA and select measures for the next phase

When all the steps are followed, then each of the efficiency measures can be scored according to the criteria mentioned in 3.3.1. Based on the scoring, the measures with potentially positive business case and highest scores should be chosen for the next phase.

3.3.2.3. Analysis of waste valorisation measures



The following steps are taken when analysing waste streams:

Step 1: Understand the waste streams generated in the facility

When analysing waste streams, one should start from generating a list of materials which are considered as by-products and are being disposed or treated without making a useful product (i.e. conversion of waste to harmless substance). The materials should be listed including annual production volumes.

Step 2: Understand the potential of the waste stream/by-product

In this phase it is looked at the "waste-to-resource'' possibilities. The following opportunities should be assessed:

- Putting the waste stream back in the process to maximise material efficiency,
- Using the material, directly or after treatment, as a substitute to a fossil feedstock,
- Separating different components from the waste stream, as in some cases separated molecules have a higher value than a mixed stream,
- Converting the substance to a different, more valuable feedstocks via for example chemical recycling, fermentation etc.

Step 3: Assess the TRL level of the waste valorisation solution

This stage involves evaluating the TRL of identified valorisation pathways to determine their technical maturity and commercial viability.

The "low-hanging fruit" technologies score higher in this assessment. These include for example:

- Mechanical separation: the use of physical technologies to isolate and recover material fractions,
- Biochemical conversion: waste streams suitable for fermentation or anaerobic digestion to produce biogas,
- Thermal recovery: Streams that can be efficiently converted into thermal energy through established combustion or gasification processes.

Step 4: Assess the maturity of the market of the valorised stream

In case the valorised product cannot be used internally in the facility, it is evaluated if this material can be sold. The market maturity for valorised products is evaluated based on several aspects, including:

- Definition of target market to determine if the products serve a direct substitute or a niche green alternative,
- Comparison of the product price versus fossil alternative,
- Assessment of the potential market volume,
- Assessment of potential local customers.

Step 5: Understand the reduction of CO_2 emissions related to valorising waste streams

Calculate the CO_2 emissions associated with improving material efficiency as described in 3.3.1.3.

Step 6: Assess which valorised waste streams are relevant to the Dutch market and if synergies can be found in the local context

Following the identification of valorised products and the analysis of market trends, the strategic importance of these materials to the Dutch economy is evaluated as well as the availability of local off takers. In the context of this study, priority is given to materials demonstrating high strategic value and local synergies, for example products that address national resource dependencies – such as critical raw materials or energy carriers, or products which can be used as direct feedstock for existing regional industrial clusters (e.g., the Port of Rotterdam or Chemelot).

Step 7: Assess the complexity of implementing the measure

Assess the complexity of the measure, follow the same approach as in Step 4 in 3.3.2.2 in the analysis of efficiency measures.

Step 8: Assess the economic potential

Assess the economic potential as described in 3.3.1.6.

Step 9: Fill in the MCA and select measures for the next phase

When all the previous steps are followed, then each of the measures can be scored according to the criteria mentioned in 3.3.1. Based on the scoring, the measures with potentially positive business case and highest scores should be chosen for the next phase.

3.3.2.4. Analysis of potential synergies in the region

This step is guided by a session in which the possible synergies between measures identified in the first phase hold opportunities for collaboration with other company's sites and operations in the surrounding region. The focus here is on measures in the categories of feedstock alternatives and waste valorisation. Assess each measure and do an analysis of data on demand of feedstock and supply of residual streams for and available in the region. Take the results as input for the evaluation of the phase next to the other criteria in the MCA.

3.3.2.5. Example MCA phase 1

In Table 4, example of MCA is shown. The maximum score is 30 points (6 criteria x 5 points maximum). For example, if a measure got 26 points, the final performance score is 26/30 = 87%.

Table 4. Example MCA longlist

Measure	Technical feasibility	Maturity of the market	GHG reduction potential	Relevance to the Dutch market	Complexity of integration	Economic potential	Score
Conversion of hydrocarbons to energy/heat	Very good (5) Mature technology	Good (4) Standard equipment but need to cope with varying composition	High (4) 3.7 kt/year	Good (4) Reduction of natural gas consumption. Lower score as it still contains fossil components.	Good (4) End of pipe integration. Lower score due to relatively high footprint and integration.	Good (4) Positive economics, weaker BuCa than green gas.	**83%**
Nutrient recovery from wastewater	Good (4) Routes established	Moderate (3) Few demo plants operating.	Low (2) < 1 kt/year	Very good (5) Strong fit: strict N regulations, manure surplus, policies make it highly relevant.	Good (4) End of pipe integration. Lower score due to high footprint and additional storage.	Poor (2) Recovered nutrients need to compete with cheap, fossil-based fertilizer.	**67%**
Minimize nitrogen losses	Very good (5) Technical solutions available.	Very good (5) Mature service providers and technologies.	Very low (1) 0.1 kt/year	Good (4) Requires monitoring, repairs and improved maintenance programs, not fundamental redesign of the process.	Very good (5) Strong cost avoidance, rapid payback time.	Very good (5) Substantial savings can be achieved with low CAPEX.	**87%**

3.4. Phase 2 – Deep Dive & Selection

In this phase, the selected measures are re-evaluated using additional data and new site-specific criteria. The purpose is to eliminate options that cannot be implemented at the specific site under consideration. The result of phase 2 is a selection of 3 or more technically feasible options with the greatest chance of success. At this stage, the measures are listed as specific technical solution, therefore the assessment is done in the same way across all three categories (feedstocks, efficiency and waste streams).

3.4.1. Criteria used in phase 2

In phase 2 the criteria which are selected evaluate the feasibility of the options for the specific site. Evaluating site-specific criteria in this phase ensures that the measures selected are not only promising in concept but actually feasible, cost-effective, and strategically aligned for the specific plant where they will be implemented.

Table 5. Criteria used in the second selection funnel

Criteria	Very good (5)	Good (4)	Moderate (3)	Poor (2)	Very poor (1)
GHG reduction potential*	Very high CO_2 savings (>xx kta)	High CO_2 savings (>xx and ≤xx kt CO_2/year)	Moderate CO_2 savings (>xx and ≤xx kt CO_2/year)	Low CO_2 savings (>xx and ≤xx kt CO_2/year)	Negligible CO_2 savings (< x kta year)
Layout	No changes required in the current layout; integration within the existing space and infrastructure	Minor changes in the current layout and small additional footprint occupied.	Moderate changes to the current layout required significant additional footprint occupied.	Significant additional footprint occupied, rearranging of current layout may be required.	Not possible to integrate with current layout. Additional land required
Utilities	No need to connect to the utility infrastructure.	Straightforward connection to the existing utility infrastructure (e.g. fits within existing electrical connection).	Minor (and feasible) adaptations required in the utility infrastructure (e.g., extension of the grid connection).	Requires building a completely new utility infrastructure of kW scale.	Requires building a completely new utility infrastructure of MW scale.
Downtime / time to implement	No downtime required (integration without interrupting current operations).	Short downtime of few hours of part of the plant. Possible to integrate within scheduled shutdown.	Longer downtime but possible to integrate within scheduled shutdown.	Prolonged downtime required outside the scheduled shutdown, impacting (parts of) the operations.	Complete shutdown of the plant.
Permitting	No permit required, fully compliant with existing permit.	Change to the current permit is required but can be obtained without modifications to the project or environment.	Additional permits are required and some minor modification to the project or environment may be required, but feasible.	Several permits are required and major modification to the project or environment are required. Most likely lengthy procedures.	Obtaining permits is most likely not feasible (e.g. no approval from stakeholders, public opposition).
CAPEX	Direct drop-in replacement with existing processes; very low CAPEX (0 – 50 k€)	Minor modifications to existing layout or utility (e.g., add ons to the process); low CAPEX (50 – 250 k€)	Requires technical adaptations and adding new units but uses mostly existing infrastructure; moderate CAPEX (250 k€ - 1 M€)	Significant modifications and investments needed; high CAPEX (1- 5M€)	Requires fundamental process changes; very high CAPEX (> 5 M€)
SPBT	< 3 years	3 – 5 years	5 – 7 years	7 – 10 years	> 10 years
Strategic fit	Key company's focus and key part sustainability strategy, contributing directly to the current operations and portfolio of products.	Strong alignment with the company's focus and sustainability strategy. Fits within the existing operational framework with some adjustments.	Moderate alignment with the company's strategy, supporting sustainability goals but not a central focus of the overall company goals.	Little alignment with the company's focus and sustainability goals, most likely not supported by internal stakeholders.	The measure conflicts with the company focus and sustainability strategy.

*GHG reduction potential ranges are defined based on the size of the company and potential emissions associated with the operations.

3.4.1.1. GHG reduction potential

At this stage, the calculation is based on more detailed information than what was used in phase 1. As more data becomes available, there may be a need for additional energy input beyond the previous assumptions, or the measure may result in even greater CO_2 reductions. The goal is to refine the calculations to enable a more accurate comparison of the measures.

The net GHG reduction potential is calculated by subtracting the CO_2 emissions generated from energy use for this measure from the CO_2 savings achieved through alternative feedstocks, efficiency improvements, or valorised products (as outlined in section 3.3.1.3).

3.4.1.2. Layout

As first step in evaluating the measures, the capacity and the size of the equipment need to be calculated. The size of the equipment (e.g. reactors, storage tanks, pumps) gives input to the criteria **CAPEX** and **Layout**.

Some measures require no extra space as they are only influencing the feedstock used, while others need significant space and infrastructure for new process equipment. A qualitative assessment is done for this phase, as detailed information regarding the footprint might not be available for the measures. Even a qualitative assessment can already provide enough information if the to assess the chance of success for integration.

3.4.1.3. Utilities

To assess the **utilities**, it is essential to evaluate whether heating, cooling, or electricity is needed. This assessment involves considering the required temperature levels and whether the on-site utilities can meet the heating and cooling demands. Additionally, it is important to examine the electrical needs and estimate the maximum kW required.

Industrial facilities have electrical connections that are both physically and contractually limited. Extending these connections may be impossible for several years, especially if grid congestion in the area remains unresolved. Therefore, understanding these limitations is crucial, as they will directly impact any proposed measures.

3.4.1.4. Downtime / time to implement

Similarly to the layout, some measures require no downtime as they just replace certain feedstocks, while other measures might need a prolonged downtime because of complex integration in the current process.

Including downtime in the assessment is important as it affects the productivity of the plant, disrupts or stops the production, which will also have impact on the cashflow of the plant. By factoring downtime, the potential impact and full scope of implementation of the measure can be better understood.

To assess the downtime, one should first identify the scope of the technology implementation by evaluating which processes and systems will be affected and determining which systems will need to be shut down and how much time this will take as well.

3.4.1.5. Permitting

To determine if additional permits are required, among others, the following aspects should be considered, to determine if they fall outside the scope of the current permit:

- Identification of any new (not yet permitted) emissions resulting from the implementation of the measures,
- Whether the new process generates additional waste,
- The need for new infrastructure (e.g., buildings, roads) that would require a permit,
- The requirement to store new chemicals,
- If the new technology modifies or expands an existing process (e.g., increasing production capacity or introducing new materials), it may trigger the need for permits related to process changes or expansions.

It is important to assess the extent to which new or modified permits are necessary and evaluate the feasibility of obtaining them. Measures which score higher on this criterion should be prioritized, as circular measures are expected to drive improvements by lowering emissions and generation of waste.

3.4.1.6. CAPEX

The CAPEX of the equipment is estimated based on budget quotations, cost correlations or using scaling of costing data. High-CAPEX measures get a lower score because this often means more difficult routes through company layers, which lowers the chance of (quick) implementation and therefore impact made by the measure.

3.4.1.7. Simple payback time

Payback time (years) is the time required to recover the initial investment. To calculate the payback time, the CAPEX and all revenues (savings) generated by the measures are needed.

3.4.1.8. Strategic fit

Strategic fit is defined as the degree to which an option aligns with the company's core strategy (manufactured products), priorities, and sustainability goals, and is likely to be supported by internal stakeholders. When there is no strategic fit, less momentum is generated and therefore a lower chance of implementation is expected.

3.4.1.9. Example MCA phase 2

After all criteria for phase 2 are assessed, the MCA for this phase can be filled in. In Table 6, an example of MCA for this phase is shown. The maximum score is 40 points (8 criteria x 5 points maximum).

Table 6. Example MCA medium list

Measure	GHG reduction potential	Layout	Utilities	Downtime/ time to implement	Permitting	CAPEX	SPBT	Strategic fit	Score
Conversion of hydrocarbons to energy/heat	Moderate (3) 1.2 kt	Good (4) Moderate changes to current layout required	Good (4) Small additional capacity from utilities required for pretreatment	Moderate (3) Longer downtime but possible to integrate	Good (4) Possibility of additional permit requirements	High CAPEX (2) 3.9 M€	Very good (5) 2.6 yr	Good (4) New system, but within company operational framework	**73%**
Minimize nitrogen losses	Poor (2) 0.2 kt	Very good (5) No changes required in current layout	Very good (5) No additional utilities needed	Very good (5) Integration largely without interrupting the current operations	Very good (5) No additional permit requirements	Low CAPEX (4) 200 k€	Very good (5) 1 year	Very good (5) Key part of sustainability strategy, contributing directly to current operations	**90%**

3.5. Phase 3 – Feasibility & Shortlist

After phase 2, the most promising measures are selected. These measures are further developed into a concept design, including a detailed business case analysis.

As part of the concept design, the following deliverables are included:

- Mass and Energy Balance,
- Process flow diagram,
- If applicable, indication of tie-in points with the existing process on the process flow diagram,
- Equipment list,
- Space reservation for the measures on the plant layout.

Making those deliverable increases the level of detail of the design and allows for more accurate assessment of the costs and improves the business case analysis. Moreover, designing the process including the integration and required layout helps assess the technical feasibility of the measures.

Based on this analysis, the final implementation roadmap for the measures is prepared.

3.6. Phase 4 – Roadmap

The implementation roadmap includes Investment, OPEX, and CO_2 reduction roadmaps, as well as a project execution timeline with key milestones that considers organisational factors like timing, capacity and willingness and ability to invest.

Investment roadmap forms a strategic plan that lays out when, where, and how an organization will invest capital (CAPEX) over a defined time horizon. In the example shown on Figure 1, an implementation roadmap for 3 different measures is shown. Based on the graph, it can be concluded that the company will invest more than 6.5 M€ over a period of 3 years, with the biggest investments in 2028 and 2029.

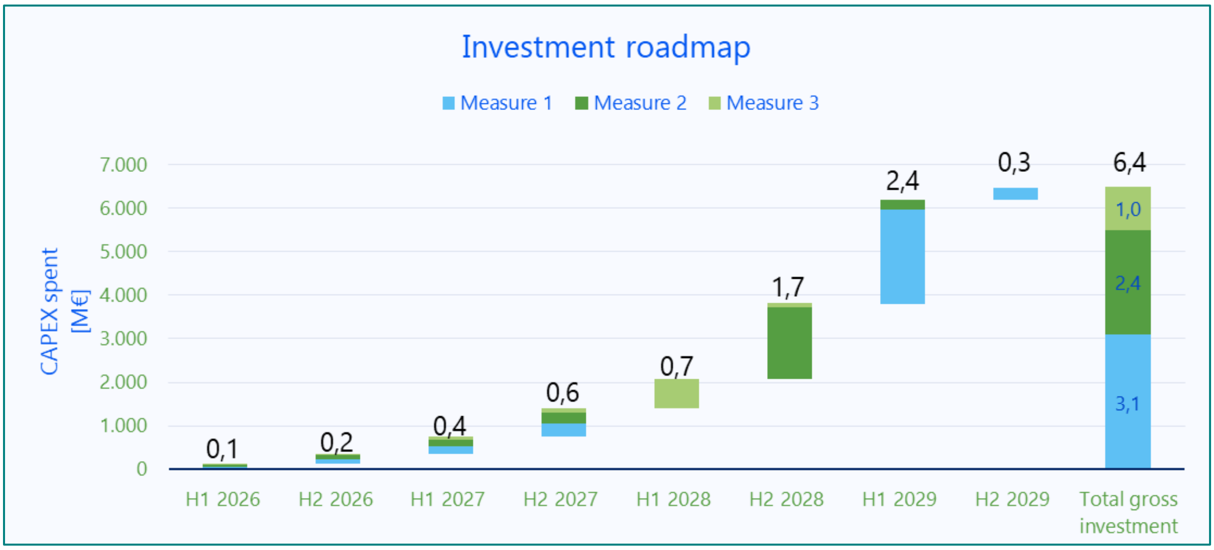


Figure 1. Example of investment roadmap for 3 measures, starting in 2026

An **operational savings roadmap** is a forward-looking plan that outlines how an organization will reduce operating costs or improve efficiency over time through the implementation of specific initiatives. Figure 2 show an example of operational savings roadmap for implementation of 3 different measures. It seems that the savings from measure 3 will be generated already in 2028, and measures 1 and 2 will implemented in 2029.

Figure 2. Example of operational savings roadmap for 3 measures, with first measure being implemented in 2028

A CO_2 savings roadmap (also called a carbon reduction roadmap) is a time-phased plan that shows how an organization will reduce its CO_2 emissions over time. In Figure 3, an example of a CO_2 reduction roadmap is shown.

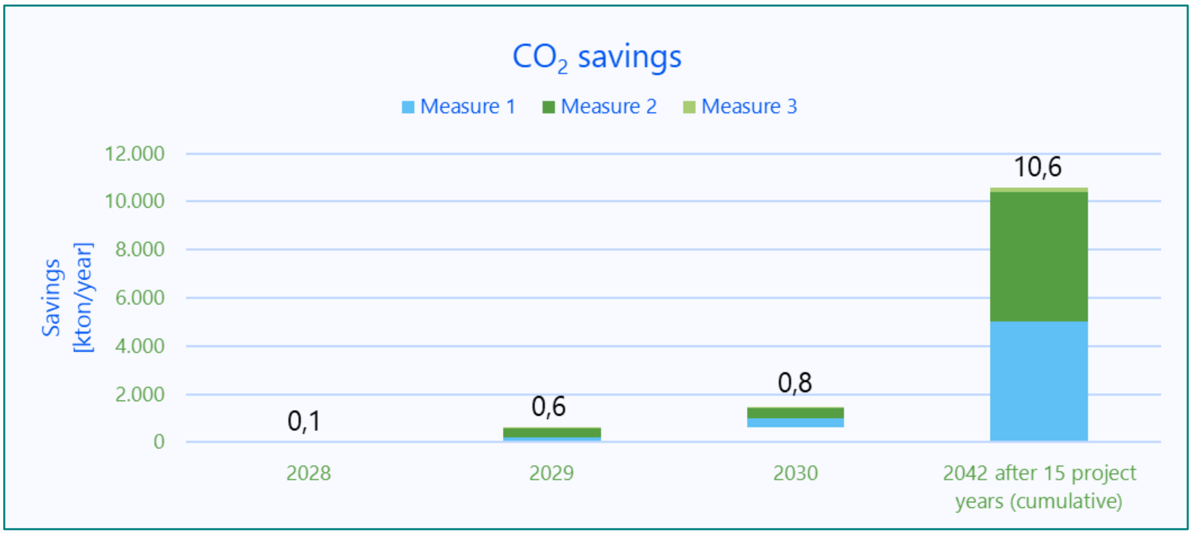


Figure 3. Example of CO_2 savings roadmap for 3 measures, with first measure being implemented in 2028

4. Lessons learned from the pilot

After piloting the methodology in a real-world case several lessons learned, and recommendations can be distilled for further implementation:

- **The team on-site is one of the key ingredients to obtain successful result.** For successful implementation of this methodology, different disciplines must participate in the project. Project manager is crucial to make sure the required team is available to support the study and to participate in decision making. It is of importance to involve professionals (e.g. process engineers, operators) who have close contact with the operations and know the details of analysed industrial process and can provide the 'advisors' with required information and data. Since new processes will have impact on the physical environment, HSE and Permitting expert should be involved as well. Plant manager therefore they should be involved in the decision-making process to align them with the plant's overall objectives. They also serve as the primary point of contact between project team and the higher management, so they need to ensure that any findings are effectively communicated.
- **The efficiency measures have the most significant impact on decarbonization (scope 1 emissions) and represent the largest area of opportunity for improving material handling within the facility.** These measures are tackled in the facility and are not only coupled with reduced emissions but also generate revenues from saving materials or energy. In contrast with feedstocks measures, which often result in negative economic potential.
- **There are inherent synergies between energy savings and feedstock efficiency measures.** Performing an energy audit (e.g. EED or Energy Innovation Study) could amplify the impact on decarbonization and operational efficiency. Combining the two audits allows for a more coordinated implementation of energy and feedstock strategies. For example, changes to feedstocks might require new equipment, different processing methods, or adjustments to energy systems. Making separate choices about energy and feedstocks can lead to system which is not optimised.
- **The waste valorisation measures can benefit from collective projects and scale.** Many chemical plants in the Port of Rotterdam share similar waste streams, therefore processing those streams in a common location can lead to lowering the cost for individual companies, lowering investment risks and can benefit from the economies of scale.

5. The organizations and people behind this methodology

TEKKOO

We are new economy builders. For over ten years, Tekkoo has been accelerating innovative and sustainable initiatives with a hands-on entrepreneurial approach. Because we believe in an economy that is both green and thriving. A circular economy in which we earn more money and emit less waste. Innovations in the circular economy and energy-, feedstock- and food transition make our eyes sparkle. Together with corporate and government changemakers we push innovations beyond reports and strategies. We set up experiments, do pilots, execute strategies and run projects. We tap into our network and bring the right people together. With Tekkoo, you can be sure that things will finally *truly* start happening.

TransitionHERO

At TransitionHERO, our goal is to create positive environmental impact. We believe the industry needs to undergo a transition to enable clean production processes and a sustainable supply chain. Enabling such a transition would require a combination of innovative technology, strong business cases as well as the right people and mindset. We are not just another engineering firm. We are setting up the engineering of the future. With our multidisciplinary team, we have experience in optimizing energy systems and designing various process plants, supported startups in scaling up, built innovation programs in the industrial environment and understand what it takes – both the challenges and opportunities – to make those a success.

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