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Project 3A1: Enabling Tools and Technologies  
For Capturing Regional Synergies

# Regional Synergies for Sustainable Resource Processing: a Status Report

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## EXECUTIVE SUMMARY

### *Overview*

The notion of regional resource synergies concerns the capture, recovery and reuse of previously discarded by-products (including materials, energy and water) from one industrial operation by other, traditionally-separate, industries operating in its close geographic proximity. The realisation of such synergies in minerals-processing intensive areas provides a significant avenue towards Sustainable Resource Processing, as was recognised by establishing a research program on regional and supply chain synergies in the Cooperative Research Centre for Sustainable Resource Processing (CSRP).

This foundation project on Enabling Tools and Technologies for Capturing Regional Synergies is aimed at encouraging and facilitating the greater utilisation of regional synergy opportunities to improve the overall Eco-Efficiency of minerals-processing intensive regions. It involves three principal research tasks, i.e. (1) review, development and promotion of best practices in regional synergy development; (2) development and trial of a regional Eco-Efficiency opportunity assessment method; and (3) technology assessment for enabling synergy technologies. This report summarises the results of the desk studies undertaken towards the first research task between July 2004 and April 2005 by the Centre of Excellence in Cleaner Production (Curtin University of Technology) and the Sustainable Minerals Institute (The University of Queensland).

The research reported here provides an assessment of the status of development and application of regional resource synergies in minerals-processing intensive areas. It is based on information collected from literature sources, including industry publications and the Internet, and direct interactions with industry and other professionals associated with regional synergy development and implementation, both nationally as well as internationally.

The assessment is structured in four constituent parts.

1. Summary and review of concepts, terminology and methodology developed so far (reported in chapter 2). This links regional synergy development to the field of Industrial Ecology, and in particular its subset of Industrial Symbiosis.
2. Summary and comparative analysis of leading national and international examples of regional synergy development (reported in chapter 3). The examples have been selected for their perceived relevance for minerals processing intensive areas, and include two Australian (Kwinana and Gladstone) and sixteen international examples from North America, Europe and Asia.
3. Review of concepts, methods and metrics used for company-internal efficiency and synergy initiatives (commonly referred to as Eco-Efficiency) on their applicability for regional synergy development (reported in chapter 4).
4. Review of the status of technology development for recovery and reuse of valuable components from large volume process by-product streams from typical minerals processing operations (reported in chapter 5).

Collectively these four constituent parts provide a rich insight into the wide variety of more and less successful regional synergy initiatives, which can serve as a fertile source of ideas to inspire and facilitate synergy projects in minerals processing intensive areas. Deconstruction of these experiences to pull out universally applicable best practices is however hampered by the relative scarcity of contextual data regarding e.g. public policy and regulatory



environment, industry structure and resource prices in particular for the international examples.

### ***Conclusions***

In light of the overall aim of this foundation project to encourage and facilitate the greater utilisation of regional synergy opportunities in minerals-processing intensive regions, it is possible to conclude on the basis of the research reported here, that:

1. The science and – to a lesser extent also – the technology for creating regional resource synergies are captured in the emerging disciplines of Industrial Ecology and Industrial Symbiosis, which enjoy remarkably broad support from industry, government and the community, despite their specific theory and methodology developments still being in their infancies.
2. There is both historic and present day evidence that regional collaboration between traditionally separate industries involving physical exchange of materials, energy, water and/or by-products, or Industrial Symbiosis, can deliver both competitive advantage and environmental benefit. The evidence therefore is strongest for the two Australian regions studied (Kwinana and Gladstone), but generally supported by the other sixteen international case study regions (even though the information for these international regions is far less detailed).
3. There is strong evidence that 'self-organisation' is a critical success factor for regional synergy development, recognising that self-organisation will generally need to be facilitated and properly resourced through 'transition management'. Self-organisation occurs as businesses see and pursue opportunities to improve their businesses by engaging in regional resource exchanges with their neighbours.
4. It is without doubt that (environmental) legislation, industry policy, resource economics and technology can all act as serious barriers for self-organisation into regional resource synergies, but the picture is less clear as to whether and how each can be turned into an incentive or enabler for regional synergy development. There is little – if any – evidence that planning, public policy or legislation can drive regional synergy development and implementation beyond industrial waste exchanges or set up of shared environmental services in the industrial area. Instead, it appears that innovation and technology development support, co- and self-regulatory approaches on the basis of agreed best practice guidelines, and possibly investment support for synergy project implementation are more likely to be effective for fostering regional synergies development and implementation.
5. The recognised leading international examples of regional synergy development in heavy industrial areas are dominated by comparatively straightforward exchanges of process by-products, waste water or waste heat, between two companies, that involve minimal – if any – processing prior to (re)use by the recipient company. In many of the documented examples it appears that the Industrial Symbiosis initiative plateaus, for reasons not yet fully understood, but possibly indicating that the engineering tools, technologies, business models and policy environments to achieve more complex resource synergies are lacking.
6. Kwinana and Gladstone compare favourably with the well-regarded international examples of regional synergy development, in terms of the level and maturity of the industry involvement and collaboration, and the commitment to future regional resource



synergy projects as the cornerstone for the area's contributions to sustainable development. Moreover, Kwinana stands out with regard to the number, diversity, complexity and maturity of existing synergies. Gladstone is remarkable as among the examples of regional synergy development it stands out as an example with unusually large geographic boundaries and unusually high dominance of one industry sector (alumina and aluminium and its power supplier).

7. Regional synergies have developed opportunistically in the absence of specific methods for synergy option generation and/or synergy technology selection and assessment, despite there being a competency and track record in Eco-Efficiency methods and metrics and resource recovery technologies on which such methods could be based. There is a distinct possibility to support the development and implementation of regional synergy projects with customised methods for synergy project identification and evaluation and model applications of existing and emerging water, energy and materials recovery and use technologies therein.

### **Recommendations**

In support of this foundation project's principal aim of fostering greater utilisation of regional synergy opportunities in minerals processing intensive regions, it is recommended that:

1. ***The experience and achievements in regional synergies development and implementation in both Kwinana and Gladstone be widely and persistently communicated.*** Such is well justified in light of this research's finding that both areas compare favourable with other leading examples of regional synergy development and implementation. A detailed communication strategy needs to be developed and implemented to achieve a three-fold outcome: (i) to catalyse further synergy projects in Kwinana and Gladstone; (ii) to inspire and seed regional synergies programs in other industrial areas; and (iii) to gain recognition for sustainability leadership and industry achievement.
2. ***A method be developed to structure the generation of synergy opportunities with particular relevance to minerals processing intensive regions.*** This method will enable the development of more adequate and comprehensive sets of potential synergy projects to be considered in any minerals processing intensive region. Its development should be based on the practical advances and achievements of the regional resource synergy pilot research projects in Kwinana, Gladstone and potentially elsewhere.
3. ***Further research be undertaken so that existing and emerging technologies, in particular in the areas of heat, materials and water recovery and reuse, can deliver regional synergy opportunities.*** This will involve identification of technology needs and opportunities as these are encountered in regional synergy development and implementation in practice, and assessment of alternative ways to realise potential synergies through innovative applications of existing and emerging technologies.





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## Chapter 1: INTRODUCTION

### 1.1 Background

Sustainable Resource Processing is concerned with finding ways to progressively and systematically eliminate waste and emissions in the minerals cycle, while at the same time enhancing business performance and meeting community expectations. An important contribution thereto can be made if wastes from one process can serve as raw materials for another process. Frosh and Gallopoulos argued in their seminal 1989 publication in the *Scientific American* (Frosh *et al.* 1989) that this simple notion can turn into a powerful driver for innovation, business improvement and reduction of environmental impacts. They thereby scoped a novel field of business practice and scholarship now known as Industrial Ecology. At its core, Industrial Ecology is concerned with restoring and achieving the balance and symbiosis between industrial production and consumption and the natural ecosystems on which life on planet earth ultimately depends (e.g. (Graedel *et al.* 2003; Graedel *et al.* 2003; van Berkel *et al.* 1997)).

One profound manifestation of Industrial Ecology principles is through Regional Resource Synergies where industrial operations exchange previously discarded by-products, including low-grade water and heat, for mutual competitive advantage and collective environmental benefit. Because of the many links among the firms an industrial area is transformed into an 'industrial ecosystem' or 'industrial symbiosis' (e.g. (Lowe 1997)). The most frequently quoted example of such Regional Resource Synergies is in the Danish town of Kalundborg, where the local power station, oil refinery, plasterboard plant and pharmaceutical company have established a diverse network of water, heat/steam and other material exchanges (see e.g. (Ehrenfeld *et al.* 1997)). The Australian Mining, Minerals and Sustainable Development Project (Sheeny *et al.* 2002) focused attention on relatively well developed examples of Regional Resource Synergies in key Australian minerals processing intensive industrial areas, most notably Kwinana (WA) and Gladstone (Qld).

Building on these achievements, the Centre for Sustainable Resource Processing (CSRP) set out to further develop methodologies and technologies for regional and supply chain synergies in the resource processing industry, and foster their practical application in Kwinana, Gladstone and other industrial areas in which minerals processing and metals production are important. A foundation project entitled "*Enabling Tools and Technologies for Capturing Regional Synergies*" was formulated in early 2004 and contracted to Curtin University of Technology (through the Centre of Excellence in Cleaner Production), and The University of Queensland (through the Centre for Social Responsibility in Mining). Documentation and review of national and international best practice is one of the key components of this foundation project, along with methodology development for identifying and screening synergy opportunities and assessment of the applicability of emerging technologies for achieving regional synergies. This report completes the first stage of the best practice review, and is based on desktop study conducted between July 2004 and March 2005 at Curtin University of Technology and the University of Queensland.

### 1.2 Project Scope and Methodology

The overall aim of this foundation project on regional synergies for Sustainable Resource Processing is to encourage and facilitate the greater utilisation of regional synergy opportunities to improve the overall eco-efficiency of resource processing intensive regions, i.e. to improve at the regional level the ratios between economic outcomes (*value creation*) and environmental outcomes (in particular the use of natural resources, emissions in the environment and impact on nature). In scoping the research it was found that despite the



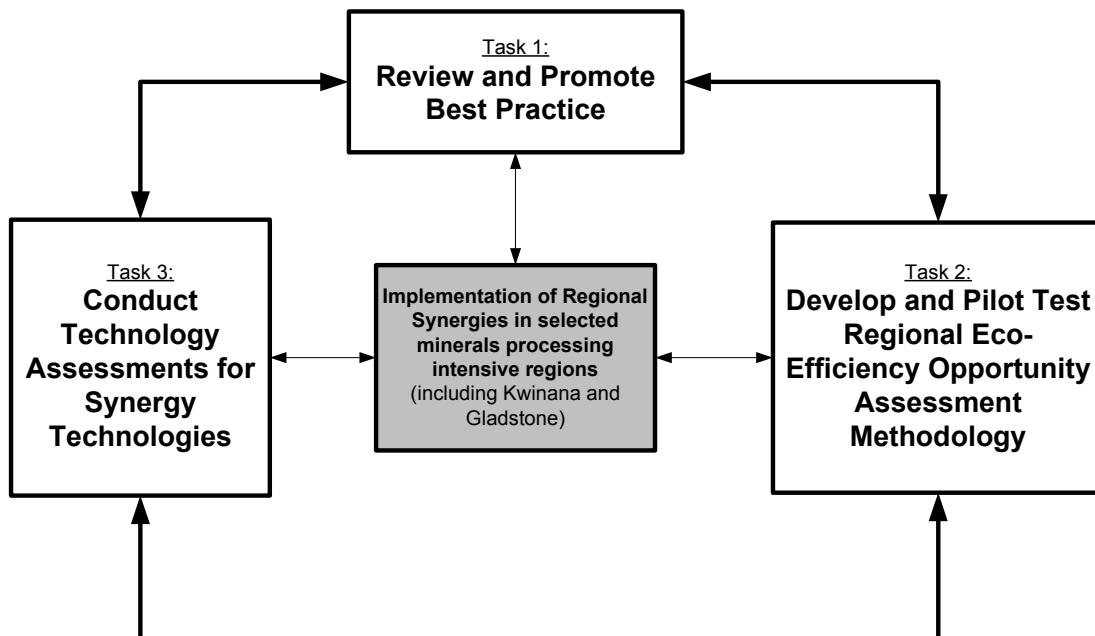
consistent increase in the number of examples of regional synergies, nationally and internationally, many of these appeared to have been more opportunistic than deliberately designed. This justified the hypothesis that deliberate design of regional synergies is in principle possible, provided practical tools are developed and trialled for the systematic identification, evaluation and realisation of synergy opportunities, including the necessary technologies required for their successful implementation.

The research was therefore structured in three research tasks, namely:

1. *Review, Development and Promotion of Best Practices in Regional Synergies*: collation and review of existing examples of regional synergies (in particular those involving minerals processing operations), extraction of best practices and the documentation and promotion of examples, including industry and government liaison to seed and support regional synergy initiatives in minerals processing intensive regions (including Kwinana and Gladstone, but not limited thereto).
2. *Develop and Trial a Regional Eco-Efficiency Opportunity Assessment Methodology*: provide a systematic method for identifying, screening and developing synergy projects in minerals processing intensive regions.
3. *Conduct Technology Assessments for Enabling Synergy Technologies*: assess whether and how existing and emerging technologies for application and recovery of low grade resources (e.g. heat, water, materials) can be applied to successfully achieve regional synergies in minerals processing intensive regions.

The inter-relatedness of the project tasks and interaction with the practical case studies in Kwinana and Gladstone is illustrated in Figure 1.1.

Figure 1.1 Overview of project tasks.





This (status) report contains the results of the first part of the research under task 1. This comprised an extensive review of existing examples of regional synergies (or Industrial Symbiosis), nationally and internationally, and the tools and technologies used therein to facilitate the generation and implementation of regional synergies. Successful (and unsuccessful) regional synergy initiatives have been reviewed and deconstructed - on the basis of existing information in the public domain - to identify key drivers and underlying principles that can be used to structure the design and realisation of regional synergies.

### ***1.3 Report Overview***

The remainder of this status report is organised in five chapters. Chapters 2 and 3 deal with the concepts and practice of regional synergy development, whereas Chapters 4 and 5 cover complementary fields to review their potential contribution to regional synergy development. The concluding Chapter 6 draws together the main findings from each of the components and explores their implications for regional synergy development in minerals processing-intensive areas.

In greater detail, the content of the four main chapters is as follows:

- Chapter 2 (Concepts and Perspectives) provides a brief overview of the concepts, terminology and methodology developed so far, both for Industrial Ecology in general as well as for the specific subset of Industrial Symbiosis which is principally concerned with the exchanges of by-products, energy, water, waste and other utilities between closely situated firms.
- Chapter 3 (Current Applications of Industrial Symbiosis) summarises the findings of the review of leading national and international examples of regional synergy development. The examples have been selected for their potential relevance for regional synergy development in minerals processing intensive regions, and are being reviewed with regard to their contributions to sustainable development, as well as the processes established and methods employed for their realisation.
- Chapter 4 (Eco-Efficiency) provides a summary of key principles, practices and methods used for the realisation of Eco-Efficiency in industrial operations. While Eco-Efficiency is concerned with resource optimisation, environmental impact reduction and productivity enhancements within the boundaries of one company, this chapter explores how this experience can be extended over the company fence to serve the development and implementation of regional resource synergies.
- Chapter 5 (Technology Gaps and Opportunities) takes on a technological angle and discusses technology needs and opportunities for key waste streams from minerals processing operations. It thereby provides a perspective on the type of technologies that might be required to achieve greater regional synergies in minerals processing intensive regions.





## Chapter 2: CONCEPTS AND PERSPECTIVES

### 2.1 Background

Industrial Ecology comprises a rapidly evolving field of research, public policy and industrial practice that is primarily aimed at achieving symbiosis between industrial production and consumption and the natural ecosystem on which life on earth ultimately depends. The term Industrial Ecology is regularly quoted as being both '*provocative*' and '*oxymoronic*' (Graedel *et al.* 2003; van Berkel forthcoming) as it calls on industry and other stakeholders to re-design industrial production within the limits of the earth carrying capacity, using natural systems and processes as model, measure and mentor (Benyus 1997).

The field originated from taking a systems' perspective at waste generation and resource consumption in the design, manufacturing, use and disposal of industrial processes, products and services. Although earlier references exist, Industrial Ecology was first put profoundly on the environmental technology map by the seminal publication of Frosh and Gallopoulos in 1989 in the Scientific American (Frosh *et al.* 1989). They reviewed the environmental trade-offs of selected 'environmental innovations', in particular of the extensive use of plastics for light-weighting of (packaging) products, of the introduction of low emission iron and steel technology, and of the use of platinum in catalytic exhaust converters. They hypothesised the benefits from adopting a holistic, systems' view of manufacturing "*wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment*" (Frosh *et al.* 1989). Many different viewpoints have since surfaced, both supportive and critical to the idea of using nature as a metaphor for industrial production and consumption.

This chapter presents pertinent concepts and perspectives in Industrial Ecology in the context of their ability to maximise the potential for regional synergies to contribute to Sustainable Resource Processing. Section 2.2 provides an overview of the Industrial Ecology field, with its distinguishing features and principal subsets of scholarly interests and industrial achievements. Section 2.3 focuses on Industrial Symbiosis, or the subset of Industrial Ecology that is primarily concerned with resource efficiencies and synergies between co-located firms. Section 2.4 contains closing observations regarding the state of theory and methodology development for Industrial Ecology and Industrial Symbiosis, their reported benefits, risks and challenges, and their applicability for achieving regional synergies for Sustainable Resource Processing.

### 2.2 Industrial Ecology

Industrial Ecology is both '*industrial*' and '*ecological*' (Lifset *et al.* 2002). It is industrial in that it focuses on product design and manufacturing processes. Industry is therefore viewed as the primary agent for environmental improvement and innovation, as it possesses the technological expertise, management capability and financial and other resources necessary for successful execution of environmentally informed design of products and processes. Industrial Ecology is ecological in at least two senses. Firstly, it looks to non-human 'natural' systems as models for industrial activity. Mature ecosystems are extremely effective in recycling of resources and therefore promoted as exemplary models for effective recycling in industry and society. Secondly, Industrial Ecology places industry – or technological activity – in the context of the larger ecosystems that support it. This focuses Industrial Ecology on examining the sources of resources used in industrial activity and the sinks that absorb and detoxify the wastes discharged by society.

Despite Industrial Ecology now having been around as a term for some 15 years, its boundaries remain fluid. This was already acknowledged in earlier work (van Berkel *et al.*



1997) which identified four distinct approaches to Industrial Ecology. One approach is *materials-specific*. It analyses the way a material or substance flows through the industrial society in order to identify, evaluate, and implement improvement opportunities, through for example dematerialisation and resource cascading. A second approach is *product-specific*. It analyses the ways in which different component material flows of a selected product may be modified or redirected to optimise product functionality and environment interactions, in particular through Design for the Environment. A third approach to Industrial Ecology is *regionally-focused*. It aims at optimisation of the exchange of materials and energy between industries at the local level, through the recovery and reuse of valuable components from waste streams. The fourth approach can be characterised as *actor-specific*. It investigates the opportunities and constraints facing different actors in the industrial society to change material and product flows in an environmentally compatible direction. Applied to producers, this actor-specific approach has much in common with the Cleaner Production, Pollution Prevention, Waste Minimisation and/or Eco-Efficiency ((van Berkel 2002), (van Berkel 2000)).

An often quoted summary defines Industrial Ecology as *'the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory and social factors on the flow, use, and transformation of resources'* (White 1994). Along similar lines, (Cohen-Rosenthal 2004) states that the end concern of Industrial Ecology is fairly easy to state. The goal is - at minimum - to generate the least damage in industrial and ecological systems through the optimal circulation of materials and energy. Highest value use with the least dissipation of resources forms therefore the core of the systematic application of Industrial Ecology. As the question whether all energy and material use or reuse connections are equally valid is rarely addressed, (Cohen-Rosenthal 2004) proposed two system conditions as guideposts. (i) The entropic effect of the transition is less than other possible choices; and (ii) The next iteration of energy/material can be transformed yet again into useful associations/cycles. This leads to a normative hierarchy of material use and reuse, starting from *'necessity/efficiency'* (reducing material requirements through Eco-Efficiency, Good Housekeeping, fit-for-use materials selection etc.); via *'extended use'* (making materials last longer in each application through reuse, repair, remanufacturing), *'pick-it apart'* (recovery of components through demanufacturing, disassembly, recycling etc) and *'back to basics'* (recovery of chemical elements and compounds, via e.g. chemical reactions and nanochemistry) to *'use what is left'* (recovery and reuse of residual wastes, involving e.g. mining from landfills, use for infill, and incineration with energy recovery).

The prime mechanism for achieving the optimal circulation of materials and energy is through greater collaboration and coordination between industrial actors, so that they become increasingly interconnected in an eco-industrial system. The choice of the optimisation domain for the material and energy flows thus influences the nature of the coordination problem. As per (Boons *et al.* 1997) the following types of boundaries are conceivable: *product life cycle* (boundary of the industrial ecosystem is drawn around the economic actors which are connected with a specific product); *materials life cycle* (the boundary of the industrial ecosystem is drawn around actors dealing with a specific material); *geographic area* (the boundary of the industrial ecosystem is geographically defined, thereby usually excluding the consumption of end-products from the system); *sectoral* (the boundary of the industrial ecosystem is drawn around companies performing similar activities); or *miscellaneous* (where the industrial ecosystem is not well demarcated, but involves a loose collection of producers and recyclers of categories of waste materials). The nature of the issues in the coordination of the economic actors in the industrial ecosystems is largely defined by such boundary choice, as are the management options to achieve cooperation. For example, product life cycle systems already achieve coordination through customer-supplier relationships (supply chain management), as



do sectoral systems through technical cooperation facilitated by industry sector and professional associations. However, for geographic bound systems, coordination and dependency are not automatically present. Although in practice many systems will have hybrid demarcations on e.g. sector, region and/or materials cycle, such hybrid systems have not been explicitly studied.

Isenman (2003) provides an extensive review of the appropriateness of using natural ecology as a normative framework for industrial systems of production and consumption. Despite conceptual and philosophical concerns, he concludes that Industrial Ecology is “*characterised by the refreshingly unorthodox use of nature as a model appreciated as an expedient ideal in order to gain valuable insight for theory and to learn to deal with natural resources and services in practice*” (Isenman 2003). Moreover, he suggested that Industrial Ecology is best described by its five distinctive characteristics:

1. Core Idea (*Industrial Symbiosis*): thinking about economy - environment interactions, viewing economic systems and their surrounding natural systems in concert rather than in isolation and looking for ways to make the natural and economic systems compatible.
2. Fundamental Perspective (*Nature as a Model*): using nature to learn from and discover new insights for dealing with industrial activity, however not as an uncritical justification for replication of natural principles and concepts in the economic system.
3. Basic Goal (*Balance Industrial –Ecological Systems*): to balance the development of industrial systems with the constraints of natural ecosystems.
4. Working Definition (*Science of Sustainability*): key attributes are systemic and integrated view of all material and energetic components of industrial economy, including its relations with the biosphere; explicit emphasis on the biophysical substratum of industrial activities representing all material and energy; and recognition that technological progress is a crucial but not exclusive element towards sustainability.
5. Main Objects (*Products, Processes, Services and Wastes*): the focus is on products, processes, services and wastes, at different aggregation levels of material and energy flows, containing local, regional and global scales.

Isenmann’s fundamental perspective of ‘using nature as a model’ can be further disentangled into ‘*the metaphor of natural ecosystems*’ and the ‘*natural analogy*’ Elsewhere (van Berkel forthcoming) this distinction is used to codify the Industrial Ecology field in systems applications and product/process applications. System applications are primarily based on the *metaphor of natural ecosystems*. These are principally concerned with the application of ecosystem principles, most importantly the circular flows of materials powered by solar energy, to industrial activity. Resource flows (materials, energy, etc) are the objects in the systems stream of Industrial Ecology and the strategic intent is to minimise the disturbance of natural resource flows by man-made resource flows. Product- and process-applications of Industrial Ecology are primarily based on the *natural analogy*. These are principally concerned with mimicking natural, biological, chemical, physical and geological processes and materials in industrial applications. Biological and other natural processes are the objects in the products and processes stream of Industrial Ecology and the strategic intent is to develop new processes and products that are more resource efficient and compatible with nature than the existing industrial processes and products these replace. Table 2.1 provides examples of subsets of Industrial Ecology activities under both the systems and product/process streams.



Table 2.1 Systems and product applications in Industrial Ecology (van Berkel forthcoming)

INDUSTRIAL ECOLOGY	
SYSTEMS APPLICATIONS	PRODUCT/PROCESS APPLICATIONS
<p><b><u>Industrial Metabolism:</u></b> Studies the integrated collection of physical processes that convert raw materials and energy, plus labor, into finished products and wastes in a (more or less) steady-state condition (Ayres 1994). It is primarily concerned with the notion of consistency of industrial metabolism and natural metabolism, as reflected in normative frameworks such as The Natural Step (e.g. (Robert 2003)) and Natural Capitalism (e.g. (Hawken <i>et al.</i> 1999)).</p>	<p><b><u>Biomimicry:</u></b> Uses nature as a source of inspiration, as Model, Measure and Mentor to inspire the development of cleaner products, materials and processes (Benyus 1997).</p>
<p><b><u>Materials Flow Analysis (MFA):</u></b> Analysis of the throughput of process chains comprising of extraction or harvest, chemicals transformation, manufacturing, consumption, recycling and disposal of materials (Bringezu <i>et al.</i> 2002). MFA develops accounts in physical units (usually in terms of tons) to quantify the inputs and outputs of those processes. The accounts can be made for natural or technical compounds or 'bulk' materials (for example wood, coal) on the one hand and chemically defined substances (for example, carbon or carbon dioxide) on the other hand. The latter is also known as Substance Flow Analysis (SFA).</p>	<p><b><u>Green Chemistry:</u></b> Design, development, and implementation of chemical products or processes to reduce or eliminate the use and generation of hazardous and toxic substances (Hjerisen <i>et al.</i> 2002). 12 Principles of Green Chemistry (Anastas <i>et al.</i> 1998) have structured the development of Green Chemistry as a research discipline and industrial practice. These are further discussed in section 4.3.1.2.</p>
<p><b><u>Industrial Symbiosis:</u></b> Engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to Industrial Symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (Chertow 2000).</p>	<p><b><u>Green Engineering:</u></b> Focuses on how to achieve sustainability through science and technology. Provides 12 principles for consideration in the design of new materials, products, processes and systems that are benign to human health and the environment (Anastas <i>et al.</i> 2003). These principles are further discussed in section 4.3.1.3.</p>

### 2.3 Industrial Symbiosis

Industrial Symbiosis deals with the exchange of by-products, energy, water and emissions among closely situated firms. It is perhaps the best-known application of Industrial Ecology principles. Because of the many links among the firms an industrial area is transformed into an 'industrial ecosystem' or 'Industrial Symbiosis'. Chertow provides the following definition "Industrial Symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to Industrial Symbiosis are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow 2000).

Several other terms are used in the literature, including "by-product synergy", "by-product exchange", "eco-industrial park", "eco-industrial network" or "industrial ecosystem". Table 2.2 provides some definitions. Depending on the system boundaries, specifics of the project, its management umbrella, or even the geographical location, the above expressions may vary but generally they are used interchangeably. Regardless of the specific terminology in use, these initiatives have one thing in common: their implementation aims at 'creating a system for trading material, energy, and water by-products among companies, usually within a park, neighbourhood, or region' (Lowe 2001).





**Table 2.2 Concepts and definitions in Industrial Symbiosis**

Industrial Symbiosis	The part of Industrial Ecology, which engages traditionally separate entities in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products. The keys to Industrial Symbiosis are collaboration and the synergistic possibilities offered by geographic proximity (Chertow 2000).
By-product Synergy	The synergy among diverse industries, agriculture, and communities resulting in profitable conversion of by-products and waste to resources promoting sustainability (BCSD-GM 1997).
By-product Exchange	.. a set of companies seeking to utilise each other's by-products (energy, water, and materials) rather than disposing of them as waste (Lowe 2001).
Eco-Industrial Park or Estate	... an industrial park developed and managed as a real estate development enterprise and seeking high environmental, economic, and social benefits as well as business excellence (Lowe 2001).
Eco-Industrial Network	...a set of companies collaborating to improve their environmental, social, and economic performance in a region (Lowe 2001).
Industrial Ecosystem	In an Industrial Ecosystem, the traditional model of industrial activity is transformed into a more integrated system, in which the consumption of energy and materials is optimised and the effluents of one process serve as the raw material for another process (Frosh <i>et al.</i> 1989).

Optimisation of material and energy flows within the industrial area is the distinctive organising principle for Industrial Symbiosis. The natural ecosystem metaphor can however be extended to the principles that drive the development ecosystems in nature. Such development of natural ecosystems is driven by four principles, respectively (Korhonen 2001):

1. *Roundput*: recycling of energy (“utilisation of residual energy”) happens through cascading in food chains with the only driver of the system being the input of infinite solar energy;
2. *Diversity*: diversity in species, organisms, interdependency and cooperation enhances ecosystem survival;
3. *Locality*: actors in the ecosystem adapt to the local environmental conditions and cooperate with their surroundings in diverse interdependent relationships;
4. *Gradual change*: information transfer and change happen through reproduction, which is a slow process.

Table 2.3 illustrates how these ecosystem principles can be applied to regional eco-industrial systems.

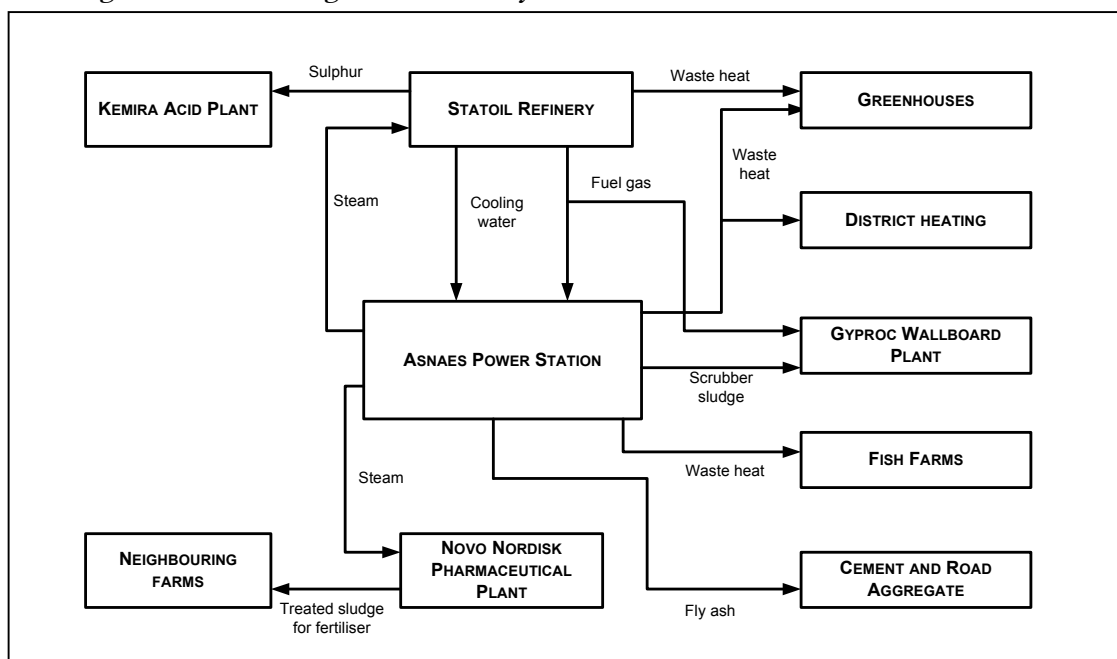
**Table 2.3 Ecosystem principles applied to natural and industrial ecosystems (adapted from Korhonen 2001)**

ECOSYSTEM PRINCIPLES	IN NATURAL ECOSYSTEM	IN INDUSTRIAL ECOSYSTEM
1. Roundput	<ul style="list-style-type: none"> <li>▪ Recycling of matter</li> <li>▪ Cascading of energy</li> </ul>	<ul style="list-style-type: none"> <li>▪ Recycling of matter</li> <li>▪ Cascading of energy</li> </ul>
2. Diversity	<ul style="list-style-type: none"> <li>▪ Biodiversity</li> <li>▪ Diversity in species, organisms</li> <li>▪ Diversity in interdependency and co-operation</li> <li>▪ Diversity in information</li> </ul>	<ul style="list-style-type: none"> <li>▪ Diversity in actors, in interdependency, and in co-operation</li> <li>▪ Diversity in industrial input and output</li> </ul>
3. Locality	<ul style="list-style-type: none"> <li>▪ Utilising local resources</li> <li>▪ Respecting the local natural limiting factors</li> <li>▪ Local interdependency and co-operation</li> </ul>	<ul style="list-style-type: none"> <li>▪ Utilising local resources, wastes</li> <li>▪ Respecting the local natural limiting factors</li> <li>▪ Co-operation between local actors</li> </ul>
4. Gradual change	<ul style="list-style-type: none"> <li>▪ Evolution using solar energy</li> <li>▪ Evolution through reproduction</li> <li>▪ Cyclical time, seasons time</li> <li>▪ Slow time rates in development of system diversity</li> </ul>	<ul style="list-style-type: none"> <li>▪ Using waste material and energy and renewable resources</li> <li>▪ Gradual development of the system diversity</li> </ul>



The most prominent example of how an industrial ecosystem can develop is found at Kalundborg in Denmark, an example that came first into the international spotlight shortly after the seminal publication of Frosh and Gallopulus in the Scientific American in 1989. At the core of this industrial system is the Asnaes Power Station (coal fired), which provides steam to the Statoil Refinery and Novo Nordisk pharmaceutical plant. In return, Statoil Refinery provides fuel gas and cooling and waste utility water to the Asnaes Power Station. The adjacent Gyproc Wallboard plant utilises fuel gas from the refinery, and scrubber sludge from the power station. The fly ash from the power station is further processed as cement and road aggregate. Waste heat, both from the refinery and the power station was initially provided to greenhouses, but this has recently changed to provide waste heat to fish farms and district heating. Finally, sulphur from the refinery is shipped to the Kemira Acid Plant, while Novo Nordisk’s Pharmaceutical plant provides treated sewerage sludge as fertiliser to neighbouring farms. The current system is the result of a dynamic evolution over about four decades. The ‘twinning’ between the three key process industries (power station, refinery and pharmaceutical plant) is generally regarded as the critical success factor at Kalundborg, since each provides large volume waste streams with valuable by-products on a continuous basis (Ehrenfeld *et al.* 1997). The principal linkages and their environmental outcomes are illustrated in Figure 2.1 and Table 2.4 below. Other examples and their achievements are summarised in Chapter 3.

Figure 2.1 Kalundborg industrial ecosystem





**Table 2.4 Environmental benefits from Industrial Symbiosis at Kalundborg** (source: Ebbensfeld *et al.*, 1997).

ANNUAL RESOURCE SAVINGS THROUGH INTERCHANGES	
Water savings	Statoil – 1.2 million cubic meters from Asnaes (Novo Nordisk – 0.9 million cubic meters available but not yet utilised)
Fuel savings	Asnaes – 30,000 ton of coal (about 2 % of throughput) by using Statoil fuel gas About 19,000 tons of oil use by using fuel gas from Statoil in Novo Nordisk's boilers and Gyproc dryer fuel Community heating via waste steam from Asnaes
Input chemicals	Fertiliser equivalent to Novo Nordisk's sludge (about 800 tons nitrogen and 400 tons phosphorous) 2,800 tons sulphur 80,000 tons of gypsum
WASTES AVOIDED THROUGH INTERCHANGES	
Fly-ash and clinker	200,000 tons fly-ash and clinker from Asnaes (diverted from landfill)
Scubber sludge	80,000 tons of scrubber sludge from Asnaes (diverted from landfill)
Sulphur (as H <sub>2</sub> S)	2,800 tons from fluegas from Statoil (diverted from air emissions)
Waste water sludge	1,000,000 tons from Novo Nordisk (diverted from sea disposal)
Sulphur (as SO <sub>2</sub> )	1,500-2,500 tons SO <sub>2</sub> avoided by substituting coal and oil (diverted from air emissions)
Greenhouse gases	130,000 ton CO <sub>2</sub> avoided by substituting coal and oil (diverted from air emissions)

In the absence of the co-location of two or preferably even more major process industries it may not be possible to develop a significant Industrial Symbiosis. Manufacturing industries, often the largest segment at any industrial estate, typically produce comparatively small volumes of mono-material waste streams (arising as cut-offs from input materials) and a mixed waste stream comprising of production rejects, packaging and other production waste. The mono-material stream is most valuable for reuse or down cycling in other industries. It is, however, only available in smaller quantities often with large fluctuations in volume over time and is generally only valuable to industries in the same sector. These factors make it difficult to achieve positive economies for symbiosis on mono-material streams within any given industrial estate. The mixed waste stream from manufacturing industries is not fundamentally different from the general municipal waste stream and likewise it has limited potential and economic value for direct reuse by industries. In sum, it may not be easy to design 'ex-ante' Industrial Symbiosis at the scale of the Kalundborg system. However on a more modest scale it may well be possible to develop symbiotic relations between companies, as for example demonstrated by the experience of the Business Council for Sustainable Development in the Gulf of Mexico (BCSD-GM 1997) and in the UK by the National Industrial Symbiosis Program (NISP 2004). Companies and their employees have seen business opportunities to reduce costs, increase revenue and/or reduce resource vulnerability by engaging in resource exchanges with their neighbours.

The Kalundborg example (and others as discussed in Chapter 3) is widely deemed to be the spontaneous result of several distinct, bilateral deals between company employees who sought to reduce waste treatment and disposal costs, to gain access to cheaper materials and energy, and to generate income from production residues (Desrochers 2004). The emergence of industrial ecosystem developments, therefore appears to have been the result of natural or spontaneous developments. In other words, such diverse regional resource exchange networks seem to self-organise rather than arise out of specific planning processes (Korhonen *et al.* 2002).



There is a perception among many that a more proactive approach, either through planning and public policy (e.g. (Lowe 1997; Lowe 2001; UNEP 1997)) and/or through engineering design (e.g. (Hawken *et al.* 1999)), would catalyse the wider uptake of Industrial Symbiosis ideas, with deeper, more significant and more beneficial resource exchanges. (Desrochers 2004), however, warns against blind optimism for planned Industrial Symbiosis, given the poor track record and inherent inefficiencies of planning economies. (Baas *et al.* 2004) have therefore applied a social sciences analytical framework to propose a prescriptive approach to fostering inter-industry coordination and cooperation for Industrial Symbiosis. They start to view Industrial Symbiosis as an extension of the traditional categories of '*collective competitive goods*' that networked industrial clusters provide (i.e. the ability of industrial districts to produce training and educational facilities, local investment schemes, collective approaches to global marketing etc.). Their theory is that Industrial Symbiosis in brown-fields will evolve through three stages: *regional efficiency* (characterised by autonomous decision making by firms complemented with coordination with local firms to decrease inefficiencies through e.g. utility sharing); *regional learning* (based on mutual recognition and trust, firms and other partners exchange knowledge, and broaden the definition of sustainability on which they act); and *sustainable industrial district* (actors develop an – evolving – strategic vision on sustainability and base their activities on this vision).

Lambert *et al.* (2002) provide a useful framework for analysing and promoting eco-industrial parks. The primary distinction is between industrial complexes (consisting of concentrations of materials and energy intensive industries which intrinsically are interconnected) and mixed industrial parks (usually housing a variety of small to medium sized enterprises). Apart from this, a third approach is to study the region, which includes interactions between communities, industries and land users. Within each category, a distinction can be made between brown-field sites (redevelopment from existing land uses) and green-field sites (first development of new industrial parks). The resulting typology is summarised in Table 2.5. Industrial complexes usually spontaneously develop exchange networks for utilities, residual products, etc. (as evidenced by the industrial complexes studied for instance in Styria (Austria), Ruhr Area (Germany), Rijnmond (The Netherlands) and Kwinana (Australia)). Most of the heavy industries attain economic benefits with materials exchange. However a further extension of such networks to lower grade residual flows, such as residual heat, often appears to fail, due to large preparation times in relation to internal dynamics of the system, high investment costs, and uncertainties in the markets and energy and other resource prices as examples. Most promising are the opportunities for clustering in greenfield areas or for fill-in in brownfield areas. Whether and how further synergies and exchanges can be realised through concerted facilitating efforts in existing complexes remains largely unresolved. Mixed industrial parks do not have an in-built incentive towards Industrial Symbiosis. Material and energy costs represent a much lower share of total operating costs for the light industries typically located in mixed industrial parks, and most manufacturing and service industries have significant variability in their resource consumption and waste and by-product generation over time. Government intervention for the operation of waste exchange type services can be effective in establishing and improving recycling networks in mixed industrial parks (e.g. (Kincaid *et al.* 2001)).



Table 2.5 Typology for Eco-Industrial Park Development (source: (Lambert et al. 2002))

<b>Industrial Complexes</b> (Geographically concentrated industrial activities, mainly process industries, with tight couplings of a relatively small number of materials and energy intensive production processes)	<b>Greenfield</b> Development of a new complex of industrial activities with tight physical couplings, taking into account the ecological impact of the complex in designing it
	<b>Brownfield</b> The revitalisation of an existing industrial complex using reduction of the ecological impact as one of the goals
<b>Mixed Industrial Parks</b> (Industrial activities, mainly SMEs, which are concentrated in dedicated areas, of a very diverse nature with no or little coupling of production processes)	<b>Greenfield</b> The development of a new industrial park, addressing ecological issues in the different stages of the development process
	<b>Brownfield</b> The revitalisation of an existing industrial park taking the reduction of environmental impact as one of the goals
<b>Eco Industrial Regions</b> (Industrial activities in a larger geographic or administrative area, usually referring to a diversity of industries, but often with a definite specialisation) Also called: virtual eco-industrial parks	<b>Greenfield</b> Developing and industrialising a region according to a well defined concept that includes the reduction of the environmental impact
	<b>Brownfield</b> Restructuring an existing industrial region, often based on definite regional qualities and accounting for environmental performance

## 2.4 Concluding Remarks

The notion of creating regional resource synergies to improve industry's contribution to sustainable development at the regional level is deeply rooted in Industrial Ecology and Industrial Symbiosis. Even though these – and other – terms are used interchangeably, it appears preferable to view Industrial Ecology more broadly as looking at nature as a model for the optimisation of materials and energy flows and inspiration for environmentally-oriented product and process design, and Industrial Symbiosis more narrowly as being concerned with exchanges of previously 'wasted' by-products between firms in close geographic proximity.

The review of concepts and principles presented here illustrates that theory, methodology and policy for the deliberate creation of regional resource exchange networks are still in their infancy. There is a general appreciation that Industrial Symbiosis does work and can manifest itself in many different ways, with regard to, for example, the types of resource exchanges and their environmental and economic benefits, the nature of coordination and cooperation between businesses and other actors, and the maturity of the symbiosis.. Some claim that the scope for synergies is limited only by the imagination and openness of companies (Cohen-Rosenthal 2000), while others are more cautious. Self-organisation emerges as a key success factor for the creation of regional synergies. However, self-organisation is unlikely to be successful in the absence of dedicated resources for analysing materials and energy flow data, bringing together businesses, and developing synergy opportunities. In turn, this underpins the importance of facilitation to provide a platform for self-organisation to happen which could be referred to as "transition management". It is without doubt that (environmental) legislation, industry policy, resource economics and technology can all act as serious barriers to self-organisation for Industrial Symbiosis, but the picture is less clear as to whether and how each can be turned into an incentive or enabler for Industrial Symbiosis.



The literature does not provide for any specific consideration of the applicability of Industrial Ecology and Industrial Symbiosis for minerals processing and metals production. There is however the prediction in (Lambert *et al.* 2002) that self-organisation is more likely to happen in materials- and energy intensive industrial complexes, which one would expect to then apply to minerals processing and metals production. In order to move beyond general industry observations, chapter 3 will focus on review of selected examples of Industrial Symbiosis, which include minerals processing and metals production facilities.



## **Chapter 3: CURRENT APPLICATIONS OF INDUSTRIAL SYMBIOSIS**

### ***3.1 Introduction***

Chapter 2 showed that the principal idea behind Industrial Symbiosis is both compelling and in principle supportive of economic development, environmental protection and social advancement, the three pillars of sustainable development. This chapter reviews practical applications of Industrial Symbiosis to assess whether and how the in principle potential of Industrial Symbiosis is being achieved in various parts of the world. This review focuses on heavy industrial areas, as lessons learned from such areas will have greatest applicability for Sustainable Resource Processing.

The objective of this review is to evaluate best practice international experience in regard to regional synergy development. It aims to provide a global picture of Industrial Symbiosis activity (current and in the past), to gather information about tools and technologies that have been used, drivers and barriers that have been identified elsewhere, and to assess whether the collected information could be used for the benefit of escalating the symbiotic relationships in industrial areas. An extensive literature search was conducted to identify and select relevant case studies for this review from scientific journals, magazines, conference proceedings, publicly available consultancy reports, local, state and federal government reports, as well as web-based case studies. The case studies were chosen on the basis of presence of heavy industries, specifically industries belonging to the resource processing sector (inclusive of oil refineries).

The focus of the review is threefold, namely:

1. To assess the practical applicability of Industrial Symbiosis, and its potential to contribute to sustainable development;
2. To review how Industrial Symbiosis opportunities have been identified in the respective industrial areas; and
3. To identify key enabling technologies (and/or technology needs) for achieving greater Industrial Symbiosis.

The review includes both Australian as well as international examples. They are discussed separately, primarily because much greater detail is available for the Australian case studies due to the parallel CSRP research projects in Kwinana (3B1) and Gladstone (3C1). This chapter therefore starts with a summary and review of international examples (section 3.2), followed by the summary of the Australian examples (section 3.3). Section 3.4 contains the comparative assessment of the international examples and addresses tools, drivers, technologies and other issues. The final section 3.5 discusses conclusions from the review and focuses on implications for research and implementation of regional synergies through the CSRP.

### ***3.2 International Examples***

Industrial areas where (heavy) industries co-locate are abundant right across the world. In many cases waste heat, effluents or solid by-products from a single operation are currently not utilised, but could be beneficially used in another operation. Cascading waste energy, wastewater and wastes is commonly practiced between different parts of large industrial operations (such as oil refineries, foundries, industrial chemicals, car manufacturing or food



processing plants). Industrial Symbiosis seems to provide the basis to adopt these practices within a network of industries.

### 3.2.1 Case Study Selection

The findings of this search for examples of Industrial Symbiosis confirms Lowe (2001) who reported that it was difficult to gather more than anecdotal reports for the achievements of various Industrial Symbiosis projects. Many reports only include qualitative information and have very limited data on features as basic as the nature of industries involved. Many reports seem to lack information on the companies participating in the projects, and the listing of the synergies in some of the cases is unclear to whether these resource exchanges are real, or are only identified as opportunities that still need to be assessed and implemented when proven feasible.

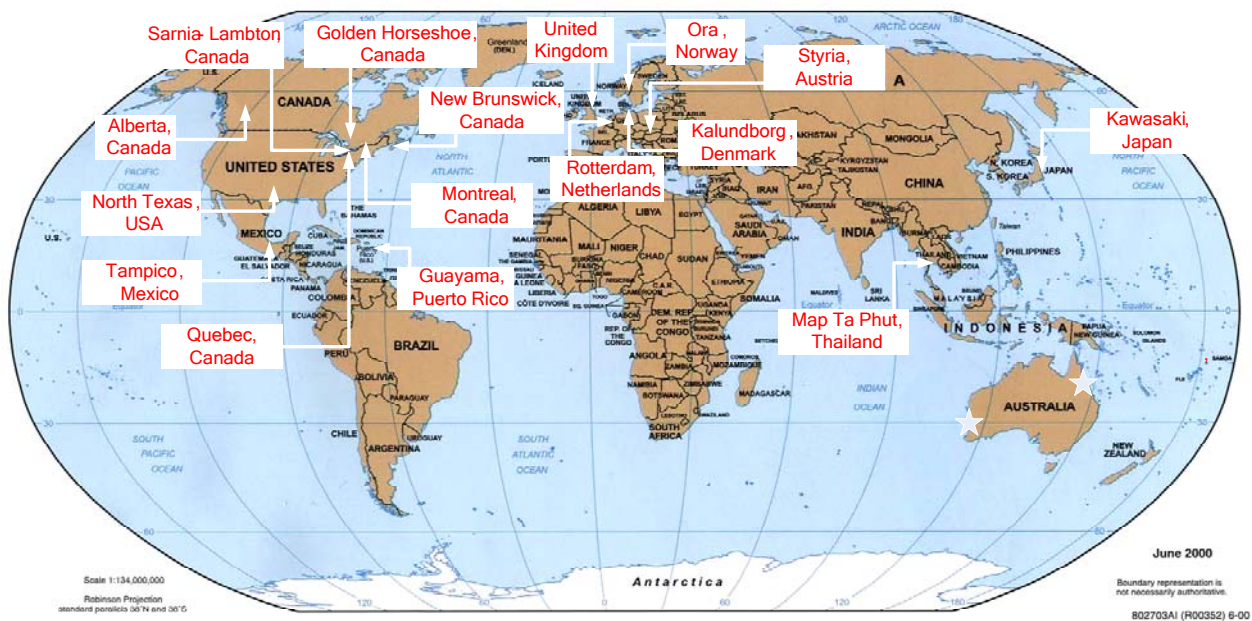
The first inventory identified 60+ eco-industrial estates/parks for which some type of Industrial Symbiosis relationship presumably exists. However few were selected for inclusion in this best practice review, given lack of information on the others. The selection of 16 examples for this review was therefore very much driven by information availability and perceived applicability for the resource processing industry (as reflected in presence of heavy processing industries in the selected areas). The 16 case studies cover a variety of programs, research and consultancy projects as well as one-off studies of selected regions, where at least one of the participating companies can be associated with the resource processing sector.

The case studies listed below were selected (in alphabetical order) with respective references. Their geographical location is illustrated on Figure 3.1:

- Alberta, Canada, (Dias *et al.* 2001), (Applied Sustainability (n.d.))
- Golden Horseshoe, Canada (Dias *et al.* 2001), (Hatch 2002)
- Guayama, Puerto Rico (Chertow *et al.* 2004)
- Kalundborg, Denmark (Ehrenfeld *et al.* 1997), (Jacobsen 2003)
- Kawasaki Zero Emission industrial Park, Japan (Lowe 2001), (ICETT (n.d.))
- Map Ta Phut, Thailand (GTZ 2000), (Homchean 2004)
- Montreal, Canada (Nisbet *et al.* 1997)
- National Industrial Symbiosis Programme (NISP), UK (BCSD-UK 2003), (Mirata 2004), (NISP 2004)
- North Texas, USA (Dias *et al.* 2001)
- Ora Ecopark, Norway (Thoresen 2000)
- Quebec, Canada (Dias *et al.* 2001), (Hatch 2001)
- Rotterdam, The Netherlands (Baas 1998), (Baas *et al.* 2004)
- Saint John, New Brunswick, Canada (Nisbet *et al.* 1999)
- Sarnia-Lambton, Canada (Venta *et al.* 1997)
- Styria, Austria (Schwarz *et al.* 1997)
- Tampico, Mexico (Young 1999), (Dias *et al.* 2001)
-



Figure 3.1 Case studies - geographical location



The large number of North American case studies could be attributed to Hatch, the Toronto-based engineering and consulting firm, which partnered with a number of local agencies and businesses to launch regional eco-industrial networking projects. These so called By-Product Synergy (BPS) Projects were executed in Alberta, Montreal, Golden Horseshoe (all in Canada), Tampico (Mexico), and North Texas (USA). The reports prepared for these individual projects are very detailed and cover not only the development of a project in its consecutive steps, and detailed description of synergy opportunities, but also cover issues such as drivers, barriers, benefits, outcomes and lessons learned. These reports are available at Hatch, Canada web site: [www.hatch.ca](http://www.hatch.ca)

In 1997 Environment Canada commissioned JAN Consultants, with the cooperation of local research and industrial partners, to carry out studies in Sarnia-Lambton, Saint John and Montreal in Canada on opportunities for eco-industrial networking in these industrial areas. The purpose of these case studies was to take stock of the existing synergies to identify what are the drivers and barriers behind such partnerships and to establish the principles for developing networks in other industrialised areas. It appears it was the flavour of the month at some point, currently well forgotten. Industrial Ecology and some of the reports are mentioned on the technical part of Environment Canada web site [http://www.ec.gc.ca/energ/industry/tech\\_e.htm#industrial](http://www.ec.gc.ca/energ/industry/tech_e.htm#industrial), which was last updated in 2001. As there are two independent studies carried out for Montreal, covering different industrial areas and featuring different industrial partners they are distinguished in this report as Montreal (carried out in 1997) and Quebec (carried out in 2000).

The other the case studies have developed in their own particular ways, either as an eco-industrial specific project or as a follow up initiative. Some of them, in particular Kalundborg in Denmark and Map Ta Phut in Thailand, have opportunistically developed industrial partnerships over the years.



The National Industry Symbiosis Programme (NISP) in the UK may not have a heavy/resource processing industry representation but the example is covered for its unique widespread approach and expansion. The original participating companies include an oil refinery, power stations, cobalt and nickel salts manufacturer, variety of chemicals manufacturers, industrial plastics manufacturer, etc. One of the synergies involves a titanium dioxide manufacturer, while another involves major steel manufacturers, which leads to the assumption that these industries are active participants in the programme. Another reason to include NISP in this review is the number and variety of synergies either implemented or in the pipeline, that can contribute to the knowledge base being built for the purposes of identification and further implementation of new synergies in Kwinana and Gladstone, as well as providing valuable information for the development of the eco-efficiency opportunity assessment methodology (task 2 of this research project, as described in section 1.2).

There are few new projects that could potentially qualify for inclusion in this comparative review, apart from the New Jersey by-product synergy project launched in 2002 and Gulf Coast project, which is under establishment (both in USA). Due to very limited available information on the participating industrial partners, these are not covered in the present review. Another one that deserves to be mentioned is the by-product synergy (slag as raw material for cement) between Chaparral Steel Company and its parent company, Texas Industries, a manufacturer of Portland cement. As this bilateral synergy between companies within a same group is the only synergy, the example has not been included in the review.

In 1999 an Alberta's Industrial Heartland (AIH) Inventory was carried out to outline the existing industries and infrastructure in the region (AIH 2000). The AIH covers four municipalities (Strathcona County, City of Fort Saskatchewan, Sturgeon County and Lamont County) adjacent to Edmonton, Alberta's Capital City, comprising an area of 194 square kilometres. The region has no port facilities and is establishing itself as a globally competitive heavy industrial area, mainly for petrochemical processing. The study collected data on product flows and supply chain interactions, revealing examples of some beneficial use of hydrogen and carbon dioxide as well as the availability of co-generation facilities. This study is not discussed here as information on waste flows was not obtained, and the report focuses on the available chemical feedstocks, not by-products.

### 3.2.2 Case Studies Description

The regional synergies examples are summarised below:

- **Alberta, Canada** - Eighty-five Alberta businesses and other participants were invited to an informational meeting in September 1998. By January 1999, a core group of industries and organisations had been mobilised and the data collection was initiated in February. Participants identified more than 80 potential synergies with more than 30 different materials. Many in the group had been aware of these synergy ideas, but found that the by-product synergy project had propelled them into activating the synergy ideas (Applied Sustainability (n.d.); Dias *et al.* 2001).
- **Golden Horseshoe, Canada** - The Golden Horseshoe is the region surrounding Lake Ontario on the Canadian side. The by-product synergy project started initially with 95 participants in January 2001 at the first of eight working meetings in total. The number of participants has been reduced down to 22 companies and 5 organisations due to economic slowdown and company restructuring (Dias *et al.* 2001; Hatch 2002).



- **Guayama, Puerto Rico** - the municipality of Guayama on the southern coast of Puerto Rico covers 169 km<sup>2</sup> and has a population of approximately 42,000. The current industrial profile began to develop in the 1950s, as Guayama primarily had before been agricultural with some light manufacturing. Puerto Rico is a commonwealth of the US, thus sharing many of its laws and business practices. Spontaneous development began in 2002 when a coal-fired power plant was brought online (Chertow *et al.* 2004).
- **Kalundborg, Denmark** - Kalundborg Municipality has approximately 20,000 inhabitants, and its network is the most published example of Industrial Symbiosis. The history of Kalundborg Industrial Symbiosis activities began in 1961 when a project was developed and implemented to use surface water from Lake Tisso for a new oil refinery in order to save the limited supplies of ground water. The City of Kalundborg took the responsibility for building the pipeline while the refinery financed it. Starting from this initial collaboration, a number of other collaborative projects were subsequently introduced and the number of partners gradually increased. By the end of the 1980's, the partners realised that they had effectively "*self-organised*" into what is probably the best-known example of Industrial Symbiosis. The material exchanges in the Kalundborg region include: conservation of natural and financial resources; reduction in production, material, energy, insurance and treatment costs and liabilities; improved operating efficiency; quality control; improved health of the local population and public image; and realisation of potential income through the sale of by-products and waste materials (Ehrenfeld *et al.* 1997; Jacobsen 2003).
- **Kawasaki Zero Emission industrial Park, Japan** - Kawasaki City is home of one of Japan's oldest and largest industrial parks. Established in 1902, Kawasaki Coastal Industrial Area houses over 50 heavy industrial enterprises, including oil refineries, steel manufacturer, power station and chemical manufacturers. During the 1970s the city and the industrial park were considered one of Japan's most contaminated areas. In 1997 the city of Kawasaki designated approximately 2,800 ha of water front property as its Eco-town Project site. It is anticipated that that the various industrial and business functions present in the zone will produce combinations needed to foster a globally-competitive, resource recycling industrial system (ICETT (n.d.); Lowe 2001).
- **Map Ta Phut, Thailand** - Map Ta Phut Industrial Estate was established in 1985 under management of the Industrial Estate Authority of Thailand (IEAT). The Estate is one of the twenty-nine estates in Thailand and it is the biggest one located in Rayong Province. It has been reserved for the petrochemical industry and its downstream processes to enhance the value of natural gas reserves from the Gulf of Thailand (GTZ 2000; Homchean 2004).
- **Montreal, Canada** - The success of Kalundborg sparked interest in Montreal. A study was conducted for a number of industrialised areas in the Montreal region to identify the extent to which partnerships and networks had been formed, and if not, to identify factors that have inhibited them (Nisbet *et al.* 1997). The study analyses successful cases and documents delayed or failed projects while looking for potential opportunities in mature industrialized areas. It also identifies the drivers and key factors for success. The study covers four industrial parks, spread over a large geographical area. The abundance of resource recovery operators facilitated the recovery and reuse of by-products in the region.



- **National Industrial Symbiosis Programme (NISP), UK** - The National Industrial Symbiosis Programme (NISP) is the first Industrial Symbiosis initiative of its kind in the world launched on a national scale and is at the forefront of Industrial Symbiosis thinking and practice in the UK. The programme is not exclusive to any particular resource and addresses raw materials, by-products, human resources, logistics, services, waste, energy and water. NISP is supported by UK Government and by industry organisations. The programme brings together companies to identify synergies that will lead to greater resource efficiency. Target regions where Industrial Symbiosis programs are at various stages of development are: Yorkshire and the Humber (Humber Industrial Symbiosis Project), West Midlands (West Midlands Industrial Symbiosis Project), North West (Mersey Banks Industrial Symbiosis Project), Scotland (Grangemouth), North East (Teesside), South East (Southampton) and Ireland (BCSD-UK 2003; Mirata 2004; NISP 2004).
- **North Texas, USA** - This initiative was launched by Business Council for Sustainable Development, Gulf of Mexico (BCSD-GM), and several consultancy companies in mid 1999. The project began with the recruitment of 10-to-20 diverse companies within about a 50-mile radius of Dallas, Texas. A group of individual companies was transformed into a dynamic cross- industry team focused on turning every gram of material running through their plants into product. Most companies opted to not report on primary products; the focus was on co-products and by-products. The analysis of data, and the participants' own analyses in the facilitated discussions, identified 105 synergy ideas with 57 different materials. Some of these ideas had previously been identified, but not been implemented. Participating companies reported a wide range of co- and by-products in categories such as water, organic material, solvents, alkalis, acids, metals, plastics, inorganic solids, paper, biomass, and other materials. The annual volumes reported are equally wide in range for the different materials, from less than 100 to several billion pounds annually (Dias *et al.* 2001).
- **Ora Ecopark, Norway** - 12 out of 60 companies in Ora industrial area were selected as partners on the Ora Ecopark. All except two are located within a radius of 400-500 metres (Thoresen 2000).
- **Quebec, Canada** – the project (known as the Montreal By-Product Synergy Project) was led by Applied Sustainability, LLC, a small start-up company based in Austin, Texas (now closed) and was assisted by Hatch Associates. They assembled a group of about forty companies in the Montreal area and facilitated the synergy-seeking process (Dias *et al.* 2001; Hatch 2001).
- **Rotterdam, The Netherlands** - This is an area of 10,000 hectares, half of which is land, run by the Rotterdam Municipal Port Management (RMPM). It is a natural deep-water harbour, stretching 50-km inland, which handles 100 million tonne of oil annually. The port is also home to more than 30 chemical manufacturing companies and four refineries. Approximately 60% of land use is in oil and chemicals sectors generating 14,000 direct jobs and 66,000 indirect jobs. The Rotterdam harbour is considered to have a good potential for companies to reuse waste streams, by-products and energy from each other. To help achieve this end the industrial eco-system project (INES) was introduced in the western region of the Rotterdam harbour area, originally initiated by the Europort/Botlek Interests industry association for the development of Environmental Management System (EMS) for 69 member companies. The project team involved a staff member from the industry



association, chairman of the environmental management communication platform, a consultant and university researchers. INES was launched to stimulate the development of cleaner production approaches; to perform network analyses of the activities, material and energy streams; and to develop a knowledge infrastructure to facilitate the functioning of the industrial eco-system in the region. The first INES project was performed in the period 1994-1997 which was followed by the INES Mainport Rotterdam, in operation in the period 1999-2002 and the Rotterdam Harbor and Industry Complex (HIC) in 2003-2007 projects (Baas 1998; Baas *et al.* 2004; Baas 2005; Heeres *et al.* 2004).

- **Saint John, New Brunswick, Canada** - One year study to investigate the potential for eco-industrial networking in the city of Saint John. The city is home to one of Canada's largest concentrations of large industries (Nisbet *et al.* 1999).
- **Sarnia-Lambton, Canada** - The aim of the project was to develop a case study of a heavily industrialised area. Sarnia-Lambton site was chosen for analysis of the potential for resource conservation and pollution reduction through establishment of an industrial ecosystem. The purpose of the case study was to identify economic costs, benefits and existing barriers (Venta *et al.* 1997).
- **Styria, Austria** - In 1993 a research study has discovered and analysed an "industrial recycling network" in the Austrian province of Styria. The research started by tracing by-product inputs and outputs of two major enterprises and soon found a complex network of exchanges among over 50 facilities (Schwarz *et al.* 1997).
- **Tampico, Mexico** - In 1997, the Business Council for Sustainable Development – Gulf of Mexico (BCSD-GM) launched a demonstration *By-Product Synergy* project in Tampico with a group of 21 local industries. The goal was to promote joint commercial development among economic sectors so that one industry's wastes became another industry's inputs. The project demonstrated that by working together, industries can maximise use of potentially profitable materials which otherwise may be treated as "waste". The synergy identification phase concluded in October of 1998 (Dias *et al.* 2001; Young 1999).

Table 3.1 below presents a brief comparison of the case studies. Drivers and barriers for industrial networking, tools and methodologies as well as technologies employed in the process of identification and implementation of synergy opportunities are discussed in more details further in this chapter.

Out of the selected 16 case studies only four are evidently still in progress featuring ongoing activities to identify and implement new synergies between industry partners, these are NISP, Guayama, Map Ta Phut and Rotterdam. Three of the case studies were intended to be once-off stocktake of existing and potential opportunities (Sarnia-Lambton, Montreal, and Saint John). Despite the intention for continuation in the remaining examples (excluding Kalundborg in Denmark, which has not been intentionally initiated as an Industrial Symbiosis project) the information presently available to the research team does not warrant to conclude there is ongoing activity in the other areas. The information flow in the public domain appears to have dried up for many of the case studies. For example:



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- Kawasaki Zero Emission Industrial Park, in Japan is expected to operate till 2010, but the available information is rather outdated considering that the project has been running for seven years now<sup>1</sup>.
- Ora Ecopark, Norway and Styria, Austria - Information is very limited, although both information sources provide an overview of the participating companies and the partnerships between them.
- Tampico, Mexico - established with the intention of repeating the data collection and synergy identification activities every few years, but there is no further information published.
- Quebec and Golden Horseshoe, Canada - expected to continue till 2005. No follow-up information available after the initial publications.

Table 3.1 Overview of case studies

NAME	YEARS OF DEVELOPMENT	LATEST INFORMATION YEAR	CURRENT DEVELOPMENT Y, N, No info *	DRIVERS IDENTIFIED	BARRIERS IDENTIFIED	TOOL OR METHODOLOGY EMPLOYED	TECHNOLOGY NEEDS IDENTIFIED
Alberta	1998-1999	2001	N	Y	Y	Y	Y
Golden Horseshoe	Established in 2001 with 5 year lifetime	2002	No info	Y	Y	Y	N
Guayama	2002	2004	Y	Y	N	N	N
Kalundborg	1961	2004	N	Y	N	N	N
Kawasaki Zero Emission industrial Park	The project is expected to operate initially from 1997 to 2010	2001	No info	N	N	N	N
Map Ta Phut	1985 - ongoing	2004	Y	N	N	N	N
Montreal	1997	1997	N	Y	Y	N	Y
NISP	2000 - ongoing	2004	Y	Y	Y	Y	N
North Texas	July 1999-April 2000	2001	N	N	Y	Y	N
Ora Ecopark	-	2000	No info	N	N	N	N
Quebec	2000-2005	2001	No info	Y	Y	Y	Y
Rotterdam	1994-1997 1999-2002 2003-2007	2005	Y	N	Y	Y	N
Saint John	1999	1999	N	Y	Y	N	Y
Sarnia-Lambton	1997	1997	N	Y	Y	N	Y
Styria	-	1997	No info	Y	N	N	N
Tampico	1997-1998 with intention to repeat the process every two years	2001	No info	Y	Y	Y	Y

\* "No info" does not entail no current development, it states that there is no published information regarding further Industrial Symbiosis activities and developments

<sup>1</sup> At the 3<sup>rd</sup> International Society for Industrial Ecology (ISIE) Conference (Stockholm, 12-15 June 2005) it was found out that there appears to be ongoing development activities in Kawasaki. Further information thereof will be pursued.



It is unclear how to interpret the lack of recent information on so many initiatives. Clearly the benefits of updating communication on Industrial Symbiosis initiatives have not been recognised or the perceived risks of communicating have been considered too high (e.g. business risks of disclosing proprietary process information, concern for regulatory or community pressure around reuse and reprocessing of “wastes”, etc.). If anything can be concluded at all, it would be that most projects appear to be opportunistic in nature. They start with good intent and enthusiasm, and early successes are often possible with regard to recovery and reuse of by-products. The initiatives appear to plateau once these “*low-hanging – fruits*” have been picked, and the initial project resources for facilitation and communication have run out. Follow up on other synergy options identified is quite likely to continue, however more often as “*traditional*” business development, and not necessarily promoted under the umbrella of Industrial Symbiosis.

Specific comments related to the quality of information for some case studies are presented below:

- North Texas - The program changed hands in 2001, and Hatch in Dallas started a new recruitment phase for the program, expanding the “5 year project” into an ongoing business with annual memberships by participants. Later in 2001 the program was moved again to a local consultant but at present there is no further information available.
- Map Ta Phut - Information about this industrial estate is rather confusing – both sources provide poor quality information, which is conflicting on many occasions.
- Kawasaki – The English information is very limited, which makes it difficult to assess this case study and whether progress is being made. There is however a remarkably hype in Japan that Kawasaki is a model of achievement.
- Styria – the paper provides incomplete information regarding industries and by-product flows, indicating that more details are available in German.
- Rotterdam – the grouping of the synergies is presented in quite vague way, causing difficulty to distinguish between different synergy opportunities.
- NISP – it is not clear which are the participating companies and which industry sector they belong to.

### 3.2.3 Common Elements

A complete list derived from the referenced information sources, covering the by-product/waste stream being exchanged is presented in Appendix A. A comparison or similarity between the synergies opportunities (existing or being implemented) is difficult to draw, as documented synergies are specific to the industry mix in each industrial area in discussion, and also to the particular economic, environmental and social conditions for that industrial region. However, in Table 3.2 an effort has been made to categorise the existing synergies and those reported to be under implementation on three dimensions:

1. Type of *resource exchange*: what resource is being exchanged between companies.
  - *Water*: exchange and reuse of cooling water and process water, any collective treatment and recycling of wastewater.
  - *Energy*: shared use of energy infrastructure, co-generation and/or recovery of waste heat from steam and electricity generation.



- *Process waste*: exchange of liquid, solid, semi-solid, or gaseous waste generated when manufacturing a product or performing a service. It also includes by-products from pollution control waste that is being generated directly or indirectly when businesses remove contaminants from air, soil, or water. Examples include baghouse dust, desulphurisation gypsum, scrubber sludge, and chemical spill cleaning material.
  - *Non-process waste*: may include waste generated while carrying out routine or emergency maintenance (oils, cooling agents, oily filters, tyres, etc.) packaging materials, machinery components, general household waste, landscape waste, construction or demolition debris.
  - *Other*: this type of exchange generally features some sort of service or utility sharing.
2. Type of *processing* involved: the degree to which the “wasted” resource is being processed before it can be utilised by the other company/ies involved in the synergy project.
- *Direct use or reuse*: without any further processing except for transport and storage.
  - *Energy recovery or alternative fuels*: covers waste heat recovery and alternative fuels for boilers and kilns. Shared electricity and gas utilities and co-generation facilities also fall into this category.
  - *Material recovery*: involves separation and recovery processes to reclaim specific materials found in the by-product/waste stream for the beneficial use (i.e. segregation of plastics before recycling).
  - *Conversion into a useful product*: processing to produce a different useful product i.e spent edible oil for bio-diesel production.
  - *Environmentally sound disposal*: collective treatment of wastewater to enable its safe disposal.
3. Type of *synergy*: the business relation governing the synergy project.
- *Bilateral*: interaction between two parties, either one-way or two-way exchange.
  - *Service*: interaction between one company on one end and two or more on the other end of the synergy. For example one company producing steam for several companies or taking wastewater from several companies for collective treatment.
  - *Network*: – multilateral interaction between more than two parties in both directions (similar to Kwinana Water Reclamation Plant example in Kwinana where several industries are taking reclaimed water and returning waste effluent).

Where explicit information for the type of synergy was not available the researchers have used their expert judgment to rate a synergy into a respective category. Unknown type of synergy is used where no information available or is impossible to define.





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Table 3.2 Types of synergies

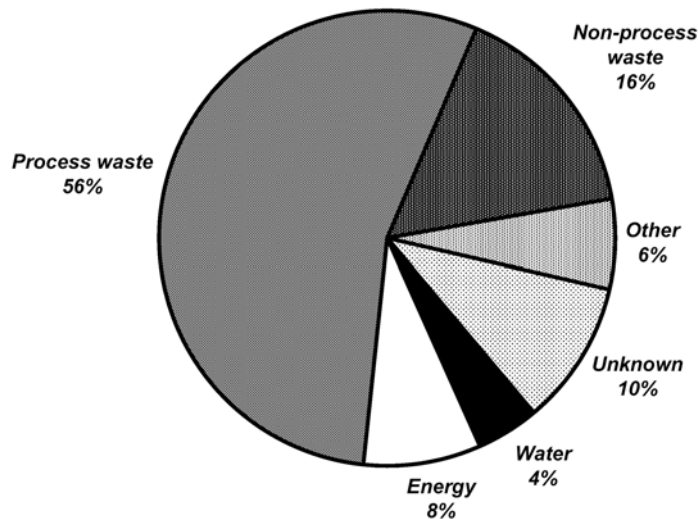
CASE STUDY	NUMBER OF DOCUMENTED SYNERGIES	RESOURCE EXCHANGE					PROCESSING <sup>1</sup>							SYNERGY TYPE				
		WATER	ENERGY	PROCESS WASTE	NON-PROCESS WASTE	OTHER	UNKNOWN	DIRECT USE/REUSE REUSE	ENERGY RECOVERY/ALTERNATIVE FUELS	MATERIAL RECOVERY	CONVERSION INTO A USEFUL PRODUCT	ENVIRONMENTALLY SOUND DISPOSAL	UNKNOWN	BILATERAL	SERVICE	NETWORK	UNKNOWN	
Alberta	1		1											1				
Golden Horseshoe	2		2				1							2			1	
Guayama	2	1	1					1			1			2				
Kalundborg	13	2	5	6			7	5			1			11	1			1
Kawasaki	9		1	6	2		1	1	4		2			2	4			3
Map Ta Phut	14	1	1	9	3		6	1	1	1	1	4		8	1			5
Montreal	24		18	5	1		5	3	6	5		5		12	10			2
Quebec	7		5	2			4	1				2		5	2			
NISP	20		1	10	3	4	2	5	4	1	4	5	1	7	7	2		4
North Texas	2		1	1					1					1				1
Ora Ecopark	10	2	1	2		5										10		
Rotterdam	3	1	1	1		1			1			1			2			1
Saint John	10		1	5	3	1	4		3	2		1		7	1	1	1	1
Sarnia-Lambton	4		2	1			2	1	1					1				2
Styria	24		1	17		3	8	5	3			8		16	8			
Tampico	12		7	3			3	2	3	4				5	4			2
<b>TOTAL</b>	<b>157</b>	<b>7</b>	<b>13</b>	<b>86</b>	<b>25</b>	<b>10</b>	<b>46</b>	<b>25</b>	<b>24</b>	<b>16</b>	<b>11</b>	<b>33</b>	<b>80</b>	<b>40</b>	<b>5</b>	<b>32</b>		

<sup>1</sup> NOTE: Total synergies in the processing category are 155, as two of them cannot be classed into any of the types herein



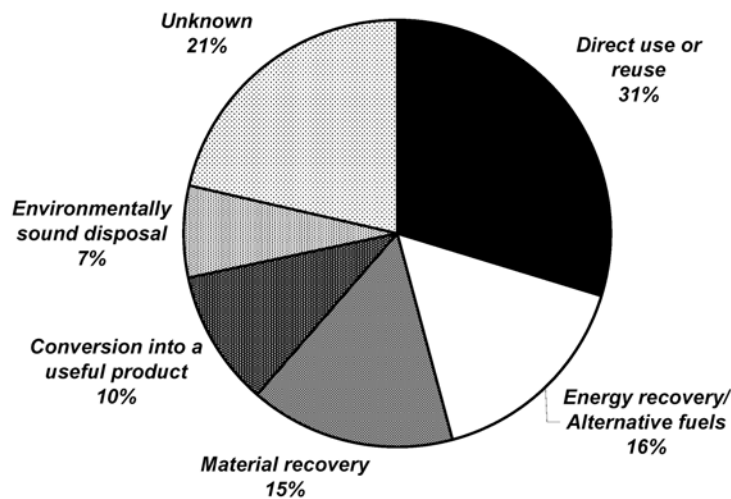
The majority of the case studies provide relatively adequate data in regard to what is being exchanged, but insufficient information of how it is being used, in terms of by-products description and any processing requirement needed, as well as how many parties are involved. As shown in Figure 3.2 below, more than half of the synergies involve process waste of some kind with surprisingly only 4% of synergies involving any kind of water treatment or reuse.

**Figure 3.2** *Categorising synergies by the type of resource exchange (existing and those being implemented: n = 157)*



All of the types of processing are employed depending primarily on the nature and contamination of the by-product/waste stream. Direct reuse (without any processing) is the most common type (31 % of the synergies) while two categories take up almost equal shares: i.e. energy recovery (16%) and material recovery (15%), followed by the conversion into a useful product category (10%). Each of these involves a considerable degree of processing. The energy recovery/alternative fuel type synergies are predominantly alternative fuel for cement kilns with few co-generation examples, as well as heat recovery. The distribution of synergies by the type of processing is shown in Figure 3.3.

**Figure 3.3** *Categorising synergies by the type of processing (existing and those being implemented: n = 155)*





As Figure 3.4 illustrates, it turned out to be fairly difficult to ascertain how many partners are involved in each synergy project and in what sort of relationship. Half of the synergies appear to be bilateral exchanges, and a quarter of the service provider type, where one company provides a resource to multiple companies or processes their wastes. Only five projects are network type, predominantly in the area of utility synergies (water and energy). Generally the network type of resource exchanges require more complex types of contractual agreements, thus, many industrial partners are somewhat reluctant to pursue them. This also could be contributed to the manner in which synergies have been described in literature. The majority of the unknown synergy types (or synergy that can not be classified) in the *processing* and *synergy type* categories belong primarily to the Map Ta Put (Thailand), Ora Ecopark (Norway) and Styria (Austria) case studies, as these are the case studies providing very limited data, especially in regard to detailed description of synergy interaction between industrial partners.

**Figure 3.4** *Categorising existing or being implemented synergies by the type of synergy* (existing and those being implemented:  $n = 157$ )

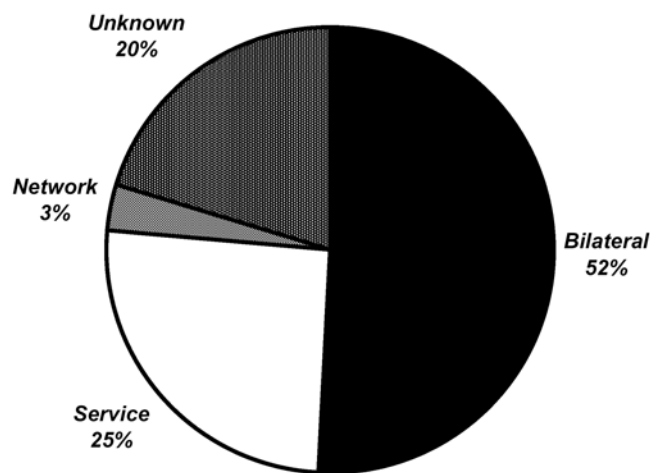


Table 3.4 below summarises the case studies with respect to common process elements illustrated by the case studies in terms of:

- *Facilitation components* - whether a facilitation body has established a platform for industry collaboration to develop synergy opportunities, set common goals for participants, facilitate brainstorming workshops and/or proceed with the development of business plans.
- *Research contributions* provided for the case studies in this review have had research components with regard to the level of documenting material flows and synergies, policy research into drivers and barriers for Industrial Symbiosis, technological research into by-product reuse technologies, and methodological research into tools and methodologies to develop and screen synergy opportunities.

One third of case studies do not have any facilitation component. These are the ones that have developed spontaneously (except for Map Ta Put, where facilitation was initiated at a later stage), the once-off case studies Saint John and Sarnia-Lambton (both in Canada), Ora Ecopark (Norway) and Styria (Austria). The Montreal (Canada) case study was executed in a similar fashion as the other once-off case studies, however it significantly differs from them, due to the involvement of facilitator groups in the respective regions forming parts of that case study.



The case studies were mainly facilitated by independent (non-research) organisations, even though the majority did at least involve two of the research components, namely in regard to documenting input/output inventories and existing, emerging, and in most cases potential synergy opportunities. Very few of the case studies give evidence of effort being focused on technological or methodological research. The two case studies featuring nil research components are the two with least information available.

Table 3.3 Process elements in synergy projects

CASE STUDY	FACILITATION COMPONENT					RESEARCH COMPONENT			
	ESTABLISHING COLLABORATION PLATFORM	VISIONING – COMMON GOAL SETTING	SYNERGY DEVELOPMENT WORKSHOPS	FEASIBILITY ANALYSIS OF SYNERGY OPPORTUNITIES	BUSINESS PLAN DEVELOPMENT	DOCUMENT EXISTING MATERIAL FLOWS AND SYNERGY EXAMPLES	“POLICY” RESEARCH INTO DRIVERS AND BARRIERS FOR INDUSTRIAL SYMBIOSIS	TECHNOLOGICAL RESEARCH INTO BY-PRODUCT REUSE TECHNOLOGIES	METHODOLOGICAL RESEARCH INTO TOOLS AND METHODOLOGIES
Alberta	X	X	X	X	X	X	X	X	
Golden Horseshoe	X	X	X	X	X	X	X		
Guayama						X			
Kalundborg						X	X		
Kawasaki	X	X							
Map Ta Phut	X	X				X			
Montreal	X	X		X	X	X	X	X	
NISP	X	X	X	X		X	X		X
North Texas	X	X	X			X			
Ora Ecopark									
Quebec	X	X	X	X	X	X	X		
Rotterdam	X	X	X	X	X	X	X		X
Saint John						X	X		
Sarnia-Lambton						X	X		
Styria									
Tampico	X	X	X	X	X	X	X		X

The collection of all synergies, existing, in the process of being implemented or simply identified as opportunities is summarised in Appendix A. Not all of the synergy examples are relevant to the resource processing industry, as they encompass a variety of interactions with smaller service and support industries that are commonly present in industrial areas, as well and linkages with operations and community within a wider regional area. The collection of existing and potential synergies presents a powerful database that could be useful in the process of synergy identification for emerging Industrial Symbiosis projects.

The quality and the detail of information for the collected synergy examples varies significantly across the case studies. Many of the sources go to in-depth analysis of each existing and possible synergy opportunity, while some case studies are simply taking stock of existing situation of the region/network. In most cases this is due to the nature of the project, its scope and required outcomes and the extent of the funding. Numerous opportunity examples are mentioned as identified throughout the information materials, but there is no specific data for them at present, thus they are not being covered herein. Due to the scarcity of available information some of the synergies categorised as potential may have



been implemented at a later date, but there is no further data to confirm that at the time of this report.

### 3.3 Australian Examples

This section provides a detailed overview of the development of regional synergies in the Kwinana Industrial Area (KIA) in Western Australia and the Gladstone Industrial Area Network (GAIN) in Queensland. In the next section, a comparative review of the selected Industrial Symbiosis projects/case studies is discussed. It focuses on taking stock of existing and potential synergies, discussion of general and specific drivers and barriers, engineering tools employed to identify linkages between partners, and technologies employed for regional synergy development.

#### 3.3.1 Kwinana Industrial Area

The Kwinana Industrial Area (KIA) is located 35 km south of Perth and 15 km south of Fremantle port. The KIA was established by a special Act of Parliament over an area of approximately 120 square kilometres along an eight-kilometre strip of coast adjacent to Cockburn sound. The area was set up to accommodate the development of major resource processing industries in the State, in 1952 when the Anglo-Iranian Oil Company (now known as BP Refinery Pty Ltd) entered into an agreement with the Western Australian government to establish an oil refinery in the region. The agreement saw the government build port facilities to handle the shipping of the oil.

Around the same time BHP struck a similar deal with the state government and a steel bar plant was established at Kwinana. It was opened in 1954. Realising the advantages in concentrating heavy industry in a small area, Alcoa established an alumina refinery in 1961 and Western Mining built a nickel refinery in 1970. The area continued to grow and is now home to an alumina refinery, a nickel refinery, an oil refinery, coal and gas fired power stations, a cement plant, three major industrial chemicals works, a pigment plant and a number of small to medium sized service and infrastructure industries. A list of the major industries in KIA with their main products is provided in Table 3.4. The initial industry development in the area with the oil, alumina and nickel refineries in the 1950' and 1960's was triggered by the areas proximity to mineral deposits, availability of infrastructure (roads and ports) and growth of the resources sector. Later on, collocation with major customers became a much stronger driver for industry establishment in the region (e.g. with the chemicals and power plants).

*Table 3.4: Summary of major Kwinana industries*

COMPANY	SUMMARY
Alcoa World Alumina Australia	Alcoa's presence in Western Australia is primarily centered on the mining and refining of bauxite for export. Alcoa World Alumina Australia operates three refineries in Western Australia between the capital city, Perth, and the port of Bunbury 200 km to the south. Commissioned in 1963 with an annual capacity of 200,000 tonnes of smelter-grade alumina, the refinery was the first of three built by Alcoa to refine Western Australian Bauxite. Over the years, modifications and technical improvements have raised the refinery's annual capacity to 1.9 million tonnes.
BP Refinery (Kwinana) Pty Ltd	The BP Refinery (Kwinana), which was opened in 1955, has a capacity to produce 138,000 barrels of crude oil a day and is Western Australia's only oil refinery. BP Kwinana produces a wide range of products including LPG (Liquid Petroleum Gas, Propane, Butane), Avgas (Aviation spirit), Motor Spirit (Lead Replacement Petrol, BP Ultimate, Regular Unleaded and Premium Unleaded), Avtur (Aviation turbine fuel for jet aircraft), Kerosene, Diesel, Bitumen, Fuel Oil and sulphur.
Cockburn Cement	The Company was established in Munster in 1955 as a manufacturer of cement. At the request of the Western Australian Government, Cockburn Cement diversified into the production of quicklime in 1971. Total manufacturing capacity exceeds 1.5 million tones of cement and quicklime pa. The company also has a specialized blending and bagging plant located in Kwinana.



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COMPANY	SUMMARY
Coogee Chemicals Pty Ltd	Coogee Chemicals is a Western Australian company established in 1970 and headquartered at Kwinana where its prime activity is the manufacture of inorganic chemicals to service the requirements of a broad range of industries including agriculture, resource processing and water treatment. Some examples are sodium aluminate, sodium silicate, ammonium chloride, copper sulphate, ferrous sulphate, aluminium sulphate and xanthates. Other major activities are the provision of tank terminal services for oil and chemical products and dangerous goods road transport distribution services.
CSBP Ltd	CSBP Limited is the largest manufacturer and supplier of fertilizers and chemicals to the agricultural, mining and industrial sectors in Western Australia CSBP operates in two main business streams – CSBP Chemicals which produces ammonia (200,000 tpa), ammonium nitrate (200,000 tpa), sodium cyanide (20,000 tpa), chlorine (5,000 tpa), caustic soda and sulphuric acid and CSBP Fertilisers developing, manufactures and markets fertilizers suited to local farming conditions.
Fremantle Ports	Fremantle Port, operating from two locations, is the principal general cargo port for Western Australia, handling more than \$15.6 billion in trade annually. The Inner Harbour, which opened on 4 May 1897, is located at the mouth of the Swan River adjacent to the City of Fremantle. The Outer Harbour, 20 km further south at Kwinana- Cockburn Sound was opened on 11 January 1955. Its deepwater bulk port facilities were developed to service the Kwinana Industrial Area, which expanded rapidly in the 1960s and 70s.
HIsmelt Corporation Pty Ltd	After developing the direct smelting technology and trials in Germany the HIsmelt Research and Development Facility with a rated capacity 100,000 tpa was established in Kwinana in 1991 to demonstrate scale-up of the core plant and provide data for commercial evaluation of the technology. In 2002 an unincorporated joint venture was formed for the purpose of constructing and operating a HIsmelt Plant (based on a 6 metre vessel) of around 820,000 tonnes pa capacity for the production of iron at Kwinana, Western Australia. Construction of the new plant commenced in January 2003 and the plant is being commissioned since Nov 2004.
Nufarm Coogee Pty Ltd	Nufarm Coogee Pty Ltd is a joint venture company between Nufarm Limited (80 per cent) and Coogee Chemicals Pty Ltd (20 per cent). The joint venture owns and operates a chlor-alkali plant in Kwinana. Based on membrane process technology, the plant was purpose built for direct supply of 18 000 tonnes per annum chlorine gas to Tiwest. Caustic soda is a co-product and is utilised by mining and other industries.
Tiwest Joint Venture	Tiwest Joint Venture - Kwinana Pigment Plant was officially opened on 21 <sup>st</sup> October 1991. Using feedstock from Tiwest's Chandala complex, the Kwinana plant currently produces 95,000 tonnes of pure white titanium dioxide pigment a year. Most of the Kwinana plant's TiO <sub>2</sub> pigment production is sold into South East Asia for use in paints, plastics, paper manufacturing and colour enhancing dyes.
Water Corporation	The Water Corporation delivers high-quality water and wastewater services to 1.8 million domestic and industrial users across Western Australia. Water Corporation has built the biggest water recycling plant of its kind in Australia. The project involves a highly sophisticated filtration and reverse osmosis plant. The plant reduces industry demand for scheme water by 6 GL a year, and reduces the amount of treated industrial wastewater discharged into Cockburn Sound by 2 GL a year. In addition, the biggest desalination plant (45GL) in the southern hemisphere is under construction in Kwinana, with expected completion in mid 2006.
Wesfarmers LPG Pty Ltd	Wesfarmers LPG owns and operates a plant at Kwinana which extracts Liquid Petroleum Gas from the natural gas stream in the Dampier to Bunbury Natural Gas Pipeline. The plant commenced production in 1988 and was originally designed to process 320 TJ/day of Natural gas, producing 150,000 tonnes/annum of LPG. The plant has undergone a number of plant upgrades since start up in 1988 and now has a design capacity of 500 TJ/day of Natural Gas with a production capacity capability of 350,000 tonnes/annum of LPG.
Western Power – Kwinana Power Station	The total generating capacity of the station is 900MW. The power station can burn coal, natural gas or fuel oil. There are six units (4 x 120MW, 2 x 200MW) and a 20MW gas turbine. Power from the station is fed into the South West Interconnected System, where it provides up to 30% of the system's requirements. In KIA Western Power also operates 240 MW gas fired combined cycle power station and a co-generation plant, providing electricity and superheated steam to Tiwest.
WMC Kwinana Nickel Refinery	The Kwinana Nickel Refinery is the world's third largest producer of refined nickel. It is an integral part of the WMC nickel business unit, which comprises mines at Mt Keith and Leinster, a smelter at Kalgoorlie and a nickel refinery at Kwinana. The Nickel Refinery was commissioned in 1970. It currently has a production capacity of 67,000 tpa of nickel.



The Kwinana Industries Council (KIC) was established in 1991 to manage the collective interests of the industries in the area, which is in close vicinity to several residential areas (Towns of Kwinana, Rockingham and Cockburn), and the Cockburn Sound, a sensitive marine environment. The KIC took right from its establishment on behalf of its member companies responsibility for the coordinated air and water monitoring of the respective air- and watersheds, and in 2001, KIC initiated an exploration into further opportunities for regional resource synergies in the area. A regional economic impact study was conducted and included an analysis of the principal material and energy flows within the area and the level of industrial integration (SKM 2002). The study also attempted to capture the contribution of the Kwinana industries to sustainable development, as illustrated in Box 3.1 below.

**Box 3.1 Triple Bottom Line Benefits from Kwinana Industrial Area (SKM 2002)**

Economic Benefits

Kwinana industries are a major driver for the Western Australian economy. The bottom line is that annual output worth \$ 8,700 Million, employee earnings of \$600 Million. 24,400 jobs are directly or indirectly dependent on Kwinana operations and investments. These industries account for 22 percent of the manufacturing sector income in WA.

Environmental Performance

Environmental initiatives are widespread around cleaner production, waste minimisation, energy efficiency, water conservation and noise abatement. The interdependency of Kwinana industries helps provide environmental benefits beyond what is achieved by widely dispersed industries.

Social Performance

Kwinana industries have a direct employment of 3,600 jobs and 70 percent of the workforce lives locally. Indirect and induced employment is over 20,000 jobs. KIC provides a permanent platform for dialogue between industry and members of the community. Industry supports a range of community initiatives, both financially as well as through contributions of staff time.

The growing interdependency of the Kwinana industries was studied in greater detail. Between 1990 and 2001, the number of core process industries increased from 13 to 28. The number of existing interactions increased from 27 to 106 (including 68 between core process industries and 38 with service and infrastructure industries). Each interaction represented either transfer of product(s) or commercial cooperation. There may be several products traded for each interaction. Based on a preliminary review of material and energy flows in the area, another 55 possible interactions with potential of many more involving service and infrastructure industries were identified, but they were not subjected to any technical and economic feasibility study. The growing complexity of the industrial integration is illustrated in the diagram in Appendix B.

The synergies captured in the economic impact study are quite diverse, but seem to fall in three principal categories, i.e.:

- *By-product Synergies* (type 1): these involve the use of previously disposed by-product from one facility by another facility to produce a valuable by-product. By-product synergies are quite elaborate with regard to industrial gases and inorganic process residues. The calcium carbonate waste from the nickel refinery is used as raw material by the cement plant. In a new gas synergy, BOC receives refinery gas from the BP oil refinery, to separate, clean and pressurise hydrogen for the hydrogen bus trial, which commenced in Perth in 2004. The full list of exchanged products identified in the SKM study is provided in Table 3.5.



Table 3.5 List of by-product exchanges in year 2000 (SKM 2002)

OUTPUT FROM	INPUT TO	MATERIAL EXCHANGED
Alcoa World Alumina Australia	CSBP Ltd	Caustic soda
BP Refinery (Kwinana) Pty Ltd	Coogee Chemicals Pty Ltd	Sulphur
BP Refinery (Kwinana) Pty Ltd	WMC Kwinana Nickel Refinery	Hydrogen
BP Refinery (Kwinana) Pty Ltd	WMC Kwinana Nickel Refinery	Molten sulphur
BP Refinery (Kwinana) Pty Ltd	Wesfarmers CSBP Ltd	Sulphur
WMC Kwinana Nickel Refinery	Air Liquide WA Ltd	Carbon dioxide
WMC Kwinana Nickel Refinery	BOC Gases Australia Ltd	Hydrogen
WMC Kwinana Nickel Refinery	BOC Gases Australia Ltd	Carbon dioxide
WMC Kwinana Nickel Refinery	Cockburn Cement Ltd	Calcium carbonate
WMC Kwinana Nickel Refinery	Coogee Chemicals Pty Ltd	Sulphuric acid
WMC Kwinana Nickel Refinery	Wesfarmers CSBP Ltd	Hydrogen
WMC Kwinana Nickel Refinery	Wesfarmers CSBP Ltd	Ammonium sulphate
WMC Kwinana Nickel Refinery	Summit Fertilizers	Ammonium sulphate
WMC Kwinana Nickel Refinery	Co-operative Bulk Handling Ltd	Carbon dioxide
Tiwest Joint Venture	Coogee Chemicals Pty Ltd	Hydrochloric acid
CSBP Ltd	Air Liquide WA Ltd	Carbon dioxide
CSBP Ltd	Air Liquide WA Ltd	Hydrogen

Details for several examples of by-product synergies are as follows:

- *CO<sub>2</sub> from CSBP to Air Liquide* - CSBP produces carbon dioxide as part of the production of ammonia. Since 1990, CSBP has sold a portion of these emissions to Air Liquide for industrial reuse such as the manufacture of carbonated beverages. This initiative reduces the emissions of carbon dioxide to atmosphere. CSBP continues to investigate potential synergies with other industries.
- *Hydrochloric acid from Tiwest to Coogee Chemicals* - Dilute hydrochloric acid is generated from scrubbing the gas stream from the chlorination step in the titanium dioxide pigment process at Tiwest. The acid was previously neutralised in the waste treatment plant. Two initiatives were realised during 1997 to recover the hydrochloric acid: (1) as acid for sale and (2) for use as ammonium chloride at the synthetic rutile production operation. For this purpose a second scrubber was installed to produce hydrochloric acid at a higher concentration that enables reuse as a low quality acid. Waste hydrochloric acid is transferred to neighbouring Coogee Chemicals, which converts it to ammonium chloride and tankers it for use to Tiwest's synthetic rutile plant some 75 km from the Kwinana plant. The cost of the ammonium chloride to Tiwest is significantly cheaper than that previously imported (DEH 2001d).
- *Utility Synergies (type 2)*: this involves the shared use of utility infrastructure. Two cogeneration facilities are already in place. The Edison Mission Energy cogeneration plant (116 MWh capacity) produces all process steam for the BP Oil Refinery, and generates electricity for BP as well as the grid. The cogeneration plant is fired with the excess refinery gas from the oil refinery, supplemented with natural gas. The cogeneration plant avoids about 170,000 ton carbon dioxide emissions per annum.





Moreover the cogeneration plant has much greater flexibility in meeting process steam requirements for the refinery, which has enabled the refinery to achieve greater process efficiencies. The second co-generation facility (40 MWh) provides power and superheated steam for the Tiwest pigment plant, with the remainder of the electricity feeding the grid. Albeit less elaborate, there are also utility synergies for the shared use of waste water treatment plants (between Nufarm and Tiwest, and between CSBP and BP), and shared use of laboratory facilities.

- *Supply Synergies* (type 3): local manufacturer and dedicated supplier of principal reagents for core process industries. Few examples of supply synergies are shown in Table 3.6 below. This third category of supply synergies is listed here, as it was included in the 2002 economic impact study. However these should be regarded as “*business as usual*”, where a business perceives a benefit from co-location with its main customers, a phenomenon well known as “*agglomeration economies*” (Desrochers 2004). These supply synergies do not meet the criteria of traditionally separate industries, as specified by Chertow (2000) for Industrial Symbiosis. The supply synergies are therefore not further focused upon.

**Table 3.6 Examples of supply synergies in Kwinana Industrial Area** (SKM 2002)

OUTPUT FROM	INPUT TO	MATERIAL/S EXCHANGED
Air Liquide WA Ltd	Tiwest Joint Venture	Nitrogen, Oxygen
Alcoa World Alumina Australia	Australian Fused Material P/L	Alumina
BP Refinery (Kwinana) Pty Ltd	CSBP Ltd	Waxes, Sulphur
Cockburn Cement	Tiwest Joint Venture	Lime
Coogee Chemicals	WMC Kwinana Nickel Refinery	Copper Sulphate
Nufarm-Coogee Pty Ltd	Nufarm Australia Tiwest	Sodium hypochlorite, Hydrochloric acid, Caustic soda Chlorine
CSBP Ltd	WMC Kwinana Nickel Refinery	Sulphur, Sulphuric acid, Ammonia

Members of the KIC have started to recognise and value the benefits of regional synergies in terms of economic returns, business efficiencies and reduced costs and liabilities from waste disposal and therefore support the further development and realisation of synergy opportunities through the KIC. These synergy development efforts focus on four themes: inorganic process residues (including fly-ash, bauxite residue, gypsum, etc.); non process waste (in particular support for the collection and recycling of dry recyclables (packaging, office, canteen wastes)); energy and greenhouse gas emissions (capture and utilisation of low grade heat, and improvement of the exchange of energy efficiency practices between the Kwinana companies) and water conservation. Two projects are being commissioned from late 2004 that will greatly enhance the regional synergies:

- *Kwinana Water Recycling Plant (KWRP)*: a joint initiative of the Water Corporation and the Kwinana industries to achieve the double benefit of greater overall water efficiency and reduced process water discharges into the Cockburn Sound. A micro filtration/reverse osmosis unit has been built (at a cost of AUD\$ 20 million), which takes secondary treated effluent from the nearby Woodman Point wastewater treatment facility to produce a low TDS (Total Dissolved Solids) water supply, which is initially used by CSBP, Tiwest, Edison Mission Energy, BP and HIs melt to replace scheme water (6 GL/year, about 2-3% of the total scheme water use in the drought-affected Perth metropolitan area). The low TDS enables the process plants to cut chemicals use in cooling towers and other process applications, thereby reducing metal loads in their effluents. In exchange for taking water from the



KWRP, the industries will be able to discharge their treated effluents into the deep ocean outfall through the Water Corporation pipeline, thereby eliminating process water discharges into the sensitive Cockburn Sound.

- *HIsmelt Pig Iron Plant:* The HIsmelt plant is the first commercial scale application of the direct smelting technology - which allows for simpler and more flexible iron making, avoiding coke ovens and sinter plants required for the standard Blast Furnace. The environmental benefits will be 20% reduction of CO<sub>2</sub>, 40% reduction of NO<sub>x</sub> and 90% reduction of SO<sub>x</sub>. Upon completion of commissioning (which began in November 2004) and successful start up of commercial operation (from mid 2005), the plant will be able to source a number of inputs locally in the Kwinana area, such as lime, lime kiln dust and treated wastewater and provide outputs with potential for supply in KIA, such as slag and gypsum. The HIsmelt Process will utilise the WA reserves of iron ore fines, which are currently not suitable for blast furnace feed due to their high phosphorous content (HIsmelt 2002).

As a response to the recommendations in the Kwinana economic impact study and the KIC initiative to identify new synergy opportunities, a number of other projects have been identified and/or implemented:

- *Gypsum from CSBP to Alcoa* - CSBP produced gypsum, calcium sulphate, as a by-product of the manufacture of phosphoric acid. This material was stockpiled at CSBP's Wellard Road site during the 1980's. Some 1.3 million tonnes is stored at the site. CSBP has extensively reviewed reuse options for this material including the use in plasterboard, sale to farmers, and use in soil amendment. During this research process, it was determined that the material could be utilised by Alcoa to assist in plant growth and soil stability in their residue areas. Alcoa continues to take this material on an ongoing basis, approximately 10 000 tonnes each year.
- *Reuse of recycled effluent* - Treated wastewater from Kwinana wastewater treatment plant is infiltrated into groundwater upstream from Alcoa groundwater abstraction bores. The bores supply water for Alcoa's process water circuit for the Kwinana alumina refinery. Thus the discharge from Kwinana WWTP is indirectly used by Alcoa in its process and is estimated at approximately 1 GL pa.
- *Perth Seawater Desalination Project* will have the potential to share intake facilities and to take used cooling water associated with Western Power's existing and planned power generating facilities at the Kwinana Power Station site (EPA WA 2004).

### 3.3.2 Gladstone Industrial Area

Gladstone, situated on the central Queensland coast about 540 kilometres north of Brisbane, has a population of about 40,000 in the region, which extends from Boyne Island in the south to Yarwun in the north.

Major industrial operations have been part of the Gladstone region since the Queensland Alumina Limited commenced operation in 1967. Today there are nine major industries (summarised in Table 3.7) operating in the region and they form an association called the Gladstone Area Industrial Network or GAIN. GAIN comprises nine industries:



Table 3.7 Summary of Gladstone industries (Corder 2005)

COMPANY	SUMMARY
Queensland Alumina Limited	Queensland Alumina Limited (QAL) has been operating since 1967 and is the largest alumina refinery in the world. Annually the refinery processes about 8 million tonnes of bauxite to produce about 3.7 million tonnes of alumina, which represents about 10% of the world alumina production, through the four stage Bayer process. The refinery covers an area of 80 hectares of a 400-hectare site on the south-east outskirts of the city. Adjacent to the plant is a wharf and storage facility on South Trees Island, which is connected to the mainland by a causeway and bridge
NRG – Gladstone Power Station	Situated a few kilometres from the centre of Gladstone, the power station is the largest coal fired power station in Queensland. A total of 1680MW is provided by six 280MW turbines from coal, which is delivered by rail from central Queensland. The plant's largest customer is the Boyne Island aluminium smelter and any power reserves are transmitted to the Queensland electricity grid.
Cement Australia	Situated at Fisherman's Landing north of Gladstone, the Cement Australia clinker plant has been operating for about 25 years. The plant receives limestone, mined from the nearby East End Limestone mine, to produce about 1,500,000 tonnes of clinker annually. Recently the old clinker kiln was re-commissioned as a quick lime kiln with a proposed annual production of 300,000 tonnes.
Boyne Smelters Limited	Situated on Boyne Island, about 20 kilometres south of Gladstone, Boyne Smelters, produces over 500,000 tonnes of aluminium annually using alumina transported by conveyor from QAL. The smelters have been operating since 1982.
Orica Chemicals Pty Ltd	The Orica chemical plant, situated about 7 kilometres west of Gladstone, began operation in 1990. It currently produces 275,000 tonnes of ammonium nitrate, 50,000 tonnes of sodium cyanide and 9,500 tonnes of chlorine annually with plans to expand the ammonium nitrate production by 25,000 tonnes by March 2005 and a further 300,000 tonnes in 2006.
Comalco Alumina Refinery	Situated in the Yarwun area, 10 km northwest of Gladstone, the Comalco Alumina Refinery (CAR) is the first new alumina refinery in Australia since 1985. The first stage of CAR became operational early March 2005 and will produce 1.4 million tonnes per annum of alumina. A further two stages can be added so that over 4 million tonnes per annum of alumina would be produced.
Central Queensland Port Authority	The Central Queensland Port Authority is an amalgamation of the Gladstone Port Authority and Rockhampton Port Authority, which came into effect from 1 <sup>st</sup> July 2004. The port handles about 40,000,000 tonne coal per year. A significant expansion is currently in progress.
Queensland Energy Resources Limited	A demonstration plant, known as Stuart Stage 1, was in operation to produce shale oil and naphtha from oil shale. In July 2004 QERL announced the completion of Stage 1 with a new focus of conducting extensive research and design studies for the next phase.
Gladstone Area Water Board	The Gladstone Area Water Board (GAWB) has only recently joined GAIN. The main objectives of GAWB are to supply water to industries and community within the Gladstone region from the Awoonga dam as well as planning, developing, operating and maintaining the infrastructure. The Awoonga dam is the only major water source for the Gladstone region.

Two recent studies have concentrated on highlighting the potential for sustainability in the Gladstone region:

- Sustainability Report for the Gladstone Region 2001 – Better Gladstone, Better World; Leading the Gladstone Region towards Sustainability
- By-Products Mapping Study

Both studies were co-ordinated by the Gladstone Region Sustainability Group and were both completed in 2001.



*Sustainable Gladstone (Anon. 2001a)*

The main aim of the Sustainability Report was to establish a list of indicators as the starting point for a sustainability roadmap for the Gladstone region. By being able to measure the state of the Gladstone region at any one time using these indicators, the report stated it would be possible to make good decisions about policy relating to sustainable development. Three categories, environment, economic and social, each with five sustainability indicators were identified and the report presents excellent information regarding relevant data, analysis and commentary on facets relevant to sustainability issues in the region. However, since the completion of this study there has been little progress along the road to a sustainable regional program.

*By-Products Mapping Study (GAPD 2001)*

The By-Products Mapping study was undertaken as part of the partnership between the Gladstone Area Promotion and Development Ltd (on behalf of the Gladstone Region Sustainability Group) and the Australian Greenhouse Office to encourage the reduction of greenhouse gas emissions and to promote and facilitate sustainable development in the Gladstone region. This study investigated the potential for minimisation of wastes and exchange of by-products within the Gladstone region.

The main focus of this study was to collate existing information on the various waste stream types and quantities of by-products being generated in the region so that this information could be stored in an MS Access database. The plan was that the database would then be available across the region so that synergies could be more easily identified between two industries or organisations.

One of the main challenges of the study as reported by the authors was the collating of information of wastes and by-products from medium to large industries, which were the target of the study. As a consequent, the MS Access database although a very good platform for storing and presenting the waste, by-product and raw material data did not contain all the desired information at the end of the study.

The report associated with the Access database provides comprehensive overview of the industries and related factors across the region plus discussion of possible waste and by-product re-use or synergy opportunities. Some of the important opportunities relevant to the GAIN industries were integration of wastewater treatment and re-use, integration of heat recovery, recovery of metals from wastes, sequestration of carbon dioxide to achieve carbon credits, recovery of combustibles for energy use, enhanced recovery and re-use of construction, demolition and road building wastes, and the development of a technology innovation program in the region to maximise use of secondary resources (by-products and waste).

This study provided a solid basis for identifying synergic opportunities within the region. In fact since the completion of the report some of the opportunities listed in the report have been implemented as synergies, such as the secondary effluent re-use as wash water and waste transfer facility both at Queensland Alumina.

Currently there are several examples of re-use of waste or by-products amongst the GAIN industries (Corder 2005):

- Alternative fuels strategy at Cement Australia
- Secondary effluent re-use at Queensland Alumina
- Waste transfer facility at Queensland Alumina
- Power station fly ash as a cement additive at Cement Australia



### Alternative Fuels Strategy at Cement Australia

Cement Australia is partly owned by the Holcim group, which has an internal and voluntary policy to use non-traditional raw materials and fuels for clinker production, due to Holcim being part of the Sustainable Cement Initiative of the World Business Council for Sustainable development (WBCSD). The policy known as the “Alternative Fuels and Raw Materials” (AFR) aims to provide environmental, economic and social benefits by reducing greenhouse gas emissions and using wastes and by-products as a fuel source to both reduce costs and replace non-renewable fuel sources, such as coal and gas (Holcim (n.d.)). Over a number of years Cement Australia has been using domestic tyres as an alternative fuel source in their cement kiln. Using tyres as fuel can improve the process of clinker production and the steel fibres present in the tyre are beneficial as an iron replacement. Another alternative fuel used at Cement Australia is solvents from Teris in Victoria, another company that is part of the Holcim group. The solvents are sent by rail transport up to Gladstone from the Teris Dandenong plant (Cement Australia (n.d.)).

In July 2004, a trial of spent cell linings from the Boyne aluminium smelter commenced. The spent cell linings (SCL), which have been accumulating at the smelter, provide calorific heating value in the kiln, while the kiln also destroys any contaminants that may have built up in the cell lining.

### Secondary Effluent Re-use at Queensland Alumina

In 2002, Gladstone suffered one of the worst droughts ever experienced in the area. For a region that has major industries and a community relying on water from a single water source, Awoonga Dam, the ramifications of the water shortage were immense. The seriousness of the water shortage resulted in the Gladstone Area Water Board initially imposing a 10% water restriction, in April 2002, which were then increased to 25% water restriction, in October 2003. If not for heavy rains in February 2003 water restrictions of 50% would have been imposed.

As a large consumer of water (approximately 40ML per day in 2001), QAL was faced with significant production limitations if they were forced to operate with 25% less water than usual (H.D.J. Stegink *et al.* 2003). Thus, QAL decided to fund a project to build an 8.5 km pipeline so that secondary treated effluent from the Calliope River Sewage Treatment Plant could be used at QAL as wash water in the red mud washing process. Some of the secondary treated effluent was already being used by the Gladstone Power Station for ash conditioning.

Not only was QAL receiving effluent water, which would be suitable for the desired duty, but the secondary treated effluent was not discharging into Calliope River. By now not discharging to the Calliope River the council will not need to construct tertiary treatment facilities if or when this is a requirement from the EPA (Doak 2004).

This synergy has several environmental, economic and social benefits:

- No more discharge of secondary effluent to the Calliope River
- Raw water usage from Awoonga Dam is reduced by about 6.5 ML per day
- No need for constructing a tertiary treatment plant if this is to become a future requirement by the EPA for discharging effluent to estuaries

### Waste Transfer Facility at Queensland Alumina Limited

In June 2003, a waste transfer facility, operated by Transpacific Industries, a Queensland-based waste specialist company which handles the sorting and segregation of materials, was



opened at QAL. One of the main incentives for building such a facility was to prevent waste from going to landfill, a non-sustainable solution for the future.

Most of QAL's waste is sorted at the facility for reuse, recycling or reselling. Apart from old asbestos waste, which is handled by specialists and bauxite residue and fly ash, which are discharged to their respective disposal areas, all other waste is delivered to the facility where it is weighed before being placed on a concrete pad for sorting by hand.

After six months of operation, QAL reported total elimination of waste going to landfill. At this time, early 2004, the reported recycle rate was about 85% of wastes, which were mostly metal, cardboard and wood, and the facility was cost neutral. Another item that is successfully recycled is old gloves. Of the 30,000 gloves that were recovered in 2003, 25,000 were recycled at an off-site facility before returning to QAL (QAL (n.d.)).

By mid-2004 the recycle rates at the facility were reported to be over 90% with the facility now operating as cash positive.

#### *Power Station Flyash as a Cement Additive at Cement Australia*

Pozzolanic Enterprises, a subsidiary of Cement Australia, collects fly ash from the Gladstone Power Station for use as cement additive in Cement Australia operations, including the operation at Gladstone (Cement Australia (n.d.)). Fly ash has chemical and physical properties, in particular its sphericity and fine size, which impart benefit to concrete in both the plastic and harden states.

Pozzolanic selects fly ash that meets the required specifications, which is approximately a third of all the fly ash that is produced by the power station. The remaining fly ash is discharged to local bunds.

The collection of fly ash from power stations for use as a cement additive is not only common practice but a synergy where both parties benefit; the power stations do not have to dispose of the fly ash in the usual manner within local bunds and the cement operations have an improved product as well as using less limestone, a non-renewal resource, to produce the same amount of cement.

### ***3.4 Comparative Review***

The overall intent of the CSRP research into tools and methodologies for regional synergies is to provide the resource processing sector and other industries and their stakeholders with practical tools to improve synergy development and maximise its contribution to sustainable development. The previous sections provided evidence that Industrial Symbiosis can be achieved and already provides real time benefits for the industries and regions involved. This section now focuses on the enabling mechanisms for the regional synergy process, both from the technical and organisational perspective.

#### ***3.4.1 Tools and Methodologies***

##### *3.4.1.1 Tools*

Traditional approaches for engineering design tend to focus on modelling and optimisation of material and energy flows within the process and a suite of design tools has been developed for that purpose. The flow of materials and energy between processes and even between facilities poses a new challenge to such engineering tools, requiring these to be able to accommodate greater complexity, in terms of number of processes, number of flows and distance between them.



- *Industrial Materials Exchange (IME) tool*

The IME (also known as IMEP – Industrial Materials Exchange Planner) tool, developed by Bechtel Corporation appears to be the most widely cited tool for Industrial Ecology design and is intended for use in the identification and analysis of by-product synergies, as well as for planning new eco-industrial projects. The IME is composed of a technology database of over 300 primary industrial processes as well as recycling and reprocessing operations, and a set of powerful scenario development and optimisation tools for evaluating alternative configurations.

The tool can be used to design new eco-industrial parks, as well as to identify new synergetic interactions between existing industrial facilities. Originally developed as a database of material flows associated with selected industrial processes, the tool can be used to search a previously assembled database for a given area to identify multiple possible material exchange links within a region. It has been used in Brownsville, Texas region (BCSD-GM 1997) and in the demonstration project in Tampico, facilitated by the Business Council for Sustainable Development – Gulf of Mexico (Young 1999). In the latter case, however, the number of synergies has been subsequently more than doubled at brainstorming workshops with participants in comparison to those generated by IME.

Unfortunately the IME tool is not available to users outside Bechtel (now Nexus).

Further collaboration between Bechtel and the US DoE's Idaho National Environmental Engineering Laboratory (INEEL), has resulted in a “next generation” version of IME, known as Dynamic Industrial Materials Exchange (DIME), that incorporates dynamic simulation of material flows to aid the design and analysis of by-product synergies that are affected by fluctuation in material availability or process requirements (INEEL (n.d.)).

Another spin-off is the MatchMaker! System based in part on the initial work carried out by Bechtel (Brown *et al.* 1997). The tool is designed as a material exchange system to find outlets for reusing materials based on generic description of candidate companies. It concentrates on materials rather than water and energy and exchanging companies may be located over a wide geographical area, i.e. “virtual” eco-industrial parks. At the time of publication The Matchmaker! System was at the underlying table design and associated queries (MS Access 97). The tool at this stage represents a database frame without data. As the authors acknowledge, the data collection would be an expensive endeavour, involving surveys, site visits, data mining and literature review.

- *Facility Synergy Tool (FaST),*

In 1997 the US EPA developed with the support of a consulting firm, a prototype Industrial Ecology tool kit to help users to identify, screen and optimise by-product utilisation opportunities at a regional scale. The toolkit consists of three interrelated components:

- *Facility Synergy Tool (FaST)*: is a database application that helps a user to identify potential matches between non-product outputs (NPO's) and the resource requirements (material and energy) of common industrial processes. This allows the user to quickly identify potential by-product synergies between facilities, or identify the types of industrial partners that can be recruited to serve as "sinks" for waste streams from existing facilities.
- *Designing Industrial Ecosystems Tool (DIET)*: uses the by-product synergy matches identified in the FaST database tool as inputs to a linear



programming model, which generates optimum scenarios for industrial synergies. DIET allows the user to simultaneously optimise the system for environmental, economic and employment objectives.

- *RealityCheck*<sup>™</sup>: a screening tool to identify potential regulatory, economic and logistical constraints (barriers) to by-product utilisation opportunities. Though originally designed as an integral part of the Industrial Ecology tool kit, it can be used as a stand alone tool.

The tool kit was applied in the design and planning of the Eco-Industrial Park (EIP) in Burlington, Vermont (Industrial Economics 1998). The facility profiles with their material inputs, energy and water usage and non-product outputs (all with quantities and costs) in FaST match the existing facilities and potential recruits for the EIP. FaST was used to identify potential linkages, while DIET has helped the planners and decision makers to investigate the estimated benefits of different EIP scenarios and the RealityCheck was applied to recognise potential constraints on potential exchanges.

One of the goals of the “Materials Flow Through the Community“ project (RBED 2000) initiated by the Chelsea Center for Recycling and Economic Development, Massachusetts, was to assess the effectiveness of the FaST tool in recording and analysing the material inputs and outputs for organisations participating in the project. The project team concluded that the tool is not suited to the project’s needs because of basic formatting flaws, a complicated design that is not user friendly and requirement for advanced MS Access skills in order to be used. For the purposes of the project a survey tool was used.

Although the FaST tool was designed to be widely used and freely available, its use has been rather limited. It is currently available to download from <http://www.smartgrowth.org/library/article.asp?resource=431> and it requires users to have Microsoft Access 97 version installed on their PCs, which significantly restricts its evaluation and/or use. The database contains limited choice of pre-determined facility profiles, which places further constraints on its use. Moreover, FaST uses 1997 input-output data, which should be considered reasonably outdated as industries are continually innovating their processes and use of materials.

DIET was a prototype that is no longer available (Giannini-Spohn 2004).

- *Use of GIS to identify and optimise synergy opportunities* (Allen *et al.* 2002b; Nobel 1998)

One of the practical barriers to the widespread implementation of waste stream utilisation schemes is the high cost of transporting materials from their sources to other facilities that may be able to use them as feedstocks. Since the cost of transporting these materials can often be prohibitive, it seems reasonable to expect that the tools used to design industrial ecosystems should be able to take transportation costs into account. Unfortunately, this is not always the case.

An interesting exception is an Industrial Ecology planning tool developed by Carolyn Nobel (Nobel 1998). The tool incorporates a Geographic Information System (GIS) to help identify feasible water reuse networks and to allow transportation costs to be explicitly included in the optimisation of these networks. By matching streams with compatible water quality criteria, the model identifies feasible water reuse opportunities within the region of interest. Since any individual wastewater stream may have several potential uses, the feasible matches are passed to a linear programming module to calculate the optimal water reuse scenario.





This tool was used to identify and optimise water use and reuse opportunities within a complex of approximately 20 different industrial facilities at the Baytown Industrial Complex in Pasadena, Texas. In this relatively simple example, economically feasible water-reuse networks were identified that had the potential to reduce total freshwater use by more than 90%, while simultaneously reducing water costs by 20%.

The tool was developed using commercial “off the shelf” GIS software and a widely available mathematical optimisation package. Although the tool was developed specifically to illustrate the optimisation of industrial water reuse networks, the underlying approach can be extended to other industrial materials with relatively little additional effort.

All of the above three tools were developed and used within the period 1997-2000. The Bechtel tool might however still be in use internally, but there is no citation in recent publications that refers to it.

Another tool of interest is *Water PINCH* – for any water-related process it is possible to construct a composite profile of water demands (sinks) and wastewater effluents (sources). Water pinch analysis is a systematic approach, using computer-modelling techniques, to optimise water reuse and recycling in complex manufacturing operations. The objective of water pinch analysis is to reduce the overall demand by quantifying potential water savings and identifying how these savings can be achieved. Water pinch has been applied in an industrial ecosystem project in the Rotterdam, The Netherlands, where it showed the possibility to develop an optimal water use and cascade circulation both within companies as well as in clusters of companies (Baas 1998). More information on PINCH analysis is provided in Section 4.3.2.1.

The reviewed case studies provide little indication of engineering tools that have been specifically used for the generation of ideas for synergy opportunities, except in the case of Tampico, Mexico where the Industrial Materials Exchange (IME) tool was used. There is some indistinct information that a customised software package is being used in NISP, UK to assist the process of matching various inputs and outputs. A process integration tool, namely water pinch was used in Rotterdam for water and wastewater analysis.

#### 3.4.1.2 Methodologies:

Generally the methodology used by the majority of the Industrial Symbiosis projects is basically the same, with the exception of few projects, where the aim was to take stock of the existing and possible synergetic opportunities, i.e. developing status quo case studies, with no intention for further progress.

The basic phases/steps of a methodology are:

- *Awareness & Recruitment:* seeking support and commitment of a core group of participant companies.
- *Data Collection:* to account for each company’s in-flows and out-flows of materials, commodities and utilities. That phase generally uses a survey instrument, usually followed by an on-site visit or telephone interview.
- *Analysis/Synergy identification:* Usually the data is entered into a database of some format. Initially a large number of rough matches is identified as a starting point. Facilitated brainstorming meetings (numbers vary with projects) are organised to either screen the recognised synergies or to identify additional ones.



- *Implementation:* through further meetings to prioritise projects and develop action plan for implementation of attractive ones.

An optional follow up phase could be included such as “monitoring and continuation” to provide on-going support, but its inclusion largely depends on the financial and contractual arrangements.

Seven of the case studies (identified in Table 3.1) have followed a similar methodology or a step-by-step approach that has resulted in a number of potential synergies, which are subject later to a feasibility analysis to result in a list of viable ones that could be pursued commercially. This sequence has been best illustrated in the case studies in Alberta, Golden Horseshoe, NISP, and Rotterdam.

### 3.4.2 Technologies for Regional Synergy Development

In many of the documented case studies there is no emphasis on technologies needed for the implementation of the synergies. In most reports featuring technology needs, only project specific technologies were mentioned rather than a comprehensive overview. All documented technology needs are presented in the Table 3.8. The majority are proven technologies that would contribute to the realisation of synergy projects.

In Sarnia-Lambton’s case study it was recognised that projects, which are outside core business, have much greater chance of success if they use developed and proven technology, and thus do not involve the added uncertainty of technological risk. Resource recovery and environmental technology providers were found to have a key role in forming linkages between companies in the Montreal case study.

**Table 3.8 Specific technology needs as identified in individual projects**

CASE STUDY	TECHNOLOGY NEEDS
Alberta	The following technologies were identified for possible synergies and all were expected to be available: <ul style="list-style-type: none"> <li>• Demonstration plant for the production of ethanol from biomass</li> <li>▪ Micro-turbine technology</li> <li>▪ Co-firing and cogeneration</li> <li>▪ SO<sub>2</sub> control technologies</li> <li>▪ Centrifuge technologies to collect fine material rich in titanium and vanadium from ores</li> <li>▪ Using steel slag in cement process using the Cemstar technologies.</li> <li>▪ Technologies that result in the conversion of biomass to bio-oils.</li> <li>▪ To use sulphur as a heat source</li> <li>▪ Coke cleaning technology</li> </ul>
Tampico	An innovative technology for recovery of polymer plastics through cryogenic processing has been proposed
Montreal	<ul style="list-style-type: none"> <li>▪ Existing technology to use sulphur polymer as an asphalt extender could be used to upgrade the physical properties of the pitch.</li> <li>▪ Technology for pyrolysing tyres and plastics</li> <li>▪ Regenerable desulphurisation technology</li> <li>▪ Vapour recompression technology to remove water from the ethylene glycol in recovered de-icing fluids</li> </ul>
Quebec	<ul style="list-style-type: none"> <li>▪ Technology for removal of zinc from Electric Arc Furnace dust;</li> <li>▪ Technology to capture, compress and transport the hydrogen gas and others.</li> </ul>
Sarnia-Lambton	<ul style="list-style-type: none"> <li>▪ Flue gas desulphurisation wet lime technology</li> <li>▪ Energy-from-waste technology: Waterfall mass burn for municipal solid waste and a fluidised bed boiler for residual hydrocarbons</li> </ul>
Saint John	A specific technology for separating contaminants such as staples and twist ties from the used plastic bags that are used as feedstock for plastic bags manufacturing



### 3.4.3 Drivers and Barriers

Drivers and barriers towards the identification and implementation of synergies between industrial partners were specifically identified in limited number of case studies, in fact only in North American case studies: Alberta, Golden Horseshoe, Montreal, Quebec, Sarnia-Lambton, Saint John and Tampico.

A wide range of drivers and incentives is listed, that encourage the implementation of by-product synergies. The primary driver behind the development of any industrial partnership between companies is economics, which is often used as the umbrella term to cover resource cost benefits, by-product revenue, process efficiency gains and lower resource vulnerability (where industries compete for a limited resource, e.g. water allocation). Secondary drivers as identified are related to the regulatory pressure or perceived future liability and pursuing synergy interaction for environmental benefits. Table 3.9 summarises the drivers described in the case studies. It should however be noted that details on drivers are mostly patchy, as for example the specific nature of the economic drivers is not disclosed.

**Table 3.9 Specific drivers as identified in individual projects**

DRIVERS	CASE STUDIES
Economic	Golden Horseshoe, Guayama, Kalundborg, Sarnia-Lambton, Montreal, Quebec, Styria, Tampico
Regulatory pressure/future liability	Montreal, Saint John, Sarnia-Lambton, Kalundborg
Eliminate wastes/Environmental benefits	Golden Horseshoe, Quebec, Kalundborg
Environmental policy	Sarnia-Lambton
To provide evidence of sustainable benefits of by-product synergy	Tampico
Government drivers – such as taxes and financial incentives	Alberta, NISP
Corporate policy	Montreal
Necessity to improve competitiveness	Montreal

Although barriers were specifically recognised in individual projects (Table 3.10), the generic barriers toward implementation of synergies as outlined in the BCSD-GM Primer on By-Product Synergy (BCSD-GM 1997) appear to be applicable to all of the case studies. These barriers include:

- *Technical*: Is conversion of the by-product technically feasible?
- *Economic*: Is it economically feasible?
- *Business*: Is it competitive compared to other investment opportunities?
- *Corporate practice*: Is the company's decision-making process hindering investment?
- *Regulatory*: Are there government-created barriers to synergies (e.g. through legislation)?
- *Risk*: Could use of or transportation of a "waste" lead to increased liability? Who is responsible?
- *Geographic*: Can the by-product be economically transported from its generator to its consumer?
- *Trust*: Are companies comfortable working together?
- *Time*: Is by-product synergy a low priority in the organisation?



Table 3.10 Specific barriers as identified in individual projects

BARRIERS	CASE STUDIES
Regulations/Permitting process	Alberta, Golden Horseshoe, Montreal, NISP, Quebec, Sarnia-Lambton, Tampico
Community acceptance	Alberta, Golden Horseshoe, Quebec Sarnia-Lambton
Lack of time	Quebec, Golden Horseshoe
Need for technical innovation	Alberta, Golden Horseshoe
Dependence on by-product supply	Alberta, Golden Horseshoe
Absence of full-cost accounting	Alberta, Golden Horseshoe
Economical	Quebec, Montreal
Economies of scale	Alberta, Quebec
Lack of internal support and commitment	Rotterdam,
Reluctance of companies to become involved in activities different to their core business	Sarnia-Lambton
Lack of awareness on potential uses of by-products	Golden Horseshoe
Competition with raw materials suppliers	Golden Horseshoe
Need for material conversion	North Texas
Distance	Alberta
Absence of industrial champion	Sain John
Technology risk	Montreal
Liability	Montreal

Successful implementation of by-product synergies is critically dependent on early identification and understanding of potential problems. Some barriers, such as trust, resources or corporate practices can be addressed and resolved within and between companies. In order to overcome social or regulatory barriers, companies need to put substantial effort in communication and cooperation with regulatory agencies and local and wider communities. Technical and geographic barriers can be overcome, providing that technological innovation could reduce the cost of by-product conversion and transportation.

Regulatory barriers toward implementation of synergies were identified in all of the individual reports as a major obstacle for progressing with what appear to be economically viable synergies. Once something is defined or even simply considered by the general public as a waste, it is subject to a unique set of regulations governing its transportation and disposal. This often excludes the consideration for re-use, making it a burdensome process for an industry to gain permission to adopt approaches other than those outlined in the regulations. For example, in Tampico, used chemical drums were classified as hazardous wastes, so companies wishing to reuse these materials would have to clear many legal and regulatory hurdles. In another case, the by-products from a state-owned company are considered “national property”. Therefore, a private facility wishing to reuse them would have to consider all of the legal ramifications (Young 1999). In the case study from Montreal spent oils and solvents are transported for use in USA, as no cement plants in Quebec are permitted to use these fuels.

### 3.5 Concluding Remarks

This chapter focused on the practical application of Industrial Symbiosis concepts in heavy industrial areas. National and international examples were identified from literature and web searches, and interaction with industry and Industrial Ecology practitioners. It showed that there is great interest in the notion of regional synergy development. Many industrial areas around the world have attempted its implementation generally with at least some success with regard to creating novel synergies that involve exchange of material, water or energy



resources, and that bring real time economic and environmental benefits to the industries and communities involved.

The detailed review involved sixteen international and two Australian examples. Given the great differences in amount and quality of the available (English) information on each it turned out to be difficult to draw definite conclusions in regards to best practice in the development and implementation of regional resource synergies. The trends are however quite clear:

- General agreement around the use of a workshop based facilitation methodology, involving elements of awareness raising, input/output inventory and quantification, synergy opportunity identification, and feasibility studies and business planing.
- Prevalence of synergies involving comparatively straightforward exchanges between two companies of process waste, with minimal -if any at all- processing of the waste stream prior to its external reuse.
- Limited attention for the technological and engineering challenges associated with creating regional synergies. Or, vice versa, focus on comparatively simple technological opportunities.
- The opportunistic nature of synergy opportunities developments so far. Firstly this may reflect the abundance of comparatively straightforward (“low-hanging-fruit”) synergies that generally emerge with an initial focus on regional synergy development in many industrial areas. Secondly, it could also imply that current efforts only scratch the surface, as more innovative and complicated synergies are not yet being identified or pursued.

The review of current practice of Industrial Symbiosis implementation confirmed that Kwinana and Gladstone compare favourably with the well-regarded international examples. This relates to the level and maturity of industry involvement and collaboration, and the commitment to future Industrial Symbiosis successes as the cornerstone for the area’s contributions to sustainable development. Moreover, Kwinana stands out with regard to the number, diversity, complexity and maturity of existing synergies. Gladstone is remarkable as among the documented examples of regional synergy development, it stands out as an example with unusually large geographic boundaries and unusually high dominance of one industry sector (the alumina and aluminium industries and its power supplier).





## Chapter 4: ECO-EFFICIENCY

### 4.1 Introduction

The boundaries between company internal and external, regional, synergies are often quite arbitrary. What is considered to be an internal synergy between different chemical plants of an integrated chemical works would be an external regional synergy if these chemical plants were owned and operated by different companies. For example CSBP in its Kwinana works uses the waste heat produced by the ammonia plant to produce electricity to (partially) power its other plants, including its fertiliser and chlor-alkali plants. It is therefore useful to review how company-internal synergy and efficiency initiatives have been developed and implemented, as a source of ideas to drive the future identification and implementation of regional synergy opportunities.

This chapter aims to do so. The overall focus is on Eco-Efficiency, the term increasingly used to refer to business and process improvements that enhance business performance while reducing environmental impacts. The key concepts are introduced in section 4.2, along with a range of examples to demonstrate their applicability to the resource processing sector. Sections 4.3 and 4.4 then subsequently focus on the tools and indicators used to drive the implementation of Eco-Efficiency in businesses. Section 4.5 contains conclusions and recommendations with regard to their application for the development and implementation of regional synergies in heavy industrial areas.

### 4.2 Concept and Practice

#### 4.2.1 Eco-Efficiency

Eco-Efficiency was first promoted as a concept by the World Business Council for Sustainable Development (WBCSD) in 1992, but has since been endorsed widely by for example Organisation for Economic Co-operation and Development (OECD), European Union (EU) and the Australian government.

*“Eco-Efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the earth’s estimated carrying capacity”.*(WBCSD 2000b)

In short, it is concerned with ‘*creating more value with less impact*’ or using natural resources more efficiently to deliver products and services that better meet consumers’ demands and cause lower environmental impact. It is important to understand that Eco-Efficiency is not limited to making incremental efficiency improvements in existing practices and processes. On the contrary, Eco-Efficiency should stimulate creativity and innovation in the search for new ways of doing things. Nor is Eco-Efficiency limited to areas within a company’s boundaries, such as in manufacturing and plant management. It is also valid for activities upstream and downstream of a manufacturer’s plant and involves the supply and product value-chains.

Eco-Efficiency is concerned with three broad objectives (WBCSD 2000b):

- *Reducing the consumption of resources:* minimising the use of energy, materials, water and land, enhancing recyclability and product durability, and closing material loops.
- *Reducing the impact on nature:* minimising air emissions, water discharges, waste disposal, and the dispersion of toxic substances, as well as fostering sustainable use of renewable resources.
- *Increasing product or service value:* providing more benefits to customers through product functionality, flexibility and modularity, providing additional services (such as



maintenance, upgrading and exchange services) and focusing on selling the functional needs that customers actually want.

The WBCSD has identified seven elements that businesses can use to improve their Eco-Efficiency (WBCSD 2000b):

- Reduce the material intensity of goods and services;
- Reduce energy intensity of goods and services;
- Reduce dispersion of toxic substances;
- Enhance recyclability of materials;
- Maximise sustainable use of renewables;
- Extend product durability; and
- Increase service intensity of goods and services.

These elements are quite generic. Applied to resource processing sector some elements can be rephrased and narrowed down to customised Eco-Efficiency themes as illustrated in Table 4.1 below.

**Table 4.1 Eco-Efficiency elements**

GENERIC ECO-EFFICIENCY ELEMENTS (WBCSD 2000B)	ECO-EFFICIENCY THEMES SPECIFIC TO RESOURCE PROCESSING (Van Berkel <i>et al.</i> 2004)
1. Reduce material intensity of goods and services	a. Effective resource utilisation and materials efficiency b. Reduction of process waste and enhancement of co-product values c. Reduction of water use and impacts
2. Reduce energy intensity of goods and services	d. Reduction of energy consumption and greenhouse gas emissions
3. Reduce dispersion of toxic substances	e. Improvement of control of minor elements and toxic materials
4. Enhance recyclability of materials	Not applicable
5. Maximise sustainable use of renewables	Improve utilisation of renewable energy sources (covered in d) Substitute fossil reductant with biomass based reductant (covered in d)
6. Extend product durability	Not applicable
7. Increase service intensity of goods and services	Not applicable

#### 4.2.2. Cleaner Production

Cleaner Production was introduced as a concept by the United Nations Environment Programme (UNEP) in the 1989, and therefore predates the Eco-Efficiency concept. According to UNEP (UNEP 1994):

*“Cleaner Production is the continuous application of an integrated preventive environmental strategy applied to processes, products, and services to increase overall efficiency and reduce risks to humans and the environment.”*

Cleaner Production aims at making more efficient use of natural resources (raw materials, energy and water) and reducing the generation of wastes and emissions at the source. This is generally achieved through – combinations of - good housekeeping, product modification, input substitution, technology modification, and (on-site) recycling and reuse (e.g. USEPA





1988; USEPA 1992). These can be modified to be more applicable for the mining and resource processing industries (van Berkel 2002), i.e.:

- *Good housekeeping*: improvements in operational procedures and management in order to eliminate waste and emission generation.
- *Input substitution*: the use of less polluting process reagents and equipment auxiliaries (such as solvents, lubricants, and coolants).
- *Technology modifications*: improved process automation, process optimisation, equipment redesign, and process substitution.
- *Resource Use Optimisation*: comprehensive utilisation of the mined resource through sequential mineral recovery, production of useful by-products, and conversion into geo-chemically stable residues for safe storage.
- *On-site recycling*: useful application of process wastes (including emissions and process heat) on site where these have been generated.

Table 4.2 contains a few examples for the application of each of these five Cleaner Production practices for both mining and resource processing. These practices clearly are also realise the five Eco-Efficiency elements (from table 4.1). Cleaner Production and Eco-Efficiency are very similar concepts, and for the purposes of this project they are considered to be two complementing sides of the same coin.

**Table 4.2 Cleaner Production prevention practices applied for mining and resource processing (van Berkel 2002)**

PREVENTION PRACTICE	APPLICATION	
	MINING	RESOURCE PROCESSING
1. Good Housekeeping	<ul style="list-style-type: none"> <li>▪ Monitoring and benchmarking of haulage fleet fuel efficiency</li> <li>▪ Staff training and awareness</li> <li>▪ Spill and leak prevention, e.g. for hydrocarbons (fuel, lubricants, hydraulic oils)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Staff training and awareness</li> <li>▪ Spill and leak prevention, e.g. for hydraulic oil, compressed air, water, chemicals</li> </ul>
2. Input Substitution	<ul style="list-style-type: none"> <li>▪ Use of biodegradable lubricants and hydraulic oils</li> </ul>	<ul style="list-style-type: none"> <li>▪ Use of environmentally-friendly and non-toxic reagents and process auxiliaries</li> </ul>
3. Technology Modification	<ul style="list-style-type: none"> <li>▪ Efficient mine design, to minimise materials movement during operation and for closure</li> <li>▪ Pit wall steepening</li> <li>▪ In pit milling and separation</li> </ul>	<ul style="list-style-type: none"> <li>▪ Alternative metallurgical processes (e.g. bio-technological)</li> <li>▪ Use of energy efficient motors</li> <li>▪ Application of fuel efficient furnaces and boilers</li> <li>▪ Better monitoring and control of leaching and recovery processes, to increase overall recovery</li> </ul>
4. Resource Use Optimisation	<ul style="list-style-type: none"> <li>▪ Better separation of overburden and other wastes to produce higher purity ore</li> </ul>	<ul style="list-style-type: none"> <li>▪ Sequential leaching to recover multiple minerals/metals from ore</li> <li>▪ Conversion of processing wastes and emissions into useful by-products</li> <li>▪ Residue processing into geo-chemically stable forms for safe storage</li> </ul>
5. On Site Recycling	<ul style="list-style-type: none"> <li>▪ Composting or heat/steam generation from site clearing green wastes</li> <li>▪ Reuse of overburden/waste rock in progressive rehabilitation of mine-sites</li> </ul>	<ul style="list-style-type: none"> <li>▪ Recovery and reprocessing of un-reacted ore from processing waste</li> <li>▪ Counter-current use of water for washing operations</li> </ul>



### 4.2.3 Applications

The Australian mining and resource processing industries have been able to benefit from the application of Eco-Efficiency strategies, as illustrated through a number of recent examples:

- Alcoa developed and implemented secondary overburden removal at its bauxite mines to prevent roots and other impurities from entering the alumina refineries, and thereby reduce energy, chemicals and waste costs from refinery operations (DEH 2001b; Power *et al.* 2002).
- Iluka Resources in Capel, WA installed a novel waste heat recovery boiler on its synthetic rutile plant to generate power and avoid having to build and operate a conventional wet scrubber system to meet air quality standards. The company is also investigating alternative processes to produce pig iron, soil conditioners and activated carbon from its waste streams (DEH 2001c).
- Tiwest at its Kwinana Pigment plant cut water use by half through a series of measures including counter-current pigment washing. It also built a synthetic rutile recovery plant to recover 12,000 tpa unreacted synthetic rutile and petroleum coke from the residue stream which was previously returned to the mine for disposal (DEH 2001d).
- Comalco Aluminium (Bell Bay) installed a new fume scrubbing and reuse technology saving \$11 million a year by achieving 75% recovery in fluoride emissions, 70% reduction in site water consumption, and by avoiding the treatment and disposal costs of off-gas wash water from the scrubber (DEH 2001e).
- Newmont, at its Golden Grove zinc/copper operations, strengthened operation and maintenance procedures for hydraulic hoses, introduced quick break degreasers and thereby reduced oil levels in mine water from 30 to 2 ppm over 2000-2002. As mine water is ultimately used as process water, the reduction of oil levels had a quick pay back through higher recoveries in the process plant (CECP 2003; Tyler 2002).
- Alcoa Portland Aluminium - the Alcoa Portland Spent Pot Lining Process combines a pyro-metallurgical process to burn carbon and melt the refractory components into an inert slag, with an innovative fluoride recovery and reactor system to produce aluminium fluoride from the exhaust gases. The new process recovers fluoride in a usable form, destructs hazardous cyanides and turns the Spent Pot Lining previously stored as hazardous waste into an inert slag (Mansfield *et al.* 2002).
- WMC Kwinana Nickel Refinery redesigned the burners of its hydrogen steam reformer fuel system to better utilise purification waste gas, enabling savings on natural gas of up to 2.5%. It also installed an innovative Ekata impeller in the leach agitation area, which improved oxygen utilisation by 5% enabling greater process throughput and efficiency (McQuade 2003)
- Queensland Alumina has achieved water reductions as a result of water restrictions in the Gladstone region. The reuse of an organic-rich purge stream, a cooling water stream and a cooling tower bleed were redirected to the mud washing circuit. These measures and further improvements in process control have led to 19% water savings (Stegink *et al.* 2003b).
- At Boyne Smelters Ltd (BSL) in Gladstone tar is a by-product from the Carbon Bake Fume Treatment Centre. The smelter has installed a tar recycling facility designed to dehydrate and return the tar into the paste-making process. BSL recycles two-thirds of the tar produced on site (Comalco 2002; Comalco 2003).
- In 1997 Pasminco Ltd (now Zinifex) ceased ocean disposal of jarosite from its Hobart Smelter in Tasmania, through a process change resulting in an intermediary product called paragoethite. The paragoethite is now reprocessed at Pasminco's lead smelter at



Port Pirie in South Australia, enabling further extraction of metals until it becomes an inert vitreous material (Pasminco (n.d.)).

In summary, these, and other examples illustrate that Eco-Efficiency and Cleaner production will generally have favourable economics due to:

- Improved process efficiency;
- Reduced consumption of energy, water, fuels and other materials and chemicals;
- Reduced treatment and disposal costs for process wastes tailings, residues, wastewater, air emissions);
- Reduced liabilities (associated with waste disposal and long term residue storage); and
- Revenue generation (from on-selling of by-products previously becoming waste)

### 4.3 Eco-Efficiency Tools

This section deals with Eco-Efficiency tools. The term tool is used to capture the range of methods, principles and practices used by companies for the identification, evaluation and implementation of Eco-Efficiency opportunities. Some of these are well articulated and have strong quantitative foundations whereas others are more intangible. The tools are therefore discussed in two broad categories: qualitative and quantitative tools.

#### 4.3.1 Qualitative Tools

##### 4.3.1.1 Cleaner Production Option Generation Method

The traditional approach to the implementation of Eco-Efficiency opportunities has been organised around engineering evaluations of production processes. The first formal description was provided by the United States Environmental Protection Agency (USEPA 1988), and subsequently improved and extended by them (USEPA 1992; USEPA 2001) and other authors (e.g. (Crul *et al.* 1991; Van Berkel 1995). These provide for systematic procedures for the identification and evaluation of Eco-Efficiency options for a production facility.

The option generation routine employed in typical Cleaner Production and/or Eco-Efficiency projects evolves in three logical steps, respectively: source inventory, cause diagnosis, and option generation (e.g. van Berkel 1996; van Berkel *et al.* 2001). The source inventory uses hierarchical process mapping to identify where materials, energy and water are used in the processes, and where these are being wasted. The cause diagnosis evolves around a structured search for the factors that influence the resource efficiency and environmental profile of the process. It is best performed using a checklist of cause categories that are used as pointers to guide the exploration of possible cause factors within the process of consideration. The option generation deals with identifying means to avoid, limit and/or manage the cause factors identified. Once again this is best performed using a checklist of prevention practices, with each prevention practice uniquely linked to one of the cause categories used for the cause diagnosis. Figures 4.2 and 4.3 illustrate the development of the cause diagnosis and option generation stages, on the basis of the standard set of five prevention practices (as illustrated in Table 4.2).

##### Step 1: Source Inventory

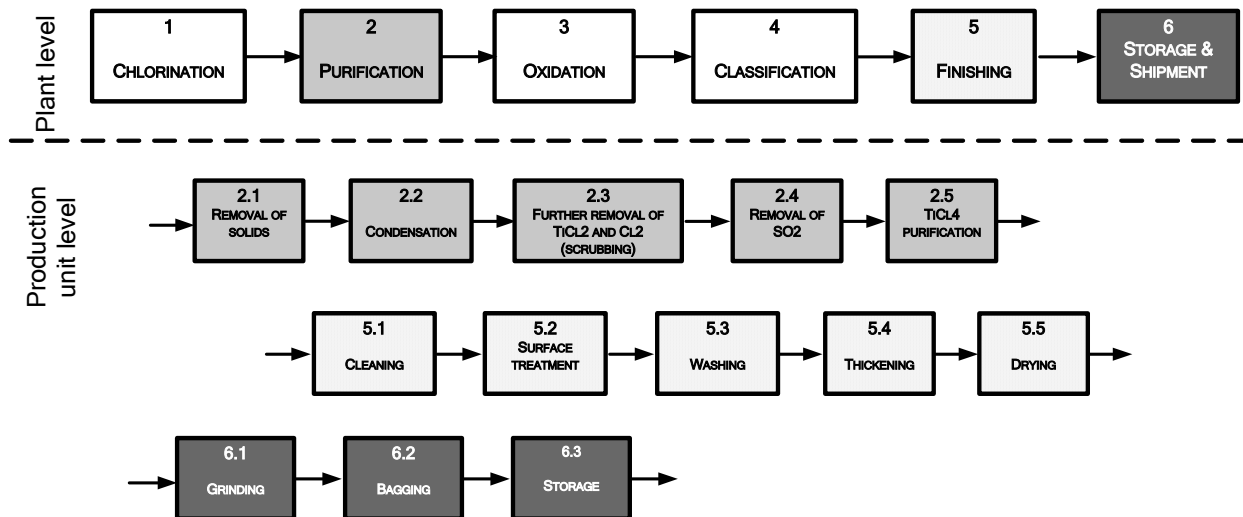
*Hierarchical process mapping* uses boxes to depict the series of process steps through which the materials and other inputs are transformed into a product. It includes a set of several maps drawn to various levels of detail, starting from a top-level map providing a broad overview of the process and working down to second or third level maps, detailing the process. An

illustrative hierarchical process map for a titanium dioxide pigment plant is presented in Figure 4.1. Boxes stand for the work steps and the arrows between them represent the movement of materials from one step to another.

Process mapping typically reveals a number of areas where improvement can be made. Process maps at lower levels are then used to:

- Figure out where materials are used and wasted.
- Allocate materials used and wasted in a facility to a particular work step allowing for *materials and cost tracking* at every process step. Vertical arrows entering the work step boxes from above and leaving them from below indicate materials that are used but that do not become part of the product.
- Identify every process step that contributes to facility's fugitive emissions.
- Picture a new process before implementing it, including the possibility to calculate the difference in the activity based costs between operational scenarios.

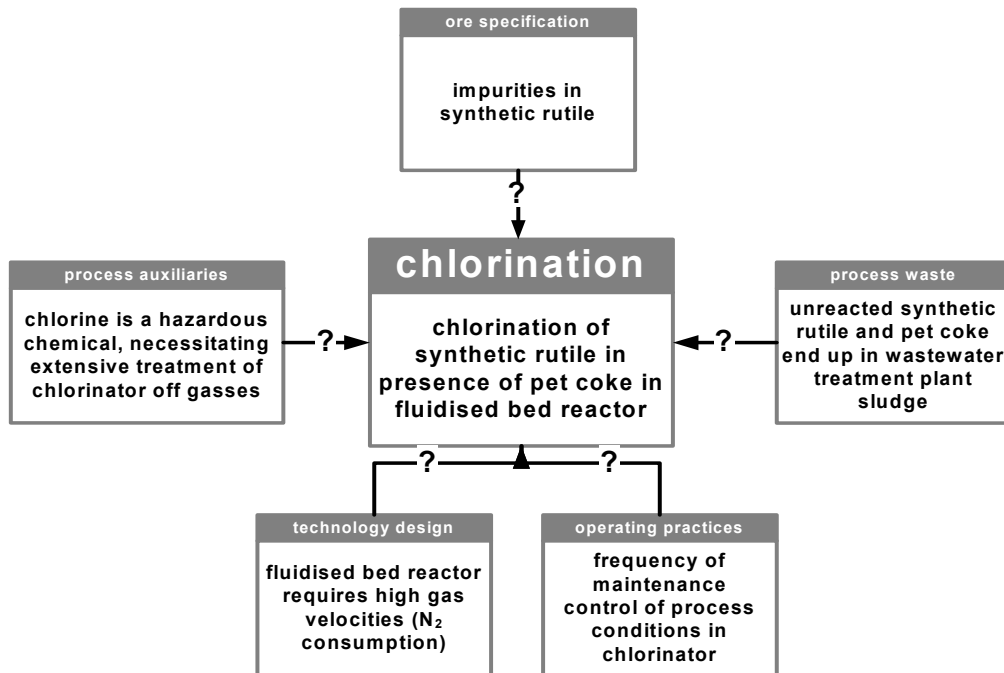
*Figure 4.1 Illustration of application of hierarchical process map to hypothetical titanium dioxide pigment plant*



### Step 2: Root Cause Diagnosis

*Cause-effect diagrams* are a well-known tool in quality and operational management. They can be applied to analyse any business process, with regard to the impacts of materials, machines, operations and people, as root causes for inefficiencies and quality deviations in that process. These root causes can then be used to develop customised solutions that alleviate the root causes identified. The principal value of a *cause and effect diagram* is that it forces the team in charge of the process to analyse the root cause of a problem instead of simply acting on the first identified cause. It provides a graphical explanation to management and other parties of exactly what is contributing to the problem, considering different categories of potential causes, such as personnel, equipment, methods and materials. A cause and effect diagram will typically reveal multiple causes of a single problem. Root cause analysis is an effective management tool for determining the true or actual causes of resource use or loss in a process, facilitating effective corrective action, and preventing recurrence of the problem. Figure 4.2 provides an illustration of the use of cause-effect diagrams for root cause analysis.

Figure 4.2 Illustration of a root cause diagnosis for chlorination unit of hypothetical titanium dioxide pigment plant



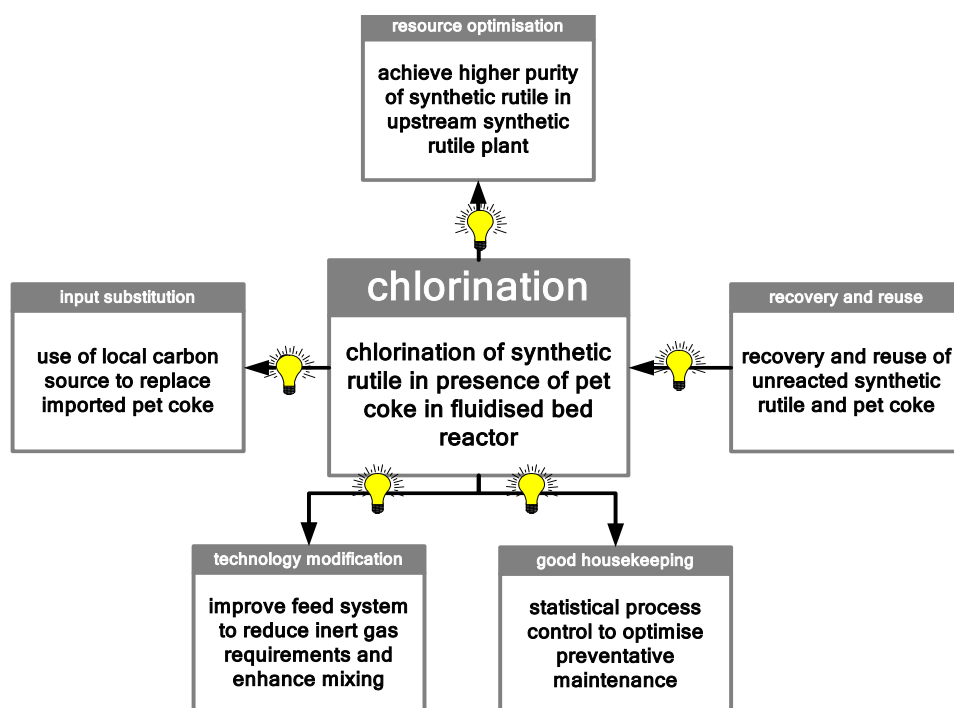
Key questions for the cause diagnosis with regard to Eco-Efficiency are:

- Do operating and maintenance practices have an impact on process wastage? If so, how?
- Do choice and quality of process auxiliaries have an impact on process wastage? If so, how?
- Do choice of process technology and design and lay out of equipment have an impact on process wastage? If so, how?
- Do mineral and/or ore specifications have an impact on process wastage? If so, how?
- Does the process wastage contain valuable components? If so, which?

### Step 3: Option Generation

Eco-Efficiency *option generation* is a creative process. The opportunities may range from simple measures such as turning off valves to complex plant modifications. Option generation is based around reversing the cause-effect diagram i.e. exploring whether and how each of the identified root causes can be eliminated or at least be controlled. Figure 4.3 provides an illustration for Eco-Efficiency option generation applied to the chlorination step in titanium dioxide pigment production.

Figure 4.3 Illustration of a option generation for chlorination unit of hypothetical titanium dioxide pigment plant



The option generation step typically involves highly structured and facilitated workshops. The facilitators guide the discussions and keep them focused on finding all possible solutions to the issues in hand. The key questions to structure option generation for Eco-Efficiency are:

- How do operating and maintenance practices have to be improved to reduce process wastage?
- What alternative (quality of) process auxiliaries would be required to reduce process wastage?
- What alternative process technologies or modifications in equipment design and lay out would be required to reduce process wastage?
- Which modifications in the mineral and/or ore specifications would be required to reduce process wastage?
- How can valuable components be reused, recycled or reclaimed to reduce process wastage?

#### 4.3.1.2 Green Chemistry

A chemist may produce a number of chemical substances, while having little knowledge about their potential hazard or potential interaction with other substances or materials in the environment (Warner *et al.* 2004). Green Chemistry is the use of chemistry for pollution prevention and Eco-Efficiency. According to the American Chemical Society, Green Chemistry is “*the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances*”. Green Chemistry is a highly effective approach for Eco-Efficiency because it applies innovative scientific solutions to real-world environmental challenges. The



green chemistry design process includes the selection of safer materials, avoiding the use of toxic solvents, using renewable materials and resources, using less energy and releasing safe outputs to the environment. The twelve principles of green chemistry originally developed by Paul Anastas and John Warner provide a road map for chemists to implement green chemistry.

At its core, Green Chemistry is concerned with the design of both *product* chemistries (i.e. chemical products that are safe and benign to use and dispose off) and of *process* chemistries (i.e. synthesis pathways that use benign materials, are efficient and do not pose hazards). Van Berkel et al (2004), therefore rephrased the green chemistry principles into chemistry design principles for product and process chemistries, as follows:

1. *Design for waste prevention* is a process related principle that calls for prevention instead of waste creation and treatment or, in other words, green chemistry is Cleaner Production at the micro scale.
2. *Design for atom efficiency* is designing for an atom efficient reaction, which has more of the reacting atoms ending up in the final product.
3. *Design for less hazardous chemical syntheses* incorporates the minimisation or elimination of hazards into all aspects of the process design.
4. *Design for safer chemicals* assumes the balance between maximum performance and function of the product while minimising its toxicity and hazard.
5. *Design for safer solvents and auxiliaries* is minimising the use or toxicity of solvents, separation agents, and other auxiliary substances in processes.
6. *Design for energy efficiency* is optimising the processes and reactions for minimum energy requirements through the use of catalysts, microwaves, ultrasonic energy, etc., as well as observing all engineering aspects.
7. *Design for use of renewable feedstocks* wherever possible.
8. *Design to reduce derivatives* is the elimination of unnecessary intermediate products.
9. *Design for catalysis* is using selective catalysts to facilitate a desired transformation, for example to reduce energy requirements, eliminate contaminants in effluent, and reduce water usage.
10. *Design for product degradation* is designing products that will not persist in the environment and their breakdown products will not pose harm on human health, ecosystem and wildlife.
11. *Design for real-time analysis and control for pollution prevention* is using methods and technologies that allow the prevention and minimisation of hazardous substances generation or contamination.
12. *Design for inherently safer chemistry* is designing products and processes taking into account the full range of hazards, such as toxicity, explosivity, and flammability for accident prevention.

Green Chemistry developments have so far been in the areas of novel chemical catalysts, polymer supported reagents, biocatalysts, application of microwaves, photochemical processes, fuel cells, ionic liquids, superheated water and supercritical solvents. The majority of the practical examples are from the chemical processing and pharmaceutical industries (as they provide broader choice of starting chemical substances, manufacturing routes and process technologies) mainly in USA. Consideration of Green Chemistry in the resource processing sector is still at best in its infancy. Examples are illustrated in Table 4.4 (located at



the end of this section), the majority of which are in the R&D phase. However, green chemistry can still be applicable to that industry sector leading to dramatic benefits, especially for large-scale operations, by focusing on alternative feedstocks and lowering the energy requirements for a chemical transformation. The introduction of minerals materials from the earth's crust into the production stream could be equally seen as the introduction of variety of chemicals in other industrial sectors. This fully justifies the contribution of green chemistry's principles to reduction of these and any other materials or chemicals associated with the resource processing. Breakthrough technologies covering new processes, processing regimes, reagent and energy sources, products and applications, which are the objectives of CSRP Program 4 are fully in line with the green chemistry as well as green engineering (see 4.3.1.3) contexts.

Green Chemistry research can develop innovative ways to address many of the goals associated with Industrial Ecology and Eco-Efficiency principles. Examples include (Fiskel 2002).

- Reducing material intensity through the use of alternative chemistries that have higher '*atom efficiency*'.
- Reducing energy intensity through lowering the energy requirements of endothermic reactions, for example by using novel catalytic methods.
- Reducing the dispersion of toxic substances through discovery of '*benign synthesis*' pathways, or through elimination of organic solvents.
- Enhancing material recyclability by developing biodegradable materials or by finding methods to regenerate feedstocks from waste products.
- Enhancing process yield and reducing waste by developing more effective separation and extraction methods, enabling by-product recovery.
- Improving the durability and performance of products by developing novel materials or multilayered composites with customised physical properties
- Maximising the sustainable use of renewable resources by developing bio-based processing methods for converting biomass (e.g. soybeans, corn, cellulose) into useful materials.
- Developing innovative products that are environmentally benign.

Most of the Green Chemistry design principles may not be applicable to the resource processing industry in terms of rearranging the make-up of molecules (*atom efficiency*), designing safer products, reduction of derivatives and other. However, some of the principles, such as waste prevention, alternative solvents and auxiliary substances, alternative catalysts and alternative fuels or reductants, can greatly aid the industry to achieve improved Eco-Efficiency and business performance.

#### 4.3.1.3 Green Engineering

While much of the focus of Green Chemistry is on developing new chemical pathways, the main focus of Green Engineering is on improving the economic and environmental performance of industrial processes through optimisation of process design and operating conditions. Listed below are the twelve principles of Green Engineering (Anastas *et al.* 2003) that can be used systematically to optimise a system or its components:

1. *Design for inherently nonhazardous material and energy inputs and outputs*, involves the evaluation of the inherent nature of the selected material and energy inputs to ensure they are as benign as possible.





2. *Design for waste prevention* is the designing of products, processes and other systems to prevent the production of waste through elemental design considerations.
3. *Design for separation* employs intrinsic physical and chemical properties, such as solubility or volatility that permit the self-separation of products rather than induced conditions (often requiring large amounts of hazardous solvents, or energy for heat and pressure) to reduce waste and processing times.
4. *Design for maximum energy, space and time efficiency* is in other words design for process intensification, where space and time issues are considered along with the material and energy flow to eliminate waste.
5. *Design for “output pulled” versus “input pushed”* is designing transformations in which outputs are continually minimised or removed from the system, and the transformation is instead “pulled” to completion without the need to be “pushed” by excess energy or material.
6. *Design for conservation of complexity* - the amount of complexity that is built into a product is usually a function of expenditures of materials, energy and time. End-of-life design decisions for recycle, reuse or beneficial disposal are based on the invested material and energy, with highly complex, high-entropy substances/products being designed for reuse, while low complexity substances/products are favoured for recycling or beneficial disposition.
7. *Design for durability not immortality* involves designing of products with a targeted lifetime to avoid immortality of undesirable material in the environment, but at the same time are durable enough to withstand anticipated operating conditions for the expected lifetime to avoid premature failure and disposal.
8. *Design to meet need and minimise excess* is limiting the expenditure of underused and unnecessary materials and energy.
9. *Design for minimal material diversity* is up-front designing that minimise material diversity (which determines the ease of disassembly for reuse and recycle) and yet accomplishes the needed functions.
10. *Design for process integration* is using the existing framework of energy and material flows within a unit operation, production line, manufacturing facility, industrial park, or locality.
11. *Design for performance in a commercial “afterlife”* is encouraging up-front modular design, which reduces the need for acquiring and processing raw materials by allowing the next generation designs of products, processes, or systems to be based on recovered components with known properties.
12. *Design for renewable material and energy inputs* wherever possible.

Green Engineering can be employed at every stage of a product life cycle beginning at the material extraction, materials processing, use and disposal to optimise and improve performance by for example reduction of process temperature, eliminating feedstock impurities, reduction of residence time or reduction of by-product formation.

While it is appropriate for engineers to focus on evaluating and improving the environmental performance of a chemical process, it is also important to recognise that this process is linked to both suppliers and customers, as well as that there are linkages to other processes and other industrial sectors. The abundance of large quantities of low-grade waste heat, wastewater and variety of waste materials generated worldwide that could be suitable for other industrial applications, places another facet to Green Engineering way of thinking. Identifying which processes could be most efficiently integrated requires that process



engineers must understand not only their processes, but processes that could supply materials, and processes that could use their by-products to create more energy-efficient, mass-efficient, and intricately networked industrial processes – i.e. an Industrial Ecology (Allen *et al.* 2001).

These approaches appear not yet common practice. Significant percentage of today's engineering students, who will design and optimise the processes in the future have little or no understanding of the local and global environmental issues and current sustainability agenda. They are often taught to design for a specific outcome and not taking into consideration how this outcome will be achieved.

The Green Engineering principles provide a common set of guidelines that can be used to devise a set of sustainable green processing criteria (or principles), to address specific aspects of resource processing from extraction to product. These criteria could provide a systematic framework for engineering design, such as environmentally benign product or process design methodologies, considering the entire life cycle for the materials employed in the production, use, and disposal of products and also contribute to the realisation of the aim of CSRP. These criteria should also encompass the concept of Industrial Symbiosis and be developed, for example, along the lines of: design for waste as a product, design for reuse, and design for alternative feedstocks.

Many of the examples presented in Table 4.4 (at the end of section 4.3) provide testimony that the developments over the last decade in the resource-processing sector are striving to improve efficiency and reduce cost through the application of Green Engineering design principles, even though consideration of such green engineering principles, has in many cases been hap-hazard and not systematically pursued as a key design objective.

### **4.3.2 Quantitative Tools**

#### **4.3.2.1 Process Integration**

Process integration is a powerful analytical method for identifying process inefficiencies and selecting technical solutions to improve them. It is also a method of connecting process streams and equipment in an optimal way. The *process integration* approach can be applied to a simple heat exchanger that recovers heat from a single process stream, to waste heat recovery from a turbine, to the optimal scheduling of reactor usage, to the integration of a number of production units, or to the complete integration of an industrial complex.

Process integration includes a variety of tools and techniques that allow engineers to evaluate entire processes or sites. They include hierarchical design methods, knowledge based systems, numerical and graphical techniques, pinch analysis (Dunn *et al.* 2003; Rossiter 2004) and exergy analysis (Sorin *et al.* 1997). Process integration, combined with other tools for process simulation can be a powerful approach to systematically analyse an industrial process and its parts to achieve process improvement, productivity enhancement, conservation in mass and energy resources, and reduction in operating and capital costs.

The past two decades have seen the development and/or application of process integration design tools for heat exchange networks (HENs), wastewater reduction and water conservation networks, mass exchange networks (MENs), heat- and energy-induced separation networks (HISENs and EISENs), waste interception networks (WINs) and heat- and energy-induced waste minimisation networks (HIWAMINs and EIWAMINs), etc (Dunn *et al.* 2003). Table 4.3 provides a summary of the process integration design, a brief description of the design task addressed, and examples of unit operations targeted by each design approach.



**Table 4.3 Summary of some methodologies for process integration design (adapted from (Dunn et al. 2003; Dunn et al. 2001))**

DESIGN METHODOLOGY	DESCRIPTION	EXAMPLE TECHNOLOGIES TARGETED
Heat integration systems or Heat Exchanger Networks (HENs)	The identification of heat recovery devices that minimise environmental emissions resulting from utility generation systems	<ul style="list-style-type: none"> <li>▪ Heat exchangers</li> <li>▪ Heat pumps</li> <li>▪ Boilers/cooling towers</li> </ul>
Wastewater minimisation systems	A design strategy for reuse, regeneration reuse, and regeneration recycling of wastewater streams that minimises water usage and minimises wastewater discharge.	<ul style="list-style-type: none"> <li>▪ Direct recycle opportunities</li> <li>▪ Regeneration reuse and recycling opportunities</li> </ul>
Mass exchange networks (MENs) and reactive mass exchange networks (REAMENs)	A network of process units that removes pollutant(s) from end-of-pipe streams via the use of physical or chemical, direct-contact, mass separating agents (MSAs).	<ul style="list-style-type: none"> <li>▪ Adsorption</li> <li>▪ Absorption</li> <li>▪ Liquid-liquid extraction</li> <li>▪ Ion exchange</li> </ul>
Heat-induced separation networks (HISENs) and energy-induced separation networks (EISENs)	A network of process units that removes pollutant(s) from end-of-pipe streams via the use of indirect-contact energy separating agents (ESAs), including stream pressurisation and/or depressurisation.	<ul style="list-style-type: none"> <li>▪ Condensation</li> <li>▪ Evaporation</li> <li>▪ Drying</li> <li>▪ Crystallisation</li> <li>▪ Compressors</li> <li>▪ Vacuum pumps</li> </ul>
Membrane separation networks	A network of process units that removes pollutant(s) from end-of-pipe streams via the use of membranes and stream pressurisation and/or depressurisation.	<ul style="list-style-type: none"> <li>▪ Reverse osmosis</li> <li>▪ Pervaporation</li> </ul>
In-plant separation design via waste interception and allocation networks (WINs)	A network of process units that removes pollutant(s) from in-plant streams via the use of physical or reactive direct-contact mass separating agents (MSAs) and/or rerouting of in-plant process streams.	<ul style="list-style-type: none"> <li>▪ Direct recycle opportunities</li> <li>▪ Adsorption</li> <li>▪ Absorption</li> <li>▪ Liquid-liquid extraction</li> <li>▪ Ion exchange</li> </ul>
In-plant separation design via heat-induced waste minimisation networks (HIWAMINs) and energy-induced waste minimisation networks (EIWAMINs)	<p>A network of process units that removes pollutant(s) from in-plant streams via the use of indirect-contact energy separating agents (ESAs) with stream pressurisation and/or depressurisation and/or rerouting of in-plant process streams.</p> <p>Full site heat integration is simultaneously addressed by this technique.</p>	<ul style="list-style-type: none"> <li>▪ Direct recycle opportunities</li> <li>▪ Heat exchange/heat integration</li> <li>▪ Condensation</li> <li>▪ Evaporation</li> <li>▪ Drying</li> <li>▪ Crystallisation</li> <li>▪ Compressors</li> <li>▪ Vacuum pumps</li> <li>▪ Heat pumps</li> </ul>

*Pinch Analysis* is the best known and commonly used process integration tool, which may be used to improve the efficient use of energy and water (Linnhoff *et al.* 1983; Wang *et al.* 1994), in industrial processes, as well as hydrogen system optimisation (CECT-Varenes 2003a). Pinch analysis has an established track record in the chemicals, petrochemicals, oil refining, steel manufacturing and other industrial sectors. Generally, the fundamental principle behind the approach is the ability to match individual demand for a commodity (energy or water of a particulate quality and quantity) with a suitable supply. The suitability of the match depends on the quality offered and the quality that is demanded. By maximising the match between supply and demand, the method provides opportunities to minimise the input of resources. Pinch analysis uses so-called composite curves that provide graphical representation of 'quality' versus 'quantity' for a resource or commodity.

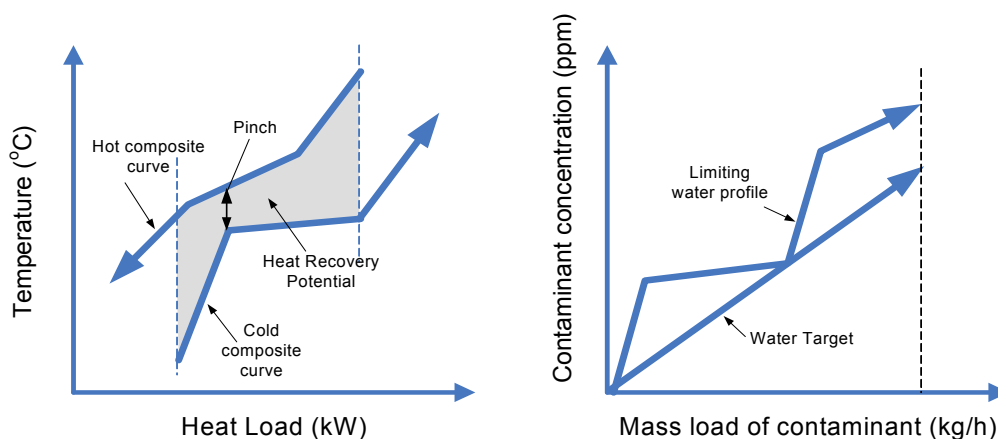
Temperature-Enthalpy (T-H) plots are known as composite curves and have been used for many years to set energy targets ahead of design. A hot composite curve consists of



temperature (T) – enthalpy (H) profiles of heat availability in the process, while a cold composite curve profiles the heat demand in the process. The composite curve consists of series of connected straight lines (see Figure 4.4 left) where each change in slope represents a change in overall heat capacity for a hot stream, or a heat demand for a cold stream. The *pinch* is the point where both curves approach most closely. The overlap between the composite curves represents the maximum amount of heat recovery possible within the process (Linnhoff *et al.* 1994).

A similar approach is applicable to composite curves for wastewater minimisation illustrated with concentration (C) versus mass load (m) (Figure 4.4 right). It considers each water-using operation as being described by the mass transfer of a certain contaminant from the process itself to the water stream. Limited profile is constructed by specifying the maximum allowable inlet and outlet contaminants concentration for each operation, flowed by combining these profiles to form a composite curve, against which a water supply line can be matched. The inverse of this line gives the target for the minimum fresh water and wastewater. The point that limits the slope of the line is called the *water pinch* (Hallale 2002).

**Figure 4.4** The general concept of composite curves applied to heat and mass transfer (adapted from (Hallale 2002; Linnhoff *et al.* 1994))



In some cases savings in energy or water are not enough to justify undertaking detailed pinch analysis and further capital improvements. Energy and water pinch analyses should be regarded as an integral part of new process design and incorporated into standard design procedures to achieve financial savings by better process heat or mass integration.

Pinch analysis is also used to optimise aggregate production planning in supply chains (Singhvi *et al.* 2004), where time is plotted against the quantity of the materials, and by representing the demand and supply as composites. It facilitates re-planning and quick decision making.

When considering the number of processes on a site, pinch analysis is rarely applied where direct integration between processes is difficult due to distance, or where processes must remain independent. Typically this situation occurs in oil refining, petrochemical, iron and steel plants as well as many of the metal refineries and smelters. In such cases a *total site analysis* (CECT-Varenes 2003b; Dhole 1995) is employed, where indirect integration may be achieved through the utility system. This generally uses the steam network, which already exists, to transfer the heat between the site sources and sinks. The methodology can also be used to thermally integrate the different process sections of the same process if direct heat



transfer is not allowed or considered impractical. The methodology is based on total site profiles (sinks and sources), which allow setting overall targets for fuel, steam, cooling and emissions.

A further development in system analysis is the *exergy analysis*. Typically a thermal energy system is addressed using energy analysis based only on the first law of thermodynamics, but it does not consider the quality of energy, i.e. the second law of thermodynamics. The main aim of exergy analysis is to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. Exergy analysis can, therefore, indicate the possibilities of thermodynamic improvement of the process.

Exergy of a system is the amount of work obtainable when the system is brought to a state of unrestricted equilibrium (that is, thermal, mechanical, and chemical) with the environment by means of reversible processes involving thermal and chemical interaction only with the environment (Kotas 1980). The loss of exergy provides a quantitative measure of a process or system inefficiency that makes exergy analysis well suited for analyzing the inefficiency of a single unit, specific process or a total plant.

A number of *process mass integration tools* exist (Rosselot *et al.* 2002) to optimise the use of materials that would otherwise be wasted:

- *Source-Sink Mapping* is used to determine whether waste streams can be used as feedstocks. It is the simplest and most visual tool for identifying candidate streams for mass integration. This tool involves the creation of a source-sink diagram where all of the processes that are “sources” and “sinks” of the particular material are identified, along with their flow rate, contaminants that are present in the source streams, the tolerance to contaminants for each sink and the concentration of these contaminants. The source inventory described in section 4.3.11 can be used for identification of sources and sinks.
- *Optimising Strategies for Segregation, Mixing and Recycle of Streams*. This tool is used when the processes to be analysed become more complex and the number of sources and sinks increase. Mathematical optimisation techniques, together with process simulation packages, are generally employed to identify opportunities for recycle, segregation and mixing of streams.
- *Mass Exchange Network (MEN) Synthesis* - Unlike source-sink mapping and optimising segregation, mixing and recycle, MEN does not achieve mass integration through re-routing of process streams. Instead, it involves direct exchange of mass between streams and is used to systematically generate a network of mass exchangers whose purpose is to preferentially transfer compounds that are pollutants in the streams in which they are found, to streams in which they have a positive value.

There are not many published examples of process integration. This may be because most of the process improvements/optimisation are proprietary and are done either in-house or by engineering consultancies, with very limited, if any, public disclosure. The vast majority of briefly described (Aspentech (n.d.)) or simply listed by company (Linnhoff March (n.d.)) implemented process integration projects belong largely to the chemical, pharmaceutical, petroleum, utilities, food processing, oil & gas, etc. industrial sectors with resource processing sector representing relatively small percentage. Since no detailed data on process integration improvements could be found, Box 4.1 below demonstrates the benefits of pinch analysis for iron and steel plants.

**Box 4.1 Pinch analysis benefits for iron and steel plants**

As an illustration of the pinch analysis benefits, the savings opportunities identified by Process Integration studies (CECT-Varennnes 2003b) in Iron and Steel plants typically amount to between 15% and 30% of the purchased fuel. Additional energy savings of between 5% and 15% can generally be obtained through good housekeeping (steam traps and leaks, furnace tuning, cleaning of fouled heat exchangers), monitoring & targeting, process modifications, etc. The numbers vary, depending on how much attention energy receives at the facility before these methods are applied, as well as on other factors such as complexity, and the fouling potential of the materials being handled.

Economic projects identified during a Process integration study are plant-specific and depend on the following: size and arrangement of the plant, required pipe distances and routes, space constraints, operating limitations, and level of engineering needed to overcome local hazards or influencing conditions. The paybacks presented below may differ from plant to plant. A non-exhaustive list of typical projects includes:

**Quick Wins:**

- Improved scheduling of processing of hot slabs from the continuous caster—"hot linking"
- Closer control of water consumption and cooling towers, etc.

**Medium-payback projects, typically within one-to-three years:**

- Introduce a new, localized, low pressure steam main, with medium pressure steam feeding it through a steam turbine
- Replace old low pressure steam boiler with high pressure steam boiler and turbine to meet the duty
- Heat recovery from hot mills through the use of additional heat exchangers
- Heat recovery from furnace exhaust to preheat combustion air
- Heat recovery from sinter plant through the use of additional heat exchangers
- Use of waste heat for space heating

**Long-term payback projects, typically within three-to-six years:**

- Increase condensate recovery to boiler plant
- Cogeneration (CHP) via steam turbine and gas turbine
- Blast furnace slag granulation

**4.3.2.2 Process Intensification**

Process intensification is the strategy of making significant reductions in the size of a (chemical) plant in order to achieve a given production objective or to generate more products with the same facility. The concept was pioneered by ICI in the late 1970s when the primary goal was to reduce the capital cost of a production system. Process intensification is being applied throughout the chemical and pharmaceutical industries to reduce investment and operating costs and to increase profitability and achieve smaller footprint. More in detail process intensification aims at new and compact unit operation designs in which two or more classical unit operations are combined into one hybrid unit. It is a practical way of a design philosophy that is aimed at making radical reductions in the size of production equipment in the process industry for getting better product outputs with installations that are an order of magnitude smaller than the conventional equipment.

Process intensification can be measured with the amount of productivity that can be accomplished per unit of process volume. This increase in process intensification occurs because miniaturisation significantly reduces the resistances to heat and mass transfer.



Andre Stankiewicz and Jacob Moulijn (Stankiewicz *et al.* 2000) offer the following definition: “Process Intensification consists of novel apparatuses and techniques that, compared to those commonly used today, are expected to bring dramatic improvements in manufacturing and processing, substantially decreasing equipment-size/production-capacity ratio, energy consumption, or waste production, and ultimately resulting in cheaper, sustainable technologies.”

The process intensification and its components generally could be divided into two areas:

1. *Process Intensification Equipment*, involving reactors and equipment for non reactive operations, such as novel reactors and intensive mixing, heat transfer and mass transfer devices
2. *Process Intensification Methods*, such as multifunctional reactors featuring integration of reaction and separation for example, hybrid separations, techniques using alternative energy sources (solar, ultrasound, microwaves, etc) and new process control methods.

The opportunities (Stankiewicz *et al.* 2002) that process intensification offers to a chemical company lie primarily in six areas: costs, safety, compactness, controlled well-defined conditions, time to the market, and company image. Despite all of these potential advantages and a number of successful commercial applications of process intensification, there are several important barriers that prevent deeper changes in the process industry, featuring the interest of value driven companies to achieve growth not via R&D but rather via trade; the R&D effort in chemical companies primarily focused on new products, not methods; lack of awareness and familiarity with process intensification in industry; and that many novel apparatuses and processing methods are not yet proven on the industrial scale, are very different to the standard equipment and methods, as well as lack of simulation and scale-up capabilities.

Some design considerations (Jachuck 2002), for intensifying a process are:

- Is the process based on batch or continuous technology?
- Identify the rate limiting step (heat transfer, mass transfer, mixing, etc);
- Identify appropriate intensification tools/modules/concepts;
- Eliminate solvents if possible;
- Use supported catalysts whenever possible;
- Reduce pressure/temperature gradients;
- Reduce the number of processing steps by using multifunction modules;
- Ultimate aim to achieve significant (orders of magnitude) enhancements in transport rates.

Practical examples from industry and under development are illustrated in Table 4.4. For the resource processing industry the future developments in process intensification will have the most impact in the areas of:

- *Mineral preparation* - mainly comminution, as it accounts for substantial portions of rock processing energy costs, labour and capital.
- *Physical separations* - improving productivity, energy and water efficiency.
- *Chemical separations* -improving heat efficiency, increasing direct conversion through reduction or elimination of processing steps.
- The greatest potential improvements could be associated with the optimisation of combined processes and the resulting synergies. For example, combining beneficiation, dewatering, and agglomeration into a single process would reduce flow sheet complexity and *materials handling*.



**Table 4.4 Resource processing examples relevant to Green Chemistry, Green Engineering and Process Intensification**

GC = Green Chemistry; GE = Green Engineering; PI = Process Intensification

PROJECTS	GC	GE	PI
<b>Existing projects</b>			
HIs melt direct smelting produces hot metal without the need for coke or agglomerated ore feeds, thereby eliminating the requirement for coke ovens and sinter plants. The process utilises fine iron ores (and other iron-bearing fines) and no-coking coals. It is designed to be energy efficient, with low SO <sub>x</sub> and NO <sub>x</sub> emissions (HIs melt 2002).	X	X	X
The innovative Hicom low-energy mill delivers ultra-fine grinding with ultra-low energy consumption, adding high value to industrial minerals. It offers the flexibility for wet or dry grinding, attrition and delamination all in the one machine (Hoyer <i>et al.</i> (n.d.)).		X	X
The Ausmelt furnace is a totally enclosed refractory lined vessel, which uses a lance to inject fuel and air into the bath. The fuel combusts at the tip of the lance, thereby heating the furnace contents, while the injected gases cause vigorous agitation and rapid process reactions thus decreasing residence time (Ausmelt 2001).		X	X
MIM's proprietary smelting process (ISASMELT), which generates much of its own heat internally thus reducing its need for external energy is being used in the copper and lead streams in MIM's Mount Isa operations, north-west QLD (DEH 2001a).		X	
Through the AJ Parker CRC for Hydrometallurgy, a comprehensive set of tools and techniques for solving problems with the operation of full-scale thickeners has now been developed. The new techniques have been used by companies in the alumina, gold, base metals and mineral sands industries to solve a range of processing problems and improve process performance. For example, at one refinery the implementation of the research findings doubled the throughput of one thickener (Process Magazine 2000).		X	X
Currently mothballed Australian Magnesium Corp project resulted in a chemical dehydration process to produce high purity anhydrous magnesium chloride suitable to feed a magnesium electrolytic cell. The process was designed to operate with high efficiencies at relatively low temperatures and pressures with low operating cost and a small environmental profile through recycling of all the process chemicals and reagents (Koenig <i>et al.</i> 2002).		X	
Outokumpu SUPAFLO thickeners operate in mineral processing such as zinc tailings in Namibia, copper concentrate in Argentina, copper tailings in Chile, mineral sand tailings in Australia, as well as in other applications throughout the world. The smaller equipment size substantially reduces capital, installation costs and plant space when compared with thickening units for the same production rates. The high rate units reduce area by 90%.		X	X
Production of Fe-Ni at Hyuga Smelter, Japan – the conventional sintering-electric furnace process was replaced with a rotary kiln-electric furnace process which resulted in increase of reduction of the iron to the ferrous state and reduction in energy consumption (Ogura <i>et al.</i> 1987).		X	X
Svedala H-8000 Hydrocone installed at Codelco's El Teniente copper mine doubles the line capacity (Mining Magazine 1999b).			X
Outokumpu Flash Technology, Direct Blister Copper Process – blister copper can be produced directly by smelting the concentrate in a flash smelting furnace. The process offers new options for using different raw materials and is suitable for lower-grade concentrates (Outokumpu (n.d.)).		X	
Direct Outokumpu Nickel process reduces the process steps by eliminating Pierce Smith converters from the nickel smelting process. High-grade nickel matte is produced from the flash smelting furnace and metal alloy from the electric furnace (Outokumpu (n.d.)).		X	X
Outokumpu Flash Smelting combined with Kennecott Outokumpu Flash converting is an integrated solution to high capacity smelting using small size equipment (Mining Magazine 1999a; Outokumpu (n.d.)).		X	X
A risk-free electrowinning process has been developed in Chile, which avoids arsine generation and which claims optimum yield of both copper and arsenic. The process has been installed at the Ventanas copper refinery. The arsenic product is a soft solid, easily removable and suitable for recycling when melted (Mining Magazine 1999a).	X	X	
Newmont's Ammonium Thiosulfate (ATS) Leaching and Recovery Technology for Au and Ag leaching and recovery from carbonaceous and oxide ore types.	X		





PROJECTS	GC	GE	PI
<b>Projects under development</b>			
Tailor-made solvent extraction technology, developed by the Parker Centre will enable HiTec Energy to produce high-value electrolytic manganese dioxide from ore waste (Process Magazine 2005).	X		
A new process, known as NewGenSR can produce synthetic rutile products exceeding 94% titanium dioxide, irrespective of the ilmenite grade. The development will mean increased utilisation of ilmenite resources, and will allow processing of different ilmenite grades with one technology (Process Magazine 2002).		X	
Novel phase contacting devices have been researched at University of Stellenbosh, South Africa. These high intensity jet reactors provide significant improvement over conventional phase contacting equipment due to the impingement of high velocity feed streams upon each other in relatively small reactor volumes, resulting in a highly turbulent mixture of phases. The jet reactor technology was applied to the leaching of gold from refractory ores. By bringing gold bearing ore into contact with cyanide, using a high-pressure jet reactor prior to agitation, gold recovery is increased and leach time dramatically reduced. Suitable for other mineral processing applications, such as the calcination of phosphate ores (Lorenzen <i>et al.</i> 2000).		X	X
Using microwave technology to assist minerals grinding operations has a potential for significant energy savings (Wang <i>et al.</i> 2005).	X	X	
Vortex Magnetic separation is a new technique which can not only greatly increase selectivity of high gradient magnetic separation but can also provide a much higher material throughput because high slurry velocity is used. This technique will have a wide range of applications in fields as diverse as mineral processing, biochemical engineering, sewage and wastewater treatment and industrial effluent treatment (Watson <i>et al.</i> 1997).		X	X
Intensification of leaching process by single and dual-frequency ultrasound leading to decrease in leaching time and reagent consumption (Swamy <i>et al.</i> 2001).		X	X
CSIRO Minerals has been investigating the use of wood biomass/char as a substitute for coke during sintering. It has a great potential to reduce the emissions from integrated steelworks and improve their environmental acceptability. Harvested biomass/char is also a renewable and sustainable resource (Dell'Amico <i>et al.</i> 2004).	X	X	
A technology that has spread from Australia is to use the red mud waste to treat another industrial waste – tailings from mines. Red mud can absorb up to 99.99% of the heavy metals in tailings, producing a very inert and stable material that supports plant growth and vegetation; the run-off water is of drinkable quality. Aughinish Alumina and University of Limerick are working together to apply this technology in Ireland (Clark <i>et al.</i> 2001).	X		
Alternative gold lixivants - sodium hypochlorite, bromine, ammonium thiosulphate and acidic thiourea as alternatives to cyanide for gold processing (Mining Magazine 2001a).	X		
Environment-friendly method of high alkaline bauxite's red Mud and ferrous Slag utilisation as an example of green chemistry (Mymrin <i>et al.</i> 2003).	X		
Liberation of minerals with microwave assistance (Wang <i>et al.</i> 2005) has a potential to greatly reduce the vast amounts of energy used to grind mined rocks and ores. Applied to sulphide flotation concentrates, the technology could have huge potential to replace pre-treatment processes such as autoclaving, roasting or smelting (Mining Magazine 2001b).		X	

#### 4.4 Eco-Efficiency Indicators

Measuring progress from the implementation of Eco-Efficiency has turned out to be complicated and often disputable. General management theory and practice stresses the point that Eco-Efficiency can only be managed if its results are being measured. On the other hand Eco-Efficiency cannot directly be measured as one cannot measure how much non-product outputs and unnecessary process inputs have been avoided (these are just no longer there to be measured). Traditionally the impact of Eco-Efficiency has been measured on a project-by-project basis, through comparison of resource consumption and waste generation ratios before and after Eco-Efficiency implementation, and cost benefit analysis for the necessary investments (e.g. USEPA 1997). Such approach does however not



consider the baseline operational environmental performance and also fails to include the indirect impacts and spin-offs from the Eco-Efficiency project on other aspects of the business operation. Others have therefore suggested measuring progress by means of changes in the gross resource efficiency of the company or business unit (WBCSD 2000a). In such business performance approach the impact of Eco-Efficiency could be blurred by a number of other factors, such as changes in product mix, changes in profit margins and production volumes. Yet others have argued that the operational environmental performance (the level of waste and emission generation etc.) should not be used as the performance indicator, as such operational environmental performance is just an outcome from performance at the level of the Eco-Efficiency program (Gallagher *et al.* 1999).

Against this background, two complementary approaches to performance measurement are now commonly used by industries, respectively: *intensity* and *efficiency* indicators. Intensity indicators express the level of environmental impact relative to a unit of productive output (e.g. tonne CO<sub>2</sub>-eq/tonnes of product output). These are also known as the operational environmental performance indicators according to both ISO 14031 environmental performance measurement standard, and the GRI guidelines for sustainable development reporting (ISO 2001), (GRI 2000). On the other hand, efficiency indicators express the level of economic value created per unit of environmental impact (e.g. tonnes of product sold/ton CO<sub>2</sub>-eq emitted). These efficiency indicators are also known as Eco-Efficiency ratios, and have been promoted primarily through business forums like the World Business Council for Sustainable Development (WBCSD 2000a).

#### 4.4.1 Intensity Indicators

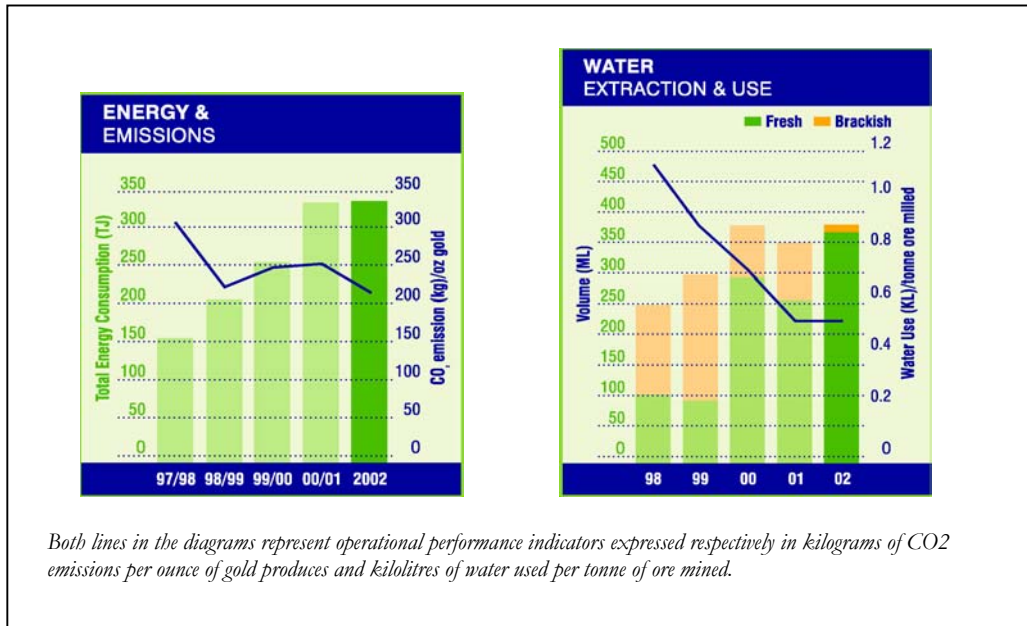
The most widely accepted framework for intensity indicators is found in the ISO 14031 series. This standard distinguishes between operational performance indicators (the level of emissions and resource consumption), management performance indicators (the effectiveness of the management system to achieve management goals for identified environmental aspects) and environmental condition indicators (generally the quality of the receiving environment but in resource processing context also the completeness of the rehabilitation process for mining areas) (see Table 4.5). Operational and management performance indicators are most practical, as the quality of the receiving environment is generally influenced by a number of other factors outside the scope of influence of the organisation, except for industries operating in isolation in remote locations. Most Australian operations report at least on a few operational performance indicators, in either absolute, relative, indexed or aggregated form. Indexing with reference to the level of productive output is most common (see e.g. Figure 4.5).

**Table 4.5 Environmental Performance Indicators (adapted from ISO 14031:2001).**

CATEGORY	SUBCATEGORIES
<b>Operational Performance Indicators</b> ➤ Provide information about the environmental performance of an organisation's performance	<ul style="list-style-type: none"> <li>• Inputs of materials, energy and services</li> <li>• Supply of inputs</li> <li>• Design, installation, operation and maintenance of physical facilities and equipment</li> <li>• Outputs of products, services, wastes and emissions</li> <li>• Delivery of outputs</li> </ul>
<b>Management Performance Indicators</b> ➤ Provide information about the management efforts to influence an organisation's environmental performance	<ul style="list-style-type: none"> <li>• Implementation of policies and programmes</li> <li>• Conformance</li> <li>• Financial performance</li> <li>• Community relations</li> </ul>
<b>Environmental Condition Indicators:</b> ➤ Specific expression that provides information about the local, regional, national or global condition of the environment	



Figure 4.5 Illustration of reporting of time-series of relative operational performance data (Newmont 2002)



#### 4.4.2 Efficiency Indicators

The business community, led by the World Business Council for Sustainable Development, has promoted the view that businesses should strive to maximise value creation per net unit of environmental impact. Indicators should assist managers to achieve this Eco-Efficiency goal. WBCSD (2000a) has therefore developed a set of Eco-Efficiency indicators to help measure corporate progress towards economic and environmental sustainable future. Eco-Efficiency indicators are mainly used as a decision making tool for performance evaluation, target setting, identification of improvement opportunities or to communicate corporation’s progress on sustainable development to external audiences. The purpose of Eco-Efficiency is businesses to achieve more value from lower inputs of materials and energy and with reduced emissions. In order to calculate Eco-Efficiency the WBCSD has developed the following ratio, which combines financial and environmental performance.

It can be represented as: 
$$\frac{\text{Product or Service value}}{\text{Environmental influence}}$$

Where *Product or Service Value* could be:

- Quantity of goods/services produced or provided to customers – it is a physical measure or count of product or service produced, delivered or sold. It can be measured in mass, volume or number.
- Net sales – is the total recorded sales less sales discounts and sales returns. Less suitable as production units are often not directly linked to sales figures and the latter are influenced by a variety of factors unrelated to Eco-Efficiency.

And *Environmental Influence* would generally include at least (WBCSD 2000a):

- Energy consumption – involves the total energy consumed, calculated for instance in J or W.



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- Materials consumption – is the total weight of all materials the company purchases or obtains from external sources. This indicator could also be calculated for a single material consumed. Could also be presented as total waste generated.
- Water consumption – this indicator quantifies the sum of all water purchased or obtained from surface and ground water sources. Wastewater generated could also be used.
- GHG emissions – this indicator includes the amount of GHG emissions to air from fuel combustion, process reactions and treatment processes. It includes CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PCFs and SF<sub>6</sub> given in metric tonnes of CO<sub>2</sub> equivalent.
- Ozone Depleting Substances (ODS) Emissions - amounts of ODS emissions to air from processes and losses/replacement from containments (chillers) given in metric tons of CFC11 equivalents.

**Table 4.6 Example Eco-Efficiency indicators applicable to the mining and resource processing industry**

PRODUCT OR SERVICE VALUE	ENVIRONMENTAL INFLUENCE
<ul style="list-style-type: none"> <li>▪ Tonnes of product output, produced or sold</li> <li>▪ Tonnes of non-product output, produced or sold</li> </ul>	<p><b>Per:</b></p> <ul style="list-style-type: none"> <li>▪ Land disturbed or rehabilitated</li> <li>▪ GHG emissions generated– total CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, etc.</li> <li>▪ Other emissions (e.g. fluoride, SO<sub>x</sub>, NO<sub>x</sub>, or PM)</li> <li>▪ Fuels or energy consumed</li> <li>▪ Total materials consumed</li> <li>▪ Raw materials consumed</li> <li>▪ Mineral waste generated</li> <li>▪ Non-mineral waste generated –general, hazardous or total</li> <li>▪ Water consumed–scheme, bore, recycled, other or total</li> <li>▪ Wastewater discharged</li> </ul>

**Table 4.7 Example Eco-Efficiency Profile WMC Limited (adapted from WMC 2002)**

ELEMENT	INDICATOR	VALUE
Organisation Profile	<ul style="list-style-type: none"> <li>▪ Company name</li> <li>▪ Business segment</li> <li>▪ Report for</li> <li>▪ System boundaries</li> <li>▪ Number of employees</li> <li>▪ Internet</li> <li>▪ Contact for further information</li> </ul>	WMC Resources Minerals, metals and fertilisers 2002 Kwinana Nickel Refinery 210 <a href="http://www.wmc.com">www.wmc.com</a> rowena.smith@wmc.com
Value Profile	<ul style="list-style-type: none"> <li>▪ Quantity</li> </ul>	Nickel 65,055 tonnes Copper sulphide: 5,606 tonnes Mixed sulphides: 3,373 tonnes Ammonium sulphate: 190,841 tonnes
Environmental Profile	<ul style="list-style-type: none"> <li>▪ Energy consumed</li> <li>▪ Material consumed</li> <li>▪ Water consumed</li> <li>▪ GHG emissions</li> <li>▪ ODS emissions</li> <li>▪ Land disturbed</li> </ul>	Total energy 3,415 TJ Nickel-in-matte: 100,693 tonnes Process chemicals 64,688 tonnes 914 ML 334,920 tonnes CO <sub>2</sub> N/R 0 ha
Eco-Efficiency Ratios	Metal produced per: <ul style="list-style-type: none"> <li>▪ Energy consumption</li> <li>▪ Material consumption</li> <li>▪ GHG emissions</li> </ul>	19.05 t/TJ Nickel-in-matte: 0.64 t/t Process chemicals: 1.01 t/t 0.19 t/tonne CO <sub>2</sub>



Eco-Efficiency Indicators should be clearly related to issues for which there is a clear need for improvement, assist decision making for performance improvement, support benchmarking and monitoring over time (to allow businesses comparison) and be understandable and meaningful to the audience they are intended for. The Table 4.6 presents several examples of financial and environmental performance that may be used to calculate Eco-Efficiency ratios for the resource processing industry.

Reporting of Eco-Efficiency ratios is not widely accepted in the Australian resource processing industry. However, some of the public environmental reports provide sufficient detail to compile an Eco-Efficiency summary profile, as illustrated in Table 4.7.

#### **4.4.3 Industrial System Indicators**

Similarly to a production facility consisting of various processes and each process comprising of many units that can be assessed independently regarding their inputs and outputs, an industrial system can be viewed as a group of individual components, leading to the possibility for the development of area-wide indicators to reflect changes in efficiencies for the industrial area as a whole.

Company indicators are frequently based on volumes of “emission” per tonne of product. In an industrial areas typically consisting of mix of processing, utility and servicing industries it is difficult to define meaningful indicators that will account for the varying degree of activities within an industrial area, as well as for closing down old or establishing new industries. In broader sustainability context the effort to construct such indicators becomes even more difficult when the economic and social dimensions also need to be included.

Many indicators could be used as a measure of improved Eco-Efficiency of a chosen industrial area. Some examples are provided below:

- Consumption of virgin materials/total material inputs
- By-product recovery/total output (solid, liquid or gas)
- Alternative inputs/total inputs
- \$sales/ton of GHG
- \$sales/ton of material use
- \$sales/kL of water use

#### **4.5 Concluding Remarks**

This chapter focused on Eco-Efficiency, i.e. the efforts of companies to improve their performance in regards to their ratios of productive outputs per net unit of environmental impact and resource consumption. Eco-Efficiency initiatives typically address a range of environmental and resource efficiency objectives, customised to the minerals processing industries these concern in particular increases in materials efficiency (i.e. effective resource utilisation, reduction of process wastes and reduction of water use and impacts), increase in energy efficiency, reduction in toxics dispersion (i.e. better control of minor elements and toxic materials) and optimum use of renewable resources (i.e. as energy or reductant source). Such objectives are achieved through combinations of prevention practices, customised to minerals processing these involve good housekeeping (better operating and maintenance practices and management and information systems), selection and use of appropriate and environmentally-compatible input materials, choice of technology, design and layout of equipment and plant, and recovery and reuse of process wastes. Even though mainstream Eco-Efficiency and Cleaner Production expertise (e.g. (DeSimione *et al.* 1997; Freeman 1995; van Berkel 1996)) does not specifically cover minerals processing, many good examples exists where Australian minerals processing operations have benefited from the



application of Eco-Efficiency principles and practices (even though in many cases not intentionally).

Eco-Efficiency projects have relied strongly on normative frameworks for the identification of improvement options. These frameworks include Cleaner Production option generation routines (which are essentially customisations of quality management/Kaizen engineering principles (Imai 1997; Pojasek 1997), and Green Chemistry and Green Engineering principles. The design and implementation of practical Eco-Efficiency solutions is facilitated with the application of more generic process optimisation tools, in particular those used for process integration and intensification purposes (e.g. (Allen *et al.* 1997; Allen *et al.* 2002a). Moreover, it is common to use a combination of (pollution) intensity and (resource) efficiency indicators to measure and track Eco-Efficiency achievements.

There is widespread recognition that Eco-Efficiency is a valuable contribution for regional synergy development, as regional synergies, or Industrial Symbiosis, can essentially be regarded as an extension of Eco-Efficiency initiatives over the company boundary. In doing so, however, complexity increases considerably for two reasons. Firstly, complexity increases because of the larger number of processes and unit operations to be considered, and the need to consider implications of the physical distance between the unit operations. Secondly, complexity is enhanced by the divergence of optimisation strategies (at the level of individual companies and at the level of the region) and the openness of the system (which impedes the ability to use mathematical optimisation models).

This suggests that it would be most appropriate to adapt and customise a normative structure as the basis for a method for regional synergy opportunity identification (similar to the logical structure of a Cleaner Production option generation routine/method). Quantitative optimisation tools will then have a supportive role, in particular for the concept and detailed design of synergy projects. Such normative structure needs more development work, to extract defining features from successful synergy projects, and combine these with existing normative solutions and design principles in Eco-Efficiency, Green Chemistry and Green Engineering.

The taxonomy for Eco-Efficiency metrics/indicators is comparatively well developed, even though reporting thereon is still not widespread for a number of reasons, including data paucity and concerns regarding data disclosure. It appears that extension of these indicators from company level to the level of industrial areas would be comparatively straightforward, providing both pollution intensity and resource efficiency indicators to measure regional resource synergy achievements. Given the diversity of operations, and hence in most important environmental and resource efficiency issues, it appears desirable to measure performance at the regional level using a limited number of indicators. This applies both to the economic value indicators (for example: total production or total value added for companies in the area) as well as the environmental indicators (for example: total materials consumption, total water consumption, total energy consumption and total greenhouse gas emissions from companies in the area).



## Chapter 5: TECHNOLOGY GAPS AND OPPORTUNITIES

### 5.1 Introduction

The notion of waste discarded from one operation being reused in other operations is straightforward, but in practice recovery and reuse is more often than not dependent on the waste material, water or energy being treated, transported, stored, etc. The technology for upgrading and transferring the wastes should therefore be available, reliable and affordable, and there should be a beneficial use of recovered waste or energy which replaces another virgin resource use, to make the synergy happen and environmentally beneficial. This justifies a focus on ‘*synergy technologies*’, which is being used as a loosely defined term to cover technologies that can be utilised to achieve regional synergies. For a regional synergy to work, a feasible technological match must be available if one industry is to accept, use and extract value from a by-product stream originating from another industry within the region. In many cases it may be theoretically possible to identify a technological match for a by-product from one industry that could be valuable in another industry in the locality. In practice such a match may not be feasible or uneconomical due to the relatively low concentration of valuable material in the by-product or the presence of contaminants, the physical or chemical form of the material in the by-product, the quantity of the by-product or some other reason. Advances in technology could make a regional synergy with a poor business case but good sustainability motives attractive.

This chapter focuses on technology gaps and opportunities. The technology scope includes, but does not necessarily limit itself to: separation and beneficiation technologies, recycling and recovery technologies, transport and storage technologies, and monitoring and control technologies. The main objective of this chapter is to identify and discuss “technology gaps” or technological opportunities and limitations that have been encountered while attempting to realise regional synergies in minerals processing intensive regions and to scope the technology developments necessary to achieve greater regional synergies.

Each section within this chapter presents a range of possible technologies from those that currently exist but may not have gained wide acceptance to those that are in their infancy and still need significant development before being suitable to deliver regional synergies. The chapter reviews technologies in terms of the physical state of the by-product, namely: solids (section 5.2); liquids (section 5.3); gases (section 5.4) and energy (section 5.5).

### 5.2 Solid By-Products

The key characteristics of any by-product (or waste solid) are both its physical properties (in particular its size and size distribution) and its chemical composition. These are important factors not only as they determine how and where these by-products can be used in other operations but how difficult or easy it will be to transport them from one site to another. For instance, fine dry powders require more sophisticated handling and transportation facilities than solid briquette material for a similar quantity. A synergy can only succeed with an appropriate technical match and secure delivery system between location of production and consumption of the by-product.

Regional synergies are more likely in industrially intense areas. Often there are a number of common industries in these areas such as power stations, cement plants, and, in Kwinana and Gladstone in particular, alumina refineries. Therefore, bigger opportunities for improving regional synergies in such areas are dependent on finding, at least initially, technological solutions to beneficial reuse of these industries’ by-products such as:

- Fly ash from power stations



- Red mud or bauxite residue from alumina refineries
- Organic wastes and spent solvents as alternative fuels for cement plants

In this section the technological opportunities are discussed in terms of typical solid wastes and by-products from heavy industrial regions.

### 5.2.1 Power Station Ash

Fly ash, the fine particle by-product from pulverised fuel coal-fired power stations, appears in principle suited for a number of re-uses. The most common at present is the use of fly ash as a cement additive, as it provides favourable qualities for cement in both elastic and hardened states. Although the use of fly ash in cement manufacturing utilises a significant portion of fly ash generated from power stations, remaining significant quantities are typically sent to local bunds or ponds.

One of the main opportunities for the re-use of fly ash is in the production of building materials, such as lightweight bricks. A number of publications describe the potential of using fly ash, along with other materials, for making bricks that would have superior qualities to conventional bricks (Freidin *et al.* 1995; Kumar 2002; Kumar 2003). Freidin *et al.* (Freidin *et al.* 1995) presented their work on developing bricks made from fly ash, slag and sodium silicate solution which are cured in open-air whilst Kumar (Kumar 2002; Kumar 2003) described an investigative study into the development of fly ash-lime-gypsum bricks and hollow blocks with sufficient strength for use in low cost housing. Earlier papers (Baradan 1987; Hansen *et al.* 1983) illustrate that the notion of using fly ash for building materials such as bricks has been under consideration for some time.

Bottom ash generated in molten form from the bottom of the power station boiler is very similar to fly ash and can be used as a lightweight free draining composite material in landscaping. Cenospheres (hollow fly ash particles), have enormous potential to reduce density, provide better insulation, improve impact resistance, and reduce shrinkage and warpage, and can be used to form lightweight materials suitable for bridge decks, pavements, and highways (Barbare *et al.* 2003). Other possible re-uses for fly ash include the reduction of leaching nitrates, ammonium, and phosphates in sandy soils (Pathan *et al.* 2002), as road base stabilisation material or acid neutralizing agents in agriculture and waste treatment (Demir *et al.* 2001).

Such solutions for the re-use of fly ash are more attractive when a matured market is available close to the fly ash source. High transport costs are likely to make production of such bricks uneconomic. This is true for two reasons: relatively cheap conventional bricks are readily available and the current cost of disposing of fly ash to local ponds or bunds is not overly expensive. Accordingly, there has not been a significant short-term financial incentive for power stations to find alternative methods of disposal or re-use of fly ash, which however neglects the ongoing accumulation of future liabilities associated with fly-ash storage. Unless fly ash bricks will be of superior quality or lower price to conventional bricks, purchasers would be unwilling to pay a premium price.

The huge distances between centres in Australia, means that transport costs can have a major effect on the final price of any by-product. For power stations close to large population areas the potential for using fly ash as part of alternative building products is a distinct possibility, especially if future legalisation makes it more difficult or costly to dispose of fly ash in the traditional manner and/or provides better guidance on how alternative raw materials can be utilised. On the other hand for power stations that are more remote from large population areas, which is common as major coal-fired power stations are usually





within the proximity of coal fields, by-products made from fly-ash would need to demonstrate their superior qualities to become marketable commodities.

The technical challenge or opportunity for fly ash or bottom ash is to develop a by-product that exhibits superior qualities to its competitors and offers multiple benefits. For example, fly ash addition to cement can improve cement properties and reduce greenhouse gas emissions from cement product. The case for continued storage of ash in local bunds or ponds remains strong until ways have been found to improve the properties of the ash by-product.

### **5.2.2 Bauxite Residue**

Vast quantities of bauxite residue, commonly known as '*red mud*', are produced annually from alumina refineries as a by-product. Depending on the geological nature of the bauxite deposit, somewhere between one to two tonnes of red mud is generated for every tonne of calcined alumina. Red mud is primarily a mixture of silica, aluminium, iron, calcium and titanium oxides and hydroxides (Hind *et al.* 1999). Given the large volumes being produced much research has already been conducted in alternative use areas.

Some of the potential uses for red mud that have been reported in literature include as substitute material (37% wt) in the production of ceramic glazes (Yalcin *et al.* 2000), as a pH modifier in the cyanidation of gold (Browner 1995), as an additive to sandy soils to reduce the leaching of phosphorus into waterways and reduce eutrophication (Summers *et al.* 2001), as a constituent in special cement (Singh *et al.* 1996) and as key agent in heavy metal and acid neutralisation (Anon. 2004a).

Even though much work has been conducted on the possible re-uses of red mud, it is still typically stored in large impoundments close to the alumina refinery. Factors that have affected the re-use of red mud are, for example, handling and transport costs, which would limit the use of red mud as a pH modifier to a distance of about 90 kilometres from source (Browner 1995) and negative publicity (Cooling *et al.* 2004). In relation to the former factor this distance may well be less given today's higher transportation and fuel costs; whilst in relation to the latter factor, technology advances may not offer much assistance but better community engagement could help.

Any viable red-mud recovery technology must be able to use vast amounts and must produce a product that has a unique feature to warrant a premium price to counter the transportation costs. At present, a number of technologies have shown promise in the potential re-use of red mud but have yet to be fully tested for potential commercialisation to reuse large quantities of red mud currently stored in red mud dams. This is probably more due to non-technical issues, such as liability, commercial agreements and community acceptance, than the need for substantial advances in technology. Nevertheless, for the successful re-use of red mud, it should be an important and cheaper constituent in a by-product that cannot be substituted by other readily available materials.

### **5.2.3 Carbon Waste**

Coke, tar and other carbon wastes represent potential alternative fuel sources. Two of the problems associated with carbon waste as an alternative fuel source is its physical form and potential contaminations that can cause emission problems upon burning.

The physical form of carbon can create handling problems; for instance as fine coke particles. Advances in the briquetting technology could allow for fine particles to be made into briquettes relatively easily and cheaply. In briquette form, the coke would be easy to handle and could be used as a recycled fuel source. CSIRO have been conducting research into the binderless briquetting of coal (Anon. 2002a) to upgrade the quality of fine coal



(particle sizes less than 5 mm). Such technology could also be applied to other fine carbon particles.

#### **5.2.4 Alternative Fuels**

The benefits of the use of alternative fuels in cement kilns have been well documented (Kaantee *et al.* 2004; Mokrzycki *et al.* 2003a; Mokrzycki *et al.* 2003b). The high temperatures, comparatively long residence times and oxidising conditions in the cement kiln make them suitable for the use of alternative fuels, such as old tyres, solvents, and oils. By using alternative fuels, which are essentially by-products from other industries or organisations, lesser virgin fossil fuel resources are consumed in cement production and also lesser waste is going to land fill or being burnt in incinerators.

Local community acceptance of an alternative fuel strategy is critical. Perceptions that the cement industry is using waste as fuel for financial advantages and at the detriment of the health and environment of the local community have been strong in some places, including the Kwinana area. Another example of concerted community effort against a cement kiln using alternative fuels is currently playing out in New Berrima, in southern New South Wales. The main community concern, which is a common concern in these cases, is the potential increase in the levels of micro-pollutants (potentially including dioxins and furans) in the emissions compared with using traditional fuels such as coal, gas or oil. Dioxins and furans are carcinogenic and teratogenic and thus can pose a serious threat to human health. Increase in dioxins and furans are, naturally, undesirable but caution must be taken whilst extrapolating emissions from a single sample from a process with a high degree of variability in emissions due to varying operating conditions (Alcock *et al.* 1999).

Use of high calorific value by-products as alternative fuels for cement manufacturing is now an environmentally acceptable strategy for many cement kilns around the globe (e.g. BatelleInstitute 2002). Care needs to be taken to avoid in particular halogenated substances (precursors for dioxins and furans formation) entering the alternative fuel, and improving process control to maintain high temperature ( $\geq 1000^{\circ}\text{C}$ ) zones in the kiln so that any traces of such micro-pollutants are effectively destroyed (Kilgroe 1996; Ruth 1998). Better instrumentation and control systems to keep the process operating at stable conditions will greatly assist in maintaining emissions well below limits stipulated by local regulatory agencies. This is particularly true for the production of clinker, which is sensitive to changes in operating conditions.

#### **5.2.5 Scrap Metal**

A wide range of scrap metal recycling companies exists from the small operations that collect domestic scrap metal to large multi-national companies. Recycling of scrap metal from industrial sites has become a common practice that suggests that the industry has attained a maturity level that is sustainable. Nevertheless, improvements in technology to recover more materials efficiently would benefit industrial synergies and result in a more efficient use of resources. A recent example is Rio Tinto's HIsmelt process which is not only a new technology that had improved use of resources but has the capability to recycle iron-containing waste streams that could so far not be recovered with conventional blast furnace technology.

One area that could benefit from scrap metal recycling is better separation technology of scrap metal from other waste. For instance, at material recovery facilities (MRFs), separation of metals from other wastes is either done by hand or Eddy currents, in case of aluminium cans, or using magnets, in case of scrap steel. Technology that would allow for reliable automated separation at source of scrap metal would greatly assist in the recycling



process. Such technologies could include image sorting, which could replace the manual sorting component of the process.

### **5.2.6 Slag**

Large quantities of slag are produced from the smelting of metallic ores and much of this gets downcycled for low-grade metal recovery. The properties of slag are such that it can be a suitable replacement material for construction purposes, such as road base, footpaths and fill for trench stabilisation (Anon. 2001b). Slag cement and ground granulated blast furnace slag, have, like fly ash, been used as supplementary cementitious materials. Whereas fly ash is usually limited to 20% to 30%, slag cement can replace up to 50% of normal concrete (Anon. 2002b). Due to the similarities between slag and fly ash in relation to their re-use, similar technological solutions are needed to increase the re-use of slag and decrease the quantity going to landfill. Further refining of the current technology to increase the use of slag as a substitute material in various applications may increase wider uptake of this particular by-product synergy. In 1993, about 30%, 1.2 million tonnes, of the slag was sent to landfill. Although this figure may have decreased it is feasible that all slag could be downcycled as valuable products, principally in the construction industry (Anon. 1993).

### **5.2.7 Other Solid By-Products**

Other solid wastes such as paper and plastics are typically recycled and in many cases as non-process wastes arising from office, canteen and other supportive functions. Proven technology for recycling these wastes exists although there are greater technology gaps for other by-products and wastes. Potential breakthroughs could be realised by finding significant improvements in making the non-office wastes recycling or downcycling feasible.

## **5.3 Liquid By-Products**

As outlined in Section 5.1, the success of regional synergies depends on making the best use of the major by-product streams. Liquids in one form or another are used extensively in the processing industry. As they are typically purchased from specialist suppliers, any opportunities to use suitable by-product liquids from nearby operations can be an attractive proposition. By-product liquids need to be supplied at the correct quantity and quality in order not to impact negatively on process efficiencies and recovery rates. Technologies that can purify and recover the by-product liquids would make the difference between a waste liquid stream and saleable by-product stream. This section therefore addresses technology improvements for water, alkalis, acids and oils.

### **5.3.1 Water**

No longer can water be considered an almost infinite resource that is readily and cheaply available. Water must now be considered a valuable commodity that is essential for the operation of industrial processes, particularly in intense industrial areas as well as for many remote operations in arid environment. Improved water use and re-use therefore deserve priority and are, in certain regions, the only alternative to allow for the expansion of industry. As such, water can be critical to the expansion of industries within a region and therefore technology improvements that could provide relatively cheap suitable quality ('fit-for-purpose') recycled water or desalinated water could be the key for further expansion. In this regard the mining and minerals industries have already established a strong track record in using comparatively low grade, highly saline waters as source of process water (see e.g. (CMEWA 2004)).

Alternative sources of water, compared with traditional sources such as dams and bore water, can – depending on location - come for two main sources: retreated or recycled



wastewater and desalinated seawater. Several technologies are available for producing high-quality water from these sources:

- Membranes have the ability to produce permeate product water of a reliably high quality almost completely independent of the feed water using denser (reverse osmosis, electrodialysis or nanofiltration), and porous membranes (ultrafiltration and microfiltration) (Nunes *et al.* 2001)
- Evaporative processes that mimic the natural water cycle in that saline water is heated, producing water vapour, which is in turn condensed to form fresh water (URS-Australia 2002). Alternative technology configurations, include: Multi-Stage Flash Distillation; Multiple Effect Distillation; and Vapour Compression Distillation

The choice of technology for recycled or desalinated water is dependent on the quality of the feedwater, product water requirements, throughput rates, recovery requirements and energy requirements (URS-Australia 2002).

One of main barriers for not using recycled or desalinated water is higher costs. Generally, in Australia the cost of producing a kilolitre of water using the above technologies is still more than the typical price of a kilolitre of water from traditional sources, namely the local dam or bore. Reverse osmosis is generally the most cost competitive with traditional mains water supplies (URS-Australia 2002). Accordingly, industry has no incentive on a purely commercial basis with current water prices to use alternative water sources. If, however, water restrictions are imposed, for instance due to drought conditions as was the case in the Gladstone region in Queensland, Australia (Stegink *et al.* 2003a), and water is not available in the quantities required by industry to maintain full production, then alternative sources are imperative. Under these circumstances, industry is willing to pay a higher price for water to prevent lost production.

From a regional synergies viewpoint, better water use on industrial sites results in less demand on traditional water sources and therefore greater opportunity for new industries in an industrial region, or reduced competition with domestic and other water uses (as in the case of the Kwinana Water Reclamation Plant). To promote recycling of wastewater or desalination of seawater, the cost must be competitive with traditional water sources, provide premium quality, or, alternatively, industry should view the higher cost of water from a recycled or desalinated process as a premium against the uncertainty of water supply from traditional sources. Given the drought conditions and low dam levels in many parts of Australia at present, the cost of recycled or desalinated water might seem a “small price to pay” to safeguard against lost production resulting from decreased availability of water from traditional sources.

There is proven technology available for reclaiming wastewater and desalinating seawater. It would be more attractive compared with traditional water sources if the technology were comparably cheaper to install and operate. To achieve the advances in technology, cheaper membranes with more energy efficient technology, for instance waste heat powered desalination process, are needed.

### **5.3.2 Acids and Alkalis**

Acidic or basic by-product liquids are either recovered for further use or neutralised before being released to the environment. In industrial processes, recovery of these liquids is often the best financial and environmental solution, especially if treatment and disposal are expensive.

Sodium hydroxide, or caustic soda, is a widely used alkali chemical, particularly in the alumina industry. Much of the caustic soda used in Australia is imported. Opportunities



exist for the production of caustic soda as a by-product in a location that is adjacent to the industries that use the chemical. As an example, the brine from a desalination process could be dried and washed to recover sodium chloride which is the feed material for the production of caustic soda and chlorine.

A similar example can be given for producing sulphuric acid by recovering flue gas sulphur dioxide, as is currently done at for instance the Kalgoorlie Nickel smelter and the Mt Isa Copper Smelter. In the latter case, the sulphuric acid, which is an essential feed materials in the production of ammonium phosphate fertilisers, is transported to Queensland fertiliser operations. Again, opportunities exist for improvements in technology so that capturing these compounds from waste streams, such as flue gases, can be performed efficiently and cost-effectively on existing operations.

### ***5.3.3 Oils and Solvents***

Used oils and solvents generally have significant calorific values and are, potentially, a valuable alternative fuel source. One of the concerns with the burning of oils or solvents is that there could be too high an increase in air emissions, in particular from halogenated or aromatic solvents (see Section 5.2.5), or due to contaminant built up during the use stage of the oil or solvent. Improved monitoring and control of the process could produce reductions in emission levels that would satisfy regulatory requirements.

Third parties commonly recycle used oils and solvents; depending on the use of the recycled oils and solvents it could be more valuable to use them as alternative fuel source.

### ***5.3.4 Other Liquid By-Products***

Other industrial by-product liquids are typically in relatively low volumes and unless they have a high value are not necessarily recovered but treated to satisfy environmental disposal regulations. Technology improvements, would therefore have limited benefits except in specific cases.

## ***5.4 Gaseous By-Products***

Numerous substances, typically at low levels to satisfy environmental regulations, are emitted into the atmosphere by industry. In theory, significant quantities of valuable substances could be collected from these emissions if cost-effective technologies were available. What makes this difficult, in practice, is the cost of current technology to extract substances in low concentrations from emission streams. For example, flue gas desulphurisation in coal-fired power stations, which could be used to produce gypsum or sulphuric acid as a by-product, is on its own right not cost-effective and therefore limited to users of high sulphur coal where desulphurisation is mandated by environmental regulations. With improvements in technology it could be possible to recover substances such as sulphur dioxide from flue gases and generate saleable by-products. To illustrate the potential available quantities, the Australian National Pollutants Inventory ([www.npi.gov.au](http://www.npi.gov.au)) reported that in the Gladstone region in Queensland over 43,000 tonnes of sulphur dioxide were emitted for the 2002-2003 year. This amount of sulphur dioxide could be used to theoretically produce nearly 65,850 tonnes of sulphuric acid.

In this section potential areas for technology improvements are discussed for the following gaseous by-products: carbon dioxide, sulphur dioxide and nitrogen oxides.

### ***5.4.1 Carbon Dioxide***

The emission of carbon dioxide from heavy industrial areas is generally quite significant, particularly if, as is often the case, a coal-fired power station is one of the main industries. Until the relatively recent threat of global warming, carbon dioxide emissions were not



considered a concern and as a consequence coal-fired power stations have not designed for easy capture of the gas. Capture of carbon dioxide from post combustion emissions can be done using a range of technologies though costs are currently high and dependent on concentrations of CO<sub>2</sub> in the emissions. Techniques include: solvent extraction, pressure swing absorption and the use of membranes as molecular sieves. Options for decreasing capture costs by increasing the concentration of CO<sub>2</sub> in the emissions stream include the use of oxyfuels (in pulverised fuel types of boilers) and by moving to integrated gasification combined cycle operations either simply for power generation or for poly generation (Bredesen *et al.* 2004; Cook *et al.* 2004a; Cook *et al.* 2004b).

A cost-effective technology to capture carbon dioxide from traditional pulverised coal-fired power stations would make huge contribution to the reduction in the carbon dioxide emitted to the atmosphere. The feature of such a technology would be the ability to overcome the problems of the current proven technologies which are hindered by the dilution of carbon dioxide with nitrogen and the resulting significant efficiency and financial penalties (Dijkstra *et al.* 2004). Although technologies are available, further development, particularly on the emerging technologies such as membranes which do hold some promise, is necessary to produce an efficient, relatively cheap carbon dioxide capture technology that can be easily fitted to existing power plants. If high purity carbon dioxide can be efficiently captured then it may be possible to use this by-product after further refining instead of processed carbon dioxide.

The challenge, as is the case with other emissions, is to develop a cost-effective solution that can be easily retrofitted to existing technology. Possibly, polymeric membranes might turn out to be the best available solution to this problem.

#### **5.4.2 Sulphur Dioxide**

The implications of sulphur dioxide emissions into the atmosphere are significant, such as the formation of acid rain. Typically, there are four methods for the removal of sulphur dioxide from flue gases (Nygaard *et al.* 2004): wet scrubbers; spray dry scrubbers; sorbent injection and regenerable processes.

The gypsum producing wet scrubber, by far the most popular technique with a market share worldwide of about 62%, removes sulphur dioxide by absorption into a slurry of gypsum and limestone and produces a solid gypsum product (Nygaard *et al.* 2004). Flue gas desulphurisation gypsum is a substitute for natural gypsum and can be used in binders, plasters, plasterboard manufacture and as additive in Portland cement production (Galos *et al.* 2003). This is one of the core synergies in the Kalundborg Industrial Symbiosis case.

For power stations, flue gas desulphurisation is best employed when the fuel, such as coal, has high sulphur content. Emissions from low sulphur-content coals, which are relatively abundant in Australia, do not generally warrant the expense of desulphurisation units, especially if there are few other sources in the same airshed.

Removal of sulphur dioxide from flue gas streams can both benefit the environment and allow for the production of useful by-products such as gypsum or sulphuric acid. Both these by-products could be easily used in other industries but the cost of recovery outweighs the benefits in many cases, especially when the fuel has low sulphur content. As for carbon dioxide capture, the need for a technology that cheaply and effectively removes sulphur dioxide from flue gases would benefit the progress of regional synergies. Also similar to carbon dioxide capture, membrane technology could be a possible solution to this problem.



### 5.4.3 Nitrogen Oxides

Nitrogen oxides are a mixture of nitric oxides and nitrogen dioxide. When in contact with atmosphere nitric oxide forms nitrogen dioxide, an odorous, brown, acidic, highly-corrosive gas, which affects the environment and people's health; nitrogen oxides contribute to photochemical smog (Anon. 2004b) and acid rain.

The NO<sub>x</sub> emissions are partially caused by burning of the nitrogen compounds in the fuel (fuel content and thus independent of burning conditions) and partially a result of process parameters during the burning process (such as temperature and air/fuel ratios). Control of nitrogen oxides (NO<sub>x</sub>) emissions can therefore be classified as follows (Kumar 2004): fuel denitrogenation (removal of nitrogen compounds from fuel before burning); low NO<sub>x</sub> burners (employing staged and catalytic combustion during the burning) and flue gas denitrogenation (employing catalytic converters or flue gas treatment in the exhaust gas).

Unless industries in an industrial area are producing nitrogen oxides emissions level close to or above statutory limits then there is little incentive to reduce NO<sub>x</sub> limits, especially as no valuable by-product is produced from nitrogen oxide capture. The technologies described here are either costly to implement or are emerging technologies that are not fully commercialised. Reduction in NO<sub>x</sub> does, however, help development of regional synergies by not preventing development due to airshed limitations.

### 5.4.4 Other Gaseous By-Products

Numerous other substances, which could be valuable if recovered, are emitted into the atmosphere. Emerging technologies such as cryogenic freezing have the advantage over other abatement technologies as it is efficient in recovering solvents even from low concentration process gas streams, in a pure uncontaminated form (Trembley 2004). These features mean that near-zero emissions are achievable and recovered solvents can be recycled or re-used. Still further research and development in this technology is necessary for it to gain a wider appeal than the current 5% of the overall Volatile Organic Compound (VOC) recovery market (Trembley 2004).

## 5.5 Waste Energy

In intense industrial areas, there is, commonly, a vast amount of energy rejected in the form of waste or low-grade heat to the local environs. Often this waste heat is not techno-economically feasible to capture for further use by conventional heat recovery technologies. To illustrate the typical quantity of waste heat, Spoelstra, Haije et al (Spoelstra *et al.* 2002) presented a cumulative plot of the waste heat generated by the refining and chemical industries in the Netherlands in 1999. Nearly 40 PJ (40 x 10<sup>15</sup> J) of waste heat had a temperature over 100°C and 100 PJ (100 x 10<sup>15</sup> J) of waste heat had a temperature over 50°C. If effective methods of low-grade heat capture and upgradation to higher temperatures are practically possible then this could have a huge impact on energy efficiency in an industrial region. In addition it would allow for one industry to benefit from the waste energy from another industry and reduce the overall emission of greenhouse gases from the region.

Waste heat is energy. By capturing waste heat, it is possible to use it for the same process that would require electricity or the burning of fossil fuel. Another possible use for waste heat from power stations near seawater is in desalination using evaporative technology. Using low-temperature flash distillation it is possible to utilise the residual heat discharged by cooling seawater for its distillation (Cohen *et al.* 2003). Alternatively, the energy in the blowdown water could run a multi-effect evaporator for desalinating seawater (Aybar 2004). Use of waste heat in this manner is more attractive when fresh water is scarce.



Although typical power stations in Australia are about 36% efficient as they use sub-critical (conventional) steam generation technology (Pagan *et al.* 2003), the ability to capture the waste energy can be extremely difficult and, hence, costly. The alternative option of changing to more efficient power generation technology, such as integrated gasification combined cycle (IGCC) which operates at about 50% efficiency, is also expensive (Pagan *et al.* 2003).

To capitalise on the vast quantities of waste heat in an industrial area, it is necessary to customise, adapt, and value engineer existing technologies (Berntsson *et al.* 1997) to capture and reuse the waste heat in a suitable manner. Attempting to capture waste heat on equipment where this was not a consideration in the design (or where the design was so efficiently dissipate heat) can be an extremely costly exercise. Ideally, waste energy or heat capture is best included in the initial design of the equipment.

With the expected increased requirements for energy efficiency in the future, technologies that can effectively utilise waste heat will become more attractive. Improved, efficient, cheaper technology for instance in the use of waste heat for water purification would have made a major contribution towards the advancement of regional industrial synergies.

## 5.6 Conclusions

Improvements in technology make an important contribution to progressing regional synergies. Although there are many factors, such as regulatory, environmental and legal, that need to be satisfied, there must be a technical solution to even consider a regional synergy for the re-use of a waste or by-product.

For many technology “gaps” in regional synergies, technical solutions have been discussed as promising propositions but not sufficiently demonstrated on a commercial scale. In the cases where commercial scale solutions are available, often the cost to install or retrofit to existing equipment does not warrant the benefits, making such an investment financially unattractive. In those cases, intensive value engineering is required to cut costs and boost benefits to businesses and society. The opportunity for new technologies to achieve greater regional industrial synergies is in the development or enhancement of existing technologies so that they are cheaper to install and operate.

As outlined in this chapter, opportunities exist for the “filling in” of technology “gaps” in a number of areas:

- The developments of high-value and quality products from large volume industrial by-products such as red mud, fly ash and bottom ash.
- The improvement in monitoring and control strategies in high temperature processes to be able to accept alternative fuels (e.g. in cement kilns).
- The developments in the technology of water reclamation from wastewater and seawater desalination to make the cost comparable or cheaper than traditional water supply strategies.
- The advancement of emission recovery technology, such as membranes, to allow for efficient separation and capture of organics and particulates from flue gases.
- The development of new technologies and enhancement of existing technologies to capture and utilise the large quantities of waste heat that are emitted from intense industrial regions.

Technology can be the key to the expansion of regional synergies. By developing cheaper, simple, and more efficient technical solutions for the re-use of wastes and by-products at a





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commercial scale, industries will benefit from greater regional synergies and sustainable development.





## Chapter 6: DISCUSSION

This status report on Regional Synergies for Sustainable Resource Processing contains the results of the first assessment and review of best practices with regard to the use of regional resource synergies as the basis for the minerals processing industry's contribution to sustainable development. It summarised dominant concepts and principles from the most relevant literature, and reviewed those national and international examples of regional synergy development and implementation, that are widely considered as leading-edge and appeared to have some relevance for heavy industrial areas with concentrations of minerals processing and metals production. Moreover, it investigated whether and how the current expertise and experience in Eco-Efficiency and recovery and reuse technologies for process wastes, waste water and waste heat, can be utilised for the further development of enabling tools and technologies for capturing regional synergies in minerals processing intensive areas.

### **6.1 Key Findings**

The notion of creating regional resource synergies to improve industry's contribution to sustainable development at the regional level is deeply rooted in Industrial Ecology and Industrial Symbiosis. Even though these – and other – terms are used interchangeably, it appears preferable to view Industrial Ecology more broadly as looking at nature as a model for the optimisation of materials and energy flows and inspiration for environmentally-oriented product and process design, and Industrial Symbiosis more narrowly as being concerned with exchanges of previously 'wasted' by-products between firms in close geographic proximity.

The literature review on concepts and principles illustrates that theory, methodology and policy for the deliberate creation of regional resource exchange networks are still in their infancy. There is a general appreciation that Industrial Symbiosis does work and can manifest itself in many different ways, with regard to for example the types of resource exchanges and their environmental and economic benefits, the nature of coordination and cooperation between businesses and other actors, and the maturity of the symbiosis. The literature does not provide for any specific consideration of the applicability of Industrial Ecology and Industrial Symbiosis for minerals processing and metals production.

Self-organisation emerges from the literature as a key success factor for the creation of regional synergies. Such self-organisation occurs as businesses see and pursue business opportunities to reduce their costs (through use of alternative input materials or water and energy sources), improve their process efficiency (e.g. through greater availability of high quality utilities), increase their revenues (from on-selling a by-product previously discarded as waste) and/or secure continued access to vital natural resources (e.g. in case of limited supply of for example water and power), through the setting up of regional resource exchanges. This self-organisation is, however, unlikely to be successful in the absence of dedicated resources for analysing materials and energy flow data, bringing together businesses, and developing and screening synergy project opportunities. In turn, this underpins the importance of facilitation to provide a platform for self-organisation to happen, which is now increasingly recognised under the umbrella of 'transition management' to make the self-organisation happen.

It is without doubt that (environmental) legislation, industry policy, resource economics and technology can all act as serious barriers to self-organisation for regional synergy development and implementation, but the picture is less clear as to whether and how each



can be turned into an incentive or enabler for such regional synergy development processes. (Inter-)national experience however shows that planning, public policy and legislation all have limited success in realising regional resource exchanges, except for industrial waste exchanges (where a waste generating company is connected to an appropriate waste management services provider) and shared environmental services (e.g. coordinated waste management and recycling services in an industrial area, or renewable energy project). On the basis of the limited policy analysis conducted within this project (<sup>2</sup>), it appears that regional synergy development will most likely benefit most from innovation and technology development support (to develop and trial processes and technologies to recover and value add to by-products currently becoming wastes), self- and co-regulation on the basis of best practice guidelines with regard to environmental risk and community health assessments for resource recovery projects and applications of recovered resources, and potentially access to risk capital for investments in resource synergy projects.

The research reported here identified in excess of 60 national and international examples of regional resource synergy development and implementation from literature and web searches, and interaction with industry and Industrial Ecology practitioners. This shows that there is great interest in the notion of Industrial Symbiosis. Many industrial areas around the world have attempted its implementation generally with at least some success with regard to creating new synergies that involve exchange of material, water or energy resources, and bring real time economic and environmental benefits to the industries and communities involved.

The detailed review involved sixteen international and two Australian examples (Kwinana and Gladstone). Given the great differences in amount and quality of the available (English) information on each it turned out to be difficult to draw definite conclusions in regards to best practice in regional resource synergy development and implementation. The trends are however quite clear:

- There is general agreement around the use of a workshop based facilitation methodology, involving elements of awareness raising, input/output inventory and quantification (for principal materials, energy and water inputs and outputs of the companies in the area), synergy opportunity identification and screening, and feasibility studies and business planing.
- Existing synergy projects are dominated by comparatively straightforward exchanges between two companies of solid or liquid process waste streams, and involve minimal – if any – processing of the waste stream prior to its reuse by the recipient company.
- Limited attention has been given to the technological and engineering challenges associated with creating regional synergies. Or, vice versa, it might be concluded that even best practice regional synergy projects have focused on comparatively simple technological opportunities.
- Synergy opportunities have so far been developed opportunistically. Firstly this may reflect the abundance of comparatively straightforward (*‘low-hanging-fruit’*) synergies that generally emerge with an initial focus on regional resource synergies in many industrial areas. Secondly, this could also imply that current efforts only scratch the

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<sup>2</sup> The parallel research project on enabling mechanisms for industrial symbiosis focuses more explicitly on the policy context for regional synergies development and implementation and should provide further insight in due course.



surface, as more innovative and complicated synergies are not yet being identified or pursued.

The review of current practice of regional synergy development and implementation confirmed that Kwinana and Gladstone compare favourably with the well-regarded international examples. This relates to the level and maturity of industry involvement and collaboration, and the commitment to further regional resource synergies as the cornerstone for the area's contributions to sustainable development. Moreover, Kwinana stands out with regard to the number, diversity, complexity and maturity of existing synergies. Gladstone is remarkable as among the examples of regional synergy developments, it stands out as an example with unusually large geographic boundaries and unusually high dominance of one industry sector (the alumina and aluminium industries and its power supplier).

There is widespread recognition that Eco-Efficiency is a valuable contribution for regional synergy development and implementation, as regional synergies, or Industrial Symbiosis, can be seen as extending Eco-Efficiency initiatives over the company boundary. In doing so, however, complexity increases considerably for two reasons. Firstly, complexity increases because of the larger number of processes and unit operations to be considered, and the need to consider the implications of the physical distance between the unit operations. Secondly, complexity is enhanced by the divergence of optimisation strategies (at the level of individual companies and at the level of the region) and the openness of the system (which impedes the ability to use mathematical optimisation models). There is a need for complex systems thinking, as it is increasingly recognised that the system of resource exchanges within one industrial plant is embedded in systems of resource exchanges within the industrial area and value-chain to which the plant contributes, which in turn are embedded in systems of resource exchanges at national and global levels.

This suggests that it might be most appropriate to adapt and customise a normative structure as the basis for a method for regional synergy opportunity identification (similar to the logical, normative structure in a Cleaner Production option generation routine/method). Quantitative optimisation tools can have a supportive role, in particular for the concept and detailed design of synergy projects. Such normative structure needs more development work, to extract defining features from successful synergy projects, and combine these with existing normative solutions and design principles in Eco-Efficiency, Green Chemistry and Green Engineering.

The taxonomy for Eco-Efficiency metrics/indicators is comparatively well developed, even though reporting thereon is still not widespread for a number of reasons, including data paucity and concerns regarding data disclosure. It appears that extension of these indicators from company level to the level of industrial areas would be comparatively straightforward, providing both pollution intensity and resource efficiency indicators to measure regional resource synergy achievements. Given the diversity of operations, and hence in most important environmental and resource efficiency issues, it appears desirable to measure performance at the regional level using a limited number of indicators. This applies both to the economic value indicators (for example: total production or value added by companies in the area) as well as the environmental indicators (for example: total materials consumption, total water consumption, total energy consumption and total greenhouse gas emissions from companies in the area).

Both the literature on and practical examples of regional synergy development have very limited focus on technology, either as incentive or barrier, despite it being imperative to have a suitable technology available to make any synergy project happen. For minerals processing intensive areas, particular attention is needed for possible capture, storage, recovery and use technologies for bulk, process-related, waste streams and emissions, i.e. for residues and



slags, ash and fines, concentrated processing solutions and waste water, waste and low grade heat, and emissions of carbon dioxide, sulphur dioxide and nitrogen oxides. Some of these are specific to minerals processing (in particular slags, residues, processing solutions), while others are of general relevance to heavy industrial areas (in particular waste water, ash, waste and low grade heat and bulk air emissions). While considerable research has been – and continues to be – done into recovery and reuse options for high volume processing wastes, those that have reached noticeable market acceptance and implementation all deal with cement manufacturing either through alternative fuels (e.g. spent pot lining, oils and solvents, tyres, plastic waste) or alternative raw materials (fly ash). Opportunities for improvement of composition and properties of bulk inorganic waste streams through separation and/or blending of different by-products have not yet been systematically investigated.

## **6.2 Conclusions**

In light of the overall aim of this foundation project to encourage and facilitate the greater utilisation of regional synergy opportunities in minerals-processing intensive regions, it is possible to conclude on the basis of the research reported here, that:

1. The science and – to a lesser extent also – the technology for creating regional resource synergies are captured in the emerging disciplines of Industrial Ecology and Industrial Symbiosis, which enjoy remarkably broad support from industry, government and the community, despite their specific theory and methodology developments still being in their infancies.
2. There is both historic and present day evidence that regional collaboration between traditionally separate industries involving physical exchange of materials, energy, water and/or by-products, or Industrial Symbiosis, can deliver both competitive advantage and environmental benefit. The evidence therefore is strongest for the two Australian regions studied (Kwinana and Gladstone), but generally supported by the other sixteen international case study regions (even though the information for these international regions is far less detailed).
3. There is strong evidence that 'self-organisation' is a critical success factor for regional synergy development, recognising that self-organisation will generally need to be facilitated and properly resourced through 'transition management'. The self-organisation occurs as businesses see and pursue opportunities to improve their businesses by engaging in regional resource exchanges with their neighbours.
4. It is without doubt that (environmental) legislation, industry policy, resource economics and technology can all act as serious barriers for self-organisation into regional resource synergies, but the picture is less clear as to whether and how each can be turned into an incentive or enabler for regional synergy development. There is little – if any – evidence that planning, public policy or legislation can drive regional synergy development and implementation beyond industrial waste exchanges or set up of shared environmental services in the industrial area. Instead, it appears that innovation and technology development support, co- and self-regulatory approaches on the basis of agreed best practice guidelines, and potentially investment support for synergy project implementation are more likely to be effective for fostering regional synergies development and implementation.
5. The recognised leading international examples of regional synergy development in heavy industrial areas are dominated by comparatively straightforward exchanges of process



by-products, waste water or waste heat, between two companies, that involve minimal – if any – processing prior to (re)use by the recipient company. In many of the documented examples it appears that the Industrial Symbiosis initiative plateaus, for reasons not yet fully understood, but possibly indicating that the engineering tools, technologies, business models and policy environments to achieve more complex resource synergies are lacking.

6. Kwinana and Gladstone compare favourably with the well-regarded international examples of regional synergy development, in terms of the level and maturity of the industry involvement and collaboration, and the commitment to future regional resource synergy projects as the cornerstone for the area's contributions to sustainable development. Moreover, Kwinana stands out with regard to the number, diversity, complexity and maturity of existing synergies. Gladstone is remarkable as among the examples of regional synergy development it stands out as an example with unusually large geographic boundaries and unusually high dominance of one industry sector (alumina and aluminium and its power supplier).
7. Regional synergies have developed opportunistically in the absence of specific methods for synergy option generation and/or synergy technology selection and assessment, despite there being a competency and track record in Eco-Efficiency methods and metrics and resource recovery technologies on which such methods could be based. There is a distinct possibility to support the development and implementation of regional synergy projects with customised methods for synergy project identification and evaluation and model applications of existing and emerging water, energy and materials recovery and use technologies therein.

### 6.3 Recommendations

In support of this foundation project's principal aim of fostering greater utilisation of regional synergy opportunities in minerals processing intensive regions, it is recommended that:

1. ***The experience and achievements in regional synergies development and implementation in both Kwinana and Gladstone be widely and persistently communicated.*** Such is well justified in light of this research's finding that both areas compare favourable with other leading examples of regional synergy development and implementation. A detailed communication strategy needs to be developed and implemented to achieve a three-fold outcome: (i) to catalyse further synergy projects in Kwinana and Gladstone (i.e. to extend to companies and resource flows not yet included and grow the environmental, social and economic benefits from regional synergies); (ii) to inspire and seed regional synergies programs in other industrial areas (inside and outside of Australia, in particular in areas with a strong resource processing base); and (iii) to gain recognition for sustainability leadership and industry achievement (with less tangible benefits with regard to government, shareholders, employees and community relations). The success of such communication and liaison strategy is contingent on the further advancement of regional synergy opportunities in both Kwinana and Gladstone, for which a framework is provided through ongoing targeted CSRP research projects in these areas.
2. ***A method be developed to structure the generation of synergy opportunities with particular relevance to minerals processing intensive regions.*** This method will enable the development of more adequate and comprehensive sets of potential synergy projects to be considered in any minerals processing intensive region. Its development



should be based on the practical advances and achievements of the regional resource synergy pilot research projects in Kwinana, Gladstone and potentially elsewhere. The method could adopt a normative basis, similar to key Eco-Efficiency methods, with such basis to be developed through deconstruction of known successful examples of regional synergies and integration of the findings thereof, with existing normative frameworks from for example Eco-Efficiency, Green Chemistry and Green Engineering. The method should also be capable of considering business relationship development potential and be piloted to support the regional synergy projects in Kwinana and Gladstone.

- 3. Further research be undertaken so that existing and emerging technologies, in particular in the areas of heat, materials and water recovery and reuse, can deliver regional synergy opportunities.** This will involve identification of technology needs and opportunities as these are encountered in regional synergy development and implementation in practice, and assessment of alternative ways to realise potential synergies through innovative applications of existing and emerging technologies. Such research will expand the set of potential technological solutions for regional synergy initiatives, enabling such initiatives to move more effectively towards the realisation of resource exchanges that are contingent on more extensive processing of the by-product. This could involve two work streams, namely process and technology development (for priority minerals' industry specific process waste streams, like bauxite residue, smelter slags, fly ash) and systems development (configuring and adapting processes and technologies developed elsewhere to capture, recover and use valuable components from non-minerals' industry specific process waste streams, such as low grade heat, waste water, carbondioxide, etc.). Process and technology development can in principle be catered for within the CSRP research project on zero waste strategies, whereas this foundation project on regional synergies could cater for further research at the level of system development and evaluation employing technologies and by-product streams that are not specific to the minerals processing industry.



## APPENDIX A

CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
Alberta, Canada	<ul style="list-style-type: none"> <li>▪ Oil refining and products (5 of them)</li> <li>▪ Oil exploration</li> <li>▪ Power generation and distribution</li> <li>▪ Commodity shipping</li> <li>▪ Hazardous waste treatment facility and</li> <li>▪ Environmental solutions company</li> </ul>	<ul style="list-style-type: none"> <li>▪ Oil refinery supplies spent caustic (NaOH) to a forest products company to compensate for NaOH losses</li> </ul>	<p>Participants identified more than 80 potential synergies with more than 30 different materials. The potential synergies are summarised below. For more details see (Applied Sustainability (n.d.))page 46.</p> <ul style="list-style-type: none"> <li>▪ Energy production (biomass utilisation, by-products as fuel for cement kilns and flares)</li> <li>▪ Sulphur and high-sulphur coke utilisation</li> <li>▪ Inorganic (including ash, fly ash, wood ash, other liming by-products and mineral tailings)</li> <li>▪ Waste heat recovery</li> <li>▪ Industrial gases (CO<sub>2</sub> and hydrogen plus small amounts of oxygen, nitrogen and argon)</li> </ul>
Golden Horseshoe, Canada	<ul style="list-style-type: none"> <li>▪ Industrial gases,</li> <li>▪ Steelmaking</li> <li>▪ Carbon black</li> <li>▪ Wood products</li> <li>▪ Solvent and refrigerant reclamation</li> <li>▪ Cement</li> <li>▪ Concrete products</li> <li>▪ Power generation</li> <li>▪ Fuel distribution</li> <li>▪ Fertilisers wholesale</li> <li>▪ Commodity shipping</li> <li>▪ Waste collection services</li> </ul>	<ul style="list-style-type: none"> <li>▪ Iron oxide containing sludge or dust from a steel manufacturer is being fed as a raw material into a cement kiln for the manufacture of Portland cement.</li> <li>▪ Off-spec material from a carbon black manufacturer used as a foaming slag additive by a steel making company</li> </ul>	<ul style="list-style-type: none"> <li>▪ Toner fines from dust collection systems of a toner manufacturer for use as an alternative polymer additive in asphalt production.</li> <li>▪ Super sacks from several companies are being considered for re-use.</li> <li>▪ Wood waste and wood pallets from several companies for manufacture of high quality compressed wood or used as an alternative fuel.</li> <li>▪ Steel slag for aggregate for road building on Ministry of Transportation highways.</li> <li>▪ Cement kiln dust for use as an activator for finely ground slag to promote and enhance the cementitious properties of the slag.</li> <li>▪ Spent caustic from oil refining for use by a paper company.</li> <li>▪ Spent caustic from oil refining for use in various neutralisation processes.</li> <li>▪ Glycol (spent hydraulic fluid) to reduce friction in clinker grinding.</li> <li>▪ Oily waste and oily sludge from steel making as cement kiln fuels.</li> <li>▪ Waste oils from auto assembly and petroleum distribution for use as an equipment lubricant in cement making.</li> <li>▪ Coke dust from a steel manufacturer as a fuel for a cement kiln.</li> <li>▪ Lime dust from steel making as a raw material in cement manufacture.</li> <li>▪ Spent catalyst/sand from a petroleum company as a raw material feed to the cement kiln.</li> <li>▪ Used tires from passenger vehicles for the production of carbon black.</li> <li>▪ Used tires from passenger vehicles as an energy source.</li> <li>▪ Steelmaking slag as a raw material into a cement kiln.</li> <li>▪ Spent caustic from a petroleum company for re-use in sister plant to replace fresh caustic in the petroleum refining process.</li> </ul>

CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
Guayama, Puerto Rico	<ul style="list-style-type: none"> <li>▪ Petrochemical refinery</li> <li>▪ Four pharmaceuticals companies</li> <li>▪ Aluminium can manufacturing</li> <li>▪ Plastic bottle manufacturing</li> <li>▪ Heavy machinery repair</li> <li>▪ Oral care and detergent manufacturing</li> <li>▪ Coal-fired power plant (since 2002)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Power plant using reclaimed water from public wastewater treatment plant</li> <li>▪ Power plant provides steam to refinery</li> </ul>	<ul style="list-style-type: none"> <li>▪ Use of coal ash in construction (cement, soil stabilisation and ash rock for highway)(Note: the coal ash generated by the power station has different characteristics than the conventional fly/bottom ash as a result of circulating fluidised bed (CFB) coal combustion technology in use in Guayama. The fly and bottom ash here are substantially higher in sulphates and lime (unreacted CaO) than traditional ash)</li> <li>▪ Power plant to provide steam to pharmaceutical companies and use reclaimed water provided by them</li> </ul>
Kalundborg, Denmark	<ul style="list-style-type: none"> <li>▪ Coal fired power station,</li> <li>▪ Oil refinery</li> <li>▪ Pharmaceuticals plant</li> <li>▪ Plasterboard manufacturer</li> <li>▪ Cement plant</li> <li>▪ Liquid fertilisers</li> <li>▪ Waste treatment</li> </ul>	<ul style="list-style-type: none"> <li>▪ Excess gas from the refinery to power station and plasterboard manufacturer</li> <li>▪ Power station supplies steam to oil refinery and pharmaceutical plant, and waste heat for district heating and cooling water for fish farming</li> <li>▪ Fly-ash from the power station is supplied to the cement plant</li> <li>▪ Gypsum from the power station is supplied to plasterboard manufacturer</li> <li>▪ Cooling water and wastewater from oil refinery is supplied to the power station</li> <li>▪ Yeast slurry from pharmaceuticals plant to local farmers</li> <li>▪ Sludge from the municipal water treatment plant in Kalundborg is utilised for soil remediation purposes</li> <li>▪ Liquid sulphur from oil refinery to fertilise industry</li> <li>▪ Treated sludge from pharmaceutical plant for fertiliser</li> </ul>	
Kawasaki Zero Emission industrial Park, Japan	<p>There is no specific information which are the industries involved in the project but from the available literature, power station, cement manufacturing, iron making plant and various recycling facilities are evident to be present in the park</p>	<ul style="list-style-type: none"> <li>▪ Source-separation facility for the wastes generated within the industrial park</li> <li>▪ Waste paper generated in the park recycled within centralised kitchen waste composting</li> <li>▪ Material joint-purchase for the park</li> <li>▪ Recycling of discarded electronic appliances providing inputs for the steel industry</li> <li>▪ A steel manufacturer utilised municipal plastic wastes instead of coal in blast furnaces</li> <li>▪ Incineration fly ash supplied for cement production</li> <li>▪ Municipal refuse, shredder dust and other industrial wastes are treated by the high-temperature gasification direct melting furnace and chemically recycled to supply carbon dioxide gas and hydrogen generated to chemical plants as synthesis material of basic chemical products such as ammonia, methane, methanol, etc.</li> <li>▪ Commercial production of ammonia using waste plastic</li> </ul>	<ul style="list-style-type: none"> <li>▪ Incinerator plants supplies fly ash and bottom ash to cement companies utilised from as inputs for manufacturing cement.</li> <li>▪ Heavy metal recovery from plating and coating waste liquids</li> <li>▪ Treated wastewater supplied by WWTP reused in the park for industrial purposes</li> <li>▪ Incineration ash generated in the city treatment centre and residues from related recycling projects in the Eco-Town to be gasified to produce molten slag. The molten slag is water-granulated and recycled as materials for civil engineering products. In addition, the waste heat discharged from gasification melting furnace, is used to generate electricity.</li> </ul>

CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
		<ul style="list-style-type: none"> <li>Plastics are recycled through the injection of waste plastics from industrial wastes into blast furnaces of iron-works as coke-substituted material.</li> </ul>	
Map Ta Phut, Thailand	<ul style="list-style-type: none"> <li>Public utility industry – 8 – power, steam, gas, etc.</li> <li>Petrochemical industry – 24 factories</li> <li>Oil refineries – 2</li> <li>Chemical and fertiliser industry – 15 factories</li> <li>Steel industry – 7 factories</li> </ul>	<ul style="list-style-type: none"> <li>Three co-generation facilities produce electricity and steam and supply these to petrochemical industry</li> <li>Bottom ash and fly ash used as an ingredient in concrete blocks or for use in cement production.</li> <li>Trichloroethylene 1,1,2 and trichloroethane 1,1,1 as by-products from H<sub>2</sub> and N<sub>2</sub> production are supplied for distillation and recycling.</li> <li>Waste oil is mixed with fuel in cement kiln or used as raw material in oil paint</li> <li>Low polymer is supplied for producing candles and wax colour</li> <li>Spent solvent, i.e. hexane for use in tinier production</li> <li>Naphtha and condensate derived as by products are used in the production process of white spirit solvent, diesel, fuel oil, etc.</li> <li>Liquid sulphur is used as raw material in fertiliser production</li> <li>Waste dust from bag house is supplied as raw material for cement production</li> <li>Scale from iron production is supplied as raw material for cement production</li> <li>Wastewater treatment plant sludge supplied as raw material for cement production</li> <li>Refractory waste recycled and supplied as raw material for cement production</li> <li>Small and medium sized factories use the central wastewater treatment</li> </ul>	
Montreal, Canada	<ul style="list-style-type: none"> <li>Industrial chemicals,</li> <li>Magnesium smelter</li> <li>Aluminium smelter</li> <li>Aluminium dross recycler</li> <li>Silicon metal and products producer</li> <li>Refractory products</li> <li>Hydrogen peroxide</li> <li>Metal working</li> <li>Nuclear power station,</li> <li>Industrial gases</li> <li>Petrochemicals</li> <li>Titanium dioxide production</li> <li>Wallboard manufacturer</li> </ul>	<ul style="list-style-type: none"> <li>Recovery of aluminium residues</li> <li>Excessive hydrogen from chlor-alkali plant is used by hydrogen peroxide producer</li> <li>Sulphuric acid used to dry chlorine gas is sold</li> <li>Sodium sulphate from brine purification stage is converted into gypsum</li> <li>Anode graphite from magnesium smelter is recycled into a range of graphite products.</li> <li>Silica fume as an addition to cement and concrete; as a filler for plastics; as a substitute for asbestos; as an ingredient in some waste stabilisation mixes.</li> <li>Residual pitch from hydro cracking process as fuel use in cement manufacturing</li> <li>Alumina catalysts are used in cement manufacture</li> <li>Hydrogen sulphide (from refineries) conversion into elemental</li> </ul>	<ul style="list-style-type: none"> <li>Inorganic sludge from magnesium smelter for agricultural applications</li> <li>CO<sub>2</sub> capture and resale or to increase photosynthesis in a greenhouse</li> <li>Co-generation plant</li> <li>Polymerisation catalysts containing phosphate are being evaluated as possible fertilisers</li> <li>Excess steam to be supplied to an industrial area adjacent to the refinery for process steam and space heating</li> <li>Ammonium sulphate production from waste ammonia stream from the hydrogen sulphide conversion</li> <li>Use of CO<sub>2</sub> as a blowing agent for Styrofoam</li> <li>Potential use of recovered sulphur in sulphur polymer-based construction materials</li> <li>Potential gas stream desulphurisation and SO<sub>2</sub> recovery</li> </ul>

CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
	<ul style="list-style-type: none"> <li>▪ Polymers</li> <li>▪ Packaging materials</li> </ul>	<ul style="list-style-type: none"> <li>▪ sulphur and sulphuric acid</li> <li>▪ Synthetic gypsum from titanium dioxide production is used as a raw material</li> <li>▪ CO<sub>2</sub> recovery</li> <li>▪ Hydrochloric acid from titanium dioxide production is sold as commercial grade acid</li> <li>▪ Conversion of pickle liquor from steel plants into ferric chloride for use in wastewater treatment as flocculant</li> <li>▪ Oversized latex particles in latex manufacturing are emulsified in a solvent and used as fuel in cement kiln</li> <li>▪ Pilot plant for pyrolysis of scrap tires, plastics and possibly shredded fluff from automobile recycling</li> <li>▪ Lead recycling from scrap car batteries</li> <li>▪ Polypropylene from plastic battery parts is isolated and sold</li> <li>▪ Industrial fluid recycling</li> <li>▪ Used oil turned into re-refined lubricating oils or asphalt extenders.</li> <li>▪ Spent solvent collected and blended to fuel cement plants</li> <li>▪ Glycol recovery from airplane de-icing fluid</li> </ul>	
NISP, UK	<p>There is no information provided which are the companies participating in the programme and what industry sectors they represent.</p> <div style="border: 1px solid black; padding: 5px; margin-top: 10px;"> <p>NOTE: since this project is currently active and provides updated information regarding its existing and potential synergies the list here might not be comprehensive, as new synergies are being identified on ongoing basis. For current information see NISP web site: <a href="http://www.nisp.org.uk">www.nisp.org.uk</a></p> </div>	<ul style="list-style-type: none"> <li>▪ Recovery and reprocessing of HDPE from waste chemical drums for reuse in drainage materials</li> <li>▪ Bakery waste to pet food</li> <li>▪ Concrete recycling in construction materials</li> <li>▪ Maximising the capacity of a wastewater treatment plant by cooperation between two companies</li> <li>▪ Wood chip fuel used to heat a local authority leisure centre</li> <li>▪ Tyre waste to cement kiln</li> <li>▪ Exchange of unused chemicals</li> <li>▪ Furniture reuse</li> <li>▪ Inert waste on Council site recycled, as alternative to landfilling at site 11 miles away</li> <li>▪ Incineration of scampi (variety of prawn) shells locally instead of being transported to France for conversion in bouillon</li> <li>▪ Gypsum resulting from neutralisation to a plasterboard manufacturer</li> <li>▪ New business opportunity mulching waste wood</li> <li>▪ Calcium salt from incinerated bone ash to house bricks</li> <li>▪ Wastewater treatment facility provides dry organic pellets to local farms</li> <li>▪ Food and fish processing supplies organic waste to pet food manufacturer</li> <li>▪ Wood dust and chips from furniture production to local farms</li> </ul>	<ul style="list-style-type: none"> <li>▪ Gasifier to use organic waste provided by local farms, food and fish processing and the dry organic pellets from the wastewater treatment plant</li> <li>▪ Wastewater treatment facility to provide process water to plaster board manufacturer and cooling water to refineries</li> <li>▪ Food and fish processing to supply waste edible oil to refineries and supply offal for protein extraction</li> <li>▪ Power plant to provide steam and electricity to local businesses and utilise refuse derived fuel supplied by the local council</li> <li>▪ Local council to provide end-of-life refrigerators to industrial plastics manufacturer for material recovery</li> <li>▪ Industrial plastics manufacturer also to utilise waste carpets and other waste plastics</li> <li>▪ Waste paper for animal bedding</li> <li>▪ Use of chipped tyres as a growing medium for effluent treatment</li> <li>▪ Use of oily drill cuttings in civil engineering applications</li> <li>▪ Conversion of waste drill cuttings to cat litter</li> <li>▪ Pulverised fuel ash reuse opportunities – in soil stabilisation, cement products, integration with soils to make low quality compost, road construction and stabilising motorway embankments.</li> <li>▪ Reuse of construction waste</li> <li>▪ Two projects involving salmon processing plant investigate the opportunities for manufacturing leather from the waste product of salmon skin and the use of waste salmon products in health care products manufacturing.</li> <li>▪ Fuelling of a cement kiln by the burning of waste tyres and Recycled Liquid Fuels</li> </ul>

CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
		<ul style="list-style-type: none"> <li>▪ Chemical industry supplies hydrogen to refineries</li> <li>▪ Polystyrene waste from food and fish processing to interior decoration products manufacturer</li> <li>▪ Installation of a power plant which will utilise cooling water stream from wastewater plant, will use by-products from the refineries and will provide steam to the chemical industry plants</li> <li>▪ Local food processors and restaurants supply waste edible oil for bio-diesel production</li> </ul>	<ul style="list-style-type: none"> <li>▪ made from waste solvents</li> <li>▪ Processing waste glass to use as a filtering medium (higher performing alternative to sand for use in water filtering equipment)</li> <li>▪ Generating power using poultry litter as fuel, with the resulting ahs being used as fertiliser</li> <li>▪ Development of pharmaceuticals using waste fish products</li> <li>▪ Decontaminating land using chicken litter</li> </ul>
North Texas, USA	<ul style="list-style-type: none"> <li>▪ Industrial gasses and liquids</li> <li>▪ Cement manufacturing</li> <li>▪ Steel manufacturing</li> <li>▪ Graphite manufacturing</li> <li>▪ Power generation</li> <li>▪ Cosmetics manufacturing</li> <li>▪ Scrap metal recycling</li> <li>▪ Fibreglass composite materials.</li> </ul>	As at the time of the reporting (Sep 2001) there are two synergies being implemented that were identified in Phase I of the project; Copper Machining Waste & Graphite Roller Waste. No further details are provided.	<p>105 synergy ideas were identified, involving 57 different materials but no details are provided in the published material, except for the following possibilities:</p> <ul style="list-style-type: none"> <li>▪ Use of fly ash in cement manufacturing</li> <li>▪ Use of fly ash in roofing shingles</li> <li>▪ Use of electrostatic precipitator dust as fertilizer</li> <li>▪ Conversion of wood wastes ad other biomass to electricity</li> <li>▪ Use of tyres as alternative fuel</li> <li>▪ Pooling similes/same wastes for recycle</li> <li>▪ Antifreeze recycling &amp; replacing hazardous solvent with non-hazardous substitutes</li> <li>▪ Laboratory chemicals clearinghouse</li> <li>▪ Spent ammonium hydroxide to replace sodium hydroxide</li> </ul>
Ora Ecopark, Norway	<ul style="list-style-type: none"> <li>▪ Titanium pigments</li> <li>▪ Fish &amp; vegetable oils</li> <li>▪ Municipal waste handling and energy generation</li> <li>▪ Chemicals</li> <li>▪ Gypsum board</li> <li>▪ Polymers</li> <li>▪ Paints</li> <li>▪ Industrial waste handling</li> <li>▪ Harbour facilities</li> </ul>	A number of symbiotic interactions have taken place for a number of years between some of the companies, such as: steam, condensate, hot & cold water, waste sulphuric acid, iron sulphate waste, polyester waste, wood chips for energy production, filter waste, industrial waste, and sludge.	
Quebec, Canada	<ul style="list-style-type: none"> <li>▪ Industrial gases,</li> <li>▪ Oil refineries</li> <li>▪ Copper refinery</li> <li>▪ Zinc smelter</li> <li>▪ Steel manufacturing</li> <li>▪ Lead smelter</li> <li>▪ Pigments</li> <li>▪ Pulp and paper</li> <li>▪ Wood panel products</li> </ul>	<ul style="list-style-type: none"> <li>▪ Ferric and ferrous sulphates to be used in wastewater treatment</li> <li>▪ Ferrous chloride for wastewater treatment</li> <li>▪ Sodium sulphate from sodium chlorate production to be used by the pulp &amp; paper industry in, and sodium sulphate from sulphur scrubbing (graphite production) to be used in fibreglass production facility nearby.</li> <li>▪ Spent caustic soda from a refinery to be used in a smelter as a desulphuriser &amp; fluxing agent instead of limestone. As well, this spent caustic soda can be put to use in the pulp &amp; paper facilities</li> <li>▪ Used oil as energy resource for smelters</li> <li>▪ Biologic sludge for soil beneficiation</li> </ul>	<ul style="list-style-type: none"> <li>▪ Small volumes of sulphuric acid to be used by a lead smelter</li> <li>▪ Sandblast residues from equipment cleaning to zinc smelter</li> <li>▪ Iron recovery from iron oxide from corrosion</li> <li>▪ Electric Arc Furnace and steel slags to cement kiln</li> <li>▪ Hydrogen from two sodium chlorate facilities for use in hydrogen peroxide facility</li> <li>▪ Limestone, lime dust and steel slag for neutralisation purposes</li> <li>▪ Non-metallic car shredding residues for fuel</li> <li>▪ Zinc recovery from Electric Arc Furnace dust</li> <li>▪ Cooling tower heat utilised in greenhouses and aquaculture farms.</li> <li>▪ Spent refractories to cement operations or construction material</li> <li>▪ Off-spec jet fuel for energy</li> </ul>

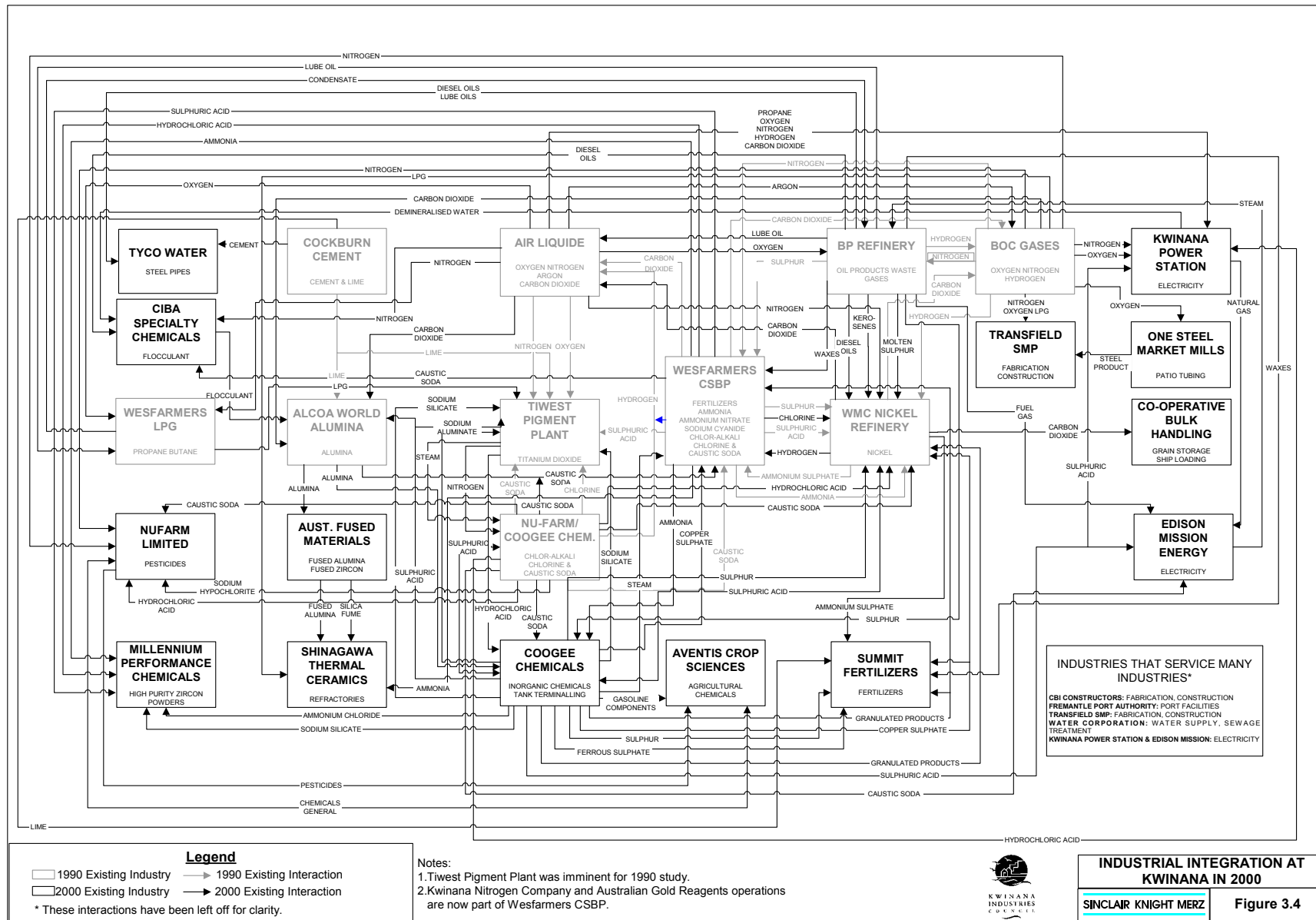
CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
			<ul style="list-style-type: none"> <li>▪ Recovery of spent vanadium pentoxide catalyst</li> <li>▪ Carbon recovery from spent electrodes</li> </ul>
Rotterdam, The Netherlands	<ul style="list-style-type: none"> <li>▪ Industrial services x 10</li> <li>▪ Refineries x 7</li> <li>▪ Inorganic chemistry x 11</li> <li>▪ Storage and transport x 15</li> <li>▪ Mass goods x 13</li> <li>▪ (Petro)chemistry x 13</li> </ul> <p>The informational sources do not reveal actual participants in the projects or even provide a list of the potential INES synergies.</p>	<ul style="list-style-type: none"> <li>▪ Compressed air utility sharing</li> <li>▪ Wastewater reuse</li> <li>▪ Bio-sludge utilisation as a substitute for coal in a power station of a cement company</li> </ul> <p>NOTE: at the time of reporting these synergies were at the stage “pre-feasibility study completed”</p>	<p>15 potential projects in total (including the 3 chosen for implementation) were identified in 4 categories:</p> <ul style="list-style-type: none"> <li>▪ Prevention – cargo waste in transit and storage; small size packaging; off-spec products.</li> <li>▪ Chain management – reuse of sulphur; desulphurisation; silicon- and aluminium – oxide; crude oil sludge.</li> <li>▪ Energy/utilities sharing – demand/supply steam; air capacity; low pressure steam; off-spec natural gas; high-caloric waste incineration for power generation.</li> <li>▪ Joint treatment – bio sludge; wastewater; ballast water.</li> </ul>
Saint John, New Brunswick, Canada	<ul style="list-style-type: none"> <li>▪ Oil refinery,</li> <li>▪ Pulp mill, a paper mill,</li> <li>▪ Tissue mill,</li> <li>▪ Oil-fired thermal power station,</li> <li>▪ Brewery, and a</li> <li>▪ Number of plastics manufacturers.</li> <li>▪ In addition to the core industries there are three industrial parks within the city limits. Two additional major operations are dairy and sugar refinery</li> </ul>	<ul style="list-style-type: none"> <li>▪ CO<sub>2</sub> from oil refiner is supplied to industrial gases plant where it's being purified and compressed for food grade CO<sub>2</sub></li> <li>▪ Spent catalysts from the oil refinery, depending on their composition are sent to cement companies as a raw material or for metal recovery</li> <li>▪ Black liquor from pulp mills in USA, waste oil collected by an environmental services company and hog fuel are used to generate steam</li> <li>▪ Lime mud from the pulp mill is sent to farms for agricultural use</li> <li>▪ Ash from the bark boiler at the pulp mill is used in forest culture</li> <li>▪ Waste plastic wrap from the brewery is sent to a plastic bags manufacturer</li> <li>▪ Spent grain and yeast from the brewery to farmers, for addition to feed</li> <li>▪ Contaminated plastic from a plastic bottle company is either sold to another plastics manufacturer where is mixed into their pipe manufacturing process, or it is used by another plastics manufacturer for plastic lumber</li> <li>▪ A plastic bags manufacturer collects approx 4.5 million kilograms of used plastic bags from the nearby province for use as resource</li> </ul>	<ul style="list-style-type: none"> <li>▪ Sludge is the main waste from the paper mill. Opportunities are investigated whether it can be used for agricultural needs, or to be used as a fuel in the pulp mill</li> <li>▪ There is potential symbiosis between the brewery and the pulp mill for steam supply</li> <li>▪ Co-generation</li> </ul>
Sarnia-Lambton, Canada	<ul style="list-style-type: none"> <li>▪ Petrochemical</li> <li>▪ Polymers</li> <li>▪ Plastics</li> <li>▪ Oil refinery</li> <li>▪ Industrial gasses</li> <li>▪ Insulation wool</li> <li>▪ Resin plant</li> </ul>	<ul style="list-style-type: none"> <li>▪ Power/steam co-generation project jointly operated by 3 of the largest companies, utilising the excess power generated by chemical and resin manufacturer to the grid and supplying steam to a neighbouring polystyrene manufacturing plant</li> <li>▪ Flue gas desulphurisation gypsum supplied by power station to gypsum board plant</li> <li>▪ By-product steam cascading</li> <li>▪ Collective brine capture and recovery program</li> </ul>	<ul style="list-style-type: none"> <li>▪ Pelletised mixture of fly ash and wastewater treatment sludge to produce a marketable lightweight aggregate for concrete manufacture</li> <li>▪ Energy from post consumer plastics</li> <li>▪ Reuse of co-product sulphuric acid for fertiliser manufacture or paper manufacture</li> <li>▪ Co-generation facility</li> <li>▪ Energy from waste</li> </ul>

CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
Styria, Austria	<ul style="list-style-type: none"> <li>▪ Iron manufacturing</li> <li>▪ Cement manufacturing x 6</li> <li>▪ Construction materials</li> <li>▪ Power station x 2</li> <li>▪ Paper producing x 6</li> <li>▪ Textile industry x 2</li> <li>▪ Chemical industry</li> <li>▪ Colour industry</li> <li>▪ Stone and ceramic industry x 2</li> <li>▪ Waste water treatment</li> <li>▪ Iron scrap dealer</li> <li>▪ Used oil dealer x 3</li> <li>▪ Waste paper dealer</li> <li>▪ Saw mills</li> <li>▪ Plastics manufacturing</li> <li>▪ Fuel producing</li> <li>▪ Agricultural associations</li> </ul>	<ul style="list-style-type: none"> <li>▪ Bark from one paper production to another</li> <li>▪ Fibre muds from paper production to stone and ceramic industry</li> <li>▪ Power plant waste heat for district heating</li> <li>▪ Gypsum from power plant for cement manufacturing</li> <li>▪ Fly/bottom ash from power plant to mining company, for cement manufacturing and in construction materials industry</li> <li>▪ Ash from paper production to mining company</li> <li>▪ Steel mill slag as construction material</li> <li>▪ Blast furnace sand as construction material and for cement manufacturing</li> <li>▪ Sewage sludge utilised in construction material industry</li> <li>▪ Iron scrap fed as input in iron manufacturing</li> <li>▪ Waste paper and carton from one paper manufacturer used by another</li> <li>▪ Textile waste used by stone and ceramic industry</li> <li>▪ Wood residuals from saw mills in paper manufacturing and stone and ceramic industry</li> <li>▪ Used plastics from paper manufacturing utilised in plastics industry</li> <li>▪ Residues from flax refining to stone and ceramic industry</li> <li>▪ Petrol coke from fuel production as fuel for cement manufacturing</li> <li>▪ Collected used oils and spent solvents as fuel for cement manufacturing</li> <li>▪ Bark flue ash from paper manufacturing to cement kiln</li> <li>▪ Flue ash from one cement plant to another</li> </ul>	
Tampico, Mexico	<ul style="list-style-type: none"> <li>▪ Chemical/Petrochemical (chemicals for rubber industry, synthetic rubber, rubber products, petroleum refinery)</li> <li>▪ Industrial minerals (silica and titanium dioxide)</li> <li>▪ Metallurgical (manganese sulphate, ferromanganese, silicomanganese)</li> <li>▪ Miscellaneous (industrial gasses, power station).</li> </ul>	<ul style="list-style-type: none"> <li>▪ Polyethylene/polypropylene waste to be used in the manufacture of plastic cargo palettes.</li> <li>▪ Residual PVC as a raw material for the manufacture of rubber shoe soles.</li> <li>▪ Spent butadiene to replace natural gas fuel in another facility</li> <li>▪ Recovery and reused of the reported empty chemical drums and barrels</li> <li>▪ Polymer residuals to be used as impermeable membranes used on exterior roofing</li> <li>▪ Two companies are reusing HCl streams. One company recovers the chemical on demand. The other, with a smaller quantity, is bottling the spent acid on small scale, and selling it as muratic acid for domestic and semi- industrial uses</li> <li>▪ Local CO<sub>2</sub> facility for its recovery and reuse for beverage production and neutralisation of alkaline soils</li> <li>▪ Innovative plastics recovery technology, which uses liquid</li> </ul>	Although 63 potential synergies were identified the available documentation provides details only for the 13 synergies chosen to be pursued commercially.

CASE STUDY	SECTORS REPRESENTED	SYNERGIES DOCUMENTED	
		EXISTING OR BEING IMPLEMENTED	POTENTIAL
		nitrogen to pulverise oily, resin, and plastic residues, and homogenises them into a high-quality primary material. <ul style="list-style-type: none"> <li>▪ Slag to cement</li> <li>▪ Reuse of ferric chloride in wastewater treatment</li> <li>▪ Development of higher uses for fibreglass material used as insulation material in heat exchangers.</li> <li>▪ Waste-to-energy project</li> </ul>	



APPENDIX B







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