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Analyse av energirelaterte tiltak for utvekslinger og forbedringer i industrielle økoparker

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MASTER THESIS

for

Student Marte Veivåg Aase

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Analyzing energy-related symbiosis opportunities in eco-industrial parks

Analyse av energirelaterte tiltak for utvekslinger og forbedringer i industrielle økoparker

Background and objective

This project addresses energy savings and reuse by shared energy transformation and distribution systems in eco-industrial parks. An eco-industrial park (EIP) is an industrial park in which businesses cooperate with each other and with the local community in an attempt to reduce waste and pollution, efficiently share resources (such as information, materials, water, energy, infrastructure, and natural resources), and help achieve sustainable development, with the intention of increasing economic gains and improving environmental quality.

The objective of this MSc thesis is to carry out a literature study and case study on energy saving and reuse in relation to EIPs, and to develop a framework for a decision-making model for the evaluation of specific measures for energy-saving technologies. The literature study should cover common strategies and measures, resulting benefits and achievements, and pricing and contract issues, and what are feasible methods and models for examining energy savings and their corresponding benefits (energy demand, greenhouse gas emissions, costs) in EIPs. The case study should propose and outline the framework of a quantitative decision-support model that could be used for evaluation of selected EIP measures on energy savings and reuse opportunities. This framework is expected to be a follow-up development of what has already been proposed in a pre-thesis student project. More emphasis should be given to issues such as identification of performance criteria and corresponding indicators/metrics, and normalisation method across different types of performance indicators, as part of the multi-criteria decision support. Attention should also be given to how to document and visualize the specific contributions and cost/benefit issues of individual companies that are involved in the realisation of measures for increased performance within an EIP.

The thesis work is carried out in collaboration with SOFIES, Switzerland.

The following tasks are to be considered:

1. Carry out a literature study on issues of particular relevance to this project.
2. Define and describe the EIP case(s) you examine, with its context for industrial symbiosis opportunities, and description of specific measures that can be taken in order to realise energy saving and give associated environmental and economic benefits.
3. Develop the framework of a decision-making model for multi-criteria evaluation of the effect of the measures described above, including calculation of their obsolute and relative contributions to the set of chosen performance indicators. Focus the inclusion of relevant performance criteria, and the use of normalization methods and documentation and visualization principles of results that are considered important in an EIP practical, contractual and financial setting when exploring industrial symbiosis opportunities.
4. Apply the model to the case study you work with and report results and recommendations you find relevant.
5. Discuss the applicability and potential use and benefits of the model. Discuss your main findings, and strengths and weaknesses of your work. Suggest issues for further work in this field of research.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, that they are presented in tabular and/or graphic form in a clear manner, and that they are analysed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)

☐ Field work

Department of Energy and Process Engineering, 28. January 2014

Olav Bolland	Helge Brattebø
Department Head	Academic Supervisor

Contact person at SOFIES: Dr. Guillaume Massard

Preface

This Master Thesis completes the five year master program in Energy and Environment at the institute of Energy and Process engineering at Norwegian University of Science and Technology. The work has been carried out in Switzerland during the spring semester of 2015 in cooperation with the consulting company SOFIES in Geneva.

The objective of the thesis is to propose a generic framework for a qualitative and quantitative decision-support tool for evaluating specific measures for energy recovery technologies and reuse opportunities in eco-industrial parks. The finalized framework should be structured to support the three main phases in the process: opportunity generation, sustainability screening and finally the implementation of the alternative measures.

Some modifications to the work methods in the project had to been done along the way. During the initial months of the work, the opportunity generation tool showed to be more time consuming than initially thought. To be able to finish this thesis in a satisfying manner, the outline for the finalizing third phase of the tool has therefore not been started on. Due to all the time put into the first phase of the tool, not all of the objectives of phase 2, sustainability screening tool, was fulfilled during this work. In the project description it is also stated that the framework will be outlined based on a specific case study. However, the idea of using case specific data as a basis for the tool was excluded from the objective as it was suggested that creating a more generic framework had a higher utility. These adaptions to the initial objectives has been clarified in agreement with Sofies and supervisor Helge Brattebø at NTNU.

I would like give my sincere gratitude to my supervisor Prof. Helge Brattebø for helpful guidance and encouragement throughout my work. A great thanks to my co-supervisors in the consulting company SOFIES, Anne Verniquet and Dr. Guillaume Massard, for giving me this great opportunity to write my master thesis in cooperation with them. I want to thank, not only for the great academic support, but also for and motivating me the times where the barriers to finishing this work has felt high. Their help and support throughout this year has been invaluable to finish my work.

Thanks to Marleen for all the lovely coffee-mornings on the balcony throughout this semester. Last but not least, thanks to Ben, who transformed his terrace in Le Châble into a wonderful alp-view work space the very last weeks of my work. I couldn’t ask for a more beautiful place to finish my studies.

Marte Veivåg Aase

August 2015

Abstract

"Without some evidence of the economic and technical feasibility of EIPs and their potential for reducing the environmental burden of industry, the business and community leaders will hesitate to embrace it.."(Martin et al., 1996).

Three of the main challenges to overcome in eco-industrial development is related to technical, economic and regulatory barriers and the framework outlined in this work is a step towards identifying and overcoming these barriers. The objective of this master thesis is developing a user-friendly framework for a qualitative and quantitative decision-support tool in order to evaluate specific measures for energy-saving technologies and reuse opportunities in eco-industrial parks. Information gathered through a literature study on; common strategies for energy savings and reuse in industrial areas, feasible methods and models for examining energy savings and their corresponding benefits and multi-criteria decision aid (MCDA), provides the basis for the model development.

The complete framework consist of 3 phases:

- *Opportunity generation tool*: high level preliminary sorting of alternative measures
- *Sustainability screening tool*: evaluation of sustainability performance of alternative measures.
- *Implementation helping tool*: overcoming barriers related to contractual and financial issues of measures to be implemented.

Because development of phase 1 of the framework turned out to be much more time consuming than initially thought, phase 2 of the framework was delegated significantly less attention than what was fist planned. More focus was put into trying to advance as much as possible in the important phase 1 of the framework. Already early in the work it was decided that phase 3 would be excluded from the scope and left to further work in order to put more focus on the two initial phases. The three types of energy streams included in the assessment is steam, exhaust/flue gas, and water. Material flows are excluded from the assessment.

The opportunity generation tool in phase 1 will work as a discussion opener and provide a brief qualitative evaluation of some of the possible alternatives for synergy. It can be used as support in discussing possible energy recovery opportunities for different streams in a variety of cases concerning industrial symbiosis in industrial areas. It suggests different reuse opportunities and technologies for each type of stream on a generalized high level and link to literature where more specific appliances of the technologies has been implemented before. With help from this tool, the users will become aware on various symbiosis opportunities. Even the combinations in lack of enough data to provide a feasibility assessment, will create awareness just by having different recovery possibilities identified.

One of the main barriers in developing this phase was related to the compromise between making a generic model that at the same time was refined enough to screen alternatives for various specific cases. Much time was spent trying to classifying the stream types in a manner that would provide the user with an accurate sorting of purposes and technologies according

to the specific stream type. Finally, the sorting of the different stream types was done in a more simple manner, because of troubles finding enough parameter specific literature for purposes and technologies to make this initial, general screening of opportunities. Streams could be classified in a more exhaustive way with respect to e.g. pressure, temperature and volume flow, or in terms of useful energy content (exergy). In order for the tool to reach its maximum potential, the tool has to be filled with information and evolve over time to create an exhaustive, informative database for energy recovery opportunities for waste streams in an industrial area. The initial version of the tool demonstrated in this work is not completed, and there is a large potential for improvement both in terms of the structure of the tool and how to program it.

For further work it is recommended that after defining the classification it is recommended to start focusing on one type of stream until a satisfying amount of information on relevant energy recovery and reuse purposes and technologies for that stream are implemented and evaluated in the tool, before moving on to the next stream type.

Phase 2 is the follow up development of what was started in the preliminary thesis: *Methods for assessment of energy saving and reuse technologies in eco-industrial parks* (Aase, 2015). Due to limited time, it was not possible to advance as much as intended in this phase. In this work it has been focused on making the sustainability screening tool in a more generic manner than in the preliminary thesis, adaptable to various cases. This phase is where the identified measures in through the screening of opportunities in phase 1 is given a more detailed, case specific feasibility assessment. A set of the most relevant technical, economic, environmental and socionomic criteria are listed and the user of the tool selects which of these to include in the assessment of the case specific measures. When the results from the calculations on the criteria are put in to the model, normalized results are calculated using four different methods. Hence, the user have a possibility of choosing what method to utilize. The objective of this tool was also looking in to different ways of weighting, aggregating displaying the final evaluation scores. However, due to an increased focus on phase 1, this was not found time for.

Phase 3 of the framework not initiated in this work. It is suggested to be a toolkit with a list of common contractual and pricing issues and successful models/templates. Developing this is left to further work. When the complete first version of the framework is finalized it should be demonstrated using a case study.

Sammendrag

Tre av de største utfordringene relatert til øko-industriell utvikling er knyttet til tekniske, økonomiske og regulatoriske hindringer. Hensikten med dette arbeidet er ¨komme et skritt nærmere i å identifisere og overkomme disse gjennom ved å utvikle et brukervennlig rammeverk for et kvalitativt og kvantitativt beslutningsstøtteverktøy for å vurdere konkrete tiltak for energisparende teknologier og gjenbruksmuligheter i øko-industriparker. Litteraturstudiet som grunnlag for modellutviklingen tar for seg; strategier for energisparing og gjenbruk i industriområder, gjennomførbare metoder og modeller for å undersøke energisparing og resluterende fordeler multi-kriterie beslutningsverktøyet (MCDA).

Det komplette rammeverket består av følgende 3 faser:

• *Opportunity generation tool* (verktøy for mulighetsgenerering); preliminær forhåndssortering av alternative tiltak for utnyttelse og gjenbruk av tilgjengelige energistrømmer

• *Sustainability screening tool* (screening verktøy for bærekraftig gjennomførbarhet); case-spesifikk kvantitativ evaluering av gjennomførbarheten til alternative tiltak

• *Implementation helping tool* (verktøy for implementeringshjelp): overkomme barrierer knyttet til kontraktsmessige og økonomiske problemer for tiltak som skal implementeres

Fordi utviklingen av fase 1 av rammeverket viste seg å være mye mer tidkrevende enn antatt, ble fase 2 gitt betydelig mindre fokus enn hva som først var planlagt. Det ble besluttet å bruke mer til å prøve å avansere så mye som mulig i den viktige fase 1 av rammeverket. Allerede tidlig i arbeidet ble det besluttet at fase 3 ville bli ekskludert og overlatt til videre arbeid. De tre typene energistrømmer som inngår i verktøyet er damp, eksosgass, og vann. Materialstrømmer er ekskludert fra vurderingen.

Verktøyet for generering av muligheter i fase 1 gir en overordnet kvalitativ vurdering av aktuelle alternativer, og kan brukes til å innlede og støtte opp under diskusjoner angående muligheter for energigjenvinning industriområder. Modellen foreslår ulike formål og teknologier for hver type strøm på et generalisert og overordnet nivå og kan linke til litteratur der anvendelse av teknologiene er dokumentert. Dette verktøyet er med på å skape bevissthet, og synliggjøre muligheter for industriell symbiose. Også de kombinasjonene i mangel på nok data til å gi en overordnet evaluering, vil skape bevissthet bare ved identifisere muligheter for energigjenvinning.

En av de viktigste barrierene knyttet til utviklingen av denne fasen var kompromisset mellom å lage en generisk modell som samtidig skulle være raffinert nok til å screene alternativer for ulike konkrete caser. Mye tid ble brukt på å prøve å klassifisere strømmene på en måte som ville gi brukeren en nøyaktig sortering av formål og teknologier i henhold til den spesifikke typen strøm. Grunnet problemer med å finne nok parameterspesifikk litteratur for ulike formål og teknologier, ble de forskjellige strømtypene ble til slutt klassifisert på en enklere måte for å kunne gjøre en overordnet sortering av teknologier. Den første versjon av verktøyet

demonstrert i dette arbeidet ikke er ferdigstilt, og det er stort potensiale for forbedringer både når det gjelder strukturen av verktøyet og hvordan det er programmert.

Ved videreutvikling og oppgradering av modellen kan strømmer klassifiseres på en mer utfyllende måte med hensyn til f.eks trykk, temperatur og volumstrøm, eller i form av det nyttige energiinnholdet (exergi). For at verktøyet skal nå sitt maksimale potensiale, må verktøyet utvikles videre og fylles med informasjon. Over tid kan verktøyet utvikle seg til å bli en utfyllende, informativ database for muligheter for energigjenvinning av energistrømmer i et industriområde. Ved videre arbeid er det anbefalt (etter at alle klassifisering for strømmene er definert) å starte med å fokusere på én type strøm inntil en tilfredsstillende mengde informasjon om aktuelle formål og teknologier for energigjenvinning er implementert og evaluert i verktøyet, før en tar for seg neste.

Fase 2 er videreutviklingen av arbeidet som ble påbegynt i prosjektoppgaven: *Metoder for vurdering av teknologier for energisparing og gjenvinning i industrielle økoparker* (Aase, 2015). På grunn av begrenset tid, var det ikke mulig å avansere så mye som først planlagt i denne fasen. I dette arbeidet har det vært fokusert på å utvikle et mer generisk verktøy enn i den foregående prosjektoppgaven. De mest relevante tekniske, økonomiske, miljø og sosioøkonomiske kriteriene er opplistet i verktøyet, og det er opp til brukeren av å velge hvilke som er relevante å bruke i evalueringen av de aktuelle tiltakene. Resultatene fra beregninger og evalueringer er gjort utenfor modellen, men resultatene blir fylt inn i tabeller, og normaliserte verdier for fire ulike metoder blir beregnet. Det er opp til brukeren av verktøyet å velge hvilken metode som er den optimale for det aktuelle caset. Målet med dette verktøyet var i utgangspunktet også å beregne vektede resultater på ulike måter og til slutt legge frem den endelige evalueringen. På grunn av økt fokus på fase 1, ble det ikke tid til dette.

Fase 3 av rammeverket ikke påbegynt i dette arbeidet. Det kan bestå av en liste over vanlige kontrakts- og prisingsspørsmål og vise til vellykkede modeller/maler. Når første versjonen av det komplette rammeverket er ferdig, bør det bli demonstrert ved anvendelse av et case studie.

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Key terms

EIP	**Eco-industrial park**. A community of clustered industries with an increased focus on sharing resources like material, energy, water, infrastructure and information to obtain a collective benefit, in terms of both economic and environmental gains, greater than the benefit each company would realize on their own.
IE	**Industrial ecology**. The study of interactions and interrelationships within the industrial system and between the industrial system and the natural environment. The idea of IE is to understand how the industrial system works, how it is regulated and how it interacts with the biosphere, in order to restructure it and make it compatible with the functions of the natural ecosystem.
IS	**Industrial symbiosis.** A concept within the field of industrial ecology, principally concerned with cyclical flow of resources through a network of companies. These industrial networks can by optimizing resource flows based on energy, material, by-product exchanges and utility sharing, achieve a collective benefit greater than the sum of individual benefits from each facility acting alone. An eco-industrial park is considered a practical example of industrial symbiosis.
MCDA	**Multi criteria decision aid.** Tool providing elementary methods for reducing complex problems to a singular basis for selection of a preferred alternative.
DM	**Decision maker.** In this context responsible for choosing solutions related to decision making regarding IS in EIP’s.
NPV	**Net Present Value.** Sum of the present value of incoming and outgoing cash flows over a period of time.
IRR	**Internal rate of return.** The annualized yield obtained over the lifetime of the project given by the percentage return on each unit of money invested in the project.

1 Introduction and objectives

1.1 Context

One of the greatest challenges in today's society is battling the climate change, caused by the enormous increase of accumulated greenhouse gases in the atmosphere in the course of the last decades. Urbanization, evolving economies and the high share of fossil energy sources, result in emission of gases that disturb the energy balance of the earth and result in the increase of the global mean temperature. According to the IPCC Fifth assessment report (AR5), the surface of the Earth has been successively warmer in each of the three last decades than any preceding decade since 1850. The report also states that "it is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentration and other anthropogenic forcing together" (Working Group III IPCC, 2014).

Despite the last two decades have shown relatively active efforts in designing and adopting policies to mitigate emissions of pollutants that affect the climate (such as the Kyoto Protocol), the global emission trend the last years has seen no sign of stabilization. From year 2000 to 2010, there has been a global average increase in greenhouse gas emissions of 2% per year, which is twice the rate than in any other decade since 1970. This trend stands in large contrast to the rapid decline that would be needed to reach the 2°C target (Working Group III IPCC, 2014).

In Europe, the energy consumption from the industry sector constituted about 62% of the total energy consumption in 2011 (Brückner et al., 2015). Shifting the energy system to being less carbon intensive and more sustainable with respect to resource extraction, requires an improved understanding of interactions between different industries and other economic sectors. Within the concept of industrial symbiosis lies a great potential for environmental improvement. The collaborative system activities between the sectors, can through industrial symbiosis in eco-industrial parks improve the outcome effect of mitigation measures. Environmental benefits through decrease in resource consumption and greenhouse gas-emissions, and economic benefits through the corresponding reduction of fuel costs can be obtained through utilization of these residual streams from industrial processes (Chae, Kim, Yoon, & Park, 2010; M. R. Chertow, 2000).

Challenges within eco-industrial development is often related to technical economic and regulatory barriers and "without some evidence of the economic and technical feasibility of EIPs and their potential for reducing the environmental burden of industry, the business and community leaders will hesitate to embrace it.."(Martin et al., 1996). Hence, in order to attract and retain companies to engage in mutually beneficial collaborations in eco-industrial parks, it is critical for the involved parts to understand the direct and indirect business benefits, opportunities and sustainability challenges (Veleva, Todorova, Lowitt, Angus, & Neely, 2015). Many EIP-programs have been challenged with respect to the identification, evaluation and implementation of potential symbiosis (Behera, Kim, Lee, Suh, & Park, 2012). A framework providing support in all of these phases in eco-industrial development, will therefore be useful for simplifying these processes.

A central element to the technology infrastructure of an EIP is the technologies that allows companies to use a by-product that would otherwise exit the industrial ecosystem as waste (Martin et al., 1996). For stakeholders to gain knowledge on the maturity and the potential economic and environmental gains of these technologies, will be an important asset to generate symbiosis opportunity. According to Eilering & Vermeulen (2004) "..quantitative data about the economic benefits and environmental gains generated by the measures could be an important stimulus for other companies in industrial parks to try and work toward symbiosis and/or utility sharing in practice". Therefore, developing an opportunity generation tool as part of the framework, in order to collect and provide an initial qualitative evaluation of possible alternatives for symbiosis, would be useful for the awareness phase to encourage stakeholders to engage in symbiotic collaboration.

Environmental issues, such as implementation of measures for energy saving and reuse opportunities in eco-industrial parks involve shared resources and broad constituencies, and group decision processes are necessary (Kiker, Bridges, Varghese, Seager, & Linkov, 2005). When coupling production processes, this calls for complicated organizational processes and interdependence between the involved parts. In order to take part in industrial symbiosis, companies participating in a cooperative approach in industrial symbiosis need a clear picture of the benefits and the preconditions of the different options (van Leeuwen, Vermeulen, & Glasbergen, 2003). As stated by Chertow & Lombardi (2005) there are several studies on the costs of synergy measures, but with less focus assessing and quantifying the benefits of the synergies. Through quantifying the changes in energy consumption and natural resource resulting from energy cascading, by-product exchange and increased rate of recycling, the benefits of IS measures can be assessed (Chertow & Lombardi, 2005).

Multi-criteria decision aid (MCDA) can provide elementary methods for reducing complex problems to a singular basis for selection of a preferred alternative (Kiker et al., 2005). Applying a systematic analysis will help overcoming the limitations of unstructured group decision-making (van Leeuwen et al., 2003) through methods for eliminating the difficulty of the complex interaction of the energy system. MCDA is also helpful in the weighting and valuation of the environmental interventions and impacts (Lahdelma, Salminen, & Hokkanen, 2000). A sustainability screening tool should therefore follow up the opportunity generation phase in the framework in order to give a case-specific quantitative evaluation of the measures chosen based on the high-level qualitative evaluation.

With the absence of political and administrative support, or because of legal or financial obstacles, decision-making processes can be seriously delayed, or in worst case, entirely break down (Eilering & Vermeulen, 2004). For the completion of the framework, an implementation tool for helping decision-makers overcome barriers related to e.g. contractual and pricing issues would be required. This would consist of a toolkit with a list of common issues, and successful models and templates able to handle and mitigate these obstacles. Because of time limitations, this finalizing phase is left out of the objective of this thesis and is proposed as a suggestion for further work.

1.2 Objective

This master thesis is the follow-up development of a preliminary project work executed during the fall semester of 2014 where a suggestion for a decision-making framework was presented (Aase, 2015). The objective of this work is to develop a user-friendly framework for a qualitative and quantitative decision-support tool in order to evaluate specific measures for energy-saving technologies and reuse opportunities in eco-industrial parks. Information gathered through a literature study on; common strategies for energy savings and reuse in industrial areas, feasible methods and models for examining energy savings and their corresponding benefits and multi-criteria decision aid (MCDA), provides the basis for the model development. The framework proposed in this thesis will consider three different phases. However, only the two first have been worked on, where the main focus is given the initial, first phase of the tool. Phase 3 is left up to further work in order to finalize the complete framework.

Phase 1: Opportunity generation: useful for the *awareness* phase for engaging and motivating stakeholders. The output of this phase will consist of a dynamic table for different types of energy streams, the corresponding opportunities (purposes and technologies) on how these streams can be reused in symbiotic exchanges in EIP's. The goal for the tool is to give an evaluation of their expected environmental and economic impacts. It is outside the objective to make this initial feasibility assessment of all the combinations suggested, but a few exhaustive examples will demonstrate the function of the tool.

Phase 2: Sustainability screening: useful for helping managers in decision-making processes regarding energy-saving technologies in EIP's. This phase of the framework aims at giving a case specific sustainability screening of the criteria the user of the tool has selected to go forward with from the opportunity assessment in phase 1. It will assess relevant performance criteria, and should be simple, flexible, and adaptable. Since more attention has been given phase 1 of the tool, the objective for this phase is not to finalize, but to take a step further from the work initiated in the preliminary thesis.

1.3 Scope

The proposed framework in this master thesis includes three phases, but only the tools for the two first; *opportunity generation* and *sustainability screening* has been outlined in this thesis. However, due to an increased focus on phase 1, the outline of phase 2 has been less prioritized in this work. Phase 3, considering *implementation-helping* is left as suggestion to further work.

In the model framework, only streams used for energy recovery and reuse purposes has been assessed. These are divided into three main stream categories;

- High, medium and low temperature exhaust/flue gas
- Saturated and superheated steam
- Water (all temperatures)

Only streams for *energy* recovery purposes are considered. Material streams, including those that has an obvious potential for energy recovery are left out of the scope, hence industrial excess energy in the form of combustion of waste gases or by-products has not been included.

Making an initial feasibility assessment of all the different combinations of purpose and technology in the first phase is not achievable within the limited time of this work. However, the opportunity generation tool will be demonstrated using a couple of examples where information in all steps are completed.

1.4 Outline of thesis

Chapter 2 gives an insight into the literature considered important for the framework developed in this master thesis. The terms *industrial ecology, industrial symbiosis and eco-industrial park* are explained, followed by a more in-depth literature review over common methods and technologies for implementing industrial symbiosis measures for resource sharing, methods for quantifying cost and benefits of these measures and a literature review on how to employ decision-making models for multi-criteria environmental problems. Finally, examples are given on successful eco-industrial parks and their savings.

Chapter 3 is the methodology chapter explaining the methods used, the target groups for the tools in the framework and the system boundaries used for the framework.

Chapter 4 goes into the proposed methodology for phase 1 and phase 2 of the framework. For phase 1 the classification of streams, the various evaluation criteria, the classification of initial evaluation scores, and the development and usage of the tool is outlined. For phase 2, the evaluation criteria for sustainability screening tool are explained, and the development and usage of the tool is outlined.

Chapter 5 discuss the main achievements in the work, the main barriers to development of the framework, how the tool can be utilized, and its strengths and weaknesses. Recommendations to how the framework can be upgraded and taken to the next step finalizes this chapter.

Chapter 6 concludes and sums up the most important, achievements, barriers to development and recommendations for further work for the framework.

2 Literature study

2.1 Industrial ecology

Industrial ecology (IE) is the study of interrelationships within the industrial system and the interactions between the industrial system and the natural environment (Graedel, 1994). The biological analogy is used to promote the cyclic economy and synergic interactions between the industrial and the environmental systems (McDonough & Braungart, 2010). The idea of IE is understanding how the industrial system works, how it is regulated and how it interacts with the biosphere in order to restructure it and make it compatible with the functions of the natural ecosystem (Erkman, 1997).

Graedel (1994) separates the term of IE into three types of systems, depending on the degree of dependency from external resources in the industrial ecosystem:

Type I: The system has linear resource flows and high dependency on external resources and assumes the external environment has unlimited capacity of producing resources for input to the system and output sinks for waste output from the system.

Type II: The system has quasi-cyclic resource flows, where there is a certain degree of circulation of flows within the system. Hence, the dependence of the need for external resource inputs and waste output is reduced compared to the Type 1 system.

Type III: The system has the highest degree of cycling and is self-sufficient with a closed-loop circulation of resources.

One can also say that industrial ecology can be operated at three different levels (Figure 1) ranging from the global level, through the inter-firm level to the level of the individual facility (M. R. Chertow, 2000). At the facility or firm scale, design for environment, pollution prevention and “green accounting” is included. The concept of industrial symbiosis and eco-industrial parks comes at the inter-firm scale of industrial symbiosis. At the regional/global level budgets and cycles, in addition to materials and flow studies (the principle of industrial metabolism) is included. Although the firm and unit process is important, much of the focus in industrial ecology lies within the inter-firm and inter-facility level. When a broader scope is used, significant environmental gains can be obtained (Ayres & Leslie Ayres, 2002).

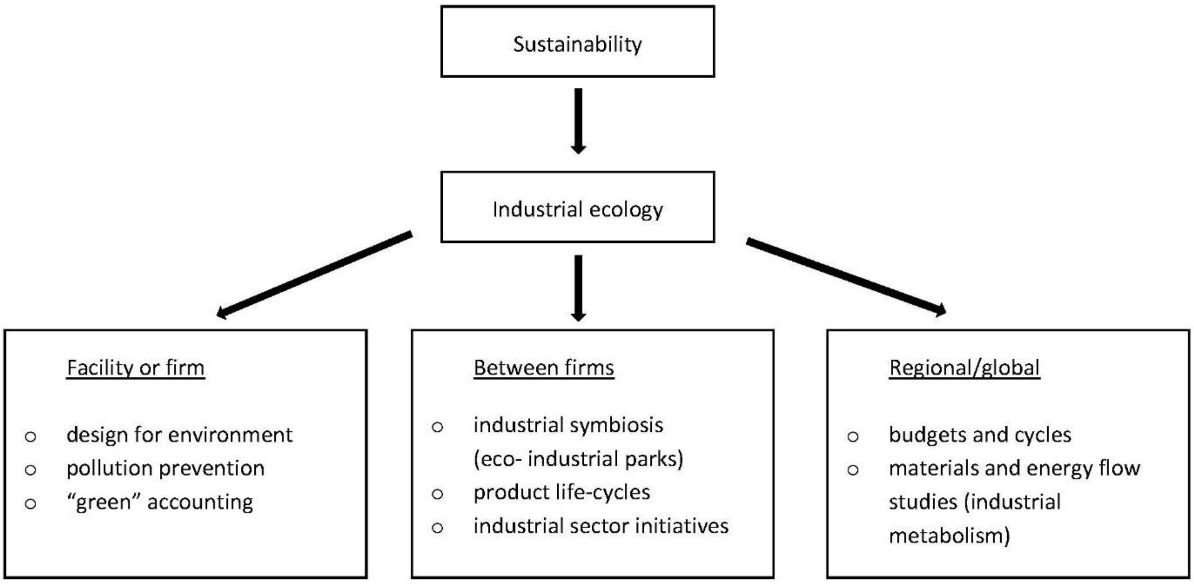


Figure 1. The three levels at which industrial ecology operates (M. R. Chertow, 2000).

Industrial ecology provides a basis of thinking about ways of connecting processes and industries in an operating web. Waste and energy that would otherwise go to disposal sinks, would be reused to a greater extent by creating a loop rather than ”comprising isolated components in a system of linear flows” (Gibbs & Deutz, 2007). This metaphor of an industrial ecosystem that mimics a natural ecosystem is the underlying concept of the term *industrial symbiosis* (M. R. Chertow, 2000).

2.2 Industrial symbiosis

Industrial symbiosis (IS) is a concept within the industrial ecology, principally concerned with cyclical flow of resources through a network of companies, pushing them to think beyond the boundaries of the individual firm towards a broader systems level (M. R. Chertow & Lombardi, 2005). These industrial networks can by optimizing resource flows based on energy, material, by-product exchanges and utility sharing, achieve a collective benefit greater than the sum of individual benefits from each facility acting alone. Waste output (in the form of e.g. material, water, steam/heat) from one facility can be turned into raw material for another facility. This can result in environmental benefits by reducing the intake of virgin material and/or give reduced emissions (Jacobsen, 2006). An idealized industrial system will similarly to a mature natural ecosystem not use non-renewable fossil stocks of carbon or oil and not exceed the reproduction rate of renewable resource of the ecosystem (J. Korhonen, 2002). Symbiosis opportunities are best when there are large and continuous waste streams. Cooperation on industrial symbiosis develops over time, however, information sharing and efficient stakeholder processes can possibly speed up the process (M. R. Chertow, 2000).

Chertow et. al., (2008) looks at the environmental benefits of collocated companies through industrial symbiosis and links the concept to the theory of *agglomeration of economies*, a concept describing the positive externalities that are accumulated from geographic concentration between industries. Three types of collaborative arrangements leading to the development of industrial symbiosis between companies has been noted (M. R. Chertow, Ashton, & Espinosa, 2008).

- <u>Utility sharing:</u> Through sharing of utilities, companies can ensure a reliable supply of fundamental resources like energy heat and water. A group of firms jointly undertake the responsibility of providing utility or infrastructure services as e.g. water heat and energy systems, a task which in general is undertaken by municipal authorities. Utility sharing, will under the industrial symbiosis framework, be considered a private cost (operation of the service) as well as a private benefit (shared fix costs, economies of scale and improved business stability) by traditional agglomeration economies. In addition public benefits like the reduction of emissions, increased use of renewable energy sources, and reduction of impacts on water systems can be attained.

- <u>Joint service provision:</u> When firms collectively meet their ancillary needs through joint provision of materials and services, which are not related directly to the core business of a company. This provides a collective access to a wider variety of services and inputs and a higher degree of specialization between firms. Typical benefits are increased product and service quality, cost reduction and increased efficiency. Materials and energy intensity may be improved through joint service provisions and the environmental gains can add up to significant savings on the regional scale.

- <u>By-product exchanges:</u> Traditional discarded materials are used as substitutes for commercial products or raw material. Exploiting waste material in this way is a key in the transitioning from linear to circular material and energy flows in industrial systems. Geographical proximity is of importance in order for this to be economically feasible. Transport costs has the potential of limiting the economic viability of certain by-product exchanges. Benefits in the form of reduced transport (Parr, 2002) and transaction costs , lower inventory requirements, better customization of inputs to customers through collaborative agreements (Feser, 2002), lowering input costs and the reduction of material and energy requirements through reduced recycling. Some of the by-product exchanges can involve the cascading reuse of materials where each subsequent process requires energy or material of lower quality.

Heavy process industries that has to comply with existing norms and regulations, are those where industrial symbiosis has the highest occurrence (Van Berkel, 2006) andne of the most often cited examples of industrial symbiosis in practise is Kalundborg *eco-industrial park* in Denmark.

2.3 Eco-industrial parks

Since the middle of the 19th century, industrial areas has been grouped in specific areas to isolate them from housing and agricultural areas. These areas are, depending on their scale, defined as an industrial area, estate or park. Many of these parks are planned, built and managed without environmental concern, and the impacts of these parks with respect to activities and produced products will therefore cause a lot more environmental damage than if ecologically optimized. (M. R. Chertow, 2000; Massard et al., 2014).

Eco-industrial parks can be seen as an example of an organized form of an industrial ecosystem (Liwarska-Bizukojc, Bizukojc, Marcinkowski, & Doniec, 2009) and can be refered to as industrial symbiosis in practise. For industrial symbiosis to be achieved between two or more companies in an industrial park is that there is a complementary need for energy, water and/or substance flows(Eilering & Vermeulen, 2004).

Chertow (2000) defines an eco-industrial park as: "a community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials. By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimized its individual performance only."

When the principles of industrial ecology, pollution prevention and sustainable design are applied to communities of businesses and regionally localized firms, the direct benefits that can be obtained are (Desrochers, 2001);

- reduction of virgin materials
- emission reductions
- increase in energy efficiency
- reduction of waste material
- increase of types of process outputs with a market value

and obtainable indirect benefits (Veleva et al., 2015):

- improved reputation
- innovation
- supply security
- operational resiliency
- ability to attract and retain employees

There are numerous studies considering the development of industrial symbiosis in eco-industrial parks, however most of them are qualitative and there is less attention to the quantification of the scale and significance for the actors in the symbiosis (Berkel et al., 2009; Betts et al., 2005; Mattila et al., 2010). Because of this lack of quantitative data available, the empirical foundations of eco-industrial parks are still fairly week (Eilering & Vermeulen, 2004).

Eilering and Vemeulen (2004) categorizes the ambition level for eco-industrial parks into three categories:

- ‘low’: the IS measures are targeted at individual companies
- ‘average’: the IS measures relate to achieve utility sharing
- ‘high’: the IS measures relate to realising symbiosis and also achieving utility

The article also presents an integrative environmental science approach framework for analysing the establishment of eco-industrial parks. This framework includes the disciplinary perspectives of natural science, business administration and policy studies.

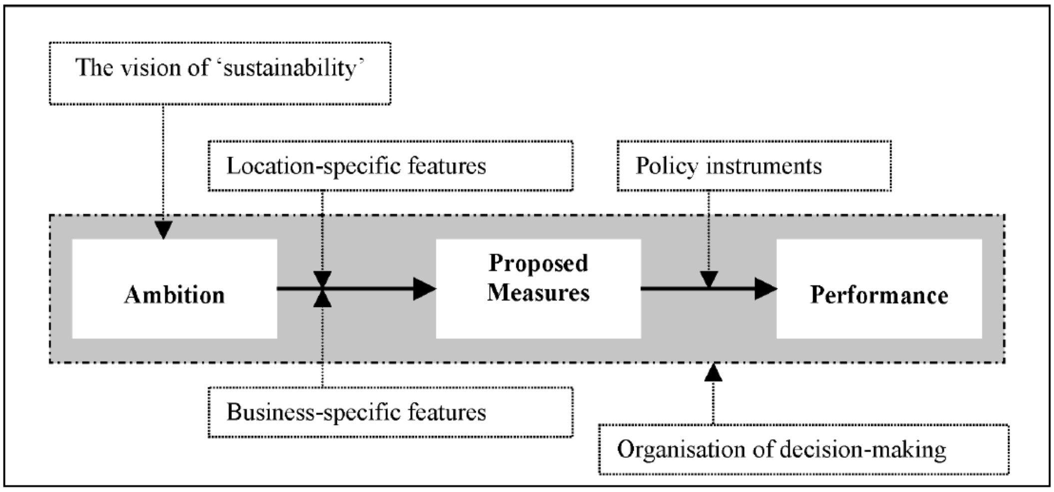


Figure 2. Framework of analysis (Eilering & Vermeulen, 2004)

- *The vision of sustainability:* describes the initial ideas on what type of eco-industrial park to be developed and the goals the developers want to achieve.
- *Business-specific features and location-specific features*: have an impact on eco-industrial parks because they affect which kinds of measures that can be chosen.
- *Policy instruments*: may be employed to ensure the measures are carried out.
- *Organisation of decision-making:* organises all processes between initial ambitions for implementation of measures to the final performance of the measures.

It is the latter of these perspectives, namely the *organisation of decision-making*, which is the most relevant with regards to the objective of this thesis. This phase considers the way the ambition is translated to performance (Eilering & Vermeulen, 2004). The success factor related to these different phases is further investigated in the following subchapter.

2.3.1 Barriers and success factors in development of EIP’s

For the development of an eco-industrial park to become successful, there are numerous barriers to overcome. Some of the limitations can be fragility of the systems, material fluctuations causing vulnerability, engaging with the firms and the public and deliberately trying to design an EIP (Tudor, Adam, & Bates, 2007). Symbiotic networks evolved spontaneously over time appear to be more resilient than planned ones (M. Chertow, 2007) and they can be difficult to plan, design and manage (Desrochers, 2004; Ehrenfeld & Gertler, 1997; Jouni Korhonen & Snäkin, 2005). Hence, creating a context that enables collaborations to emerge is important. Behera et al. (2012) identifies several points required for an efficient retrofitting of current industrial complexes into EIP’s:

- An economic principle to reduce costs and generate an enlarged revenue among businesses
- Environmental policy streamlined into increasing the resource flows and transaction for industrial symbiosis.
- New or existing technology available to or able to be developed to make the industrial symbiosis successful.
- There is a close relation between enhanced economic performance of participation businesses and making relationship to communities through business attraction and improved quality of life
- Environmental benefits across a community, such as improved health and reduced GHG-emissions.
- The EIP projects should encourage public participation through active promotion in order to build a strong foundation for the future expansion.

According to Eilering & Vermulen (2004), the main barriers is the establishment of the essential “symbiotic” exchange relationship between the companies participating in the project. These barriers can be divided into five different types (Eilering & Vermeulen, 2004):

- Technical: an exchange is technically not feasible
- Economic: an exchange can be economically risky from a company perspective
- Informational: the right information cannot be provided at the right time
- Organizational: the intended exchange does not fit in the organizational structure
- Regulatory/legal: caused by environmental laws and regulations

The challenges in EIP development are closely related to the success factors in EIP, or rather, the lack of success factors. Eilering & Vermeulen (2004) pose the question regarding what determines the success in achieving symbiosis and/or utility sharing in eco-industrial parks and combines a theoretical and practical research to answer that question (Eilering & Vermeulen, 2004). The article reviews some EIP-cases which are compared with respect to the factors presented in Table 1. below.

This study points to four different factors important for achieving success in eco-industrial parks (Table 1.). However, the features playing the most important role are:

- *Physical* location specific and business specific features
- *Social* location specific and business specific features

At least one of the points from each of these two categories needs to be satisfied for symbiosis and/or utility sharing to be obtained

In contradiction to category 1, 2 and 3 in the analysis in Eilering and Vermeulens work does not give a clear impression on the relationship between *implementation of policy measures* and the degree of success in the EIP in latter category.

1. Physical location specific and business specific features	**2. Social location specific and business specific features**	**3. Organisation of the decision making process**	**4. Policy instruments**
The quantity of demand must be the same as the quantity of supply (quantitative)	The companies must *trust each other.*	The organization is done in a *joint process* or in a *bottom-up* approach.	Promotion and acquisition(voluntary)
The quality of the supply must correspond with the quality of the demand (qualitative)	There must be an *anchor company* in the industrial park.	There must be a joint defining of process.	There is facilitation
Mutual exchange of energy, water and (residual) substances between companies calls for simultaneity	There must be a *pioneer* in the industrial park to take initiative, which has a financial interest of eco-industrial development. A pioneer displays vision and is convinced that the principles of industrial ecology are correct.	There are connections with community.	There is park management
The physical distance between the companies must be small	The mental distance between the parties concerned must be short.	There is communication of proposed initiatives/results.	There exists financial incentives.

	There must be a *core group of companies with a distinct environmental profile* in the industrial park, to establishing the cooperation needed.	There are no financial obstacles.	There exists establishment requirements and private law agreements
	The companies in the industrial park must have a *high degree of organisation.* A well-organised industrial federation or business association is able to represent the joint interests of the users of the industrial park and provide ideas for cooperation	There are no legal obstacles.	There exists legislation (binding).
	The companies are *tied to the vicinity.* The degree to which a company has a bond with its location plays a role in achieving symbiosis or utility sharing	No lack of political/administrative support	
		There is no lack of expertise	
		There is no change in context	

Table 1. Physical, social, organisational and politic features enhancing success in eco-industrial parks. Source: (Eilering & Vermeulen, 2004)

In all the successful cases from the work by Eilering and Vermeulens (2004) the companies had a shared history and knew each other. Relationships with short mental distance, openness, good communication and trust have a higher potential for successful development (Bain, Shenoy, Ashton, & Chertow, 2010). The results from a case study by Chae et al., (2010) show that one of the difficulties related to the realization of energy networks in the lack of trust for information sharing among the participants of the symbiosis due to competition and security issues. In order to solve this there is a need for constructing legal and/or social environments of trust (Chae et al., 2010).

With the absence of political and administrative support, or because of legal or financial obstacles, decision-making processes can be seriously delayed or in worst case, entirely break down. An example of this is the case of AICD, Agro Industrial Complex Dinteloord, where redrawing of local authority boundaries complicated the decision-making process (Eilering & Vermeulen, 2004).

Financial risks is a common reason why companies choose to not to invest in symbiotic exchanges and the political approach must seek to a more active involvement of the participating companies in order to make cooperation on eco-industrial parks successful. The case study by Heeres et. al., (2004) found that the companies which were responsible for financing the realization of projects (instead of local/regional government and other interested parties) are the ones, which are expected to gain from the implementation of the exchanges (Heeres, Vermeulen, & de Walle, 2004). Substantial investment is required for eco-industrial park development including infrastructure for material and energy flows and construction of shared facilities. The continuity of the processes can be endangered when problems relating to the costs and the investment risks occur. How to divide the process cost is also something which has to be considered (Eilering & Vermeulen, 2004).

The companies has to be convinced of the economic and environmental gains that will be achieved through the symbiotic exchanges, by for example referring to other successful cases or arranging conferences with participants of other symbiosis (Heeres et al., 2004).

Table 2 below shows success factors sorted from highest to lowest occurrence from 168 case studies by Massard et. al., (2014).

Success factor	Description/example
1) *Coordinators (109/168)* Organizational and institutional setups	Organization and setups for the operation of the park. Coordination bodies, e.g. trust companies in charge of the coordination and services for stakeholders (e.g. environmental services, risk analysis, information and training, marketing and communication, help for getting permits, “plug and play” services) and providing a platform for cooperation among stakeholder. Monitoring through independent authorities and management of common mutualized infrastructures.
2) *Coop. S&T (81/168)* Cooperation with Science and Technology institutions	Cooperation with e.g. universities, science and technology enterprises and research centres, knowledge sharing.
3) *Eco-innovation park (78/168)* Clear designation of the park as eco-innovation park	Large opportunity to create sets of feedback flows due to the diversity of economic activities. Companies on site with activities in different sectors (e.g. wood industry, heat power generation, chemical operations and paper manufacturing(Costa & Ferrão, 2010)
4) *Value added (65/168)* Economic value added	Direct business interests of companies in reducing expenses and/or increasing profit by implementing synergies with other companies in the park (implementation, development, perpetuation).
5) *Policy (59/168)* Policy & regulation frameworks	Legislation enhancing eco-innovation, sustainable development, public private partnerships, industrial symbiosis and eco-industrial development strategies through local and regional policy action for implementation and regulatory instruments combined with innovative models.
6) *Location (55/168)* Geographical factors and regional infrastructure	Location (close to seaport, airport, highway, urban centres, historical and natural conditions), Infrastructure, size, potential for expansion.
7) *Incentives (46/168)* Financial incentives	Tax reduction and/or financial support for companies committing to sustainable practices.

8) *Diversity(41/168)* Local diversity of economic activities	Large opportunity to create sets of feedback flows due to the diversity of economic activities. Companies on site with activities in different sectors (e.g. wood industry, heat power generation, chemical operations and paper manufacturing.

Table 2. Success factors identified for eco-innovation parks (Massard et al., 2014)

2.3.2 Successful eco-industrial parks and their achievements

Finding statistics on the potential material, energy and emission savings in industries practicing symbiotic exchanges is not an easy task, as literature has centred more on qualitative studies with less attention on quantification of the IS benefits (Berkel et al., 2009). However, some examples of studies quantifying benefits of symbiotic relationship between industries can be mentioned.

Rizhao Economic and Technology Development Area (REDA), China

Yu et al. (2015) have studied the evolution of industrial symbiosis in Rizaho Economic and Technology Development Area (REDA), an industrial area in China (Yu, Han, & Cui, 2015b). REDA was formed as a National Demonstration Eco-industrial park in 1991. Since the formation of the park, a complicated IS network including by-product exchange, energy graded utilization and water exchange has been designed over three stages. Figure 3 below shows the industrial symbiosis network in REDA and its evolution through the stages.

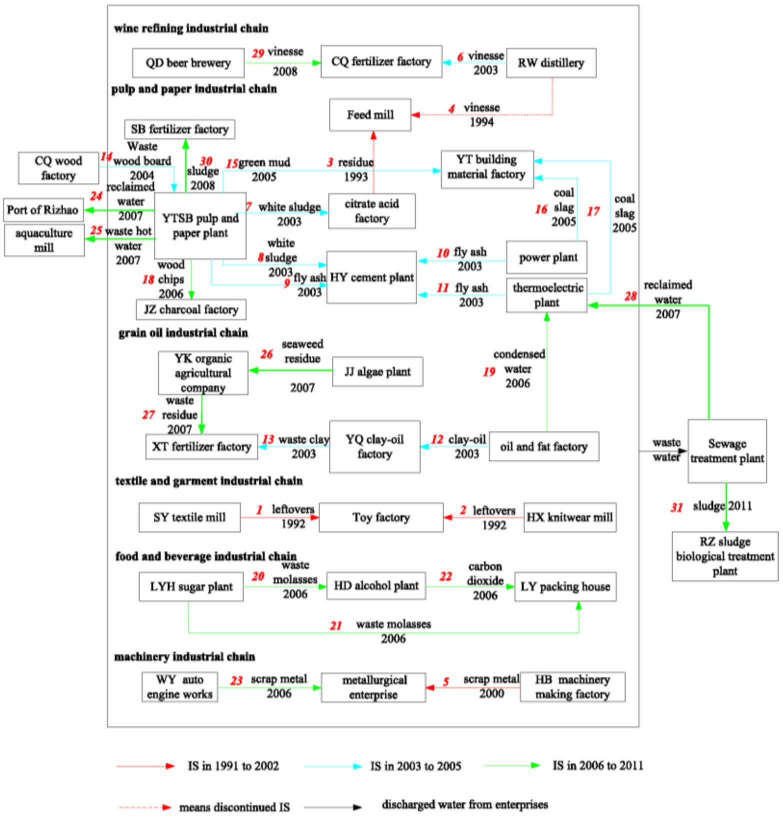


Figure 3. Industrial symbiosis network in REDA from 1992-2011

In the first development stage, from 1991-2002 the IS performances mainly evolved through self-organization of enterprises and affected by public policies. The two next stages, from 2003-2006 and from 2007-2011 both resulted mainly from government propaganda, policy guidance, advertising and financial support.

There are 13 key enterprises involved in the IS, and among the 31 IS-performances identified, by-product exchange accounted for 90%. Symbiosis based on energy and water exchange is, because of the heavy infrastructure investment, more difficult to establish. Water exchange and energy graded utilization therefor only accounted for only 6% and 4% percent, respectively. Results of the REDA IS in 2011 are presented in below:

By-product exchange:

- 71 446 tons of white sludge from YTSB was used instead of calcium carbonate in citric acid factory and cement factories
- Over 66 000 tons of fly ash and more than 20 000 tons of green mud were used for cement production and new building materials
- Over 19 000 of wood chips were utilized to produce wood charcoal
- 27 000 tons of sludge, 7400 tons of seaweed slag and 2250 tons of waste clay were used to produce organic fertilizer.
- 9100 tons of waste molasses replacing cassava for alcohol production
- 85 tons of metal scraps retrieved by smelting plants
- 6.9 tons of carbon dioxide were reused in beverage factory.

Energy and water exchange:

- 142 000 m^3 of high-temperature condensate water were reused in the thermoelectric plant
- 4 million m^3 of reclaimed water reused in the Rizaho Port and thermoelectric plant.

Kwinana industrial area

This industrial area in Western Autstralia's mayor heavy industrial region is recognized as a leading edge example in regional synergi development (Beers & Biswas, 2008) with 32 byproduct synergies and 15 utility synergies. This park stands out when it comes to the number, diversity, complexity and maturity of the excisting synergies (Massard et al., 2014)

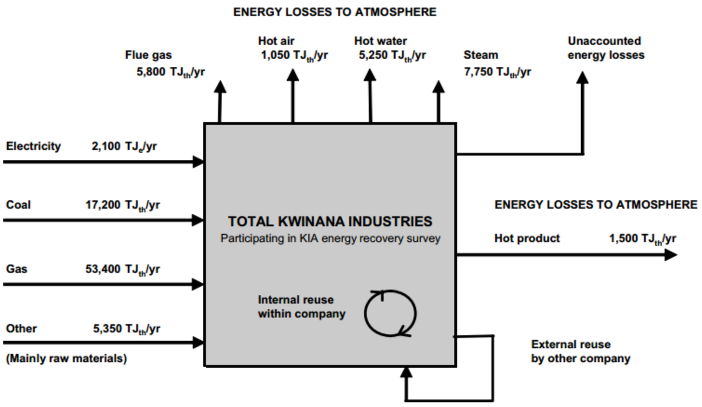


Figure 4 Kwinana industrial area: energy use and release diagram (Beers & Biswas, 2008)

Some of the keys to success in this park involves factors like the awareness of economic value added and the cooperation with intitutions for science and technology. There is also high expectations from community with regard to safety and environmental performance.

Kalundborg Eco-Industrial park, Denmark

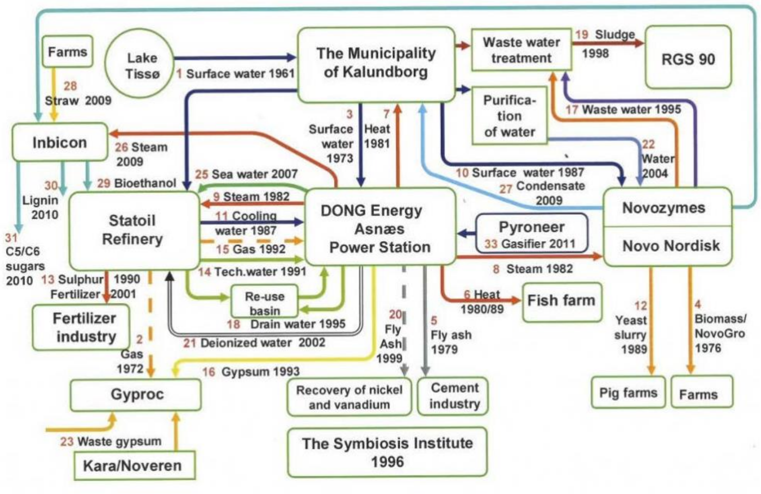


Figure 5. Industrial symbiosis in Kalundborg (Massard, Jacquat, & Zürcher, 2014)

Kalundborg is a well-known successful example on an eco-industrial park, which has implemented 30 successful symbiosis in the park network (Figure 5). The park area includes nine public and private enterprises and substantial reductions in both material and energy inputs have been achieved compared to what would have been the case if all enterprises operated independently. In a study of emission savings from the cogeneration of heat and power at the Asnæs power plant, a scenario study by Jacobsen et al. concluded with emission saving of 154 788 tons of CO_2 and 309 tons of NO_X compared to the same amount of energy delivery from a hypothetical natural gas plant in the period 1997-2002 (Jacobsen, 2006).

The Kalundborg industrial park now aims at a higher focus on renewables and recently pledged for the Asnæes Power Station (which currently uses coal as their main fuel) to switch to 50% renewable sources by 2050 (Massard et al., 2014).

The cooperation on industrial symbiosis in Kalundborg is based on mutual trust and openness, which is identified above as one of the most important factors for success in the section above. The emergence of the network has been facilitated by the awareness of the economic value added from the symbiosis (Massard et al., 2014).

Kawazaki, Japan

In a quantitative assessment of the urban and industrial symbiosis in Kawasaki, Japan it is documented 14 symbiosis that connect nine distinct companies (steel, cement, chemical and paper firms), the municipal waste collector in the city, the municipal waste collection and waste water treatment plant, and a group of industrial and commercial waste management companies (Berkel et al., 2009) (Figure 6).

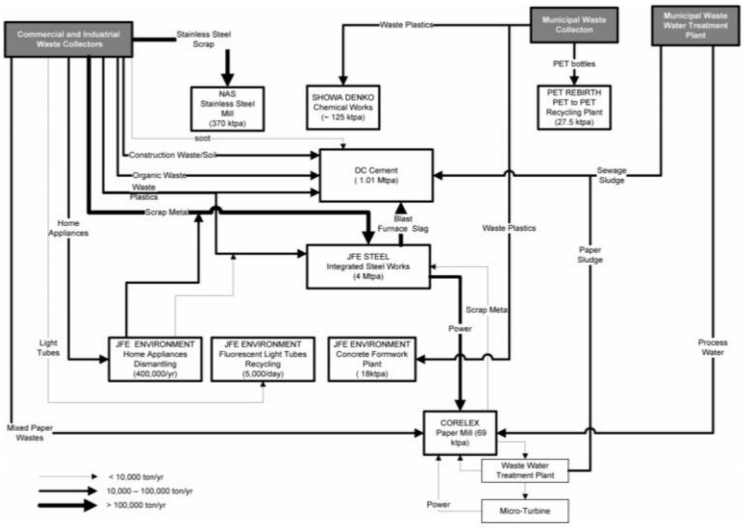


Figure 6. Industrial symbiosis Kawasaki, Japan (data from 2009). (Berkel, Fujita, Hashimoto, & Fujii, 2009)

This is an eco-town project which promotes an effective usage of residential, commercial and industrial waste that can be used in the heavy industries (cement, steel, iron) located in the area. A material flow analysis was conducted for identifying benefits for seven of the flows.

Some of the benefits:

- 315 ktpa clinker is replaced by granulated BF slag annualy
- 564 ktons is diverted from landfill every year, substituting 513 ktons of virgin materials per year.

The estimated annual benefits equates to approximately 130 USD per year.

Some of the key factors to success for this eco-town is the policy support and incentives provided by the national government. The proximity to energy facilities, the good transportation infrastructures and the cooperation with science and technology institutions are also factors making it easier achieving success (Massard et al., 2014).

Campell industrial park, Hawaii, US

In this work, LCA (substitution through system expansion) has been used to determine the energy and environmental benefits of the existing pattern of exchanges. In this industrial park there are 11 facilities exchanging water, materials and energy (Figure 7).

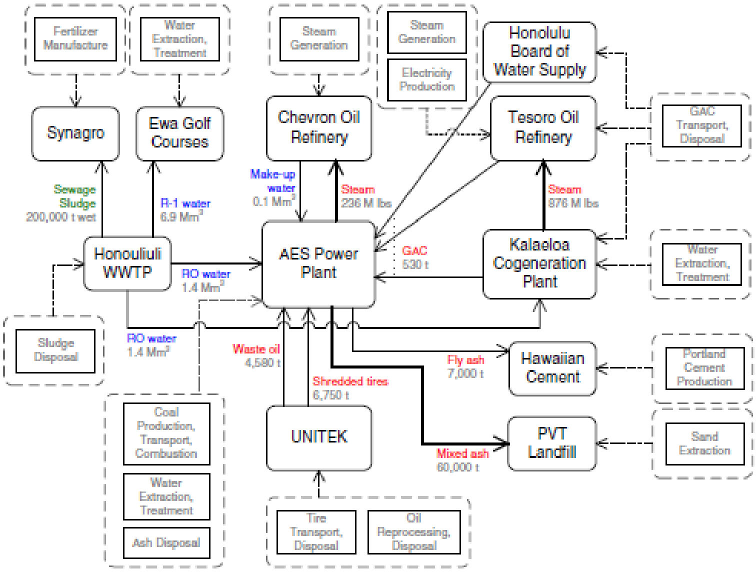


Figure 7 Industrial symbiosis in Campell industrial area, Hawaii.

A total of 200 000 tCO2-emission savings is achieved through the symbiosis in Campbell industrial park. This is primarily due to the usage of AES steam in the Chevron refinery (Behera et al., 2012).

2.4 Technologies for recovery and reuse of waste energy streams

Normally, large amounts of energy are used in the industrial sector and large amounts of waste heat is therefor produced (Chae et al., 2010). In Europe, the energy consumption from industry constituted 62% of total energy consumption in 2011 (Blesl et al., 2009).

Utilization of this waste heat can provide economic benefits by the reduction of fuel costs and economic benefits by reducing resource consumption and greenhouse gas emissions. The utilization of industrial waste heat has received a lot of attention on a global scale. However, while a great amount of research has been done in the water-recycle network area, little attention has been given waste heat recycle network among different companies (Chae et al., 2010).

Industrial waste heat can be recovered through numerous methods and Brückner et al. (2015) separates between active and passive technologies (Table 3) (Brückner et al., 2015). By taking advantage of energy recovery and reuse opportunities, the efficiency of industrial energy use can be enhanced and the emissions can be reduced at a low cost. To extend the reductions beyond the total sites, energy recovery and reuse between multiple plants to exploit the synergies between the heating and cooling requirements between the industries (Stijepovic & Linke, 2011).

	Passive technologies	**Active technologies**
Description	Heat is used directly at the same or for lower temperature purposes	Heat is transformed to another form of energy or to a higher temperature
Examples	Heat exchangers, heat storage	Organic Rankine cycle, Kalina cycle, mechanically driven heat pumps
Applications	Providing heat (WHTH)	Providing heat (WHTH), providing cold (WHTC), providing power/electricity (WHTP).

Table 3 Active and passive heat recovery technologies (Brückner et al., 2015)

The energy can be reused within the same process or transferred to some other process replacing fossil fuels (Kumar & Karimi, 2014).

Johnson et al., (2008) defines three essential components required for waste heat recover (Figure 8). First of all, an accessible source of waste heat is required, secondly an applicable recovery technology for the actual waste heat medium and lastly there has to be a suitable end-used for the recovered heat (Johnson et al., 2008).

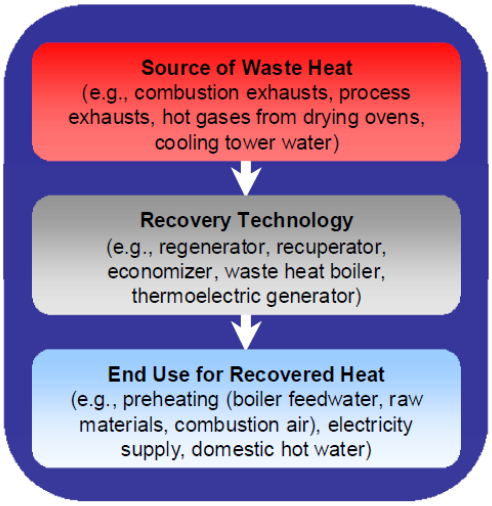


Figure 8 Three essential components required for waste heat recovery (Johnson, William, Choate, & Amber Davidson, 2008)

The recovery potential of the waste energy streams are linked to the quality of the waste energy. Temperature is one of the most important criteria when considering whether the waste stream can be used for producing valuable heat or used as a source of energy. Examples of recovery methods for low-, medium-, and high-grade waste streams are listed below.

Low temp. heat recovery	Medium temp. heat recovery	High temp. heat recovery
• Space heating (DH) (Torio & Schmidt, 2010) • Temperature- and pressure upgrade (heat-pump) (Kapil, Bulatov, Smith, & Kim) • Feedwater preheating • Domestic hot water • Low-temp power generation (Kumar & Karimi, 2014). • Low-temperature process heating • Distilling • Drying	• Steam generation • Power generation • Furnace load preheating • Feedwater preheating • Combustion air preheat • Transfer to low-temperature/pressure processes	• Steam generation • Power generation • Furnace load preheating • Combustion air preheat • Air pre-heating • Transfer to med-low temperature/pressure processes • Waste heat recovery • Co-generation • By-product exchange
(Kapil et al.; Madhawa Hettiarachchi, Golubovic, Worek, & Ikegami, 2007; Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011; U.S. Department of Energy, 2012)	Bertrand F. Tchanche et al., 2011; U.S. Department of Energy, 2012)	(Tchanche et al., 2011; U.S. Department of Energy, 2012)

Table 4. Purposes for low, medium and high temp heat recovery

Industrial processes release considerable amounts of waste heat at a wide temperature scale (Chae et al., 2010) and low-grade waste heat accounts for 50% or more of the total heat generated in industry (T. C. Hung, Shai, & Wang, 1997).

One of the challenges related to low-temperature heat recovery is corrosion on the heat exchanger surface, which calls for using advance materials or frequently replacing components of the heat exchanger. Also, since low temperature waste heat involve a smaller temperature gradient a large heat exchanger surface is required. Example of different low temperature recovery opportunities are; Organic Rankine cycle for power generation, economizer for boiler feedwater preheating, heat exchangers for space heating or absorption chillers for space cooling. Due to high costs and because facilities lack an end-use for the recovery of low-temperature heat, commercializing has been limited (Kumar & Karimi, 2014).

In industrial processes, one can separate between three principle forms for energy used: electricity, direct-fired heat, and steam. Electricity can be used for many purposes including heating, electrochemical reactions and mechanical drive. Direct-fired heaters will transfer heat directly from a fuel combustion to a process. Steam can be used for process heating, pressure control, component separation and mechanical drive (U.S. Department of Energy, 2012).It can be recovered and reused directly to offset heating requirements locally or externally. Either, waste heat can be used locally to increase the efficiency of the process itself, e.g. through preheating of the feeding water or combustion air in a boiler, or it can be transferred and reused in external processes, e.g. in water desalination or waste-heat power generation (Fang, Xia, Zhu, Su, & Jiang, 2013).

Important factors when it comes to waste heat recovery are as follows (Johnson et al., 2008):

- Quantity of stream (energy content as a function of function of mass flow rate, composition, and temperature)
- Quality/temperature of stream (temperature of exhaust and the total amount of recoverable energy)

- Composition of stream (
- Minimum allowed temperature (? Don't quite understand this?)
- Logistic factors like availability and operation schedules and transport distances.

One of the main variables affecting the feasibility of energy recovery is the distance between the source and sink (Van Beers, 2009) , and the maximum suggested heat distribution distance is 10-20 km (Jouni Korhonen, 2001). Industrial areas are therefor often divided into clusters, where collaborative opportunities are assessed within each cluster but not between industries located in different clusters (Van Beers, 2009).

2.5 Methods for quantitative evaluating of measures

Industrial symbiosis in eco-industrial parks can be studies for various purposes. Mattila et al., (2012) divides the research questions in studies related to IS into five groups (Table 5. Groups of IS studies).

Group	**Research questions**
1	Analysis (accounting) of impacts of an existing symbiosis.
2	Improvement of industrial symbiosis. Assessing which parts should be improved and how.
3	Expansion of systems. Assessing how new processes should be included and how this affects the impacts.
4	Design of an EIP. Assessing whether or not IS approach provide benefits compared to other design options
5	Circular economy. Assessing the environmental impacts of a circular economy and what kind of systematic change would this shift cause

Table 5. Groups of IS studies (Mattila, Lehtoranta, Sokka, Melanen, & Nissinen, 2012)

The three first categories are aimed at assessing already existing symbiosis, while the two last to aims at evaluating future hypothetical systems. In the preliminary thesis, a review over different methods for assessing costs and benefits from industrial symbiosis (MFA, cost-benefit, and input-output analysis, see Appendix A: Additional literature: 8.1.2) The next sections will however look more into LCA as a method for analysing and evaluating energy savings in industrial clusters and their corresponding benefits, according to the research questions in the first of the groups listed above.

2.5.1 Life Cycle Assessment methodology

"Reusing industrial waste may have impressive potential environmental benefits, especially in terms of the total life cycle, and life cycle assessment (LCA) has been proved to be an effective method to evaluate industrial symbiosis (IS).." (Yu, Han, & Cui, 2015a)

In studies related to industrial symbiosis, there has been little appliance of the decision-oriented consequential LCA. When costs and benefits of industrial symbiosis measures are assessed, the significant amount of emissions occurring outside the boundaries of the industrial park are usually not accounted for (Mattila et al., 2012).

A fully consequential LCA would be beneficial for comparing implementation of IS to reference systems and avoiding shifting problems from the local symbiosis to elsewhere in the supply chain (Mattila et al., 2012).

Sokka et al (2013) looks into the methodological aspects of applying LCA to industrial symbiosis. For existing IS systems to be analysed, it is common to have a reference case based on the data of the IS, but that operates without the by-product exchanges.

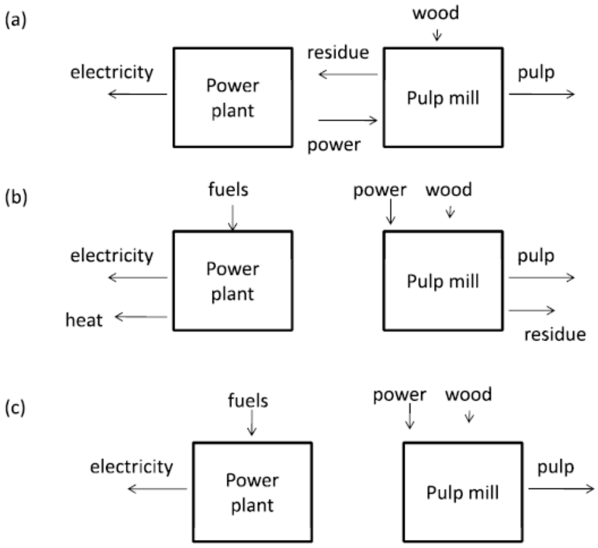


Figure 9. Assessing industrial symbiosis using LCA

Figure 9. Assessing industrial symbiosis using LCA illustrates a system with symbiotic exchange of by-products (a) and a system without by-products where the by-products are released as waste outside the system boundaries (b). In LCA terminology, the functional unit in these two systems are different (total output larger in b), and the system to be analysed (b) is not comparable to the reference scenario (a).

What has to be done is that additional net outputs has to be removed from the reference case, which can be done using the system expansion approach. In figure 2 c), the system the net output is compared to production with sector average technology. This is a reasonable assumption in the cases where it is questionable if the plants operating in symbiosis can operate in isolation, since by-product exchange often is a requisite for profitable operation in symbiosis. Some of the studies that has applied this LCA methodology to assess strategies for reducing environmental impact in existing industrial clusters are; Sokka et al. (2011), Dong et al (2013) Røyne, Berlin, Ringstrøm (2015), and Yu et al., (2015a).

Sokka et al (2011) uses LCA to analyse industrial symbiosis in an industrial ecosystem centred around a pulp and paper mill situated in the town of Kouvola in southeaster Finland. The functional unit was the total annual production of energy (in 2005) of the industrial eco-system at the gate of the symbiosis. Two hypothetical reference systems where the actors operate in isolation are used for comparison. In both of these systems the total energy use and the amount of products produced by the actors are the same as in the original case, with one exception. The heat and power plant produces less heat and electricity, which is replaced by external production purchased by the town. The results from the comparison between the original and reference cases showed that the net improvements from industrial symbiosis lies between 5-20% in most impact categories. It showed that upstream processes made a significant contribution to the overall results (Sokka, Lehtoranta, Nissinen, & Melanen, 2011).

Yu et al., (2015a) uses system expansion is used to assess the environmental impacts caused by material, energy and water exchanges, which directly offsets other material and energy production processes and transportation. Still, some additional environmental emissions are generated in some of the by-product utilization processes. In this system, using a hypothetical average system is preferred over the sector average production which in this case would cause higher deviation because of imbalance of the domestic market development in China.

Dong et al., (2013) and Røyne et al., (2015) has both used LCA as an assessment tool to provide grounds for deciding which inflows should replaced. This correspond to group 2 in Table 5. Groups of IS studiesand is therefore less relevant to look deeper into in this section. Dong et al. (2013) used tiered hybrid LCA to assess the life cycle carbon footprints of the industrial park at current state, not for assessing the economic and environmental effect of specific measures. Røyne et al. (2015) conducted an attributional LCA to assess the environmental impact of an industrial cluster. Similar to the work by Dong et al. (2013), only the current state of the industrial cluster was assessed. Through the LCA assessment, the most important part of the value chain and the scale of the impact was identified for the purpose of being put into a decision making context. In both studies it is emphasised that the processes outside the industry cluster may account for the most significant part of the impacts (Røyne, Berlin, & Ringström, 2015).

These studies shows different ways LCA can be an useful assessment tool for IS purposes. However, Stokka et al. (2008) claims that in order to provide a holistic assessment of industry cluster, more than one type of analysis is necessary.

2.6 Decision making in eco-industrial parks

2.6.1 Multiple-criteria decision aid

Because of the diversity of actors implying diverse economic, social, cultural or ecologically oriented interest, agreeing on an environmental plan can be challenging. Multiple-criteria decision-aid (MCDA), developed for decision-making and environmental planning, analyses decision-making alternatives based on different preferences of different actors (Lahdelma et al., 2000). These multiple-criteria tools are suitable for decisions that are either characterized by intangible criteria or is difficult to formalize in purely economic terms (Giove, Brancia, Satterstrom, & Linkov, 2009).

By addressing complex problems with high uncertainty, conflicting objectives, multi-interests and perspectives, MCDA can provide a method of eliminating the difficulty of the complex interaction of the energy system and can be helpful in the weighting and valuation of the environmental interventions and impacts (Lahdelma et al., 2000).

The problem setting in a MCDA can be choosing one or more best alternatives, complete or partial ranking of alternatives or acceptability analysis of alternatives. Lahdelmah et al. (2000) presents five important points for the multi-criteria decision aid (Lahdelma et al., 2000).

1. The method must be well defined and easy to understand, especially regarding central elements (criteria and definition of weights).
2. The method must support the number of decision makers
3. The method must support the numbers of criteria and measures

4. The method should be able to handle the inaccurate or uncertain criteria information.
5. The preference information from decision makers should be as small as possible due to constraints on time and money.

A generalized road map to environmental decision problems is given in Figure 10. The figure illustrates the *people*, the *processes* and the *tools* required for a successful decision making process.

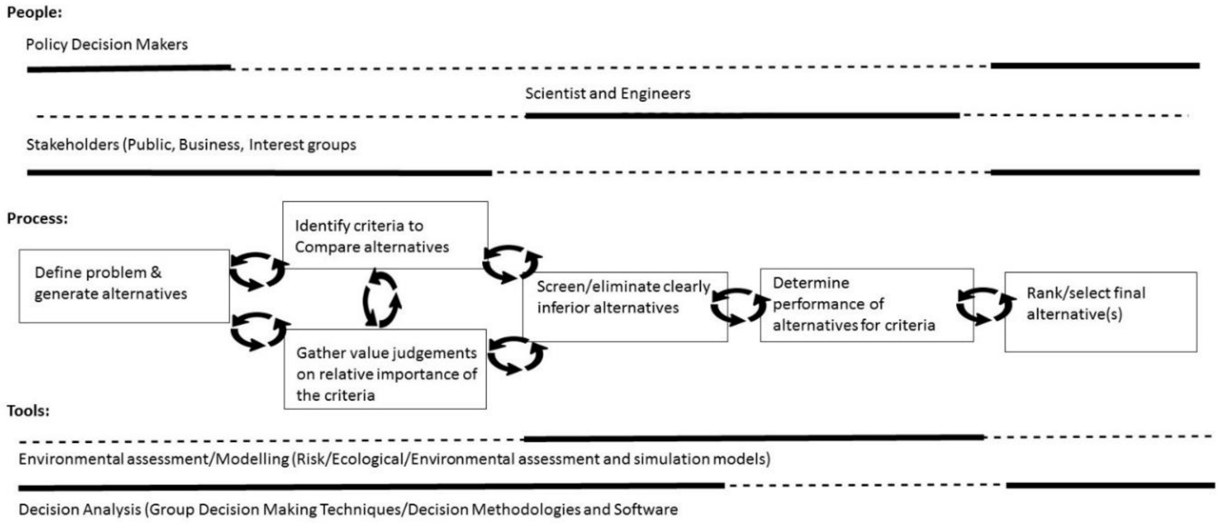


Figure 10. Generalized roadmap to environmental decision making (Kiker et al., 2005).

The first essential element to have the correct combination of people involved in the right phases of the decision making process. Involvement of stakeholders is increasingly recognized as an essential element in successful decision-making. In order to collect the largest amount of information required, the role of these groups are essential but membership and functioning of these may intersect or vary. Dark lines in the figure illustrates direct involvement, while dotted lines illustrates less direct involvement. The main responsibility of the three groups are as follows:

Policy and decision makers:

- defining problem context and decision constraints
- may also have responsibility of selecting the final decision and its implementation

Stakeholders

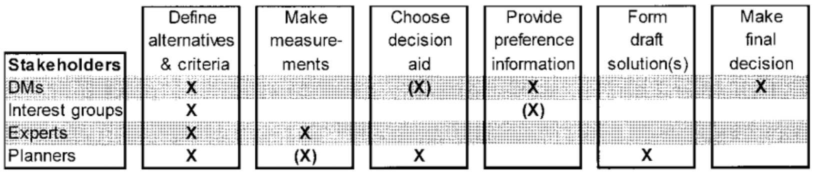
- may provide input to the definition of the problem
- has the highest degree of action in formulating and assigning weights to the success criteria
- may also have some contribution in ranking and selecting the final options (depending on the context)
- Scientist and engineers:

- provide technical details required for the decision process: measurements or estimations of the desired criteria that determine success of various alternatives
- The second essential part in the road map is the actual decision making *process*, which consist of two main parts:
- generating management alternatives, success criteria, preferences and value judgements
- ranking the alternatives by applying the criteria levels and value weights. First screening mechanisms (e.g. overall cost, technical feasibility, and general social acceptance) are applied. A more detailed ranking of the options are generated, using decision analysis techniques (MAUT/MAVT, AHP or outranking models).

The last part is the decision-making *tools*, which has the purpose of:

- guiding the preferences of the stakeholder groups or the individual value judgements into organized structures
- displaying the gathered information in an understandable format using graphical methods and visualization techniques

Another, similar model, for decision-making is presented by Lahdelma et al (2000) (Figure 11). The processes are also here split into several phases and shows which of the stakeholders that need to participate in the different phases (Lahdelma et al., 2000).



Stakeholders	Define alternatives & criteria	Make measure-ments	Choose decision aid	Provide preference information	Form draft solution(s)	Make final decision
DMs	X		(X)	X		X
Interest groups	X			(X)		
Experts	X	X				
Planners	X	(X)	X		X	

Figure 11. Phases and stakeholder participation in environmental multicriteria decision process (Lahdelma et al., 2000).

2.6.2 Criteria selection

A prerequisite for selecting the best alternatives is developing criteria and methods that can measure sustainability in a reliable way and monitor the alternatives' impact on the social environment. These criteria can inform decision-makers of the integrated performance of the alternatives to be evaluated and help identify non-sustainable solutions (J.-J. Wang, Jing, Zhang, & Zhao, 2009).

The literature usually divides the evaluation-criteria into four aspects; technical, economic, environmental and social and involves both quantitative (efficiencies, emission and economic savings etc.) and qualitative (reliability, viability, decision makers attitudes etc.) (Mattiussi, Rosano, & Simeoni, 2014). Common subcategories of these four aspects are presented in Table 6. Typical evaluation criteria (Mattiussi et al., 2014; J.-J. Wang et al., 2009)

Aspects	**Technical**	**Economic**	**Environmental**	**Social**
Criteria	➢ Efficiency ➢ Exergy efficiency ➢ Primary energy ratio Safety ➢ Reliability ➢ Maturity	➢ Investment cost ➢ Operation and maintenance cost ➢ Fuel cost ➢ Electric cost ➢ Net present value (NPV) ➢ Payback period ➢ Service life ➢ Equivalent annual cost (EAC)	➢ NO$_X$ emission ➢ CO$_2$ emission ➢ CO emission ➢ SO$_2$ emission Particles emission (NMVOCs) ➢ Land use ➢ Noise	➢ Social acceptability ➢ Job creation ➢ Social benefits

Table 6. Typical evaluation criteria (Mattiussi et al., 2014; J.-J. Wang et al., 2009)

According to Keeney & Raiffa (1993) the set of criteria should satisfy the following points

- Completeness: all important points of view of the problem is covered
- Operationallity: the criteria can be measured and used in a meaningful way in the analysis
- Nonredundancy: two or more criteria should not measure the same thing.
- Minimality: the problems dimension should be kept at a minimum (Montastruc, Boix, Pibouleau, Azzaro-Pantel, & Domenech, 2013).

2.6.3 Normalization methods

In order to avoid difficulties related to the different dimensions of the criteria, normalization is required to allow for a comparison of the values which is not possible in their original unit (Rochat, Binder, Diaz, & Jolliet, 2013). If there is no hiarchial structure, and the different criteria are independent from each other, the options of the often ranged from the best to worst by normalization (Huang, Keisler, & Linkov, 2011).

The table below shows 3 of the most common normalization methods. A multi-criteria decision problem normally consist of *m* alternatives (A_i=1, 2, 3…m), which are evaluated based on a set of *n* attributes (C_j=1, 2, 3…n).

Procedure 1 (max method) is the most widely used method. It is simple to interpret and respects proportionality. It adjusts the scores relative to the best performance rate for that attribute (which is given the value of 1). *Procedure 2* (max-min method), is an evolved version of *procedure 1*. In this method, the worst score is given the value 0 and the scores are calculated so that they fall between the worst value 0 and the best value of 1. The scale transformation in this procedure is not proportional to outcome. In *procedure 3 (sum-method)* the performance ratings of each attribute are divided by the sum of performance ratings for that attribute. The normalized vectors for one criteria summarizes to 1. *Procedure 4 (vector normalization)* each of the performance ratings is divided by its norm (Chakraborty & Yeh, 2007).

	Procedure 1 Max method	**Procedure 2** Max-min method	**Procedure 3** Sum method	**Procedure 4** Vector normalization
Definition	$v_{ij} = \frac{x_{ij}}{\max x_i}$	$v_{ij} = \frac{x_{ij} - \min x_i}{\max x_i - \min x_i}$	$v_{ij} = \frac{x_{ij} - \min x_i}{\sum_j^n x_j}$	$v_{ij} = \frac{x_{ij}}{\sqrt{\sum_i {x_i}^2}}$
Normalized vector	$0 \geq v_{ij} \leq 1$	$0 \geq v_{ij} \leq 1$	$0 \geq v_{ij} \leq 1$	
Constraint	$\max x_i = 1$	$\max x_i = 1$	$\sum v_{ij} = 1$	

Table 7. Normalization (Chakraborty & Yeh, 2007) (Lakshmi & Venkatesan, 2014)

2.6.4 Weighing methods

In multi-criteria problems, each criterion is assigned a number deciding its importance. The decision maker's subjective preferences are reflected through these weights. How the weights are interpreted is completely dependent on the decision making model (Lahdelma et al., 2000).

J.-J. Wang et al., (2009) separates weighing methods into two main categories; *equal weights* method and *rank-order weighting* method. The *equal weights* method requires minimal knowledge of the priorities of the DM. If an attribute matters it receives an equal weight to the other attributes considered (Jia, Fischer, & Dyer, 1998; J.-J. Wang et al., 2009). The *rank-order weighting* method are classified into 3 sub-categories: *subjecting weighing* method, *objective weighing* method, and *combination weighing* method. In *subjecting weighing* it is the preferences of the decision-makers that determines the criteria weight. In *objective weighing*, however, mathematical methods based on analysis of initial data determines the weighing. An integrated *combination weighing* method could also be used to determine the weight of criteria. Objective weighing methods include the *entropy* method, *TOPSIS* method and *vertical and horizontal method*. Different methods of *subjective weighing* is described in Table 8. Methods of subjective weighing (J.-J. Wang et al., 2009). below.

Subjective weighing methods	**Description of method**
SMART -Simple multi-attribute rating technique	Assign points to the least important criteria (10 points), and an increasing number of points (without explicit upper limit) to the other criteria, relative to the lowest. Weights are calculated by normalizing points so they summarize to one.
SWING	Assign points to the most important criteria (e.g. 100 points), and add a decreasing number of points to the other less important criteria. All criteria are assigned values relative to their value ranges. Weights are calculated by normalizing points so the total summarize to one.
SIMOS	"Playing cards" with criteria. The criteria (coloured "cards") are ranked from most important to least important. Another set of white "cards" is introduced to express strong preference between criteria. A number of

	these cards, proportional to the difference between the importance of the different criteria, are put between to successive coloured "cards". The rank positions are then divided by the total sum of positions of the considered criteria. Weights are normalized so the total summarize to one.
Pairwise comparison	Decision makers compare two criteria at a time, and give a score to the preferred criteria depending on the level of preference. Results are consolidated by adding up the relative scores obtained in each of the comparison. Weights are normalized so that they summarize to one.

Table 8. Methods of subjective weighing (J.-J. Wang et al., 2009).

As can be seen within the different weighing methods described in Table 8, all weights are usually normalized so that they summarize to 1 ($\sum_{j=1}^{n} w_j = 1$).

Additional information on MCDA and aggregation methods are found in Appendix A: Additional literature: section 8.1.1.

3 Methodology

3.1 Objective for model development

When symbiosis strategies are to be assessed at industrial site, moving from the idea of industrial symbiosis to actually realizing and implementing the measures is difficult (Gibbs & Deutz, 2005). Barriers to the establishment can be technical, economical, informational, organisational regulatory or legal (Heeres et al., 2004). In multi-party relationships it can be hard understanding the advantages for each of the parties and stakeholders. To make the business and community leaders embrace EIP's and their potential for reducing impacts, it is important to provide evidence of the economic and technical feasibility that can be obtained (Martin et al., 1996). Eco-industrial development projects therefor require a broad array of community involvement techniques and methods to obtain "buy-in" from participants and to create appropriate conditions for inter-firm networking to take place (M. R. Chertow, 2000; Gibbs & Deutz, 2007). The framework generated in this work contributes to increase knowledge for the involved actors, aiming at simplifying and structuring the assessment of opportunities, evaluation of the opportunities and the final implementation of IS-measures in an industrial park.

3.2 The model and its phases

The basic outline of the methodology framework as a whole, consisting of three phases, is showed in Figure 122. Each phase of the framework is discussed separately in the following sections.

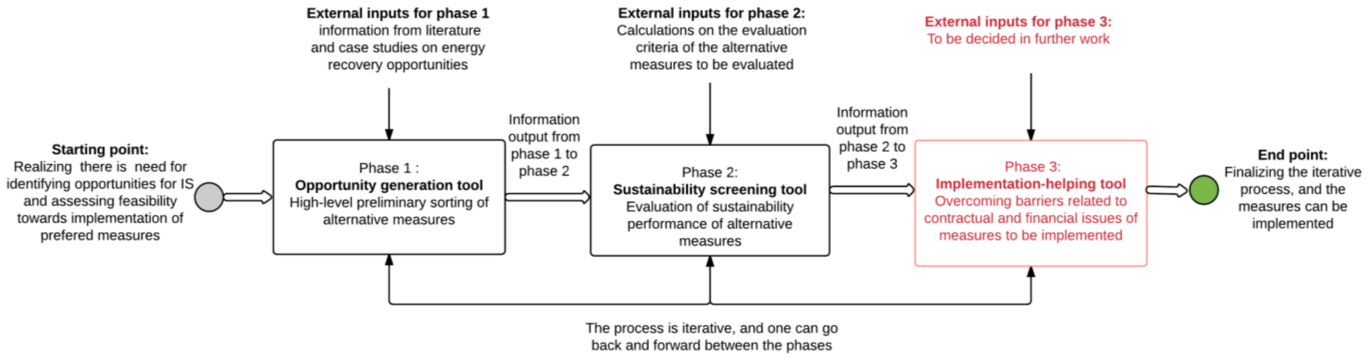


Figure 12. The model and its phases.

The involved parts (park owner, stakeholders etc.) are at a point where they have identified one or several surplus/waste energy streams and their characteristics, but are unsure which are the potentially feasible options for recovering and exploiting the symbiosis potential of these streams. Phase 1 of the framework, the opportunity generation tool, can be used as an asset in e.g. an opportunity evaluation workshop to help identifying options for symbioses between the industries involved. By feeding information on the identified stream and its properties into the tool, the potential purposes and corresponding technology for energy recovery will be provided together with an initial qualitative score on the potential feasibility and success rate of the technologies. The criteria that set the basis for the evaluation in this phase are:

- Technologic maturity
- Economic feasibility
- Energy saving potential

These will be explained in more detail in further sections.

Based on this first assessment, the decision makers can chose which of the options they want to investigate in more detail in phase 2 of the framework where a feasibility screening on the technical, economic, environmental and social criteria specified for the individual case. However, the technology specific calculations according to the evaluation criteria on the different options are done outside of the main framework and needs to be fed into the multi-criteria decision model in phase 2. This MACD-model will provide a thorough comparison of alternatives, which will be the final basis for selecting the best-alternative. Among the suggested evaluation criteria to be selected for this phase is:

Technical criteria:

- Delivered energy saved from measure
- Primary energy savings (PER)
- Exergy efficiency of measure
- Energy efficiency of measures

Environmental criteria:

- CO2 emission savings
- NO_X emission savings
- SO_2 emission savings

Economic criteria:

- Net present value (NPV) for measure
- Investment cost for measure
- Payback time for measure

Social criteria:

- Number of jobs created
- Social acceptability

Phase 3 finalizes the tool by helping the decision-makers overcome barriers related to contractual and pricing issues when implementing the measures for symbiosis in the industrial park. The output could be a toolkit with a list of common contractual and pricing issues, and successful models/templates for handling and mitigating these issues. Because of time limitations, this phase has not been worked on, and is left as a suggestion for further work in order to complete the framework.

3.3 Phase 1: Opportunity generation

3.3.1 Aim and target group for the tool

When available waste energy for symbiotic measures are identified among industries, knowing how to exploit these energy streams in the most efficient way, considering both the economic and environmental terms, is not possible for non-experts without a thorough research of the technology options for the specific waste streams considered. According to Bossilkov (2007) it appears to have been used very limited use of specific tools for synergy option generation. Either they have been too generic or too resource specific (Bossilkov, 2007).

The aim for the opportunity generation tool is mainly to be a support for consultants and experts in order to evaluate and compare different recovery and symbiosis opportunities of energy streams at an industrial site at a high-level. It is useful for creating awareness and motivating stakeholders through facilitating the identification of symbiosis opportunities. The opportunity generation tool will serve as a preliminary, generic evaluation of possible energy streams for symbiosis opportunities and work as a first step in sorting the possible alternatives to make a judgement whether or not they should be further investigated in the next, more detailed assessment in phase 2. Listings of potential synergy opportunities based on streams in three main stream categories; exhaust/flue gas, steam and water will be provided, based on available information from literature.

The tool presented in this has been developed with a focus to be easily updatable and it is therefore outside the scope to finalize this first version of the tool with all relevant details on the technologies. The table is a helpful tool for decision makers to gain information on how to best take advantage of surplus energy streams and how these can become feedstock in symbiotic exchanges.

The magnitude of the IS-benefits is likely to vary greatly with the case-specific circumstances like: which industries are involved, the location of the involved parts, the political and regulatory involvement etc. (Martin et al., 1996). Also, the actual costs are highly dependent on the characteristics of the resources like: flow rates, temperature, composition, operating hours, regulatory requirements (Van Beers, 2009). Since this opportunity generation tool will provide information on symbiosis opportunity and potential gains, all evaluation criteria at this stage will be given in a qualitative scale.

3.3.2 Methods and data

The presented methodological framework for this phase of the tool has been based on literature review and by the help and inputs of energy strategy experts. Data have been collected from literature on energy recovery technology of energy streams and qualitative and quantitative case studies on industrial symbiosis. The energy streams were divided into three main categories; *exhaust/flue gases*, *water* and *steam*. Information about these three categories of energy streams, their symbiotic potential and the different technologies to maximize the economic and environmental gain are categorized in an comprehensible and updatable opportunity generation table in excel. Stakeholders can in a simple manner withdraw useful information on possible symbiosis opportunities concerning the specific energy streams, based on a quantitative evaluation of the most important parameters. The alternatives chosen to investigate further will be taken into the next phase of the framework.

3.4 Phase 2: Feasibility screening tool

3.4.1 Aim and target group for the feasibility screening tool

The aim of phase 2 is to provide a simple, flexible and adaptable tool to make a more thorough analysis of the possible symbiosis alternatives. In phase 1, the alternatives is analysed through a preliminary sorting and the ones chosen to go forward with are those that are taken to phase 2. The feasibility screening tool aims at assessing the cost and benefits of the synergy opportunities identified in the previous phase. It provides guidance in assessing which of the symbiosis options are the preferable for the specific case.

The evaluation criteria to be used, and the weighing of these are created in cooperation between the experts and the stakeholders. Not all potential synergies provide significant benefits for the involved parties. The elimination of clearly inferior alternatives and the evaluation of the performance is done by scientist and experts, while it is up to the stakeholders to make the final ranking of the options.

3.4.2 Methods and data

Complex problems with high uncertainty, conflicting objectives and multi-interest and perspectives, can be problematic to assess. Multi-criteria decision support can provide a method of eliminating the difficulty of the complex interaction of the energy system and can be helpful in the weighting and valuation of the environmental interventions and impacts (Hokkanen, Lahdelma, & Salminen, 2000; Lahdelma et al., 2000; J.-J. Wang et al., 2009). The objective of this phase of the tool is to facilitate decision-making between different alternatives and technologies for the reuse and exploitation of waste streams in industrial parks. A multi-criteria decision-making model quantifying and comparing the environmental performance of industrial symbiosis measures will be presented with the purpose of deciding best technologies for energy saving and reuse in an eco-industrial park

3.4.3 System boundaries

The general system boundaries for measurements for the technologic and environmental criteria in the multi-criteria decision making model is shown in Figure 133. These boundaries include the eco-industrial park, the energy delivered at the park and the supply chain of upstream activities until primary energy extraction of energy sources. All of these activities should be taken into consideration when assessing the environmental effect of the symbiosis measures done at the park scale. The circles marked in red illustrates the measuring points for the different types of indicators. Material flows are excluded from the boundaries, and only stream that can be used for energy purposes are included within the system boundaries.

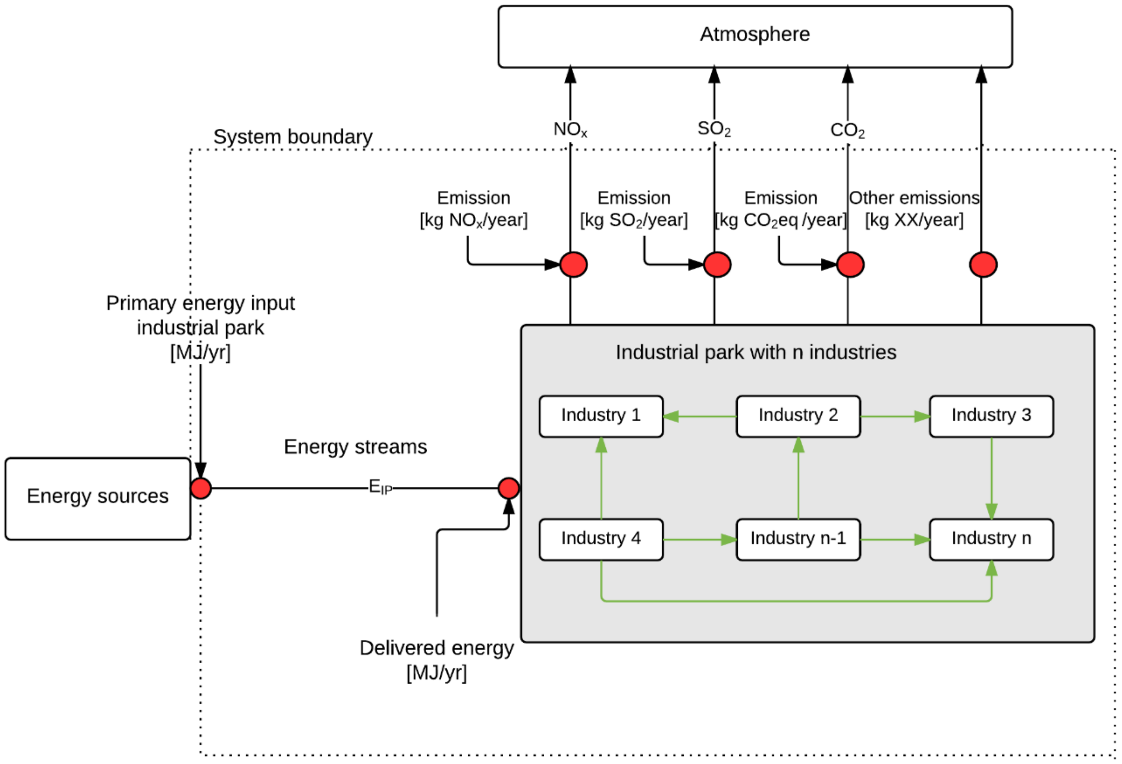


Figure 13. System boundaries for assessing criteria performance in decision making model.

As for the social and economic criteria, these measure points are not displayed in the system boundaries.

4 Results

4.1 Proposed methodology for phase 1: Opportunity generation

4.1.1 Evaluation criteria

In eco-industrial development the industries seek enhanced economic and environmental performance (Côté & Cohen-Rosenthal, 1998). This first assessment phase has to point to a general case-independent potential for gains from implementation of different IS-measures to assess its feasibility. Description of the evaluation criteria used for the initial qualitative evaluation of industrial symbiosis options in the opportunity generation phase is listed below.

Evaluation categories used in the *Performance evaluation input* matrix

- *Technological maturity*

Within the technological maturity criteria it is considered how available the technologies are from a technological standpoint (Feiz et al., 2014). This is one of the feasibility criteria that can be evaluated as a generic non-case-specific term. However, despite of the technology's commercial availability and maturity, capital investment and space capacity on the process sites can constraint the implementation (Oluleye, Jobson, & Smith, 2015).The degree of technological maturity refer to how widespread the technology is internationally (J.-J. Wang et al., 2009) and gives an indication on the reliability of the technology and the safety of the investment (Beccali, Cellura, & Mistretta, 2003). A traditional, widely used and tested technology is considered to have a high technological maturity and will provide less costumer/supplier risk than a new, unverified measure that might only be a theoretical research or tested on pilot plants. Information given by excising literature can indicate the state-of-the-art and thereby the technological maturity of the measures. This criteria will also indirectly reflect economic aspects since there is a greater chance a mature technology can be optimized at a lower cost than an emerging one (Feiz et al., 2014).

- *Economic feasibility*

Economic value added is one of the five most important success factors of eco-industrial development. Commonly this criteria is evaluated by payback period or interest rate (Brückner et al., 2015). Resource efficiency from implementation of measures can generate additive revenue for the economic players (Massard et al., 2014). However, the evaluation of the different technologies at this level is not linked to specific cases. Hence, the economic feasibility of proposed technologies is not based on fixed specific parameters like e.g. Net Present Value (NVP), Return on Interest (ROI) but is only assumed on a general qualitative level based on cases from literature where the technology has been applied.

- *Energy saving potential*

Cost savings are often a benefit from more efficient processes and reduced energy use, and these two criteria often correlate. Thus, many of the technologies which are economically feasible will also provide gains in terms of energy saved. At this level of assessment, the technologies ability to save energy is only on the general level. However, in this first draft of the tool, not enough information on found in the literature of the technologies evaluated for the examples to be evaluated for energy saving potential of the measures.

Evaluation categories in the *Performance qualitative input* matrix

These are created on the same base as for the *Performance evaluation input*. However, this matrix is created with the purpose to collect some of the most important information, and link to related case studies for each of the technologies. An extra category is added in this matrix to collect essential information on technological details which are important regardless of the case-specific circumstances.

- Maturity details
- Economic details
- Energy saving details
- Technological details

The intention is that for the matrix can be built up to be a comprehensive and detailed information source for the different energy recovery technologies for the various streams and purposes, and that the evaluation of the technologies (N/A, Poor, Medium, High) in the *Performance evaluation matrix* can be made based upon this source of information.

Through this first level of assessment the stakeholders should have identified the measures that are likely to be feasible to further evaluated phase 2, in a more quantitative decision-making analysis.

4.1.2 Classification of evaluation scores

At this stage of evaluation this has been done on a very general basis because the technologies evaluated at this early stage is not connected to a specific case and it is therefore impossible to perform a meaningful and simple quantitative assessment. The categorization of the evaluation criteria in the opportunity generation phase are divided into four different grades; *N/A*, *Poor*, *Medium* and *High*. Evaluations of the grading scale of each technology at this level will be based on case studies, demonstrations and evaluations of the technologies found in literature.

	N/A	Poor	Medium	High
Technological maturity	Not applicable	**Early development:** The measure is in an early research and development stage (laboratory and pilot testing)	**Emerging practice:** Some successful demonstrations exist (application in small scales, potential for improvement)	**Established practice:** The technology is applied in several cases for this purpose under various conditions (consolidated technologies, close to reaching theoretical limits of efficiency)
Economic feasibility	Not applicable	May be economically feasible, but not demonstrated	Proven to be cost-effective in limited applications	Very likely to be cost-effective. Proved in several cases under various conditions.

Energy saving potential	Not applicable	Limited potential for energy saving (not demonstrated in literature)	Examples of cases where technology provides energy savings exist in limited applications	High potential for energy reduction. Proved in several cases under various conditions
Technological feasibility	*Not yet added as a criteria in the Performance evaluation matrix*			

Table 9 Classification table for evaluation scores for recovery and reuse purposes. Based on the classification in the article by Feiz et al. (2014) and (J.-J. Wang et al., 2009)

4.1.3 Classification of the energy streams

The streams chosen to be included in the tool are streams that can be recovered for energy purposes and are divided into three main categories namely exhaust gas/air-, steam- and water streams.

The intention of further dividing the stream types into temperature and pressure intervals is to give a preliminary sorting of what can be categorized as *low-grade, medium-grade* and *high-grade* waste energy. As this is a first version of the tool, the grading of the waste stream has been done in a simple manner and the level of details on the properties of the energy streams is limited. Also, the source of the streams has been left out. The quality level of exhaust gas and water has mainly been classified by means of temperature while steam has been classified by means of state (saturated, superheated). As stated by Chertow (2000), symbiosis opportunities are best when there are large and continuous waste streams. However, volume flows has not been used as a parameter to classify the quality of the different waste streams, because of the difficulty of finding purposes and corresponding technology options for streams with that detailed properties. Ideally all three stream-categories should have been classified in terms of low, medium and high pressure, temperature and volume flow. However, this would give each of the three stream types 27 different classification categories and finding information on reuse purposes and technologies for that detailed classification would be too much work with respect to the time limitations of this work.

Industrial exhaust gas/air

The high temperature of flue gases provides a high capability for energy conservation (Thumann, 2002). In order to sort the recovery opportunities for exhaust gas/air streams, a scale dividing the streams into high, medium and high temperatures is used. The classification of the temperature intervals for this type of energy stream is based directly on the work of U.S. Department of Energy (2012).

	Low temperature	**Medium temperature**	**High temperature**
Industrial exhaust air/gas	<230°C	230-650°C	>650°C

Table 10. Classification of temperature intervals for exhaust air/gas. Source: (U.S. Department of Energy, 2012)

Low temperature heat recovery:

Numerous product steams contain large quantities of low-temperature heat, however, there are few end-users. Large heat-exchange surfaces are required for heat-transfer. For combustion exhaust, low-temperature heat recovery is less practical due to acidic condensation and corrosion on the heat exchanger.

More feasible end-user alternatives for low temperature heat are space heating and domestic hot water. Alternatively, a heat pump can either be used for upgrading the waste heat to a higher temperature or for using waste heat as input for driving an absorption cooling system.

Medium temperature heat recovery:

Medium temperature heat sources are more compatible with heat exchanger materials, and is also practical for power generation. Typical purposes for heat reuse in this temperature category is combustion air preheat, steam/power generation, Organic Rankine cycle for power generation, furnace load preheat, feedwater preheat, and transfer to low-temperature processes.

High temperature heat recovery:

High temperature waste heat has a high energy content and is available for a higher end-use range compared to the low- and medium-temperature waste heat sources. For power generating purposes, high temperature waste heat provides a high efficiency. The thermal transmittance (heat transfer per unit area) for high temperature waste sources is also high. Some of the disadvantages of recovering high temperature waste heat is the high temperatures creates increased thermal stress on the heat exchange materials, and the chemical corrosion is also more likely compared to recovery from lower temperatures. Typical recovery methods are combustion air preheat, generation of steam for process heating, mechanical or electrical work, furnace load preheat and heat-transfer to processes of lower temperature.

Industrial steam

Steam systems are a part of almost every mayor industrial process today (Einstein, Worrell, & Khrushch, 2001). Using steam as a medium for delivering energy has many advantages, including low toxicity, high heat capacity and high efficiency, easy transportability and the energy can be extracted as mechanical work through a turbine or as heat for process use (U.S. Department of Energy, 2012). The condition of steam is determined by three variables: vapour pressure, volume flow and temperature of the steam. Steam is one of the mayor energy sources used in chemical and petrochemical companies and the overall efficiency can be increased if the most efficient industry produce steam and provide it to other companies in an industrial complex. Some companies reuse their own discharged steam by reheating it, however, most companies vents the low pressure steam into the air. There are many use areas for steam in industrial applications as for example use (U.S. Department of Energy, 2012).

- process heating
- mechanical drive
- source of hydrogen in steam methane forming (in chemical and petroleum refining applications)

- pressure and temperature control in chemical processes
- separating contaminants from a process fluid (distillation)
- fractionate hydrocarbon components

Some plants employ a combination of these uses, and the resulting high-pressure superheated steam is used in a turbine to generate electricity and the exhaust steam is used for heat-transfer application (Energy Efficiency Best Practice Guide Steam, Hot Water and Process Heating Systems).

Typical end use equipment for steam includes:

- heat exchangers: the latent heat from steam is transferred to a process fluid
- turbines: energy from steam transferred into mechanical work through pumps, compressors or electric generators
- fractionating towers: steam facilitates separation of various components of a process fluid
- strippers: the steam pulls contaminants out from a process fluid
- chemical reaction vessels

Steam can generally be divided into four different grades, by temperature and pressure (Kim, Yoon, Chae, & Park, 2010). However, in this work, instead of classifying by steam pressure, temperature and volume flow, the two categories simply separates between saturated and superheated steam.

Saturated steam:

Saturated steam has properties that make it an excellent source of heat. Typical purposes for saturated steam is heat exchange in process fluid heat exchangers, reboilers, reactors, and combustion air preheaters (TLV, 2015).

Superheated steam:
The superheated steam is used in industry mainly for heating, drying and is used almost exclusively in turbines. The heat transfer capacity of superheated steam is poor, even though the temperature is higher and it contains more energy than saturated steam. It is ideal for power generation and in turbines because of the higher energy content. Superheated steam is better for heat transport (steam flow in long pipelines) because it will not, unlike saturated steam, lose sufficient heat through condense (Lalonde, 2010).

Industrial water

Industrial activities represent a major user of reclaimed water, primary for process needs and cooling where the latter represents the single largest industrial demand (approximately 90% of the total industrial water consumption) (Broberg Viklund & Johansson, 2014). However, industrial process hot water can be recovered and reused with significant saving in costs. In industry, water is often seen as a utility and is an attractive substance because of its physio-chemical properties. The temperature levels in water are lower than in flue gases, ranging from 50°C to 100°C (Broberg Viklund & Johansson, 2014).

Literature on reuse and recovery of waste water in the context of industrial symbiosis is often related to the direct reuse of water in water-recycle networks and recovery of urban waste water from buildings. (Cipolla & Maglionico, 2014; Dürrenmatt & Wanner, 2014). However, less literature has been found on energy recovery of waste water.

Using liquid cooling can provide large savings in the total energy requirement for the cooling system. Due to the higher heat transfer coefficients and the higher volumetric specific heats, liquid cooling is a much more efficient way of transferring concentrated heat loads than air (Greenberg, Mills, Tschudi, Rumsey, & Myatt, 2006).

District heating is a common waste-heat recovery technology which is both economically and ecologically feasible and is suitable for low-grade waste heat like water. The waste water passes a heat pump that recovers it to a district heating system (Ebrahimi, Jones, & Fleischer, 2014).

Whether the water is categorized cold or hot, is very depending on the purpose and technology. For simplicity reasons, water for energy recovery has not been subdivided into more categories.

4.1.4 Development and usage of the tool

Excel has been used to develop the opportunity generation tool. The sheets completing tool are the following:

Lists: This sheet contains the complete lists of streams, purposes and technologies. The list-function in excel is used to name the lists so that dependent drop-down lists can be created in the *Main model* sheet.

Performance qualitative input: Performance matrix assessing all relevant combinations of purposes and technologies for all stream types and criteria. The matrix contains (and can be updated on) relevant information from technology reviews and case-studies and technology assessment found in literature. The assessment categories are: *maturity details*, *economic details*, *energy saving details* and *technical details*.

Performance evaluation input: Performance matrix assessing all relevant combinations of purposes and technologies of all stream types. In this matrix, the suggested combinations are evaluated to be either: *N/A*, *Poor*, *Medium* or *High* for all stream types and criteria. The evaluation criteria are: *technological maturity*, *economic feasibility*, *energy saving potential*.

Main model: This is the main assessment sheet of the tool. Information from the three sheets above are linked to the *Main model* sheet through IF-statements. The user of the tool can in a simple manner based on the defined streams, stepwise choose from drop-down lists which recovery purpose and corresponding technologies to be assessed.

The intention of structuring the model like this is that when the tool is filled with adequate information, the user of the tool doesn't have to navigate between the tools to collect information, but all essential information will (based on the choice of stream, purpose and technology) be served as outputs in the *Main model sheet.*

Step 1: Listing of streams, purposes and technologies

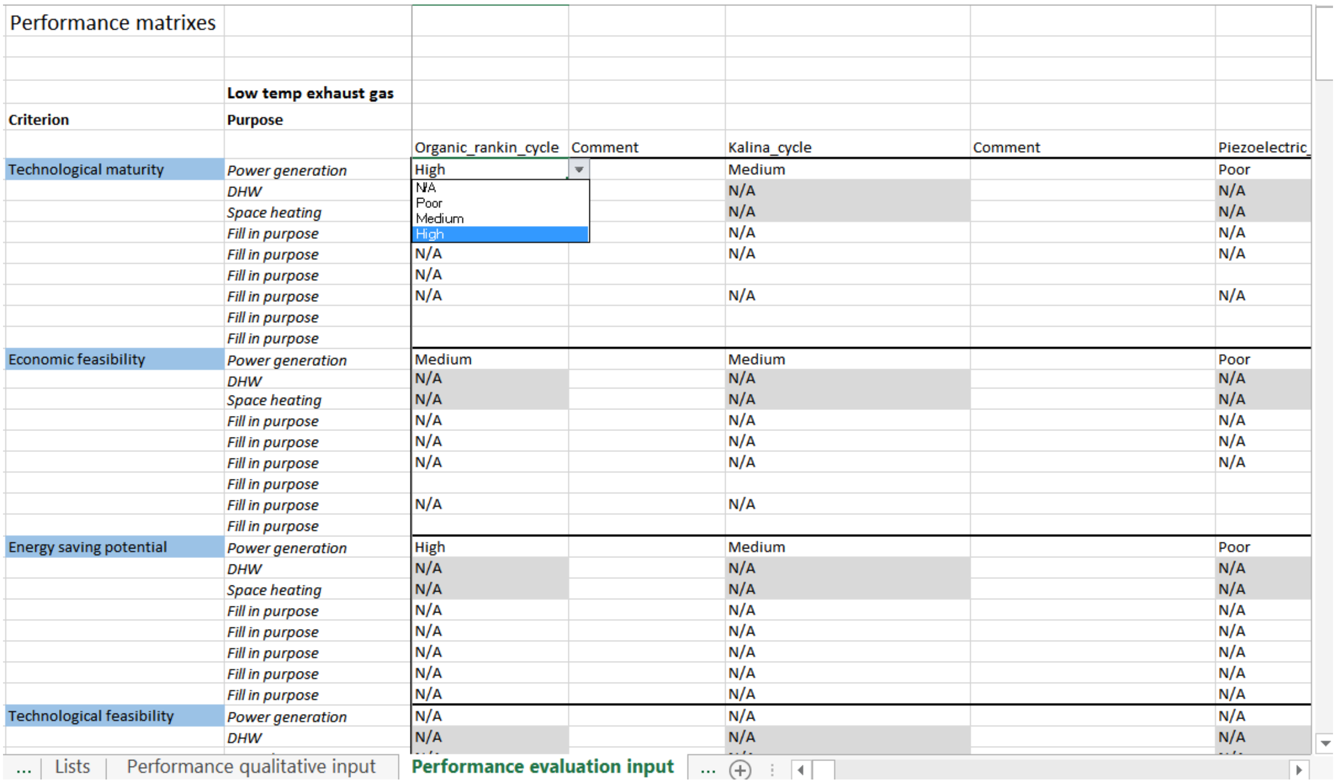
Firstly, the different stream categories has been defined using the list function. Next, the purposes for all the stream categories, and the corresponding technologies for all the purposes are also defined and named using the list function in excel (Figure 15).

By giving names to the lists, dependent drop-down lists are created and are used as input-information in the *Main model* sheet, making it easy for the user of the tool to navigate between the purposes and technologies for the different streams. Each has been made so that it can include up to 9 purposes per stream type and 6 technologies for each purpose before the list has to be re-defined. New purposes can be added in the space for *Fill_in_purpose*. However, a new list for corresponding technologies has to be made for the new purpose created. For an already defined purpose, new technologies can easily be added in the space *Fill in technology*. All updates and changes in the *List* sheet has to be manually implemented into the two *Performance* matrix sheets.

Step 2: Performance matrixes

The performance of the different combinations of stream, purpose and technology is presented in two two-dimensional *Performance* matrix sheets. For each stream and evaluation criteria, the different purposes are listed in rows, where each of the columns represents one technology.

One of the matrices ranks the combinations of technology and purpose as either: *N/A*, *Poor*, *Medium* or *Good* (explained in the classification table below), with respect to the evaluation criteria defined at this stage for all stream types (Figure 14. Performance matrixes in opportunity generation tool.). These alternatives can be chosen from drop down lists.

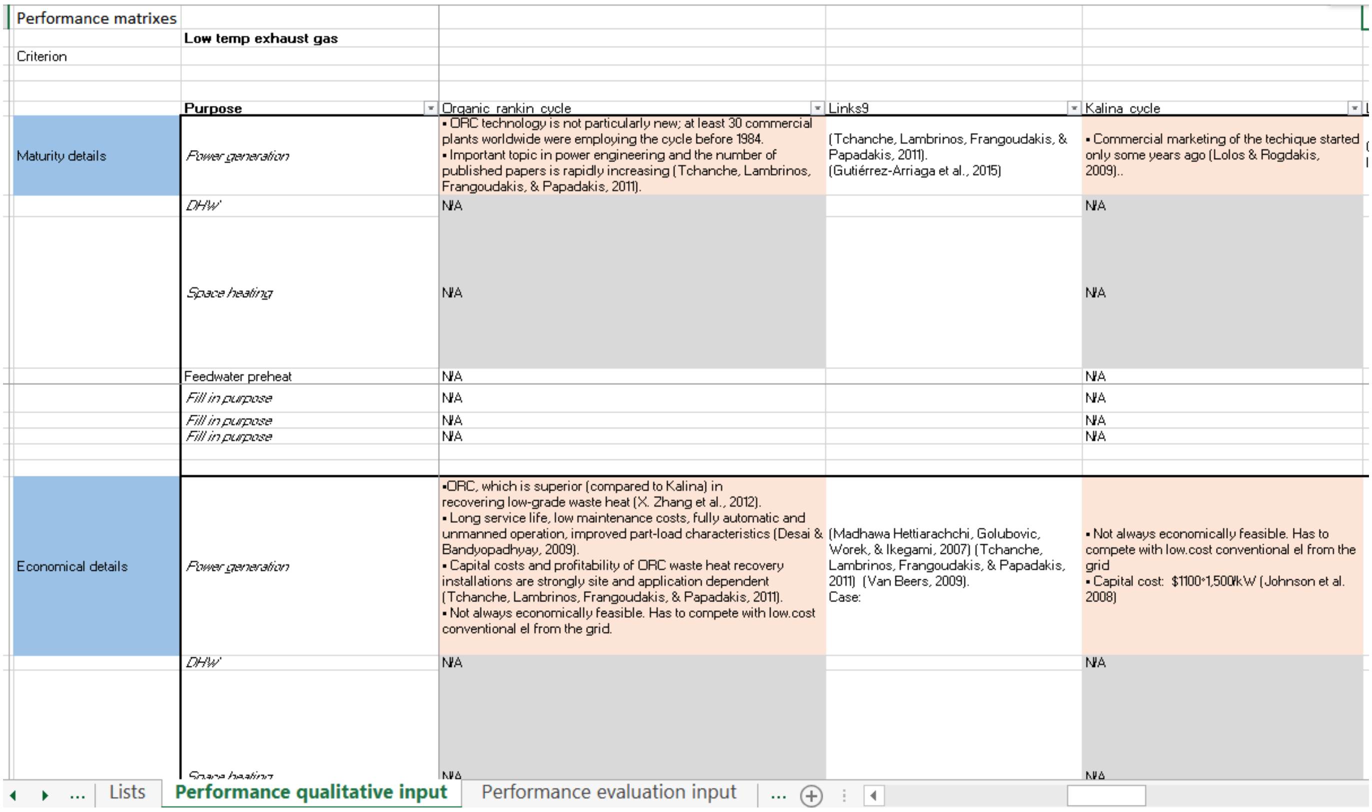


Performance matrixes

Criterion	Low temp exhaust gas Purpose	Organic_rankin_cycle	Comment	Kalina_cycle	Comment	Piezoelectric_
Technological maturity	*Power generation*	High		Medium		Poor
	DHW			N/A		N/A
	Space heating			N/A		N/A
	Fill in purpose			N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose	N/A				
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose					
	Fill in purpose					
Economic feasibility	*Power generation*	Medium		Medium		Poor
	DHW	N/A		N/A		N/A
	Space heating	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose					
	Fill in purpose	N/A		N/A		
	Fill in purpose					
Energy saving potential	*Power generation*	High		Medium		Poor
	DHW	N/A		N/A		N/A
	Space heating	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
	Fill in purpose	N/A		N/A		N/A
Technological feasibility	*Power generation*	N/A		N/A		N/A
	DHW	N/A		N/A		N/A

Figure 14. Performance matrixes in opportunity generation tool.

The other sheet contains useful information about the technology options concerning the evaluation criteria. The example below (Figure 15. Maturity and economic details for ORC and Kalina cycle for low temp exhaust gas power generation.) shows details on maturity for *exhaust low temperature* power generation using ORC and Kalina cycle. For each of the criteria, essential information from literature can be implemented in this sheet. Links to literature and relevant cases can be noted in the cell to the right for every combination of purpose and technology.


Performance matrixes

Low temp exhaust gas

Criterion

	Purpose	Organic_rankin_cycle	Links9	Kalina_cycle
Maturity details	*Power generation*	▪ ORC technology is not particularly new; at least 30 commercial plants worldwide were employing the cycle before 1984. ▪ Important topic in power engineering and the number of published papers is rapidly increasing (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011).	(Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011). (Gutiérrez-Arriaga et al., 2015)	▪ Commercial marketing of the techique started only some years ago (Lolos & Rogdakis, 2009)..
	DHW	N/A		N/A
	Space heating	N/A		N/A
	Feedwater preheat	N/A		N/A
	Fill in purpose	N/A		N/A
	Fill in purpose	N/A		N/A
	Fill in purpose	N/A		N/A
Economical details	*Power generation*	▪ORC, which is superior (compared to Kalina) in recovering low-grade waste heat (X. Zhang et al., 2012). ▪ Long service life, low maintenance costs, fully automatic and unmanned operation, improved part-load characteristics (Desai & Bandyopadhyay, 2009). ▪ Capital costs and profitability of ORC waste heat recovery installations are strongly site and application dependent (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011). ▪ Not always economically feasible. Has to compete with low.cost conventional el from the grid.	(Madhawa Hettiarachchi, Golubovic, Worek, & Ikegami, 2007) (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011) (Van Beers, 2009). Case:	▪ Not always economically feasible. Has to compete with low.cost conventional el from the grid ▪ Capital cost: $1100-1,500/kW (Johnson et al. 2008)
	DHW	N/A		N/A
	Space heating	N/A		N/A

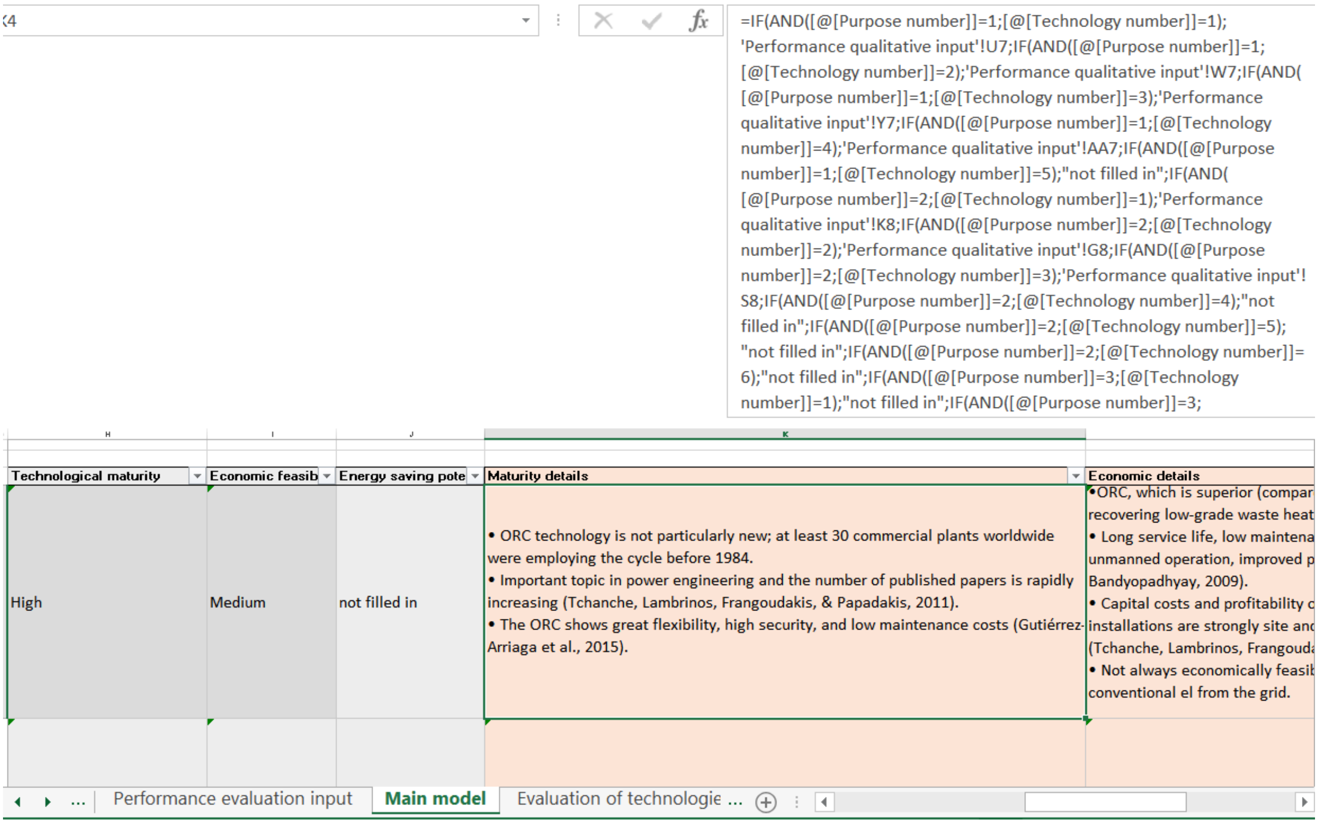
Figure 15. Maturity and economic details for ORC and Kalina cycle for low temp exhaust gas power generation.

In both *Performance* sheets, the cells containing non-relevant combinations of purposes and technologies are marked in grey and are not linked to in the *Main model* sheet. If these combinations at a later point are found to be relevant, they have to be manually added in as a technology for the actual purpose in the *List* sheet and assigned a number. IF-sentences has to be made in the *Main model* sheet to link to these specific new combinations of purpose and technology.

Step 3: Assessment model

In the *Main model* sheet, three rows are assigned each of the stream types, in order to compare different technologies for the chosen purpose simultaneously. In the List sheet, each technology for each purpose are assigned a number. The *Main model* sheet is programmed so that when the purpose or technology is changed, the number changes correspondingly in the cell to the left. This has been done in order to make the programing of the resulting evaluation of the combinations simpler, and also easier to update. Simple IF-statements combine the different purpose-number and technology-numbers and link to the corresponding cells in the two *Performance* matrix sheets.

Figure 16. shows how parts of the IF-statements combine the purposes and technologies and link to the cells in the *Performance* sheets. This is the way the information is linked to in all of the output cells in the *Main model* sheet.



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=IF(AND([@[Purpose number]]=1;[@[Technology number]]=1);
'Performance qualitative input'!U7;IF(AND([@[Purpose number]]=1;
[@[Technology number]]=2);'Performance qualitative input'!W7;IF(AND(
[@[Purpose number]]=1;[@[Technology number]]=3);'Performance
qualitative input'!Y7;IF(AND([@[Purpose number]]=1;[@[Technology
number]]=4);'Performance qualitative input'!AA7;IF(AND([@[Purpose
number]]=1;[@[Technology number]]=5);"not filled in";IF(AND(
[@[Purpose number]]=2;[@[Technology number]]=1);'Performance
qualitative input'!K8;IF(AND([@[Purpose number]]=2;[@[Technology
number]]=2);'Performance qualitative input'!G8;IF(AND([@[Purpose
number]]=2;[@[Technology number]]=3);'Performance qualitative input'!
S8;IF(AND([@[Purpose number]]=2;[@[Technology number]]=4);"not
filled in";IF(AND([@[Purpose number]]=2;[@[Technology number]]=5);
"not filled in";IF(AND([@[Purpose number]]=2;[@[Technology number]]=
6);"not filled in";IF(AND([@[Purpose number]]=3;[@[Technology
number]]=1);"not filled in";IF(AND([@[Purpose number]]=3;
```

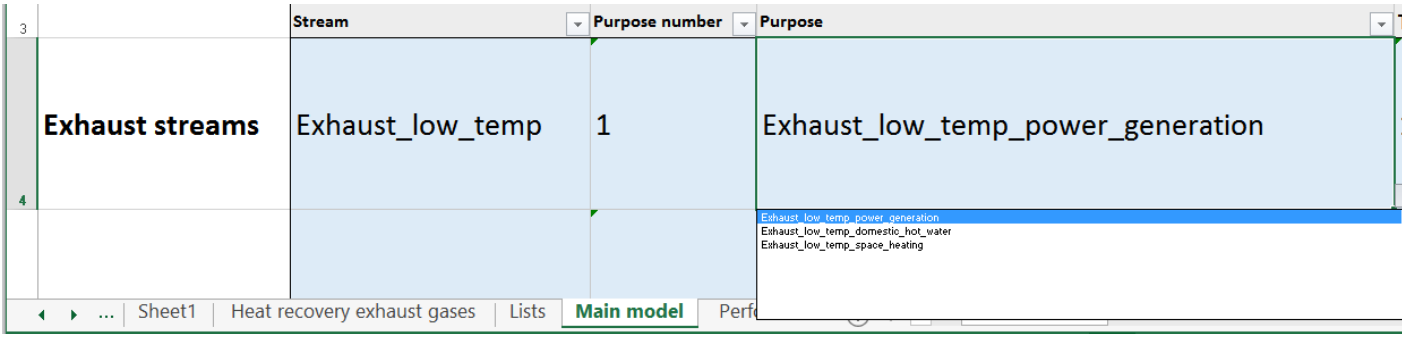
Technological maturity	Economic feasib	Energy saving pote	Maturity details	Economic details
High	Medium	not filled in	• ORC technology is not particularly new; at least 30 commercial plants worldwide were employing the cycle before 1984. • Important topic in power engineering and the number of published papers is rapidly increasing (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011). • The ORC shows great flexibility, high security, and low maintenance costs (Gutiérrez-Arriaga et al., 2015).	•ORC, which is superior (compar recovering low-grade waste heat • Long service life, low maintena unmanned operation, improved p Bandyopadhyay, 2009). • Capital costs and profitability c installations are strongly site anc (Tchanche, Lambrinos, Frangouda • Not always economically feasib conventional el from the grid.

Figure 16. Example on some of the if-statements combining purposes and technologies.

Simple IF-statements are used to define each possible combination of purpose and technology for each type of stream and feeds in the information from the *Performance matrix* sheets. If a new technology or new purpose are to be added to one type of stream, these will have to be implemented in the *List* sheet and assigned a number. The evaluation of this combination will be fed into the two *Performance matrix* sheets and a new IF-statement linking to the reference cell has to be put into the *Main model* sheet. The three rows assigned for the same stream are programmed the exact same way, so when updates are made the easiest is to implement the updates in one of the rows, and just copy the code to the two others. When information on the different technologies and purposes that are already linked to in the *Main model*-sheet are to be updated, this can simply be done by editing the information in the *Performance matrix* sheets, and this will be directly updated in the model.

Figure 20 and Figure 18 shows the simple procedure of choosing which purpose and corresponding technologies to be assessed. The example shows the option of low temperature exhaust gas for power generation using the Organic Rankine Cycle. The resulting evaluation, both from the *Performance evaluation input* matrix and the *Performance qualitative input* matrix is showed in Figure 19.

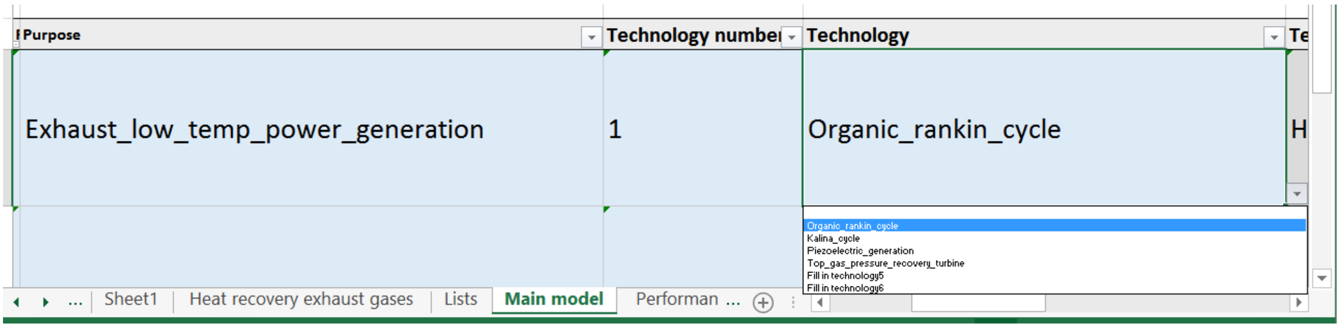
- Choice of purpose



	Stream	Purpose number	Purpose
Exhaust streams	Exhaust_low_temp	1	Exhaust_low_temp_power_generation

Figure 17. Main model: Choice of purpose

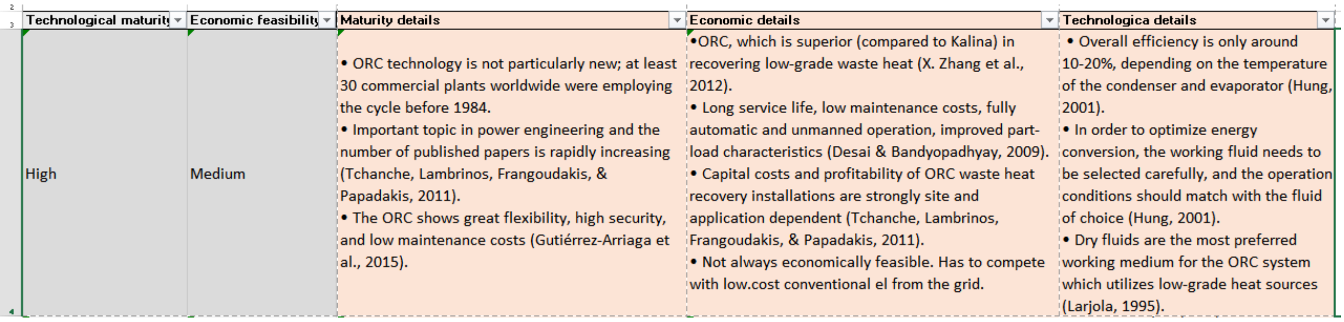
- Choice of corresponding technologies



Purpose	Technology number	Technology	Te
Exhaust_low_temp_power_generation	1	Organic_rankin_cycle	H

Figure 18. Main model: Choice of corresponding technology

- Evaluation results



Technological maturity	Economic feasibility	Maturity details	Economic details	Technologica details
High	Medium	• ORC technology is not particularly new; at least 30 commercial plants worldwide were employing the cycle before 1984. • Important topic in power engineering and the number of published papers is rapidly increasing (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011). • The ORC shows great flexibility, high security, and low maintenance costs (Gutiérrez-Arriaga et al., 2015).	•ORC, which is superior (compared to Kalina) in recovering low-grade waste heat (X. Zhang et al., 2012). • Long service life, low maintenance costs, fully automatic and unmanned operation, improved part-load characteristics (Desai & Bandyopadhyay, 2009). • Capital costs and profitability of ORC waste heat recovery installations are strongly site and application dependent (Tchanche, Lambrinos, Frangoudakis, & Papadakis, 2011). • Not always economically feasible. Has to compete with low.cost conventional el from the grid.	• Overall efficiency is only around 10-20%, depending on the temperature of the condenser and evaporator (Hung, 2001). • In order to optimize energy conversion, the working fluid needs to be selected carefully, and the operation conditions should match with the fluid of choice (Hung, 2001). • Dry fluids are the most preferred working medium for the ORC system which utilizes low-grade heat sources (Larjola, 1995).

Figure 19. Main model: Evaluation results of using ORC for power generation for low temperature exhaust heat.

Based on the information provided in the *Main model* sheet, the decision makers can make a superficial assessment of the energy recovery alternatives, and choose which specific technologies they want to go forward with and assess further in the next phase of the tool.

In addition to this evaluation model, a sheet containing an overview over different EIP-cases and available information on the characteristics of the symbiosis is made as a supplementary to the model. This overview over cases is created to work as a database for the users of the tool to access information on similar cases, and look how implementation of various symbioses has been carried out, and what are the resulting benefits. The informational categories in this table are the following: source of stream, sink of stream, purpose, technology, efficiency of technology, technology substituted, stream pressure, stream temperature, stream flow rate, name of EIP, environmental benefits, economic benefits and source of article. The full tables divided into the three categories of stream assessed can be found in Appendix B: Opportunity generation.

Sensitivity/feasibility analysis of the results of the opportunity generation

4.2 Proposed methodology of phase 2: Decision-making model

4.2.1 Defining evaluation criteria

When assessing the eco-efficiency of the symbiotic measures in this model, the evaluation tools used is quantifiable, transparent indicators to recognize the impacts of the measures.

A set of criteria, covering the technical, economic, environmental and social aspects are created to evaluate the IS-measures in the model. The model is set up to serve as a generic tool, where the user itself chooses from a list which criteria to be evaluated. Table 11. Potential evaluation criteria phase 2: feasibility screening tool below shows some of the most widely used technical, environmental and social criteria used in environmental decision making (J.-J. Wang et al., 2009) which are among the criteria to be selected in the model.

Criteria category	Description	Unit
Technical criteria	Amount of energy exchanged through symbiosis	GJ/year
	Delivered energy savings from measure	*GJ/year*
	Primary energy savings (PER)	*GJ/year*
	Efficiency of measure	
	Exergy efficiency of measure	
	Other	
Environmental criteria	CO_2 emission savings	*Tons of CO_2/yr*
	NO_X emission savings	*Tons of NO_X/yr*
	SO_2 emission savings	*Tons of SO_2/yr*
	Particles emission	*Tons of PM/yr*
	Other emission savings	-
Socioeconomic criteria	Employment opportunities created	*Number of jobs created*
	Social acceptability	*Social acceptability indicator*
	Other social benefits	-
Economic criteria	Investment costs for measure	€
	Operation and maintenance cost	€/yr
	Net present value for measure	€
	Payback period for measure	years
	Other economic criteria	

Table 11. Potential evaluation criteria phase 2: feasibility screening tool

Technical:

- Amount of energy recovered
  -delivered energy to the industrial park (MJ/year)
  -primary energy recovered (MJ/year)
- Energy efficiency of measure
- Exergy efficiency of measure

Energy consumption is a global environmental issue and is a very important parameter for evaluating the effectiveness of an industrial symbiosis network (Park & Behera, 2014). Large amounts of energy can be saved when recovered energy on-site can substitute external energy production, both when measuring energy delivered to the park and primary energy extracted. In this model, material flows are neglected and only energy streams (steam/water/exhaust/flue gas) are considered. Energy efficiency is the most used technical criteria for evaluating energy systems and refers to the amount of useful energy from an energy source (J.-J. Wang et al., 2009). Exergy efficiency gives the amount of useful energy output per energy input.

Environmental:

- Tons of CO_2-equivalent saved (tpy)
- Tons of SO_2-equivalent saved (tpy)
- Tons of NO_x saved (tpy)
- Saving of particle emissions (tpy)
- Other emissions (tpy)

Emissions of CO_2 is an important element of GHG-emissions resulting from combustion of fuel (coal/lignite, oil and NG), treatment processes and process reactions (J.-J. Wang et al., 2009). Reduction of the net emissions is an important benefit from symbiotic energy streams between companies in the industrial park.

Emissions of SO_2 and NOx from combustion of fossil fuel is a significant source of air pollution that threatens the environment and affects human health (C. Wang et al., 2011). Measuring the reduction of NO_x and SO_2-equivalents from the implementation of a measure will indicate to what extent acidification and respiratory effects can be reduced.

Economic:

- Net present value (NPV) for measure
- Internal rate of return (IRR)
- Payback period
- Investment cost for measure

Net present value (NVP) gives the sum of the present value of incoming and outgoing cash flows over a period of time. It is a standard method for appraising long-term energy projects and is often used to assess the feasibility of an energy project (J.-J. Wang et al., 2009). *Internal rate of return* (IRR) is the annualized yield obtained over the lifetime of the project given by the percentage return on each unit of money invested in the project (Kumar & Karimi, 2014). *Payback period* reflects the period of time it takes for the return on investment to recoup the sum of the initial investment (J.-J. Wang et al., 2009). *Investment costs* are all costs related to purchase of mechanical equipment, technological installations, construction of roads, connections to the grid, engineering services, and other construction work, but excludes labour and equipment maintenance costs.

The mostly used methods in energy conservation and waste heat recovery measures are simple payback period, NPV and IRR (Kumar & Karimi, 2014). When evaluating energy systems, investment cost is the most used economic criteria (J.-J. Wang et al., 2009).

Socioeconomic:

- Social acceptability
- Employment opportunities

Social criteria has been the most important one with respect to people's acceptance of the projects. The opinion of the population and pressure groups, *social acceptability*, plays a large importance because these might have a heavy influence on the amount of time needed to complete a project. This qualitative criteria can be measured in terms of social acceptance indicators which are measurable elements (Lipošćak, Afgan, Duić, & da Graça Carvalho, 2006). Pairwise comparison of measures can be done to decide their degree of acceptance (Chatzimouratidis & Pilavachi, 2008). Symbiosis measures creating *employment opportunities* gives benefits improving living quality for the local community. This criteria reflect the increase in direct (and indirect) numbers of employment opportunities (Doukas, Andreas, & Psarras, 2007).

4.2.2 Normalization method

In the preliminary project, the simple and widely used normalization method, described as *Process 1* was used. In the feasibility screening model proposed, when the results are implemented for the different criteria, they are normalized using the four different methods explained in Table 7. Normalization *(Chakraborty & Yeh, 2007) (Lakshmi & Venkatesan, 2014)* in section 2.6.3 (page 37);

- Max method
- Max-min method
- Sum metod
- Vector normalization

4.2.3 Development and usage of the tool

Excel has been used to develop the feasibility screening tool. Structuring the model like this gives a good overview where each assessment step is assigned one sheet. This makes it easy moving stepwise through the whole process.

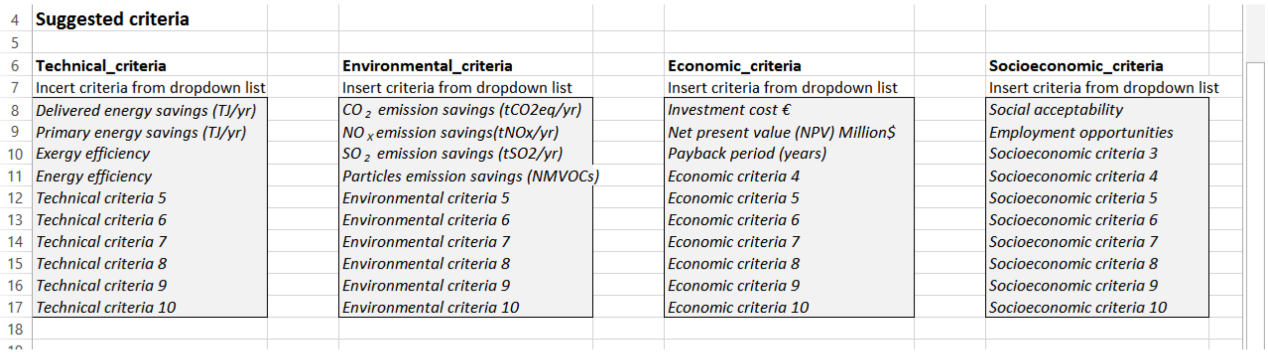
The sheets completing tool are the following:

Lists: In the lists sheet, the different technical, environmental, economic and socioeconomic criteria defined in section 4.2.1 (page 56) are saved using the list-function in excel in up to 10 criteria for each categories

Generalized normalization : in this sheet, the calculated values for the measures are put in the *Results from calculations* table for each of the chosen criteria. Normalized values are calculated using four of the most used normalization methods in MCDA and illustrated in graphs.

Step 1: List

The most relevant technical, environmental, economic and socioeconomic criteria (described in section 2.6.2 are listed and named using the list-function in excel. Hence, these can be linked to and selected in dropdown lists in the *Generalized normalization* sheet. The lists are made so that up to 10 criteria can be added to the list for each category.

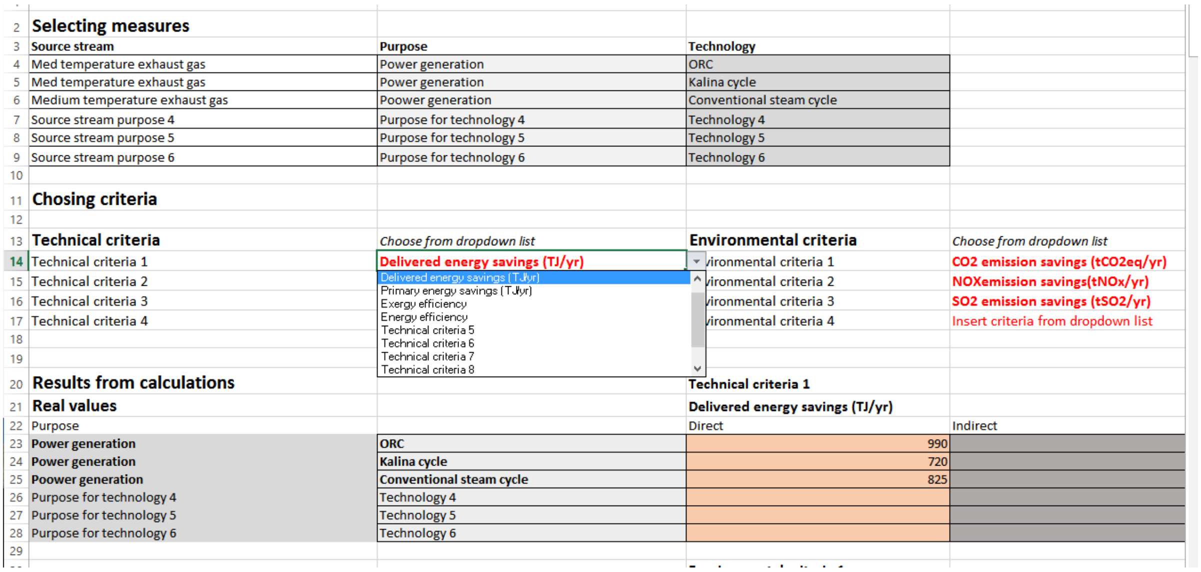


4	**Suggested criteria**			
5				
6	**Technical_criteria**	**Environmental_criteria**	**Economic_criteria**	**Socioeconomic_criteria**
7	Incert criteria from dropdown list	Insert criteria from dropdown list	Insert criteria from dropdown list	Insert criteria from dropdown list
8	*Delivered energy savings (TJ/yr)*	*CO_2 emission savings (tCO2eq/yr)*	*Investment cost €*	*Social acceptability*
9	*Primary energy savings (TJ/yr)*	*NO_x emission savings(tNOx/yr)*	*Net present value (NPV) Million$*	*Employment opportunities*
10	*Exergy efficiency*	*SO_2 emission savings (tSO2/yr)*	*Payback period (years)*	*Socioeconomic criteria 3*
11	*Energy efficiency*	*Particles emission savings (NMVOCs)*	*Economic criteria 4*	*Socioeconomic criteria 4*
12	*Technical criteria 5*	*Environmental criteria 5*	*Economic criteria 5*	*Socioeconomic criteria 5*
13	*Technical criteria 6*	*Environmental criteria 6*	*Economic criteria 6*	*Socioeconomic criteria 6*
14	*Technical criteria 7*	*Environmental criteria 7*	*Economic criteria 7*	*Socioeconomic criteria 7*
15	*Technical criteria 8*	*Environmental criteria 8*	*Economic criteria 8*	*Socioeconomic criteria 8*
16	*Technical criteria 9*	*Environmental criteria 9*	*Economic criteria 9*	*Socioeconomic criteria 9*
17	*Technical criteria 10*	*Environmental criteria 10*	*Economic criteria 10*	*Socioeconomic criteria 10*
18				

Figure 20. List-sheet defining technical, environmental, economic and socioeconomic criteria

Step 2: Generalized normalization

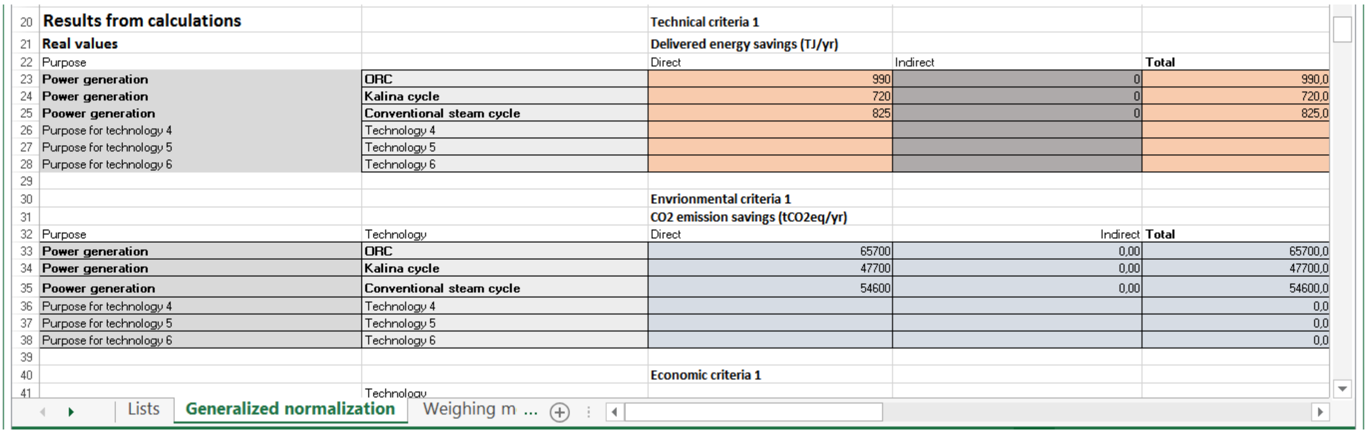
In the next step the types of measures (source stream, purpose and technology) can be filled in on top of the sheet. Then the criteria to be evaluated are selected from drop-down lists in all four categories. This information only needs to be filled in this place, and are automatically updated in the normalization tables.



2	**Selecting measures**			
3	**Source stream**	**Purpose**	**Technology**	
4	Med temperature exhaust gas	Power generation	ORC	
5	Med temperature exhaust gas	Power generation	Kalina cycle	
6	Medium temperature exhaust gas	Poower generation	Conventional steam cycle	
7	Source stream purpose 4	Purpose for technology 4	Technology 4	
8	Source stream purpose 5	Purpose for technology 5	Technology 5	
9	Source stream purpose 6	Purpose for technology 6	Technology 6	
10				
11	**Chosing criteria**			
12				
13	**Technical criteria**	*Choose from dropdown list*	**Environmental criteria**	*Choose from dropdown list*
14	Technical criteria 1	**Delivered energy savings (TJ/yr)**	vironmental criteria 1	**CO2 emission savings (tCO2eq/yr)**
15	Technical criteria 2	Delivered energy savings (TJ/yr)	vironmental criteria 2	**NOXemission savings(tNOx/yr)**
16	Technical criteria 3	Primary energy savings (TJ/yr) Exergy efficiency	vironmental criteria 3	**SO2 emission savings (tSO2/yr)**
17	Technical criteria 4	Energy efficiency Technical criteria 5	vironmental criteria 4	Insert criteria from dropdown list
18		Technical criteria 6 Technical criteria 7		
19		Technical criteria 8		
20	**Results from calculations**		**Technical criteria 1**	
21	**Real values**		**Delivered energy savings (TJ/yr)**	
22	Purpose		Direct	Indirect
23	**Power generation**	**ORC**	990	
24	**Power generation**	**Kalina cycle**	720	
25	**Poower generation**	**Conventional steam cycle**	825	
26	Purpose for technology 4	Technology 4		
27	Purpose for technology 5	Technology 5		
28	Purpose for technology 6	Technology 6		
29				

Figure 21. Inserting which measures to be evaluated and selecting which criteria to be evaluated

In the first table *Results from calculations*, the calculated costs and savings are filled in for all the different criteria to be evaluated. shows a section of the table for only a few criteria, where he numbers used to illustrate the example are taken from a case study found in literature (Van Beers & Biswas, 2008).

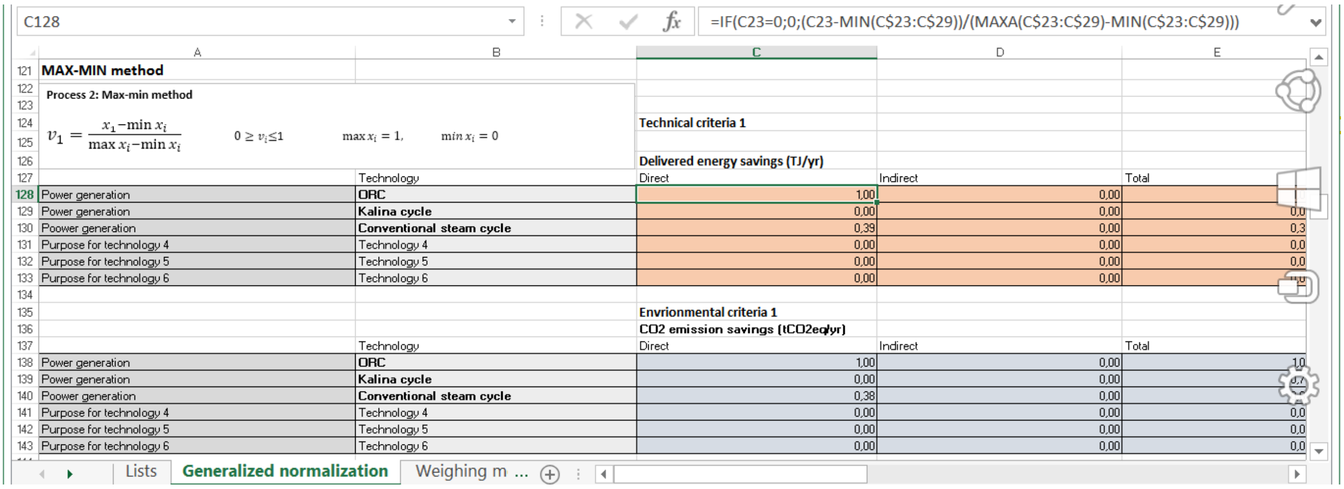


20	**Results from calculations**		**Technical criteria 1**		
21	**Real values**		**Delivered energy savings (TJ/yr)**		
22	Purpose		Direct	Indirect	**Total**
23	**Power generation**	**ORC**	990	0	990,0
24	**Power generation**	**Kalina cycle**	720	0	720,0
25	**Poower generation**	**Conventional steam cycle**	825	0	825,0
26	Purpose for technology 4	Technology 4			
27	Purpose for technology 5	Technology 5			
28	Purpose for technology 6	Technology 6			
29					
30			**Envrionmental criteria 1**		
31			**CO2 emission savings (tCO2eq/yr)**		
32	Purpose	Technology	Direct	Indirect	**Total**
33	**Power generation**	**ORC**	65700	0,00	65700,0
34	**Power generation**	**Kalina cycle**	47700	0,00	47700,0
35	**Poower generation**	**Conventional steam cycle**	54600	0,00	54600,0
36	Purpose for technology 4	Technology 4			0,0
37	Purpose for technology 5	Technology 5			0,0
38	Purpose for technology 6	Technology 6			0,0
39					
40			**Economic criteria 1**		
41		Technology			

Figure 22 Filling in resulting calculations for all criteria

When the results from calculation for the chosen criteria for the case are implemented in the table, tables containing formulas calculating the normalized results for the four different methods are found below the *Results from calculation* table. The user can then chose which of the normalization methods to go forward with.

Figure 26 shows an example on how the normalization tables are listed and how the normalization formulas are programmed. This is done for all criteria that are chosen to include in the assessment.



=IF(C23=0;0;(C23-MIN(C$23:C$29))/(MAXA(C$23:C$29)-MIN(C$23:C$29)))

MAX-MIN method

Process 2: Max-min method

$$v_1 = \frac{x_1 - \min x_i}{\max x_i - \min x_i} \qquad 0 \geq v_i \leq 1 \qquad \max x_i = 1, \qquad \min x_i = 0$$

	A	B	C	D	E
124			**Technical criteria 1**		
126			**Delivered energy savings (TJ/yr)**		
127		Technology	Direct	Indirect	Total
128	Power generation	**ORC**	1,00	0,00	[illegible]
129	Power generation	**Kalina cycle**	0,00	0,00	0,0
130	Poower generation	**Conventional steam cycle**	0,39	0,00	0,3
131	Purpose for technology 4	Technology 4	0,00	0,00	0,0
132	Purpose for technology 5	Technology 5	0,00	0,00	0,0
133	Purpose for technology 6	Technology 6	0,00	0,00	[illegible]
135			**Envrionmental criteria 1**		
136			**CO2 emission savings (tCO2eq/yr)**		
137		Technology	Direct	Indirect	Total
138	Power generation	**ORC**	1,00	0,00	1,0
139	Power generation	**Kalina cycle**	0,00	0,00	[illegible]
140	Poower generation	**Conventional steam cycle**	0,38	0,00	[illegible]
141	Purpose for technology 4	Technology 4	0,00	0,00	0,0
142	Purpose for technology 5	Technology 5	0,00	0,00	0,0
143	Purpose for technology 6	Technology 6	0,00	0,00	0,0

Figure 23 Example on normalization table for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation. From case found in literature (Van Beers & Biswas, 2008)

All tables and the normalization results displayed in graphs for all criteria and normalization methods are illustrated in graphs. These can be found and are commented in section 8.3 Appendix B. The examples are taken from a case in Kwiwana industrial area for three different technologies on thermal and power generation from exhaust gas using Organic Rankine Cycle, Kalina cycle and Conventional steam cycle (Van Beers & Biswas, 2008). There is a proportional relationship between the criteria for *Delivered energy savings* and *CO_2-emissions* between for all three measures and the normalized values between the measures are therefore the same between these categories in each of the methods. This is because for all three measures, it is assumed that the substituted energy is from same energy source (natural gas/coal) and the CO2 equivalent per kWh is thereby equal for all these measures. For this specific example, only three different measures are compared. From the graphs in section 8.3 Appendix B, it can be seen that e.g. the Max-min method is not ideal when only three measures are compared , since the worst criteria is set to 0 and the best criteria set to one.

This is as far as it was possible to proceed the development of phase 2 during the time of this thesis. Ideally, work would have been left for looking into the different methods for weighing (from literature) aggregation, and displaying of final scores.

5 Discussion

5.1 Main findings and achievements

As stated in the literature review, three of the main challenges in eco-industrial development is related to technical economic and regulatory barriers. The framework suggested in this thesis is a step towards identifying and overcoming these barriers.

The opportunity generation tool presented in the first phase of the framework encompasses three main types of industrial energy streams and gives an initial sorting on possible energy recovery and reuse purposes and technologies with a corresponding initial qualitative evaluation. It is aimed at being utilized in workshops for discussing and evolving the first steps towards implementation of economic and technically viable energy recovery opportunities among the participating parties of the symbiosis.

The sustainability screening tool in phase 2 is the follow up development of what was started in the preliminary thesis: *Methods for assessment of energy saving and reuse technologies in eco-industrial parks.* The intention of the sustainability screening tool is to be able to make a case specific assessment of the feasibility and sustainability potential of the different measures the user of the tool has selected to go forward with from the opportunity screening in phase 1. The user of the tool fills in which stream, purpose and technology to be assessed and chooses which technical, economic, environmental, and socioeconomic criteria should be a part of the multi-criteria decision analysis of the selected measures. Results from calculation of the benefits and costs of the measures are done outside the framework, and the resulting values are filled in to the table and normalized within the excel-model. The model calculates the normalized values using four different procedures. The user of the tool can thereby choose which of these methods to go forward with. In the preliminary thesis, only the most widely normalization method, max-method, was used because of its simplicity. In this version of the tool the user can choose which normalization method to apply. Due to the time consumed in the first phase of the tool, it was not possible to advance as much as first intended in this second phase of the tool.

Finding the optimal balance between developing a generic tool which at the same time is informative enough to be helpful for specific cases is not easy. As stated in the project description, the initial idea was to outline the framework based on a case study. This would have made the demonstration of the function of the tool easier. It would also be more achievable to fill the tool with adequate information because of the natural limitation of the purposes and technologies needed to be assessed based on the energy streams available in that specific case. On the other hand, the review of different purposes and technologies would be more narrow and in-depth and the tool might only be usable on other very similar cases. It was therefore clarified early in the work that creating a more generic framework had a higher utility because it can be applied to a variety of cases.

In the first phase of the framework, the first step of identifying the possible recovery and reuse purposes and corresponding technologies has been carried out, and is easy accessible for the user in the model. The complete development goal for the tool, is to review a high-level generic technological maturity, economic feasibility and energy saving potential for all the technology options on a qualitative basis, using the evaluation scores defined. However, filling the performance matrixes and make an initial evaluation and assessment of all proposed technologies is something that has to be done over time. Due to difficulties compiling the various data found in literature into a set of preliminary quantitative scores for the different technologies, only some of the technologies has been evaluated, and was used to demonstration in the tool in the result chapter.

A large amount of the time was spent screening the possibilities and purposes for the three main types of energy streams in order to identify which technologies are most widely used in the context of industrial symbiosis and the feasibility of these. Including all three types of streams to the tool simultaneously gave rise to obstacles in making a good, easy understandable model in excel, able to handle and sort all the inputs in an intelligent manner and at the same time filling it with as much relevant information as possible. Initially the thought was also to include the material streams with obvious characteristics for being used for energy recovery purposes, but this was excluded from the scope due to time constraints. Narrowing down the scope even further to including for example only one main type of stream (e.g. exhaust/flue gas) instead of three would have made it easier to focus on the functionality and quality of the model as well as doing a more thorough literature review on the identified stream-specific recovery and reuse options.

Before the methodology for the framework could be developed properly, an important factor to get settled was the classification of the three stream types, which showed to be more time consuming than assumed. Much time was spent trying to classify the streams in a way that would make it simple to find a purpose that would fit exactly according to the parameters of the particular stream to be assessed. Initially, the idea was to classify the streams by pressure, volume flow and temperature, where each of these properties could be categorized as *low*, *medium* and *high*. This would be too many for the tool to stay simple and finding literature that classified streams at this level of detail with corresponding exchange purposes and technologies would require much more time. Because of the difficulties finding enough literature on parameter specific energy exchanges, it was easier to classify the streams in broader categories.

When steam is classified in case studies on recovery and reuse opportunities found in literature, they are often just categorized according to its state (saturated, superheated) or its level of pressure (high, medium or low) without further information. For exhaust/flue gas, literature focused on the recovery purpose and technology according to the temperature. By using a less specific categorization of the streams, it became easier to fill in information from literature into the tool. However, making an assessment of the feasibility of the different opportunities became more difficult because of the lack of defined data on feasibility relevant parameters like e.g. pressure, temperature and volume flow of the stream. If more time was available, the tool would have been developed so that more than just *one* stream-specific parameter decides what possible recovery purposes and technologies that exist for a stream to make the assessment more accurate.

However, the state of the tool at this point it is meant to be used on a generalized level. No matter how stream specific and detailed the tool is, there will always be case specific conditions that will influence the feasibility and applicability of the suggested technologies. Hence an optimal utilization of the tool requires that the user possess a certain degree of knowledge in the field of energy recovery technologies and industrial symbiosis to be able to evaluate and criticism the proposed suggestions for the actual stream.

This tool has been made with the intention to be easily updatable. It is developed so that each time it is applied for a case, it can be updated and filled with more information through expert knowledge from the user, literature studies and case-studies related to the specific case the tool is used for. Information can be added or modified in the *Performance matrices* containing the qualitative information and the evaluation inputs for the main assessment model. When enough information is collected for a specific technology, the user of the tool should be able based on the information output in the *Main model* sheet, to evaluate whether or not they want to take the technology to the next phase of the framework to make a more detailed assessment.

5.2 Resulting agreements with literature

As stated in literature, to attract and retain companies to engage in mutually beneficial collaborations, the parts should understand the corresponding benefits, opportunities and sustainability challenges (Veleva et al., 2015). Quantitative data about economic benefits and environmental gains resulting from by energy recovery and reuse measures in an industrial area can challenge other companies to study their possibilities and work towards symbiosis and utility sharing in practice (Eilering & Vermeulen, 2004). Even though literature states that the most successful cases of industrial symbiosis in are those that develop spontaneously over time, the framework proposed in this work might speeding up the processes of identification, evaluation and implementation of symbiosis.

In the chapter on MCDA in the literature review Ladhelma et al., (2000) listed important points to take into account when choosing multi-criteria models. It was stated that the model should be able to support the number of decision makers, criteria and measures for the specific case. It should also be well defined and easy to understand regarding central elements like criteria and definition of weights. Making a generalized tool, applicable to various cases, for giving a multi-criteria assessment for the measures chosen from the first phase is therefore not easy, as the optimal would be for a case to have a decision-making framework specially selected for the actual case. This is why the intended purpose for the tool is to give the opportunity to select between different normalization, weighing and aggregation methods.

5.3 Strengths and weaknesses of the framework

Since this is a type of tool that has to be continuously updated and supplied with new information an important feature is that it is easy to update. The structure of the tool is set up in a simple and comprehensive manner, which makes adding and updating information easy. It consist of 4 sheets and information is added in a stepwise manner. When programming the model, IF-statements have been implemented in every output cell to combine all possible combinations of purposes and technologies. It is made so that when the tool is filled with adequate information, all essential information will be in a simple manner given as output in the *Main model* sheet. If all actual combinations are stated and linked to in the *Main model*, updates of the existing technologies can simply be done by editing or supplying information to the *Perfomance matrices*.

However, even though the structure of the framework is simple and comprehensive and adding information is easy, there is still a large potential of making it simpler. The ideal would be if information could be added one place, and the other sheets would be automatically be updated correspondingly. As the model is programed now, this only partly the case. When a new technology and purposes are added in the *List* sheet, these are automatically added as new selection options in the *Main model* sheet through dropdown lists. However, new rows and columns for these categories has to be manually added in the two *Performance* matrix sheets.

Keeping the tool at a broad generalized level will make it applicable to a larger variety of cases. As stated in the methodology chapter, the output of possibilities for energy recovery for the various streams are *suggestions* to which solutions should be further investigated. Case specific factors as e.g. type of industry of source and sink, transport distance between source and sink, if the recovered energy is to be used internally or externally, existing infrastructure, investment capital etc., will be important when evaluating the suggested measures. These factors are not taken into consideration when purposes and measures has been proposed at this first stage of the framework. This first phase is supposed to give an overall evaluation of the possibilities regardless of these case specific factors. In the next phase of the tool these will play a more important role.

For simplicity reasons and because of time limitations, the purposes has also been suggested based on a very broad classification of streams. E.g., exhaust gas has been categorized only with respect to temperature. When sorting the different purposes and technologies for the streams, no consideration has been given on pressure or flow rate levels. Steam has been subdivided into superheated and saturated steam, also without further details on the level of pressure, temperature or flow rate. The proposed purposes and technologies are therefore very general and superficial, which can be a weakness. Suggested purposes and corresponding technologies are based on information available in literature. However, their evaluation on degree of feasibility might be based on very few cases in literature, and generalized. This means that when the tool is applied, the users have to take this into consideration when evaluating the suggested purpose and technologies for their specific streams, and the alternatives should be considered with caution.

The current state of the information added in the *Performance matrixes* is weak. However, this is something that has to be implemented in the tool over time.

5.4 Future work: taking the framework to the next step

Creating a three phase framework as outlined in this thesis is a time consuming work. During this thesis, the main focus was given phase 1 of the tool. In order to finalize what has been started in this thesis, some recommendations to further work will be given.

Earlier in the discussion it is mentioned that this initial version of the tool can be used to get an overview over different purposes and technologies for the different types of streams assessed, even though it's not completed and filled in with information and evaluation of all combinations. The structure of the tool has been outlined in a way so that it can easily filled with new information. The way the streams are classified with their suggested purposes and technologies is already a good starting point for a further, development of the tool. If big changes to the information input to the tool, the structure as it is can still be kept, or used as a pin point to how it could be designed.

Increasing the level of parameter details of the streams, to including i.a. intervals of pressure, temperature and volume flow for each stream, is one of the first things that should be worked on to increase the utility and level of details of this tool. These does not play as large part as they should have in this first version of the tool. It would make it easier to evaluate the feasibility of the technologies when more specific details on the appliance are stated, given that enough parameter specific cases from the literature is found.

One idea is to categorize the streams with respect to its potential exergy content. However, the challenges in doing that in this work, was the lack of time to find enough parameter specific literature to in order to classify the streams with this level of detail. With more time available this is feasible.

Another feature that should be improved is the classification table for the *Performance evaluation input* matrix. The background for evaluation is very brief because of the large scope of the streams. The reasoning basis for evaluating a technology to be *Good*, *Medium* or *Poor* should be more specified in classification table shown in this work. The evaluation scale should maybe be different for the different types of streams where the score is the same, but the criteria for the score is adapted for each stream. E.g., to be able to state that a technology has a *High* maturity, a specified minimum number of articles from literature should support this evaluation.

The tool should be so that the information would transfer more easily between the sheets so when information was changed one place, it would make corresponding changes in every sheet. At current state there is a direct connection between the *List* sheet and the *Main model* sheet. Also, there are IF-statements making links between the *Performance matrices* and the *Main model* sheet. The ideal solution would be to make a linkage also between the *List* sheet and the *Performance matrices* so that when the lists were updated, the new additions or changes to stream types, purposes and technologies would be updated automatically. As the model is structured now, if changes are made in the List sheets (e.g. a new purpose or technology is added), this will have to be automatically updated in both of the performance matrix sheets.

Initially, the goal for the sustainability screening tool was also to implement different weighting methods in the model so that the user of the tool could also choose the weighing method best suited for that specific case. Finally, comprehensive ways of displaying the aggregated final results from the multi-criteria evaluation should be demonstrated. These scores should display the cost/benefits of each of the individual companies involved in the symbiosis.

The goal for the last and finalizing phase of the proposed framework is to overcome barriers related to contractual and pricing issues, when implementing energy saving strategies. The output is suggested to be a toolkit with a list of common contractual and pricing issues and successful models/templates able to handle and mitigate these issues.

Since this first version of the framework is not finalized, no case has been used to demonstrate the function of it. Hence, it is left to further work in order to finalize the framework and demonstrate its function using a case.

6 Conclusion

Literature on industrial symbiosis and eco-industrial parks pointed to the need for a tool to provide an overview over potential costs and benefits of various symbiosis options in order to create awareness and encourage stakeholders in engaging in symbiotic collaboration.

The initial objective of this work was therefor to develop a framework for all three phases of the tool. Because development of phase 1 of the framework turned out to be much more time consuming than initially thought, phase 2 of the framework was delegated significantly less attention than initially planned. More focus was put into trying to advance as much as possible in the important phase 1 of the framework. Already early in the work it was decided that phase 3 would be excluded from the scope.

Phase 1 is a suggestion to an opportunity generation tool that can be helpful in giving a preliminary sorting of energy recovery opportunities and technologies for energy streams at an industrial site. The tool will work as a discussion opener and will help in giving a brief qualitative evaluation of some of the possible alternatives for synergy. It can be used as support in discussing possible energy recovery opportunities for different streams in a variety of cases concerning industrial symbiosis. It will suggest different opportunities for each type of stream on a generalized high level and link to literature where more specific appliances of the technologies has been implemented before. Even for the options in lack of enough data to provide a feasibility assessment, the users of the tool can take a step further towards creating awareness and opportunities just by having the different recovery possibilities identified.

The initial version of the tool demonstrated in this work is not completed, and there is a large potential for improvement both considering the structure of the tool and the way it is programmed. Even though the tool is made with the aim to be simple, creating it to asses so many combinations of purposes and technologies has been time consuming. Making this type of excel-table with drop-down lists and programming codes linking combinations of technologies and purposes, would therefore have been more suitable if the scope was smaller which would make demonstrating the function of the tool easier. The tool as it is now, has to be modified and filled over time in order to create an exhaustive, informative database for energy recovery opportunities for waste streams in an industrial area.

Some of the most time consuming tasks in developing this phase was related to the compromise between making a generic model that at the same time was refined enough to screen alternatives for various specific cases. Much time was spent trying to classifying the stream types in a manner that wold provide the user with an accurate sorting of purposes and technologies according to the specific stream type. Finally, the sorting of the different stream types was done in a more simple manner, because of troubles finding enough parameter specific literature for purposes and technologies to make this initial, general screening of opportunities. When upgrading this first proposal to the framework it is suggested to spend time finding a more specific, exhaustive way of classifying the energy streams using the most important parameters of pressure, temperature and flow rate of the streams. An idea is to classify the streams with respect to the useful energy potential in the stream (exergy). The need for narrowing down the scope was realized quite early in the work. However, the quality of the model, and also the exhaustiveness of stream specific recovery purposes and technologies would have been more exhaustive if it was focused on only one type of stream to begin with. For further work it is therefore recommended that after defining the classification it is recommended to start focusing on one type of stream until a satisfying amount of information on relevant energy recovery purposes for that stream are implemented and evaluated in the tool, before moving on to the next stream type.

Phase 2 is the follow up development of what was started in the preliminary thesis: *Methods for assessment of energy saving and reuse technologies in eco-industrial parks.* However, due to limited time, it was not possible to advance as much as first intended in this phase. In the preliminary work, the framework developed was based on hypothetical measures from a case study. In this work has been focused on making the sustainability screening tool in a more generic manner, adaptable to various cases. This phase is where the identified measures in through the screening of opportunities in phase 1 is given a more detailed, case specific feasibility assessment. A set of the most relevant technical, economic, environmental and socionomic criteria are listed and the user of the tool selects which of these to include in the assessment. When the results from the calculations on the criteria are put in to the excel-model, the normalized results are calculated using four different methods. Hence, the user have a possibility of choosing what method to utilize.

When working further on this tool, both the work done in the preliminary thesis, and the work initiated in this thesis can be used as a basis for further development of this phase. Main points left for finalizing phase 2 is the weighing, aggregation and displaying of final decision-making results. Phase 3 of the framework not initiated in this work. It is suggested to be a toolkit with a list of common contractual and pricing issues and successful models/templates, is left to further work.

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8 Appendix

8.1 Appendix A: Additional literature

8.1.1 Additional information on MCDA

Aggregation of decision alternatives

A work by Løken (2007) divides MCDA into three broad categories, namely; value measurement methods, goal, aspiration and reference level models and outranking methods (Løken, 2007). For the MCDA-model developed in this work, the *value measurement methods* are the most relevant.

Multi-attribute value theory, multiattribute utility theory or (MAVT/MAUT) and the analytical hierarchy process (AHP) are optimizations process that apply numerical scores to compare the benefit/costs of one option with the other alternatives. The overall performance of a measure is formed by aggregating the individual scores of each criterion into an overall score.

$$U(A_{i)} = \sum_{j=1}^{m} w_j u_j(c_j(A_i))$$

Where U is the utility functions, A_i is a set of i alternatives, c_j is a set of j criteria for the alternatives and w_j is the set weights for the j criteria (Rochat et al., 2013).

Multi-attribute value theory has a simple and user-friendly approach. In cooperation with analysts, the only thing decision makers has to do is to specify value functions and define weights of criteria. Each of the alternatives are assigned a value *V*, which is the sum of the weighted and normalized partial value function for all of the criteria assessed. If four criteria are assessed for measure A, the numerical score is given by the formula below.

The process of assessing utility functions will help decision makers to identify the issues with the highest importance in addition to generating and evaluating alternatives. However, Siskos et al. (1983) claims that this methodology presents several operational complications, especially concerning the probability and utility attached to the criteria (Siskos & Hubert, 1983).

According to Rochat et al. (2013) “the objective of MAUT is to obtain a conjoint measure of the attractiveness (utility) of each outcome of a set of alternatives (scenarios)” (Rochat et al., 2013). Compared to MAVT, multiattribute utility theory is a more rigorous methodology when it comes to incorporating risk preferences and uncertainties into the MCDA methodology (Siskos & Hubert, 1983). According to Turskis et al. (2011) MAUT is “widly recognized as a rigorous, practical and accessible set of principles for helping people make better decisions" (Turskis & Zavadskas, 2011). Utility functions are established for each criteria, where the risk preferences are reflected directly in the values (Kiker et al., 2005; Løken, 2007).

Because of its simplicity the *simple additive weighing* (SAW) method, is one of the most widely used methods within the MAVT. The additive aggregation of decision outcomes are controlled by weights expressing the importance of the criteria (Shakouri G, Nabaee, & Aliakbarisani, 2014).

$$V(a) = \sum_i w_i * v_i(a), \text{ where } w_i \geq 0, \quad \sum w_i = 1$$

The weight w_i should ideally indicate how much the DM is willing to accept in the tradeoff of criteria i related to the other measures. The partial value function v_i(a) reflects the performance of criterion i in alternative a (Løken, 2007). No interaction between the criteria can be modelled and its applicability should therefore be limited to the cases where independency is satisfied (Giove et al., 2009).

The *weighted sum* method is used especially in single dimensional problems and is quite strait forward (Mateo, 2012). When there is m alternatives and n criteria, the expression for the weighted average is the following:

$$A^*{}_{wsm} = Max \sum_i^j a_{ij} w_j, \qquad for\ i = 1,2 \ldots \ldots, m$$

$A^*{}_{wsm}$ is the weighted sum method score of the best alternative, m is the number of decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion. The weighted criteria are summarized for all the alternatives, and the alternative with the highest score is the best. When combining different dimensions and different units, this method cannot be applied.

In the *weighted product* method, the different alternatives are compared with the others by multiplying a number of ratios, one for each criterion. Two criteria can be compared by the following expression:

$$R\left(\frac{A_k}{A_l}\right) = \prod_{j=1}^{n} \left(\frac{a_{kj}}{a_{lj}}\right)^{w_j}$$

If $R\left(\frac{A_k}{A_l}\right)$ is greater than 1, A_k is more desirable than A_l, and the overall best alternative is the one that is better than or at least equal to the other alternatives.

8.1.2 Additional literature on methods for quantifying benefits in IS

From preliminary thesis (Aase, 2015)

Material and energy flow model

Mass flow analysis is a widespread and standardized methodology that has mostly been used for analysing social metabolism in countries and regions. This method has not commonly been used for analysing industrial areas. Input-output analysis (which will be explained in more detail in subchapter 2.5.4) and substance flow analysis has been more frequently used for this purpose (Bailey, Allen, & Bras, 2004; Hashimoto & Moriguchi, 2004).

A paper by Sendra et al. (2007) proposes using indicators derived from MFA along with energy and water indicators to analyse the energy efficiency and materialization ranks in an industrial area (Sendra et al., 2007). The aim is to apply MFA as an assessment tool for analysing an eco-industrial park located in Catalonia. The methodology is applied to each company individually and to the industrial area as a whole. Eurostat methodology was used for the classification of flows.

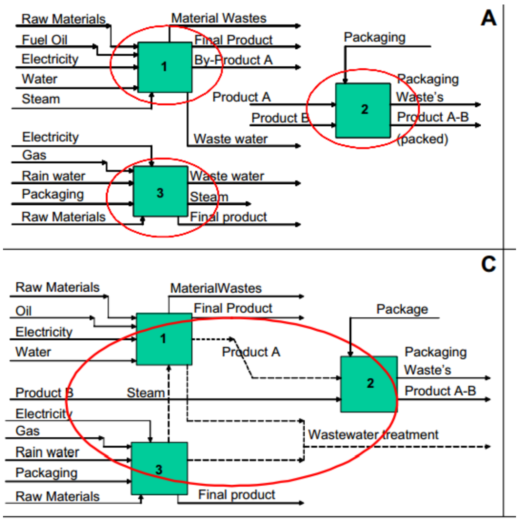


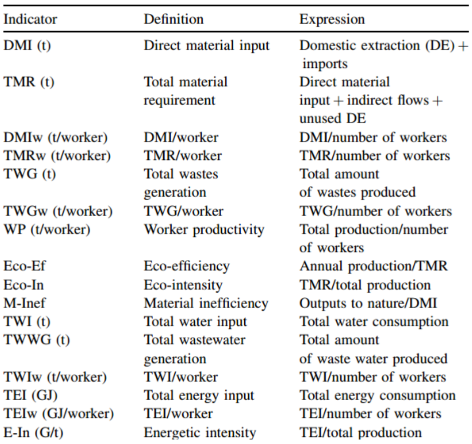
Figure 24 System boundaries for a theoretical system for assessing benefits of symbiosis exchanges (Sendra et al., 2007)

Figure 28 is taken from the article and shows the system boundaries (marked by red circles) of a theoretical system. It illustrates the input and output flows in each of the three individual firms without symbiosis (A) and for the system as a whole after symbiotic exchanges between the companies (C). When an MFA is applied to the whole industrial area, the flow exchanges between the companies is not accounted for because they don't cross the system boundaries (C). This system illustrates that an increase of by-product exchange between the companies the direct material input of the system as a whole will decrease.

The article points out five aspects that should be considered when applying MFA is adapted to industrial parks.

1) MFA should be combined with energy and water flow analysis as the use of all resources, not only material, should be quantified and improved.
2) At national level, most data is statistical, but in industrial parks data is given by the companies. Coefficients used at national level can give erroneous values, thus the indirect flows associated to companies production should be estimated on site.
3) The material input should be measured per unit of product instead of as GDP/capita (as it is at national or regional level)
4) In order to measure the companies' flows and for the MFA to evaluate the whole industrial area, the system should not be considered a *black box* (as it is at national level).

5) The main tool for detecting opportunities for improvement is the data basis created to evaluate the MFA's indicators.



Indicator	Definition	Expression
DMI (t)	Direct material input	Domestic extraction (DE) + imports
TMR (t)	Total material requirement	Direct material input + indirect flows + unused DE
DMIw (t/worker)	DMI/worker	DMI/number of workers
TMRw (t/worker)	TMR/worker	TMR/number of workers
TWG (t)	Total wastes generation	Total amount of wastes produced
TWGw (t/worker)	TWG/worker	TWG/number of workers
WP (t/worker)	Worker productivity	Total production/number of workers
Eco-Ef	Eco-efficiency	Annual production/TMR
Eco-In	Eco-intensity	TMR/total production
M-Inef	Material inefficiency	Outputs to nature/DMI
TWI (t)	Total water input	Total water consumption
TWWG (t)	Total wastewater generation	Total amount of waste water produced
TWIw (t/worker)	TWI/worker	TWI/number of workers
TEI (GJ)	Total energy input	Total energy consumption
TEIw (GJ/worker)	TEI/worker	TEI/number of workers
E-In (G/t)	Energetic intensity	TEI/total production

Table 12. Environmental indicators (Sendra, Gabarrell, & Vicent, 2007)

The case study on the industrial park in Catalonia focus on a heterogeneous industrial area where collective and individual objectives are combined in order to convert the area into an EIP. Indicators (Table 12) are defined and used as tools for reflecting and measuring the current state of the system. They can be calculated for the industrial area as a whole and for each of the companies. Hence, both a global vision of the system and a comparison of the consumption and efficiency of the different subsystems can be facilitated.

From the results obtained in the study it can be seen that the indicators defined is useful in detecting the critical points of the system which are found to be; resource consumption, the usage of the systems own resources, waste generation and efficiency. These critical points can be used in combination with other tools to plan strategies for improvement in the industrial system. In this study, these improvements are not implemented in the model to calculate the resulting benefits. However it is stated in the article that after applying the strategies the indicators can be able to reflect the changes in the system to evaluate the effectiveness (Sendra et al., 2007).

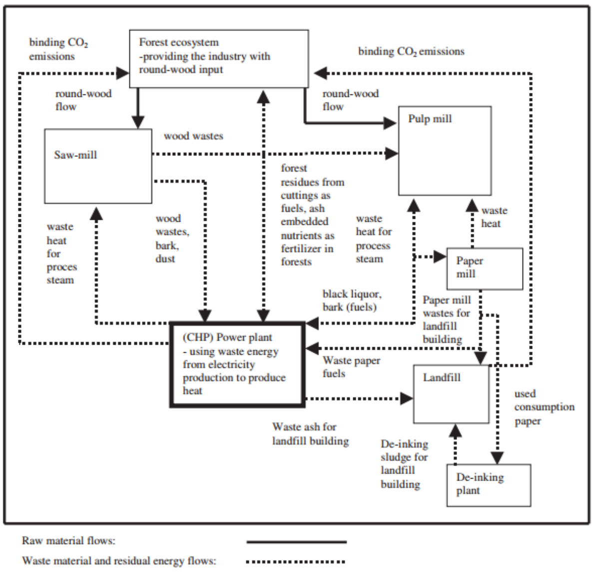


Figure 25. Recycling of matter and cascading of energy in a local forest industry system (integrate) with focus on waste flows (Jouni Korhonen & Niutanen, 2003)

Another work which discusses the use of material and flow modelling in industrial system is by Korhonen & Niutanen (2003). The energy and material flow model presented here can be used to study the forest industry and be utilized for the planning of environmental policies. Figure 29 illustrates a general description of the material and energy flows of a local forest industry in Finland.

This local forest industry demonstrates, as in other industrial ecosystem models, the important features in the network. Using an industrial ecology system approach makes it possible to discover in which parts of the system improvements can be made (Jouni Korhonen & Niutanen, 2003).

Cost-benefit assessment of implementation of industrial symbiosis: Puerto Rico

A case study of a network of inter-firm exchanges in Guyama, Puerto Rico provides an example of a quantitative analysis of environmental and economic costs and benefits for the implementation of industrial symbiosis. Both existing and potential exchanges are assessed where a fossil fuel power generation plant and an oil refinery are critical participants. Steam and water opportunities are influenced by regulatory conditions in the area and the article concludes that there are substantial benefits from implementing symbiotic measures. These benefits, however, fall unevenly on the participants. Figure 30 shows the existing and proposed exchanges in Guyana, Puerto Rico (M. R. Chertow & Lombardi, 2005).

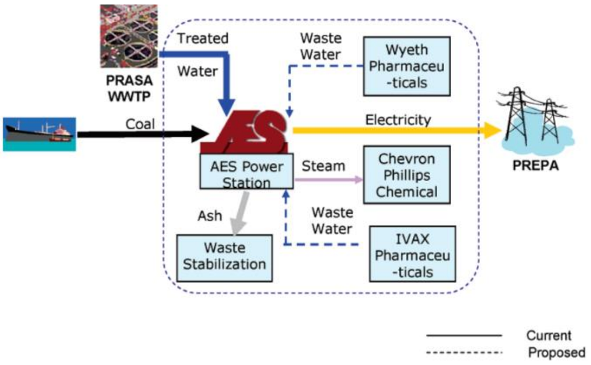


Figure 26. Schematic illustration of existing and proposed exchanges in Guyana, Puerto Rico.

The AES coal fired power plant uses reclaimed water from a public waste water treatment plant for cooling and provides steam to an oil refinery. Neighbouring pharmaceutical plants, the refinery and the power plant are negotiating on additional steam and wastewater exchanges. Nine sighting conditions has been defined and weighted on a scale from 1-10, with 10 being the most important. Two of the 4 factors weighted as 10, namely “proximity to steam user” and “sufficient water supply”, embody the resource-sharing concepts of industrial symbiosis and are proved to be challenging criteria to meet. Another limiting factor for co-generation, which makes it critical for AES to achieve QF (qualifying facility) status, is the lack of availability of industrial hosts with sizable steam and/or process heat requirements.

Cost and benefits of steam, water and other exchanges are analysed from an environmental point of view, using net air emissions as indicators and from an economic point of view independent on tax considerations. Upstream extraction and transportation of fuel oil and other inputs are not considered.

The assessment is divided in three parts in the article, quantifying steam, water and resource exchange. A summary of the resulting benefits from the steam exchange in the article are summarized in the following section.

Analysing materials and energy flows in industrial areas using input-output modelling

For a sustainable usage of resources handling, materials and energy flows in a more efficient manner is essential. Issues regarding policies for product recycling, by-product reuse, re-manufacturing, efficient waste management and energy use that are developed at the level of industrial districts can be addressed and modelled using input-output techniques (Albino, Dietzenbacher, & Kühtz, 2003).

In a work by Albino et al. (2003) an enterprise input-output model has been developed for an industrial district which allows for a detailed, quantitative analysis of materials and energy flows for assessing the consequent generation of waste and pollution. The intention of the model is accounting and forecasting results from economics-energy and environment interactions. How the system will respond on changes in the demand of the final product, changes in technologies used in production processes and the resulting environmental effect (in the form of pollution, energy and waste reduction) can be analysed. The model can be used as a planning tool for making quantitative choices in order to plan and evaluate alternative options for development strategies and help in negotiating a common policy among the different firms in the industrial district. Using the model for more complex situations is also a possibility.

Some of the application areas for the model is listed below:

- support for alternative methods of producing the final output in a more effective way and the consequent investment decisions that has to be made
- evaluate alternative options on how to satisfy the accounted demand for energy of the local production processes
- evaluating how the input mix or import rate may be changed to be able to take account for local restrictions.
- evaluating how a change in final demand affects the new amount of purchased inputs
- planning local development strategies
- analysing in how recycling of waste can benefit the system

Firstly a DPP (district production process) model based on an input-output table in physical units is modelled. To overcome the drawback of the model where only one main product can be used per production process an separate production process, namely an EPP (energy production process) network, is made based on the case where some of the waste types are used as inputs to produce energy within the district.

These models are applied to a leather sofa industrial district in Italy and the production process network distinguishes between eight production processes. Different activities (wood frame assembling, leather cutting, polyurethane preparation, sofa assembling) are performed by different firms within the district.

The DPP is used firstly to consider the energy consumption and the resulting output of waste in the industrial district. After that, the EPP-model is used for evaluating an alternative plan for districts energy supply by reusing wood scraps. When evaluating the results from reusing wood scraps in a biomass plant, less electric power needs to be purchased from external sources and a considerable amount of low temperature heat becomes available for sale to external sources (Albino et al., 2003).

8.2 Appendix B: Opportunity generation

8.2.1 Cases with steam exchanges

Type of stream	***Source***	***Sink***	***Purpose***	***Technology***	***Eff. of techn.***	***Substituting***	***Pressure***	***Temp***	***Flow rate***	***EIP***	**Energy consump**	**Primary energy (TJ)**	**t CO2 eq**	**t SO2eq**	**NVP**	**Sales income**	**Payback period**	***Reference***	**Link**
Steam	Cogeneration plant	Industrial comercial and residental users	N/A	N/A	N/A	N/A	N/A	N/A	N/A	TEDA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China*	(Shi, Chertow, & Song, 2010)
Steam	Cogeneration plant	Desilanation plant (TEDA)	N/A	N/A	N/A	N/A	Low pressure	N/A	N/A	TEDA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China*	(Shi et al., 2010)
Steam	Chemical (Cabot chemical)	Chemical park cooperation (TEDA)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	TEDA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*Developing country experience with eco-industrial parks: a case study of the Tianjin Economic-Technological Development Area in China*	(Shi et al., 2010)
Steam	Chemical plant (Hansol, KP Chemical)	Chemical plant (SKC)	N/A	N/A	N/A	B-C fuel oil	N/A	N/A	30 t/h	Ulsan EIP	66 ton/h (ipcc conversion factors)	N/A	44 468 tons/year	N/A	N/A	N/A	2,18 years	*Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks/ Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework*	(Park & Behera, 2014) (Behera et al., 2012)
Steam (and CO2)	Zink manufacturer	Paper mill	N/A	N/A	N/A	B-C fuel oil	N/A	N/A	70 t/h (8t/hour)	Ulsan EIP	70 tons/h (ipcc conversion factors)	N/A	63 643 tons/year	N/A	N/A	N/A	3,46 years	*Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks/ Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework*	(Park & Behera, 2014) (Behera et al., 2012)
Steam	Chemical plant	TPA manufacturing company	N/A	N/A	N/A	B-C fuel oil	N/A	N/A	80 t/h	Ulsan EIP	80 ton/h (ipcc coversion factors)	N/A	16 tons/h	N/A	N/A	N/A	N/A	*Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks*	(Park & Behera, 2014)
Steam	Petrochemical (SK Energy)	Industrial waste incinerator (NCC)	N/A	N/A	N/A					Ulsan EIP	N/A	N/A						*Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks*	(Park & Behera, 2014)
Steam	Industrial waste incinerator (Yoosung)	Paper mill (Hankuk)	N/A	N/A	N/A		N/A	N/A	12 t/h	Ulsan EIP	12 tons/h	N/A	19 258 tons/yr	N/A	N/A	N/A	0.37 years	*Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks/Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework*	(Park & Behera, 2014)
Steam	Transport (Hyunday)	Transport and steel (Hyunday Hysco & Motor)	N/A	N/A	N/A	LNG	N/A	N/A	20 t/h	Ulsan EIP	N/A	N/A	14000 tons/yr	N/A	N/A	N/A	1.75 years	*Evolution of "designed" industrial symbiosis networks in the Ulsan Eco-industrial Park. (2012)*	(Park & Behera, 2014)
Steam	Petrochemical (Aeykung)	Petrochemical (Evonik)	N/A	N/A	N/A	Coal	N/A	N/A	15 t/h	Ulsan EIP	N/A	N/A	30 094 tons/yr	N/A	N/A	N/A	0.63 years	*Evolution of "designed" industrial symbiosis networks in the Ulsan Eco-industrial Park. (2012)*	(Behera et al., 2012)
Steam	Municipal waste incinerator (Sungam)	Petrochemical (TPA) (Hyosung)	N/A	N/A	N/A		16 bar	N/A	45 t/h	Ulsan EIP	20 ton/h	N/A	55 500 tons/yr	N/A	N/A	N/A	0.7 years	*Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework*	(Park & Behera, 2014) (Behera et al., 2012)

Steam (low pressure)	AS Guyama (powerplant)	Refinery (Chevron Phillips)	N/A	N/A	N/A	Oil boilers	13 bar	N/A	83 t/h	IS network Guayama, Puerto Rico	N/A	N/A	-51000 tons/yr	1978 t/yr	N/A	N/A	N/A	*Quantifying Economic and Environmental Benefits of Co-Located Firms*	(M. R. Chertow & Lombardi, 2005)
Steam (high pressure)	AS Guyama (powerplant)	Refinery (Chevron Phillips)	N/A	N/A	N/A	Oil boilers	48 bar	N/A	48 t/h	IS network Guayama, Puerto Rico	N/A	N/A			N/A	N/A	N/A	*Quantifying Economic and Environmental Benefits of Co-Located Firms*	(M. R. Chertow & Lombardi, 2005)
Steam	Power plant (Åsnæs)	Refinery (Statoil)	N/A	N/A	N/A	N/A	N/A	N/A	197 000 GJ/year	Kalundborg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects*	(Jacobsen, 2006)
Steam	Power plant (Åsnæs)	Petrochemical (Novo group)	N/A	N/A	N/A	N/A	N/A	N/A	829 000 GJ/year	Kalundborg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	*Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects*	
Steam	Iron/steel plant (JIS steel)	Community	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Jinan city (China)	320 TJ/yr (10 900 tce/yr)	N/A	N/A	N/A	N/A	N/A	N/A	Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China	(Dong et al., 2014)
Steam	Iron/steel plant (JIS steel)	Chemical plant	N/A	N/A	N/A	Ammonia production	N/A	N/A	N/A	Jinan city (China)	221 TJ/ yr (7546 tce/yr)	N/A	N/A	N/A	N/A	1.90 M USD/yr	N/A	Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China/ Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan	(Dong et al., 2014)((Dong et al., 2013)
Steam	Power generation plant	Chemical plant	Alternative fuel for ammonia production	N/A	N/A	Ammonia production	N/A	N/A	N/A	Liuzhou city (China)	737 TJ/yr (25 153 tce/yr)	N/A	N/A	N/A	N/A	N/A	N/A	Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China	(Dong et al., 2014)
Steam	Power generation plant	Machinery	N/A	Heat exchange	N/A	N/A	N/A	N/A	N/A	Liuzhou city (China)	368 TJ/yr (12 575 tce/yr)	N/A	N/A	N/A	N/A	N/A	N/A	Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China	(Dong et al., 2014)
Steam	Chemical pulp mill	Saw mill	N/A	Turbine	N/A	N/A	0,4 Mpa	N/A	N/A	(Hypothetical)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry	(Karlsson & Wolf, 2008)
Steam	Chemical pulp mill	District heating system	N/A	Turbine	N/A	N/A	0,4 Mpa	N/A	N/A	(Hypothetical)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry	(Karlsson & Wolf, 2008)
Steam	Biofuel upgrading plant	Chemical pulp mill	N/A	N/A	N/A	N/A	0,4 Mpa	N/A	N/A	(Hypothetical)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry	(Karlsson & Wolf, 2008)
Steam	Chemical pulp mill	Biofuel upgrading plant	N/A	N/A	N/A	N/A	1,2 Mpa	N/A	N/A	(Hypothetical)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry	(Karlsson & Wolf, 2008)
Steam	Cogeneration system	Density board factory	N/A	N/A	N/A	N/A	1.6 Mpa	204 °C	2.0 Mt/year	Xinfa Group in Shandong Province	N/A	9000 TJ/yr	12000 tCO2eq/yr	900 000 t SO2eq/yr	N/A	N/A	N/A	Assessment of life cycle environmental benefits of an industrial symbiosis cluster in China	(Yu, Han, & Cui, 2015a)
Steam	Pulp and paper mill	Chemical plant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Kymenlaakso, Finland	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Industrial symbiosis contributing to more sustainable energy use – an example from the forest industry in Kymenlaakso, Finland	(Sokka, Pakarinen, & Melanen, 2011)

Steam	Pir iron plant	Industrial gas producer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Kwinana	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Industrial Symbiosis in the Australian Minerals Industry	(Van Beers et al., 2007)
Steam	Titanium dioxide producer	Chloralkali plant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Kwinana	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Industrial Symbiosis in the Australian Minerals Industry	(Van Beers et al., 2007)
Steam	Cogeneration plant	Titanium dioxide producer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Kwinana	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Industrial Symbiosis in the Australian Minerals Industry	(Van Beers et al., 2007)
	Cogeneration plant	Oil refinery	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Kwinana	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Industrial Symbiosis in the Australian Minerals Industry	(Van Beers et al., 2007)
Steam	Power plant	Paper mill/textile mill	N/A	N/A	N/A	N/A	N/A	N/A	N/A	The Shuozhou Eco-Industrial Park	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Emergy evaluation of Eco-Industrial Park with Power Plant	(L. Wang, Zhang, & Ni, 2005)

Table 13. EIP cases for recovery of steam.

8.2.2 Cases with exhaust/flue gas exchanges

Type of gas	*Source*	*Sink*	*Purpose*	*Technology*	*Eff. Tech.*	*Substituting*	*Pressure*	*Temp*	*Flow rate/volume*	*EIP*	*Energy consumption(TJ/yr)*	*Primary energy*	*tCo2 eq/yr*	*tSO2eq*	*NPV*	*Sales income*	*Payback period*	**Name of article**	*Reference*
Blast-furnace gas	Iron/steel plant	Ammonia plant	Supply as fuel	N/A	N/A	N/A	N/A	N/A	N/A	Jinan city (China) (Kawazaki)	320 TJ/yr (10900 tce/yr)	N/A	N/A	N/A	N/A	N/A	N/A	Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China	(Dong et al., 2014)
Coke-oven-gas	Iron/steel plant	Ammonia plant	N/A	N/A	N/A	N/A	N/A	N/A	47.16 Mm3/year	Jinan city (China) (Kawazaki)	850 TJ/yr (28 970 tce/year)	N/A	N/A	N/A	N/A	N/A	N/A	Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China	(Dong et al., 2014)
Coke-oven-gas	Iron/steel plant	Chemical	Alternative hydrogen production	N/A	N/A	N/A	N/A	N/A	N/A	Liuzhou city (China) (Kawazaki)	1404 TJ (47 915,4 tce/yr)	N/A	N/A	N/A	N/A	N/A	N/A	Uncovering opportunity of low-carbon city promotion with industrial system innovation: Case study on industrial symbiosis projects in China	(Dong et al., 2014)
Blast-furnace gas	Iron/steel plant	Paper mill	Electricity generation	Top pressure recovery turbine/ Coke dry quenching	N/A	N/A	N/A	N/A	50 Mkwh/yr	Kawazaki eco-town	N/A	N/A	N/A	N/A	N/A	4,86 M USD	N/A	Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan	(Dong et al., 2013)
Cement kiln gas	Salty gypsum production plant	Cement kiln production	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Shandong Lubei eco-industrial park	N/A		N/A	N/A	N/A	N/A	N/A	Ecological network analysis of an industrial symbiosis system:A case study of the Shandong Lubei eco-industrial parkYan	(Y. Zhang, Zheng, & Fath, 2015)
Gas (not specified)	Waste water treatment plant	Petrochemical plant	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Ulsan EIP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks	(H.-S. Park & Behera, 2014b)
Lanfill waste gas	Municipal waste landfill (Sungam)	Municipal waste incinerator (Sungam)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Ulsan EIP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Methodological aspects of applying eco-efficiency indicators to industrial symbiosis networks	(H.-S. Park & Behera, 2014b)

Flue gas (not specified)	N/A	N/A	Supply of preheated liquid	Heat exchanger	65-75% (el)	Gas fired boilers	N/A	N/A	N/A	Kwinana industrial area, Western Australia	445-615	N/A	24400-33900 t/yr	N/A	15,8-22,7 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008) (Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Supply of preheated liquid	Heat exchanger	65-75% (el)	Gas fired boilers	N/A	N/A	N/A	Kwinana industrial area, Western Australia	515-620	N/A	28500-34200 t/yr	N/A	19,2-23,3 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Supply of preheated liquid	Heat exchanger	65-75% (el)	Gas fired boilers	N/A	N/A	N/A	Kwinana industrial area, Western Australia	345-490	N/A	18900-26800 t/yr	N/A	12,1-17,8 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity and thermal energy	Kalina cycle/heat exchanger (el/thermal)	47-58% (el), 65-75% (th)	Natural gas/coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	1070-1420	N/A	71000-93900 t/yr	N/A	-8,2- -5,8 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity and thermal energy	Kalina cycle/heat exchanger (el/thermal)	47-58% (el)	Natural gas/coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	720-900	N/A	47700-59700 t/yr	N/A	-5,7- - 3,8 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity	Centralized kalina cycle (el only)	47-58% (el)	Natural gas/coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	840-1330	N/A	55800-88100 t/yr	N/A	-36,9--30,2 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity	Organic rankine cycle/heat exchanger (el/thermal)	20-25% (el)	Natural gas/coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	990-1285	N/A	65700-85200 t/yr	N/A	13,1-85,2 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity and thermal energy	Organic rankine cycle/heat exchanger (el/thermal)	20-25% (el)	Natural gas/coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	665-820	N/A	44200-54200 t/yr	N/A	8,7-12 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity and thermal energy	Centralized organic rankine cycle (el only)	20-25% (el)	Natural gas/coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	360-545	N/A	23700-38000 t/yr	N/A	-22,5--18,3 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity and thermal energy	Conventional combined cycle/heat exchanger (el/thermal)	40-50% (el) , 65-75% (th)	Natural gas/coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	825-1120	N/A	54600-74000 t/yr	N/A	-3-12,8 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity and thermal energy	Conventional combined cycle/heat exchanger (el/thermal)	40-50% (el) , 65-75% (th)	Natural gas/ coalpower plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	705-880	N/A	46600-58400 t/yr	N/A	-1,1-10,1 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Electricity and thermal energy	Centralized conventional cycle/heat exchanger (el/thermal)	40-50% (el) , 65-75% (th)	Natural gas/ coal power plant	N/A	N/A	N/A	Kwinana industrial area, Western Australia	1655-2650 TJ/yr	N/A	109700-175400 t/yr	N/A	-59,3--6,4 mill dollar	N/A	N/A	A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia	(Van Beers & Biswas, 2008)

Flue gas (not specified)	N/A	N/A	Steam production	Waste heat boiler	70-85% (th)	Gas fired boiler	N/A	N/A	N/A	Kwinana industrial area, Western Australia	175-430 TJ/yr	N/A	9600-23600 t/yr	N/A	2 ,7-13,5 mill $	N/A	N/A	*A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia*	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Steam production	Waste heat boiler	70-85% (th)	Gas fired boiler	N/A	N/A	N/A	Kwinana industrial area, Western Australia	410-645 TJ/yr	N/A	22500-35500 t/yr	N/A	11,3-21,4 mill $	N/A	N/A	*A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia*	(Van Beers & Biswas, 2008)
Flue gas (not specified)	N/A	N/A	Steam production	Waste heat boiler	70-85% (th)	Gas fired boiler	N/A	N/A	N/A	Kwinana industrial area, Western Australia	155-475 TJ/yr	N/A	8500-26200 t/yr	N/A	1,1-14,6 mill $	N/A	N/A	*A regional synergy approach to energy recovery: The case of the Kwinana industrial area, Western Australia*	(Van Beers & Biswas, 2008)
Exhaust gas from CHP steam generator	CHP plant	N/A	Steam production /superheating water	Steam generator/ economizer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Economical comparison of CHP systems for industrial user with large steam demand	(Giaccone & Canova, 2009)

Table 14. EIP cases for exhaust/flue gas exchange

8.2.3 Cases with water exchanges

Type of water stream	***Source***	***Sink***	***Purpose***	***Technology***	***Effi. of tech.***	***Substituting***	***Pressure***	***Temp***	***Flow rate/volume***	***EIP/area***	***Energy cons (TJ/yr)***	***Primary energy***	***tCo2 eq/yr***	***tSO2eq***	***NPV***	***Sales income***	***Payback period (years)***	***Notes***	***Name of article***	***Reference***
Cooling water	Refinery (Statoil)	Power plant (Åsnæs)	Feeder water	N/A	N/A	N/A	N/A	N/A	N/A	Kalundborg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Industrial Symbiosis in Kalundborg, Denmark	(Jacobsen, 2006)
Salty cooling water	Power plant	Fish farm	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Kalundborg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Industrial Symbiosis in Kalundborg, Denmark	(Jacobsen, 2006)
Waste water from pharm. Industry	Pharmacutical industry	District heating network	District heating	Isopropanol–hydrogen–acetone chemical heat pump	COP= 1,40	N/A	N/A	25–35 °C	N/A	City of Delft, Netherlands	N/A	N/A	N/A	N/A	2 800 M €	N/A	5 years	Showed to be technically, economically and institutionally feasible	Integrated conceptual design of a robust and reliable waste-heat district heating system	(Ajah, Patil, Herder, & Grievink, 2007)
Waste water from electricity generation	Combined heat and power plant (Sirrkala)	District heating network (Joensuu)	District heating	N/A	N/A	N/A	N/A	N/A	N/A	Joensuu	N/A	N/A	N/A	N/A	N/A	N/A	N/A	The consumption of external fuels in the energy supply system, e.g. of imported fossil coal and oil, is 40% lower than it would be without waste utilization strategies, and this has reduced the costs of the district heating net-work	Regional industrial recycling network in energy supply - the case of Joensuu city, Finland	(Jouni Korhonen, Niemeläinen, & Pulliainen, 2002)

Table 15. EIP cases for exhaust/flue gas exchanges

8.2.4 Tables over exhaust/flue gas heat recovery technologies (Ulhasanah & Goto, 2012)

Reuse category	**Example of streams**	**Temperature category**	**Temperature interval**	**Purpose**	**Heat recover technology**
Heat recovery	Boiler exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, boiler feedwater preheat	Metallic Heat wheel, plate-type heat exchanger
Heat recovery	Incinerator exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, hot water or steam generation	Plate-type heat exchanger, waste heat boiler
Heat recovery	Turbine exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, hot water or steam generation	Plate-type heat exchanger
Heat recovery	Curing ovens exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Metallic Heat wheel, plate-type heat exchanger, heat pipe
Heat recovery	Drying ovens exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Metallic Heat wheel, plate-type heat exchanger, heat pipe
Heat recovery	Baking ovens exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Plate-type heat exchanger, heat pipe
Heat recovery	Air dryer exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Kiln exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Reciprocating engine exhaust	Low temp	<503K [<230°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Waste-heat boilers
Heat recovery	Reverberatory furnace	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Air dryer exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Boiler exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, boiler feedwater preheat	Heat pipe
Heat recovery	Kiln exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Curing ovens exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Drying ovens exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Baking ovens exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Incinerator exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat, space heating, hot water or steam generation	Convection recuperator, ceramic heat wheel, plate type heat exchanger, waste heat boiler
Heat recovery	Turbine exhaust	Medium temp	503-923 K [230-650°C]	combustion air preheat, space heating, hot water or steam generation	Plate-type heat exchanger
Heat recovery	Soaking or anealing ovens	Medium temp	503-923 K [230-650°C]	Combustion air preheat	Convection recuperator
Heat recovery	Melting furnaces	Medium temp	503-923 K [230-650°C]	combustion air preheat, space heating, hot water or steam generation	Convection recuperator, ceramic heat wheel

Heat recovery	Radiant tube burner exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat	Convection recuperator
Heat recovery	Reheat furnace exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat	Convection recuperator
Heat recovery	Large boilers exhaust	Medium temp	503-923 K [230-650°C]	Combustion air preheat	Ceramic heat wheel
Heat recovery	Soaking or anealing ovens	Medium temp	503-923 K [230-650°C]	Combustion air preheat	Convection recuperator
Heat recovery	Soaking or anealing ovens	High temp	>923K [> 650°C]	Combustion air preheat	Radiation recupurator
Heat recovery	Melting furnaces	High temp	>923K [> 650°C]	Combustion air preheat	Radiation recupurator
Heat recovery	Incinerator exhaust	High temp	>923K [> 650°C]	Combustion air preheat, hot water or steam generation	Radiation recupurator
Heat recovery	Radiant tube burner exhaust	High temp	>923K [> 650°C]	Combustion air preheat	Radiation recupurator
Heat recovery	Reheat furnace exhaust	High temp	>923K [> 650°C]	Combustion air preheat	Radiation recupurator
Heat recovery	Large boilers exhaust	High temp	>923K [> 650°C]	Combustion air preheat	Ceramic heat wheel
Heat recovery	Air dryer exhaust	High temp	>923K [> 650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Kiln exhaust	High temp	>923K [> 650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Reverbreratory furnace	High temp	>923K [> 650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Drying ovens exhaust	High temp	>923K [> 650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Curing ovens exhaust	High temp	>923K [> 650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Baking ovens exhaust	High temp	>923K [> 650°C]	Combustion air preheat, space heating, boiler makeup water preheat, DHW	Heat pipe
Heat recovery	Gas turbine exhaust	High temp	>923K [> 650°C]	Hot water or steam generation	Waste-heat boilers

Table 16. Heat recovery sorted by type of gas for exhaust/flue gas. Source: (Johnson et al., 2008)

Purpose	**Industry**	**Example of stream**	**Temperature**	**Recovery technology**
Heat recovery	Iron/steel	Waste gas from coke oven	200°C	Regenerator
Heat recovery	Iron/steel	Hot blast stove exhaust	250°C/130°C	Heat wheel
Heat recovery	Iron/steel			Passive air preheater
Heat recovery	Iron/steel			Thermal medium system
Heat recovery	Iron/steel	Basic oxygen Furnace Gas	1700°C	Regenerator
Heat recovery	Iron/steel			Recuperator
Heat recovery	Iron/steel			Passive air preheater
Heat recovery	Iron/steel			Heat wheel
Heat recovery	Iron/steel			Low T P cycle
Heat recovery	Iron/steel	Electric arc furnace off gas	1200°C/204°C	Regenerator
Heat recovery	Iron/steel			Recuperator
Heat recovery	Iron/steel			Heat wheel
Heat recovery	Iron/steel			Passive air preheater
Heat recovery	Iron/steel			Low T P cycle
Heat recovery	Glass industry	Cement kiln	338°C	Waste heat boiler
Heat recovery	Glass industry			Load preheat
Heat recovery	Glass industry			Process spesific
Heat recovery	Aluminum industry	Melting furncaces	1,300°C-1,540°C	Low T P cycle
Heat recovery	Aluminum industry			Recuperator
Heat recovery	Aluminum industry			Regenerator
Heat recovery	Aluminum industry			Load preheat
Heat recovery	Metal casting	Iron cupola	820°C-980°C	Recuperator
Heat recovery	Cross cutting technology	Steam boiler exhaust	230°C-480°C	Recuperator
Heat recovery	Cross cutting technology			Heat wheel
Heat recovery	Cross cutting technology			Passive air preheater
Heat recovery	Cross cutting technology			Thermal medium system

Table 17. Commercial, technical and economical feasible recovery technologies. Soruce: Johnson et al., 2008.

Sources of waste heat: High, medium and low temperature

Heat sources: high temp	**Temp interval (°C)**
Fume incinerators	650-1000
Nickel refining furnace	650-1450
Glass melting furnace	1370-1650
Aluminum refining furnace	1000-1550
Copper refining furnace	650-760
Zink refining furnace	900-1100
Cement kiln	620-730
Hydrogen plants	650-1000
Steel electric arc furnace	1370-1650
Basic oxygen furnace	1200
Steel heating furnace	930-1040
Coke oven	

Table 18. Heat sources high temp

Heat sources: medium temp	**Temp interval (°C)**
Steam boiler exhaust	230-480
Gas turbine exhaust	370-540
Drying and baking ovens	230-600
Catalytic crackers	425-650
Annealing furnace cooling systems	425-650

Table 19. Heat sources medium temp

Heat sources: low temp	Temp interval (°C)
Process steam condensate (CW)	50-90
Internal combustion engines (CW)	66-120
Hot processed liquids and solids (CW)	32-232
Annealing furnaces (CW)	66-230
Drying, baking and curing ovens (CW)	93-230
Welding and injection molding machines (CW)	32-88
Bearings (CW)	32-88
Air compressors (CW)	27-50

Table 20. Heat sources low temperature

8.3 Appendix B: Feasibility screening tool

		=C20											
MAX method		**=B14**			**=B15**			**=B16**			**=B17**		
Technology		=C22	=D22	**=E22**	=F22	=G22	**=H22**	=I22	Indirect	**=K22**	=L22	Indirect	**=N22**
=B4	**=B23**	=C23/MAXA(C$23:C$25)	=IF(D23=0;0;D23/MAXA(D$23:D$25))	=IF(E23=0;0;E23/MAXA(E$23:E$25))	=F23/MAXA(F$23:F$25)	=IF(G23=0;0;G23/MAXA(G$23:G$25))	=IF(H23=0;0;H23/MAXA(H$23:H$25))	=I23/MAXA(I$23:I$25)	=IF(J23=0;0;J23/MAXA(J$23:J$25))	=IF(K23=0;0;K23/MAXA(K$23:K$25))	=L23/MAXA(L$23:L$25)	=IF(M23=0;0;M23/MAXA(M$23:M$25))	=IF(N23=0;0;N23/MAXA(N$23:N$25))
=B5	**=B24**	=C24/MAXA(C$23:C$25)	=IF(D24=0;0;D24/MAXA(D$23:D$25))	=IF(E24=0;0;E24/MAXA(E$23:E$25))	=F24/MAXA(F$23:F$25)	=IF(G24=0;0;G24/MAXA(G$23:G$25))	=IF(H24=0;0;H24/MAXA(H$23:H$25))	=I24/MAXA(I$23:I$25)	=IF(J24=0;0;J24/MAXA(J$23:J$25))	=IF(K24=0;0;K24/MAXA(K$23:K$25))	=L24/MAXA(L$23:L$25)	=IF(M24=0;0;M24/MAXA(M$23:M$25))	=IF(N24=0;0;N24/MAXA(N$23:N$25))
=B6	**=B25**	=C25/MAXA(C$23:C$25)	=IF(D25=0;0;D25/MAXA(D$23:D$25))	=IF(E25=0;0;E25/MAXA(E$23:E$25))	=F25/MAXA(F$23:F$25)	=IF(G25=0;0;G25/MAXA(G$23:G$25))	=IF(H25=0;0;H25/MAXA(H$23:H$25))	=I25/MAXA(I$23:I$25)	=IF(J25=0;0;J25/MAXA(J$23:J$25))	=IF(K25=0;0;K25/MAXA(K$23:K$25))	=L25/MAXA(L$23:L$25)	=IF(M25=0;0;M25/MAXA(M$23:M$25))	=IF(N25=0;0;N25/MAXA(N$23:N$25))
=B7	**=B26**	=C26/MAXA(C$23:C$25)	=IF(D26=0;0;D26/MAXA(D$23:D$25))	=IF(E26=0;0;E26/MAXA(E$23:E$25))	=F26/MAXA(F$23:F$25)	=IF(G26=0;0;G26/MAXA(G$23:G$25))	=IF(H26=0;0;H26/MAXA(H$23:H$25))	=I26/MAXA(I$23:I$25)	=IF(J26=0;0;J26/MAXA(J$23:J$25))	=IF(K26=0;0;K26/MAXA(K$23:K$25))	=L26/MAXA(L$23:L$25)	=IF(M26=0;0;M26/MAXA(M$23:M$25))	=IF(N26=0;0;N26/MAXA(N$23:N$25))
=B8	**=B27**	=C27/MAXA(C$23:C$25)	=IF(D27=0;0;D27/MAXA(D$23:D$25))	=IF(E27=0;0;E27/MAXA(E$23:E$25))	=F27/MAXA(F$23:F$25)	=IF(G27=0;0;G27/MAXA(G$23:G$25))	=IF(H27=0;0;H27/MAXA(H$23:H$25))	=I27/MAXA(I$23:I$25)	=IF(J27=0;0;J27/MAXA(J$23:J$25))	=IF(K27=0;0;K27/MAXA(K$23:K$25))	=L27/MAXA(L$23:L$25)	=IF(M27=0;0;M27/MAXA(M$23:M$25))	=IF(N27=0;0;N27/MAXA(N$23:N$25))
=B9	**=B28**	=C28/MAXA(C$23:C$25)	=IF(D28=0;0;D28/MAXA(D$23:D$25))	=IF(E28=0;0;E28/MAXA(E$23:E$25))	=F28/MAXA(F$23:F$25)	=IF(G28=0;0;G28/MAXA(G$23:G$25))	=IF(H28=0;0;H28/MAXA(H$23:H$25))	=I28/MAXA(I$23:I$25)	=IF(J28=0;0;J28/MAXA(J$23:J$25))	=IF(K28=0;0;K28/MAXA(K$23:K$25))	=L28/MAXA(L$23:L$25)	=IF(M28=0;0;M28/MAXA(M$23:M$25))	=IF(N28=0;0;N28/MAXA(N$23:N$25))

Table 21. Example on how normalization table for max-method is programmed

Real values

Below can the real and normalized values for three different technologies on thermal and power generation from exhaust gas using Organic Rankine Cycle, Kalina cycle and Conventional steam cycle. The examples are taken from a case in Kwiwana industrial area (Van Beers & Biswas, 2008). As can be seen, is that there is a proportional relationship between the delivered energy savings and CO_2-emissions for all three measures and the normalized values between the measures are therefore the same between these categories. This is because for all three measures, it is assumed that the substituted energy is from same energy source (natural gas/coal) and the CO2 equivalent per kWh is thereby equal for all these measure.

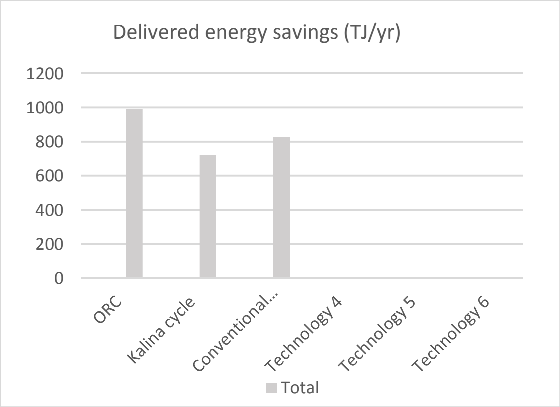


Figure 27. Real values. Delivered energy savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

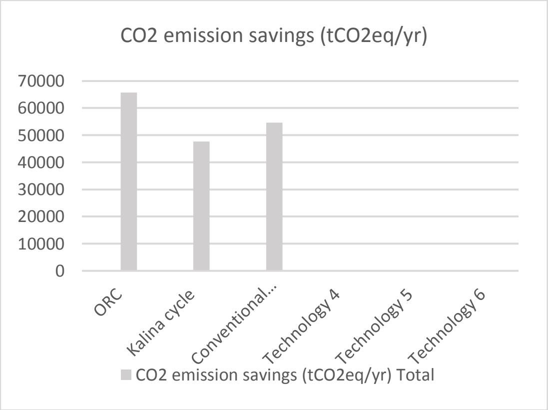


Figure 28. Real values. CO2 emission savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

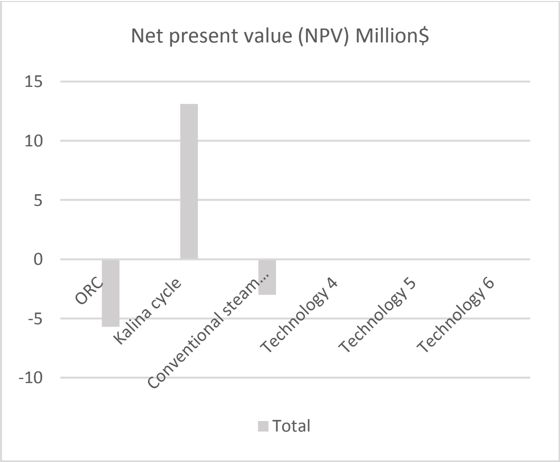


Figure 29. Real values. CO2 emission savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation

Max method

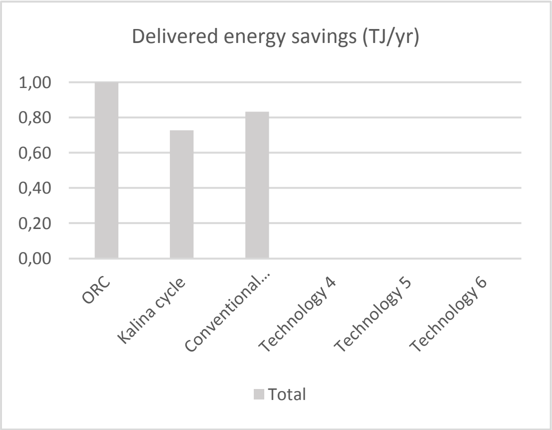


Figure 31. Max method: Normalized value for delivered energy savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

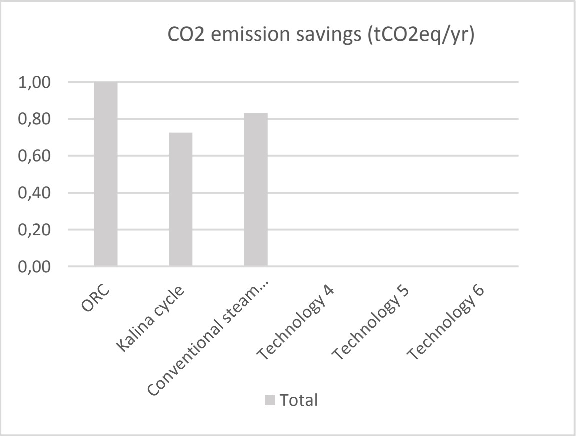


Figure 30. Max method: Normalized values for CO2 emission savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

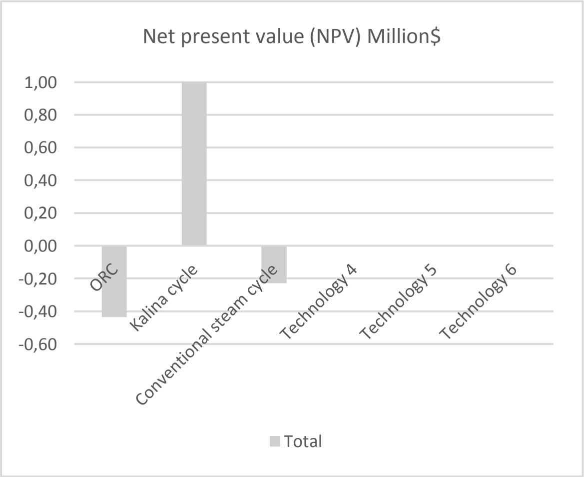


Figure 32. Normalized value for Net Present Value for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

Max-min method

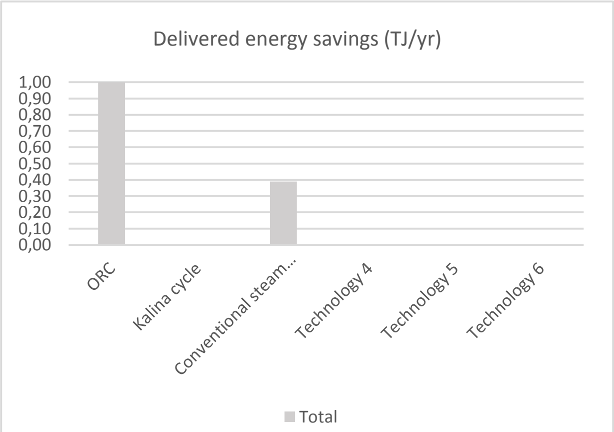


Figure 30. Max-min method. Normalized value for delivered energy savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

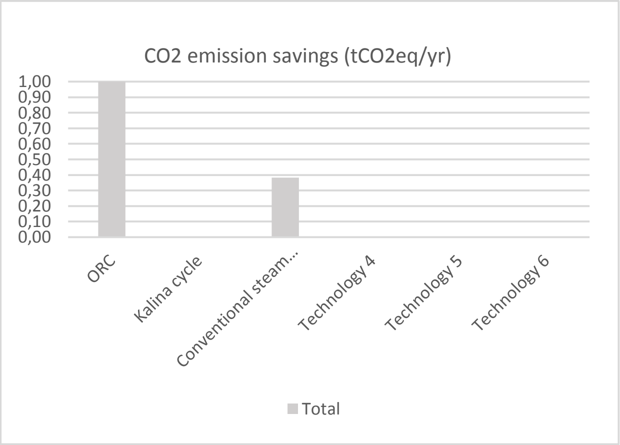


Figure 33 Max-min method. Normalized value for CO2 emission savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

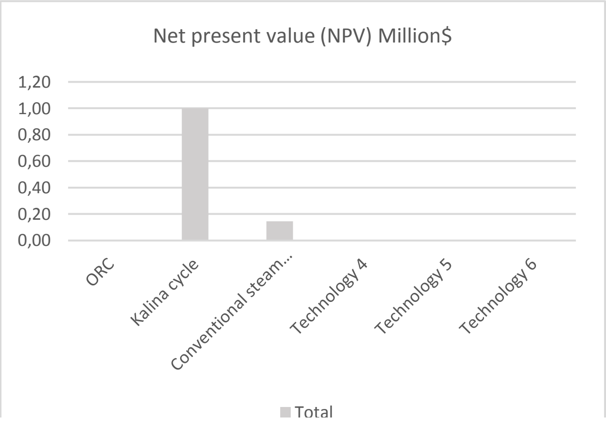


Figure 34. Max-min method. Normalized value for NPV for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

Sum method

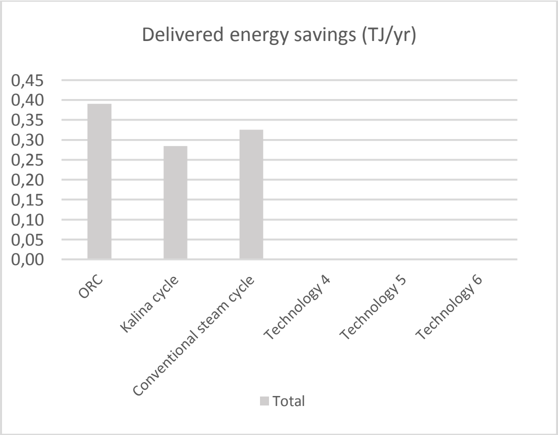


Figure 35. Sum method. Normalized value for delivered energy savings Max-min method for CO2 emission savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

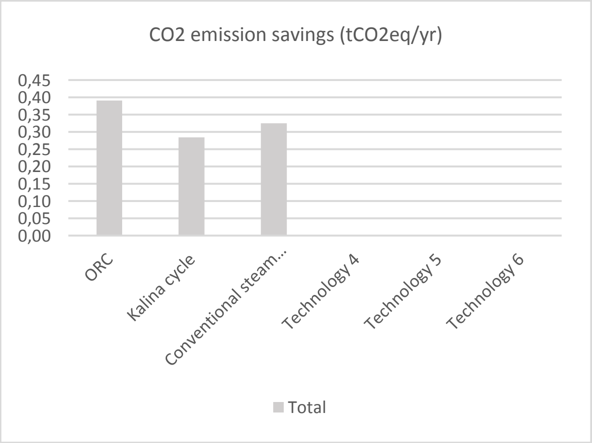


Figure 36. Sum method. Normalized value for CO2 emission savings Max-min method for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

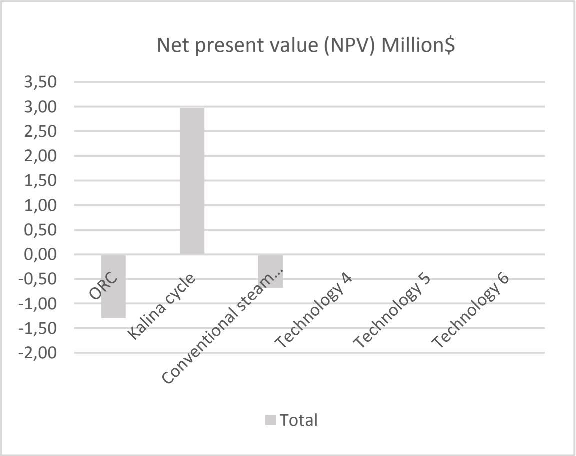


Figure 37. Sum method. Normalized values for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

Vector method

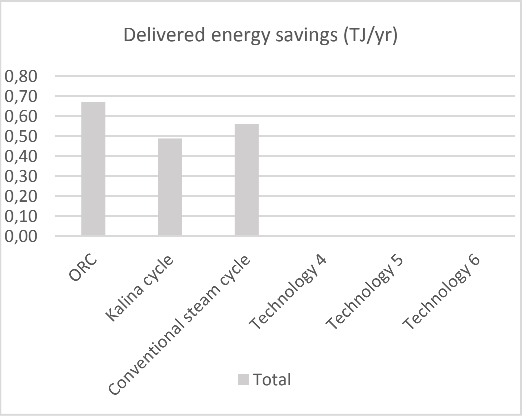
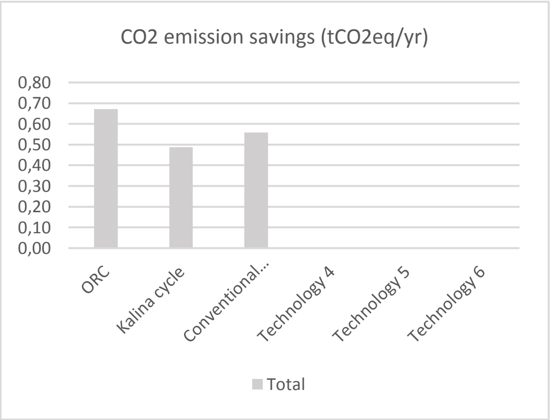


Figure 38. Vector method. Normalized value for delivered energy savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.



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.Figure 40. Vector method. Normalized value for CO2 emission savings for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal generation.

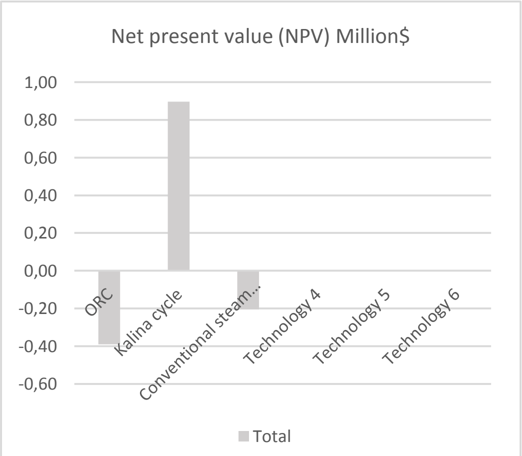

Figure 39. Vector method. Normalized value for Net Present value for using ORC, Kalina or conventional steam cycle to recover exhaust gas for el/thermal

8.4 Appendix C: Excel codes from opportunity generation tool

Combining purpose and technology:

Low temperature exhaust gas

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=IF([@Technology]=Lists!D28;Lists!C28;IF([@Technology]=Lists!D29;Lists!C29;IF([@Technology]=Lists!D30;Lists!C30;IF([@Technology]=Lists!D31;Lists!C31;IF([@Technology]=Lists!D32;Lists!C32;IF([@Technology]=Lists!D33;Lists!C33;IF([@Technology]=Lists!D34;Lists!C34;IF([@Technology]=Lists!F28;Lists!E28;IF([@Technology]=Lists!F29;Lists!E29;IF([@Technology]=Lists!F30;Lists!E30;IF([@Technology]=Lists!F31;Lists!E31;IF([@Technology]=Lists!F32;Lists!E32;IF([@Technology]=Lists!F33;Lists!E33;IF([@Technology]=Lists!F34;Lists!E34;IF([@Technology]=Lists!L28;Lists!K28;IF([@Technology]=Lists!L28;Lists!K28;IF([@Technology]=Lists!L29;Lists!K29;IF([@Technology]=Lists!L30;Lists!K30;IF([@Technology]=Lists!L31;Lists!K31;IF([@Technology]=Lists!L32;Lists!K32;IF([@Technology]=Lists!L33;Lists!K33;IF([@Technology]=Lists!L34;Lists!K34;IF([@Technology]=Lists!J28;Lists!I28;IF([@Technology]=Lists!J29;Lists!I29;IF([@Technology]=Lists!J30;Lists!I30;IF([@Technology]=Lists!J30;Lists!I30;IF([@Technology]=Lists!J31;Lists!I31;IF([@Technology]=Lists!J32;Lists!I32;IF([@Technology]=Lists!J33;Lists!I33;IF([@Technology]=Lists!J34;Lists!I34;IF([@Technology]=Lists!H28;Lists!G28;IF([@Technology]=Lists!H29;Lists!G29;IF([@Technology]=Lists!H30;Lists!G30;IF([@Technology]=Lists!H31;Lists!G31;IF([@Technology]=Lists!H32;Lists!G32;IF([@Technology]=Lists!H33;Lists!G33;IF([@Technology]=Lists!H39;Lists!G34)))))))))))))))))))))))))))))))))))))
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Medium temp exhaust gas:

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=IF([@Technology]=Lists!D38;Lists!C38;IF([@Technology]=Lists!D39;Lists!C39;IF([@Technology]=Lists!D40;Lists!C40;IF([@Technology]=Lists!D41;Lists!C41;IF([@Technology]=Lists!D42;Lists!C42;IF([@Technology]=Lists!D43;Lists!C43;IF([@Technology]=Lists!D44;Lists!C44;IF([@Technology]=Lists!F38;Lists!E38;IF([@Technology]=Lists!F39;Lists!E39;IF([@Technology]=Lists!F40;Lists!E40;IF([@Technology]=Lists!F41;Lists!E41;IF([@Technology]=Lists!F42;Lists!E42;IF([@Technology]=Lists!F43;Lists!E43;IF([@Technology]=Lists!F44;Lists!E44;IF([@Technology]=Lists!N38;Lists!M38;IF([@Technology]=Lists!N38;Lists!M38;IF([@Technology]=Lists!N39;Lists!M39;IF([@Technology]=Lists!N40;Lists!M40;IF([@Technology]=Lists!N41;Lists!M41;IF([@Technology]=Lists!N42;Lists!M42;IF([@Technology]=Lists!N43;Lists!M43;IF([@Technology]=Lists!N44;Lists!M44;IF([@Technology]=Lists!J38;Lists!I38;IF([@Technology]=Lists!J39;Lists!I39;IF([@Technology]=Lists!J40;Lists!I40;IF([@Technology]=Lists!J41;Lists!I41;IF([@Technology]=Lists!J42;Lists!I42;IF([@Technology]=Lists!J43;Lists!I43;IF([@Technology]=Lists!J44;Lists!I44;IF([@Technology]=Lists!L38;Lists!K38;IF([@Technology]=Lists!L39;Lists!K39;IF([@Technology]=Lists!L40;Lists!K40;IF([@Technology]=Lists!L41;Lists!K41;IF([@Technology]=Lists!L42;Lists!K42;IF([@Technology]=Lists!L43;Lists!K43;IF([@Technology]=Lists!L44;Lists!K44;IF([@Technology]=Lists!H38;Lists!G38;IF([@Technology]=Lists!H39;Lists!G39;IF([@Technology]=Lists!H40;Lists!G40;IF([@Technology]=Lists!H41;Lists!G41;IF([@Technology]=Lists!H42;Lists!G42;IF([@Technology]=Lists!H43;Lists!G43;IF([@Technology]=Lists!H44;Lists!G44;IF([@Technology]=Lists!H45;Lists!G45;IF([@Technology]=Lists!P38;Lists!O38;IF([@Technology]=Lists!P41;Lists!O39;IF([@Technology]=Lists!P40;Lists!O40;IF([@Technology]=Lists!P43;Lists!O43;IF([@Technology]=Lists!P44;Lists!O44;IF([@Technology]=Lists!H38;Lists!G38;IF([@Technology]=Lists!H41;Lists!G39;IF([@Technology]=Lists!H40;Lists!G40;IF([@Technol
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ogy]=Lists!H43;Lists!G41;IF([@Technology]=Lists!#REF!;Lists!G44))

High temperature exhaust gas

=IF([@Technology]=Lists!D49;Lists!C49;IF([@Technology]=Lists!D50;Lists!C50;IF([@Technology]=Lists!D51;Lists!C51;IF([@Technology]=Lists!D52;Lists!C52;IF([@Technology]=Lists!D53;Lists!C53;IF([@Technology]=Lists!D54;Lists!C54;IF([@Technology]=Lists!D55;Lists!C55;IF([@Technology]=Lists!F49;Lists!E49;IF([@Technology]=Lists!F50;Lists!E50;IF([@Technology]=Lists!F51;Lists!E51;IF([@Technology]=Lists!F52;Lists!E52;IF([@Technology]=Lists!F53;Lists!E53;IF([@Technology]=Lists!F54;Lists!E54;IF([@Technology]=Lists!F55;Lists!E55;IF([@Technology]=Lists!H49;Lists!G49;IF([@Technology]=Lists!H50;Lists!G50;IF([@Technology]=Lists!H51;Lists!G51;IF([@Technology]=Lists!H52;Lists!G52;IF([@Technology]=Lists!H53;Lists!G53;IF([@Technology]=Lists!H54;Lists!G54;IF([@Technology]=Lists!H55;Lists!G55;IF([@Technology]=Lists!J49;Lists!I49;IF([@Technology]=Lists!J50;Lists!I50;IF([@Technology]=Lists!J51;Lists!I51;IF([@Technology]=Lists!J52;Lists!I52;IF([@Technology]=Lists!J53;Lists!I53;IF([@Technology]=Lists!J54;Lists!I54;IF([@Technology]=Lists!J55;Lists!I52HVIS([@Technology]=Lists!L49;Lists!K49;IF([@Technology]=Lists!L50;Lists!K50;IF([@Technology]=Lists!L51;Lists!K51;IF([@Technology]=Lists!L52;Lists!K52;IF([@Technology]=Lists!L53;Lists!K53;IF([@Technology]=Lists!L54;Lists!K54;IF([@Technology]=Lists!L55;Lists!K55)))))))))))))))))))))))))))))))))))

Water

=IF([@Technology]=Lists!D72;Lists!C72;IF([@Technology]=Lists!D73;Lists!C73;IF([@Technology]=Lists!D74;Lists!C74;IF([@Technology]=Lists!D75;Lists!C75;IF([@Technology]=Lists!D76;Lists!C76;IF([@Technology]=Lists!D77;Lists!C77;IF([@Technology]=Lists!D78;Lists!C78;IF([@Technology]=Lists!D79;Lists!C79;IF([@Technology]=Lists!F72;Lists!E72;IF([@Technology]=Lists!F73;Lists!E73;IF([@Technology]=Lists!F74;Lists!E74;IF([@Technology]=Lists!F75;Lists!E75;IF([@Technology]=Lists!F76;Lists!E76;IF([@Technology]=Lists!F77;Lists!E77;IF([@Technology]=Lists!F78;Lists!E78;IF([@Technology]=Lists!F79;Lists!E79;IF([@Technology]=Lists!H72;Lists!G72;IF([@Technology]=Lists!H73;Lists!G73;IF([@Technology]=Lists!H74;Lists!G74;IF([@Technology]=Lists!H75;Lists!G75;IF([@Technology]=Lists!H76;Lists!G76;IF([@Technology]=Lists!H77;Lists!G77;IF([@Technology]=Lists!H78;Lists!G78;IF([@Technology]=Lists!H79;Lists!G79;IF([@Technology]=Lists!J72;Lists!I72;IF([@Technology]=Lists!J73;Lists!I73;IF([@Technology]=Lists!J74;Lists!I74;IF([@Technology]=Lists!J75;Lists!I75;IF([@Technology]=Lists!J76;Lists!I76;IF([@Technology]=Lists!J77;Lists!I77;IF([@Technology]=Lists!J78;Lists!I78;IF([@Technology]=Lists!J79;Lists!I79))))))))))))))))))))))))))))))))

Saturated steam

=IF([@Technology]=Lists!D99;Lists!C99;IF([@Technology]=Lists!D100;Lists!C100;IF([@Technology]=Lists!D101;Lists!C101;IF([@Technology]=Lists!D102;Lists!C102;IF([@Technology]=Lists!D134;Lists!C103;IF([@Technology]=Lists!D104;Lists!C104;IF([@Technology]=Lists!D105;Lists!C105;IF([@Technology]=Lists!D106;Lists!C106;IF([@Technology]=Lists!F99;Lists!E99;IF([@Technology]=Lists!F100;Lists!E100;IF([@Technology]=Lists!F101;Lists!E101;IF([@Technology]=Lists!F102;Lists!E102;IF([@Technology]=Lists!F103;Lists!E103;IF([@Technology]=Lists!F104;Lists!E104;IF([@Technology]=Lists!F105;Lists!E105;IF([@Technology]=Lists!H99;Lists!G99;IF([@Technology]=Lists!H100;Lists!G100;IF([@Technology]=Lists!H101;Lists!G101;IF([@Technology]=Lists!H102;Lists!G102;IF([@Technology]=Lists!H103;Lists!G103;IF([@Technology]=Lists!H104;Lists!G104;IF([@Technology]=Lists!H105;Lists!G105;IF([@Technology]=Lists!J99;Lists!I99;IF([@Technology]=Lists!J100;Lists!I100;IF([@Technology]=Lists!J101;Lists!I1

01;IF([@Technology]=Lists!J102;Lists!I102;IF([@Technology]=Lists!J103;Lists!I103;IF([@Technology]=Lists!J104;Lists!I104;IF([@Technology]=Lists!J105;Lists!I105)))))))))))))))))))))))))))))

Superheated steam

=IF([@Technology]=Lists!D111;Lists!C111;IF([@Technology]=Lists!D112;Lists!C112;IF([@Technology]=Lists!D113;Lists!C113;IF([@Technology]=Lists!D114;Lists!C114;IF([@Technology]=Lists!D115;Lists!C115;IF([@Technology]=Lists!D116;Lists!C116;IF([@Technology]=Lists!D117;Lists!C117;IF([@Technology]=Lists!D118;Lists!C118;IF([@Technology]=Lists!F111;Lists!E111;IF([@Technology]=Lists!F112;Lists!E112;IF([@Technology]=Lists!F113;Lists!E113;IF([@Technology]=Lists!F114;Lists!E114;IF([@Technology]=Lists!F115;Lists!E115;IF([@Technology]=Lists!F116;Lists!E116;IF([@Technology]=Lists!F117;Lists!E117;IF([@Technology]=Lists!F118;Lists!E118;IF([@Technology]=Lists!H111;Lists!G111;IF([@Technology]=Lists!H112;Lists!G112;IF([@Technology]=Lists!H113;Lists!G113;IF([@Technology]=Lists!H114;Lists!G114;IF([@Technology]=Lists!H115;Lists!G115;IF([@Technology]=Lists!H116;Lists!G116;IF([@Technology]=Lists!H117;Lists!G117;IF([@Technology]=Lists!H118;Lists!G118;IF([@Technology]=Lists!J111;Lists!I111;IF([@Technology]=Lists!J112;Lists!I112;IF([@Technology]=Lists!J113;Lists!I113;IF([@Technology]=Lists!J114;Lists!I114;IF([@Technology]=Lists!J115;Lists!I115;IF([@Technology]=Lists!J116;Lists!I116;IF([@Technology]=Lists!J117;Lists!I117;IF([@Technology]=Lists!J118;Lists!I118;IF([@Technology]=Lists!L111;Lists!K111;IF([@Technology]=Lists!L112;Lists!K112;IF([@Technology]=Lists!L113;Lists!K113;IF([@Technology]=Lists!L114;Lists!K114;IF([@Technology]=Lists!L115;Lists!K115;IF([@Technology]=Lists!L116;Lists!K116;IF([@Technology]=Lists!L117;Lists!K117;IF([@Technology]=Lists!L118;Lists!K118))