The Potential Role of Industrial Symbiosis in Combating Global Warming

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Summary

Industrial symbiosis (IS) is an inspiring concept and involves the inter-company exchange of by-products, water and energy. The concept has gained recognition over the past 15 years as a way to help industrial society move towards sustainability. However, there have been limited studies that specifically concentrate on the potential contribution of IS to combat climate change. This paper focuses on this by utilising findings from recent research that examined 22 best practice examples of regional IS initiatives from around the world.

Case studies are presented to show how IS can significantly contribute to reductions in material usage, energy and waste to landfill. The development of IS networks offers a potential regional platform to contribute to sustainable development by bringing together key stakeholders, such as local authorities, regulators, regional developers and sustainability groups. The paper discusses the roles of these stakeholders in IS networks and the benefits that can occur through this interaction. At the network level, benefits can occur through potential improvements in regulatory frameworks and continuous learning of best practice. In addition, by facilitating the exchange of data on material flows and collaboration between industries, IS networks also offer potential to foster technology transfer and environmental innovation. Finally, the paper suggests some policy options to support further industrial symbiosis and foster reductions in greenhouse gas emissions.

Keywords: climate change; industrial symbiosis; industrial ecology.

1 Introduction

Industrial symbiosis (IS) is a practical application of the emerging discipline of industrial ecology. Whilst industrial ecology concerns the resource flows of society and integrity of ecological systems, IS focuses on flows (i.e. exchanges) of resources (by-products, energy, water and potentially even human resources) between companies. It can most simply be described as the “waste=food” concept, with ‘symbiosis’ originating from biological ecology and referring to mutual (in most cases) benefit as in nature where nothing is wasted. Chertow (2000) provides the most commonly quoted 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”. There exists some confusion and disparity on precise definitions but lending on biological terminology industrial symbiosis can be viewed as the process that leads to an industrial ecosystem (i.e. a network of exchanges) as the outcome (CECP, 2007). Hence individual exchanges of resources within an industrial region can lead to an intricate network which mimics the ecosystems in nature.

On first appearance the application of IS can offer several benefits to the companies involved and make a significant contribution to sustainable development and the reduction of greenhouse gas (GHG). It is intuitive that the utilisation of a previously unused (e.g. in the case of released steam) or discarded (e.g. sludge to landfill) resource can typically offer financial savings to both the utilising
company and the provider, whilst reducing the use of raw materials, energy or water, and avoiding disposal to landfill. Social benefits may include job creation, reduction of emissions (e.g. gaseous pollution or dust), or aesthetic improvements (e.g. reduction of waste piles). Whilst some sustainability benefits have been reported in the literature a specific examination of the role IS can potentially play in GHG reduction has not been extensively covered.

The most examined and discussed example of symbiosis is Kalundborg in Denmark which evolved over a period of more than twenty years through voluntary cooperation, or self-organisation (Baas, 2004; Bossilkov et al, 2005; Posch, 2004). The IS exchanges that developed at Kalundborg relied on trust and long term personal and professional relationships (Dunn and Steinemann, 1998). Attempts to replicate Kalundborg began in the early 1990s, with several eco-industrial parks in the USA and throughout Asia (see for instance: Lowe et al, 1998; CECP, 2007). More recently and profoundly the National Industrial Symbiosis Programme has gained significant government funding (£13 million over 4 years (DEFRA, 2005)) and is part of a concerted waste and resource strategy for the UK. The programme began by developing 3-4 regional programmes and evolved partly due to the request of participating companies who had facilities in other regions, and was driven by growing regulation of waste in the UK (Harris, 2004).

The IS networks and programmes are based on the notion that increasing information flow (through workshops, and collection and distribution of data on inputs and outputs of companies) and facilitating collaboration between companies in a region will foster IS exchanges. This paper utilises findings and data from a recent study of 22 exemplary IS network (CECP, 2007), focusing on the contribution to GHG reduction. The study was the initial stage of an ongoing research project that examines ways to enhance the uptake of IS in heavy industrial areas, for sustainable outcomes. Firstly, a brief overview of this research is provided before examining several case studies of regional IS networks and examples of IS exchanges primarily related to GHG reduction. Next, the role of IS networks in regional sustainable development (including energy conservation) is discussed, focussing on the platform IS networks can provide for stakeholder interactions and the umbrella it can potentially provide for sustainable strategies and policies. Finally, the paper summarises the role that IS exchanges and IS networks may provide in the reduction of GHG emissions.

2 Global study of 22 Regional IS Networks

The research on which this paper is based was primarily initiated to investigate in detail the potential and actual contribution of collaborative approaches, such as regional resource synergies, industrial symbiosis and/or industrial ecology, for sustainable development at the regional level in heavy industrial areas, in particular the Kwinana Industrial Area (KIA) in Western Australia. Preliminary research of industrial symbiosis in the KIA identified three enabling mechanisms that could potentially enhance symbiosis: facilitating structures (ways to increase information sharing and collaboration), operational and contractual arrangements (ways for companies to share the risks and benefits) and evaluation tools (methods to track and quantify the sustainability benefits of industrial symbiosis). The initial research task was a baseline assessment of the theory and global practice of industrial ecology, which included a global review of 22 IS networks in heavy industrial areas (CECP, 2007). This covered six case studies in Europe, seven each from North America and Asia, and two from Australia. Below we present brief case studies of four of the most notable IS regional developments, giving examples of IS exchanges in each region that demonstrate GHG reductions. The KIA is presented first because more extensive data was obtained from this region, due to the two parallel research projects being performed there.
2.1 Kwinana Industrial Area (WA, Australia)

The KIA is the largest industrial site in Western Australia consisting of approximately 120 km² and responsible for more than A$4.3 billion of annual economic output (SKM, 2002). The area is dominated by heavy process industries and supported by the Kwinana Industries Council (KIC). Following a study that examined material and energy flows within the region, KIC initiated the Kwinana Industries Synergies Project. A comprehensive research program conducted at Curtin University of Technology supports the development of further synergies (Bossilkov et al, 2005; CECP, 2007). An inventory of existing IS exchanges at Kwinana showed that there are 47 synergy projects in place, placing the region as a leading example of industrial symbiosis (van Beers et al, 2005). Below we provide a sample of IS exchanges at Kwinana related to energy and GHG reductions:

- **Combined heat and power plants:** There have been two recent installations of combined heat and power (CHP) plants at Kwinana. The Kwinana 116 MWh CHP plant was built in 1997 on BP Kwinana oil refinery’s property. It meets all of the steam requirements for the refinery, and generates electricity for BP as well as the grid from excess refinery gas, supplemented with natural gas. This provides CO₂ savings in the region of 170,000 tonnes per annum in comparison to steam supplied from BP’s boilers and electricity supply from the grid. The partnership with the Kwinana CHP also saved BP $15,000,000 in capital expenditure whilst ensuring a reliable, cost competitive source of steam and electricity. In addition, the refinery has achieved greater process efficiencies as a result of increased availability of high pressure steam and the CHP discharges its wastewater to BP’s wastewater treatment facility. The second CHP was built in 1999 with a capacity of 40 MWh and is owned by the State’s energy company Verve Energy. It provides power and superheated steam for the Tiwest pigment process needs, with the remainder of the electricity feeding the grid.

- **Chemical plant supplying carbon dioxide to alumina refinery and gas provider:** CSBP a major chemical and fertiliser manufacturer and Alcoa (alumina refinery) will soon supply Alcoa alumina refinery with by-product CO₂ to neutralise the alkalinity in its bauxite residue. The residue carbonation process aids the drying, management and stability of the residue area whilst producing a more benign residue with increased reuse opportunities (Alcoa, 2005). The CO₂ will arrive via pipeline from the nearby CSBP ammonia plant, resulting in GHG benefit equal to at least 70,000 tons CO₂ per year. The exchange builds on the relationship that developed from an ongoing IS exchange, in which CSBP supply by-product gypsum (calcium sulphate) to Alcoa to assist in plant growth and soil stability in residue areas. Air Liquide has received CO₂ from CSBP (from its ammonia plant) and other industrial facilities in the Kwinana Industrial Area since 1990. The CO₂ is purified to food grade standard and compressed, and used in soft drinks, beer, dry ice and water treatment. Although this CO₂ is eventually released to air it reduces overall emissions because the CO₂ is reused and it avoids the energy required to produce virgin CO₂ from air.

- **Emerging by-product synergies around HiSmelt Pig Iron Plant:** The HiSmelt plant is the first commercial scale application of the direct smelting technology, which allows for simpler, more flexible iron making. It avoids coke ovens and sinter plants required for the standard Blast Furnace with a resultant reduction of emissions of 20% CO₂, 40% NOx and 90% SOx. Upon completion of commissioning (which began in November 2004) and successful commercial operation, the plant will source a number of by-products locally in the Kwinana area, such as lime, lime kiln dust and treated wastewater. In addition, the HiSmelt Process will utilise the WA reserves of iron ore fines, which are not currently suitable for blast furnace feed due to their high phosphorous content (HiSmelt, 2002). The plant will produce a range of by-products such as slag and gypsum, with strong potential for IS exchanges.
2.1.1 Illustrative Savings from Reduction in Transport

The exchange of material by-products that cannot be transported by pipeline or cable (as in the case of water and energy) may entail GHG emissions. However, our research suggests that overall IS exchanges can in fact make substantial transportation savings and therefore GHG emissions. This is particularly true in the case of KIA where companies are generally less than five kilometres from each other, when compared with the 60 km for landfill disposal. Although there are confidentiality issues restricting the release of detailed information, we provide (for illustrative purposes) some estimated CO₂ savings from reduced transport of some Kwinana IS examples in Table 1. In total this suggests that savings of CO₂ from IS in Kwinana can potentially result in at least 464 TCO₂/year. Although this is relatively small compared to other savings, the total savings from logistical issues may be more significant which subsequently suggest that transportation may be an important future policy consideration.

<table>
<thead>
<tr>
<th>Supplying Company</th>
<th>Receiving Company</th>
<th>Product</th>
<th>Notes</th>
<th>Estimated CO₂ savings from reduced transport Tonnes per annum</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP Refinery</td>
<td>Cockburn Cement</td>
<td>Spent catalyst</td>
<td>Transport to landfill site at Red Hill is 60km</td>
<td>4.8</td>
</tr>
<tr>
<td>Cockburn Cement</td>
<td>Hismelt Lime</td>
<td>Lime kiln dust</td>
<td>Limestone/sand would need to be transported from Lancelin which is 130 km</td>
<td>93.6</td>
</tr>
<tr>
<td>CSBP Alcoa</td>
<td>Gypsum</td>
<td>Transport distance for raw gypsum 240km</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>HiSmelt Cockburn cement</td>
<td>Gypsum</td>
<td>Transport distance for raw gypsum is 240km. This is a potential synergy</td>
<td>172.8</td>
<td></td>
</tr>
<tr>
<td>Cockburn Cement</td>
<td>Tiwest Lime</td>
<td>Lime kiln dust</td>
<td>Limestone/sand would need to be transported from Lancelin which is 130 km</td>
<td>96.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>464</strong></td>
</tr>
</tbody>
</table>

Table 1: Estimated carbon dioxide savings from reduced transport due to IS in Kwinana (in relation to distances between companies in KIA that are generally less than 5 km).

2.2 Forth Valley (Scotland, UK)

The Forth Valley is located in the central belt of Scotland and incorporates the city of Edinburgh and the petrochemical complex of Grangemouth, the largest industrial area in Scotland. Several other industries are distributed around the area including four large power stations, the only cement works in Scotland, three petrochemicals sites and two paper-mills. A PhD study revealed 26 existing synergies and 16 potential synergies (Harris, 2004; Harris, forthcoming). Industrial symbiosis in the region is now being driven by the Scottish Industrial Symbiosis Programme; part of a UK national programme that recently received £13 million from the UK government (DEFRA, 2005). Existing IS exchanges include:

- **Power station ash reuse**: ScotAsh (a joint venture between LaFarge cement and Scottish Power) recovers and reuses nearly 500,000 tonnes per annum pulverised fly ash (PFA) and bottom ash (65 per cent of total ash produced). In 2003/4 this provided a saving of £988,000 in Landfill Tax and a profit of £1.2m was achieved on a turnover of £7.5 million. ScotAsh also markets cenospheres, small hollow particles that form in the hot zones in the burners. These are very effective heat insulators and therefore have potentially high value (£40 /ton unprocessed or £5000 processed). Each tonne of PFA used in cement products saves on average 900kg of CO₂ emissions, which resulted in a saving of 100,000 tonnes over the three years up to 2005.
**Zero Emissions Distillery**: The North British Distillery of Edinburgh has gone one step further than many breweries/distilleries in by-product reuse. It liquefies 17-18,000 tpa of carbon dioxide produced in the whisky brewing process to sell to the food and nuclear industries. The plant utilises approximately 300,000 tpa of grains in the production of whisky, and also produces 50,000 tpa of animal feed pellets from the grain residue.

**Energy recovery from sewage sludge**: The Daldowie Sludge Treatment Centre was built at a cost of £65 million to treat approximately 54,000 tonnes per annum of sewage sludge from Scot Water’s wastewater treatment plants in Glasgow. Scottish Power uses the dry pellets in its 2.4 GW Longannet coal-fired power station. The sewage pellets provide seven per cent fuel input for one of the four 600 MW burners, enough to power 30,000 homes. The continuity of this synergy is at stake after the December 2004 court decision that the pellets remain a waste and therefore the power station should comply with waste incinerator standards, requiring modifications estimated to cost between £100-400 million.

**Alternative fuels and raw materials in cement production**: the LaFarge Dunbar cement works utilises recycled liquid fuel (RLF) and scrap tyres for fuel and ash (from ScotAsh) and recycled glass/sand as alternative raw materials. LaFarge has recently formed two joint venture companies: Sapphire Energy Recovery, a joint venture with Michelin to provide a reliable supply of waste tyres; and Glacier ARM to source alternative raw materials. Glacier sources mainly silica material because limestone and shale are sourced from LaFarge’s own quarry at Dunbar. The Dunbar plant utilises approximately three million tyres (about 22,000 tonnes) and 20,000 tonnes of RLF, saving over 40,000 tonnes of fossil fuels. In addition emissions of nitrogen oxides have been reduced due to improved combustion.

**Biomass power station**: Energy Power Resources (EPR) established in Fife a power station specifically designed to burn 110,000 tonnes per annum of poultry litter in a fluidised bed boiler to generate 81 GWh/yr electricity (supplying around 20,000 homes). The remaining ash is rich in phosphates and potassium making it a high quality fertiliser.

### 2.3 Kalundborg (Denmark)

Kalundborg is considered as the original quintessential example of industrial symbiosis that brought the concept of IS to reality. The city of approximately 20,000 inhabitants is located about 100km west of Copenhagen, and is relatively isolated. The isolation allowed the companies to develop an openness and mutual trust that resulted in close cooperation and a relatively tight-knit business community (Jacobsen, 2003). The industrial area is dominated by a large power station, a refinery, a pharmaceutical and biotechnology company, a plasterboard company and several smaller companies. The network of exchanges is generally considered to have begun in 1962 when Statoil refinery constructed a 50 km pipeline to access surface water from Lake Tisso, and began supplying others from this source. Since this nineteen IS exchanges have developed including (Ehrenfeld et al, 2002; Jacobsen, 2003):

- Since 1980, Asnaes Power plant has supplied district heating to the city of Kalundborg, and process steam to both Statoil refinery and Novo Nordisk (hence greatly increasing efficiency from combined heat and power). Fly-ash from the power station is reused outside Kalundborg in cement making (coal fly-ash) and nickel and vanadium recovery (Orimulsium fly-ash). The flue gas desulphurisation plant produces gypsum as a by-product, of which 200,000 t/yr is supplied to the...
plasterboard manufacturer Gyproc. Part of the cooling water from the power station is utilised by a trout farm to enhance growth whilst local farmers use the sludge from the fish farm as manure.

- Statoil cooling and wastewater is sent to Asnaes for reuse, with part of it returning to Statoil as steam. Statoil also has a desulphurisation plant which produces ammonium thiosulphate as by-product which is utilised in liquid fertiliser production.

- Novo Nordisk and Novozymes use process steam and Lake Tisso surface water, supplied by the power station. Enzyme production results in large quantities of biomass, which is pumped via pipelines to farmers as a replacement for fertilisers and soil improvers. The insulin production yields a fermentation cream (yeast slurry) used as pig fodder.

- Bioteknisk Jordrens/Soilrem and its affiliated divisions specialise in remediation of soils contaminated with chemicals and heavy metals. Sludge from the public wastewater treatment plant is used as a nutrient source for the bioremediation.

2.4 Map Ta Phut (Thailand)

The Map Ta Phut is the largest industrial estate in the Rayong Province and was established in 1985. It was reserved for the petrochemical industry and its downstream processes, and houses 89 factories with 11,500 employees (GTZ/IEAT, 2001). The local Industrial Estate Authority of Thailand (IEAT) provides the management platform to identify and realise industrial symbiosis opportunities. There are currently seventeen examples of industrial symbiosis including (GTZ/IEAT, 2001): five CHP plants supplying electricity and steam to the petrochemical industry (which have significantly reduced emissions of GHG in comparison to conventional supply of heat and electricity but the amount was not reported in this case); waste solvents recycled through distillation; waste oil used as an alternative fuel for cement kilns; ferrous chloride and hydrochloric acid are collected (~640,000 tonne/yr) and used in ferric chloride production.

2.5 Summary of Regional Greenhouse Gas Reductions and Sustainability Benefits

This section reviews the overall GHG reductions and sustainability benefits identified in the global review of 22 IS regions. Table 2 summarises the identified quantitative information on sustainability benefits, which was only available for 13 of the 22 regions studied. For the majority of regions available data was patchy and inconsistent. Most of the obtainable information reports on a few of the major (or “flagship”) IS exchanges of that region and the majority of information reported relates to environmental information, e.g. energy savings or waste materials diverted from landfill. Surprisingly few regions reported on CO2 savings, which together with the fact that data is patchy and inconsistent, is indicative that there is (CECP, 2007):

1. A lack of standard methodology to measure and report on effects, risks and benefits of IS.
2. Commercial sensitivity surrounding data on IS exchanges. This particularly relates to economic data, i.e. the costs of energy, water and raw materials, but also for prices of products and by-products. Also disclosing technical data regarding materials flows and processes might harm a competitive position, and also raise public scrutiny.
<table>
<thead>
<tr>
<th>Region</th>
<th>Reported Sustainability Benefits</th>
<th>Social or Economic</th>
</tr>
</thead>
</table>
| Forth Valley           | ▪ 33,000 CO2 saved using pulverised fly-ash in cement production  
▪ 17-18,000 CO2 recovered from distillery and sold to food industry  
▪ 164,000 tpa various sludge diverted from landfill  
▪ 11,000 tpa poultry litter, avoiding disposal; 81GWh/yr (renewable)  
▪ 500,000 tpa fly-ash diverted from landfill  
▪ 22,000 tpa tyres and 20,000 tpa RLF substituting for 40,000 tpa coal  
▪ 4000 tpa off-spec polymer, and 60,000 tpa other plastics recycled  
▪ 7500 solvents/tar for fuel  
▪ Other materials (compost etc) 25,000 | ▪ £1.2 million/yr profit from fly-ash reuse                                                                                                                                                                                                                                           |
| Humberside             | ▪ 183,000 tpa waste material diverted from landfill                                                                                                                                                                               | ▪ 87 jobs saved; potential for 960 jobs & 1,440 indirect jobs  
▪ £ 800 million/yr increase in economic activity                                                                                                                                                                                                                                    |
| Kalundborg             | ▪ 170,000 tonnes of CO2  
▪ 2.1 million tpa potable water replaced by surface water  
▪ Energy savings equivalent to 30,000 tpa coal and 19,000 tpa oil  
▪ 280,000 tpa diverted from landfill (fly-ash, scrubber sludge etc)  
▪ Replaced 200,000 tpa gypsum use and 2,800 tpa sulphur use                                                                                                                                                               | ▪ Total investment US 75 million resulting in annual savings of US 15 million  
▪ Accumulated savings US$ 160 million                                                                                                                                                                                                                                              |
| Moerdijk               | ▪ 85,000 tpa CO2 recovered  
▪ 3.4 million tonne/yr steam recovery  
▪ 0.5 GL/r water reuse                                                                                                                                                                                                             | No information available                                                                                                                                                                                                                                                         |
| Rotterdam              | ▪ 6 MW waste heat recovery for district heating                                                                                                                                                                                  | No information available                                                                                                                                                                                                                                                         |
| Fairfield              | ▪ No information available                                                                                                                                                                                                               | ▪ US 62 million investment in redevelopment of industrial facilities (incl. soil remediation)                                                                                                                                                                                  |
| Londonderry            | ▪ 18 ML/day reuse of treated waste water as cooling water                                                                                                                                                                             | No information available                                                                                                                                                                                                                                                         |
| Sarnia Lambton         | ▪ Some 175,000 tpa FGD gypsum diverted from landfill                                                                                                                                                                                  | No information available                                                                                                                                                                                                                                                         |
| Texas (USA)            | ▪ 192,000 tonnes CO2 due to energy savings in steel production  
▪ 250,000 tpa waste diverted from landfill (shredder residue and slags)  
▪ 18,000 tpa non ferrous metals recovered                                                                                                                                                                                | No information available                                                                                                                                                                                                                                                         |
| Kawasaki (JAP)         | ▪ 30,000 tpa waste plastics used as blast furnace reductant  
▪ 360 tpd waste plastics gasified for ammonia production                                                                                                                                                                         | No information available                                                                                                                                                                                                                                                         |
| Map Ta Phut (Thailand) | ▪ 80 tpa solvent recovered  
▪ 11,800 tpa waste oil reused as fuel and/or for oil paints  
▪ 20,000 tpa scale, dust and refractory material used as cement raw material  
▪ 640,000 tpa ferrous chloride/hydrochloric acid recovered                                                                                                                                                               | No information available                                                                                                                                                                                                                                                         |
| Gladstone (AUS)        | ▪ 6.5 ML scheme water replaced by treated waste water                                                                                                                                                                                 | No information available                                                                                                                                                                                                                                                         |
| Kwinana (AUS)          | ▪ 170,000 tpa CO2-eq emission reduction from CHP  
▪ 70,000 tonnes CO2 absorbed in alumina residue  
▪ 463 tonnes CO2 saved from reduced transport  
▪ 10,000 tpa by-product gypsum recovered for reuse  
▪ 6 GL high grade industrial water recovered from treated waste water  
▪ 260,000 tonnes diverted from landfill                                                                                                                                                                               | ▪ Investment in water reclamation plant A$ 29 million  
▪ 20% premium price on reclaimed water                                                                                                                                                                                                                                           |

Table 2: Sustainability benefits reported in case study regions (adapted from CECP, 2007; Harris, 2007).
Table 2 shows that data of direct GHG savings was only reported in six of the 22 regions. Further GHG savings can be expected from the associated reductions in raw material use from IS exchanges. This is illustrated particularly well in the Forth Valley where the use of PFA in cement reduction has reduced CO₂ emissions by 33,000 tonnes per year. Other CO₂ savings from similar use of materials cannot be reported because this data was unavailable.

3 Roles of Stakeholders

Although the regional case studies presented in section 2 involve unique circumstances, the evolution of the networks has developed under similar circumstances. Where information exists, it appears that the networks were originally formed to address common issues that affected the companies in the region. In Kwinana, the Kwinana Industries Council was developed on the back of industry cooperation to address air quality measurements and community environmental concerns (Taylor, 2001). Similarly, companies in Grangemouth (Forth Valley, UK) formed the Grangemouth Development Group to improve the competitiveness of the local chemical industry and create further jobs. These networks evolved to include working together on sustainability issues. Alternatively, one IS exchange led to another as trust between companies began to build, as happened in Kalundborg.

As discussed in section 2, networks formed to purposely foster IS concentrate on increasing information on resource flows of companies and fostering collaboration (see for instance van Beers et al, 2005; or NISP, 2005). Many networks have stakeholder groups or steering committees, which operate at different levels of involvement but bring key stakeholders together. For example the strategy of NISP has been to include key industry members, local authorities, regional developers and environmental regulators to form a steering group (Mirata, 2004). Importantly, the inclusion of these stakeholders gives them ownership of the IS network and of the challenge of fostering IS (Harris, 2004). The network can provide the platform to increase communication, understanding and knowledge flow (including technical expertise) between stakeholders. For example, there is a direct platform of communication between the regulator and industry, with the potential to more easily remove barriers to IS caused by regulation (e.g. extensive approval and monitoring procedures).

There are numerous reasons to include a diverse mix of stakeholders in the network, although there is a practical limit to numbers and diversity for operational effectiveness (Korhonen, 2004). Inclusion of local and state governments can bring networking opportunities to the IS programme development (Takahashi, 2004), support any planning processes and help remove barriers. They also have the links to communicate any barriers due to legislation and regulation to policy makers. In addition they may provide training to companies, finance for initiatives, solid waste management, and are central in the planning and location of new companies.

In developing IS networks, the inclusion of any organisation in the region that represents the interest of local industry (such as the Kwinana Industries Council), can provide a stepping stone for the initiative. They may for instance, already have members willing to take part in such an initiative. Industry associations (those representing the industry sectors) can help raise awareness of the IS network amongst its members and help communicate the benefits of IS. They may also aid technology transfer to enable the implementation of synergies. Finally regional development agencies, which are central to regional industrial strategies and planning, can bring valuable knowledge and networks to the steering committee, and may also provide finance for the network or components of its implementation.
4 Discussion

The review of IS developments covered 22 examples worldwide and found 162 distinct IS exchanges between companies. However, the available data was found to be patchy and incomplete, particularly when attempting to specifically analyse the contribution of IS to GHG reduction. Although only 6 regions had data regarding direct reductions in carbon dioxide or energy, taken as a whole the data (Table 1 and 2) and case studies suggest that IS offers significant promise to advance industrial regions towards sustainability and to reduce GHG. There appear to be four avenues in which IS can aid GHG reductions:

1. Direct energy savings from IS exchanges: For example CHP offers a much more efficient way to supply a group of collocated companies as opposed to separate boilers and grid supplied electricity. Low grade heat recovery is another promising prospect, especially when performed collaboratively, as in the Kwinana regional synergies project which is currently investigating ways to utilise flue gas with a collective energy content of nearly 6 PJ/year (van Beers, 2006).

2. Indirect energy savings: Through recycling material, including reduced transport (both transport of raw materials and disposal of material), and reduced mining of raw minerals

3. Increasing co-operation amongst industry: IS networks have the potential to investigate IS in an industrial region, increase information flow between industry, foster collaboration and greatly increase the uptake of IS opportunities. Increased communication and collaboration between companies can in turn aid technology transfer and innovation.

4. Providing a platform for co-operation amongst regional stakeholders: IS networks can provide a platform and conceptual structure for communication between key regional stakeholders (including government and community) thereby increasing understanding and knowledge flow, providing incentives and removing barriers (e.g. regulatory barriers).

Although the contribution of IS to GHG reduction has been shown to be valuable and significant, recent research strongly suggests that further savings and integration of industry is possible (Harris, 2004; van Beers 2006; CECP, 2007). For instance, NISP recently achieved CO₂ savings of over 1 million tonnes between April 2005 and June 2006, through IS in the UK (DEFRA, 2007). Recent research in Kwinana identified over 90 potential IS exchanges and efforts are now focussing on developing a further 14 IS exchanges (van Beers, 2006).

In various other regions of the world research has also identified numerous potential IS exchanges (Harris, 2004; Mirata, 2004; Mangan, 1998). However, the long development time for IS exchanges is often underestimated and common barriers identified include: liability concerns, regulation (particularly the legislative label of ‘waste’), technical (e.g. purity, regularity), capital investment requirements, core business focus (competing investment opportunities) and lack of trust (Harris and Pritchard, 2004; BCSD-GM, 1999; Schwarz and Steininger, 1997). This suggests a role for policy to remove barriers and develop drivers to foster the further uptake of IS for sustainability outcomes.

Industrial symbiosis is intrinsically linked to innovation and this is particularly true when moving beyond “low hanging fruit”. Innovation of processes, products and systems may be required, but IS also calls for innovative relationships and partnerships. In the past few decades legislation has been a key driver of environmental innovation (Rothwell, 1992; Wallace, 1995) and pressure from legislation on industry (and in a sense society itself) to improve its environmental performance is likely to continue. However, industry is still unsure of future legislation, which creates an unstable environment with high business risk that is contrary to the stable policy environment needed to induce environmental innovation (Clayton et al, 1999; Harris, 2000; Wallace 1995).
Therefore in light of the above discussion it appears that a policy framework needs to:

1. **Be predictable, in that it is stable and long-term, transparent to industry, and gives industry time to adjust and respond (thereby reducing risk).** There is little doubt that consensus for action on climate change and sustainable development is increasing and it can also be argued that establishing tough standards for industry, but within a clear timeframe, will over the longer term have less impact on competitiveness (Rothwell, 1992; Porter, 1995; 1998).

2. **Use a range of policy instruments to provide a clear incentive to establish IS exchanges, including market (e.g. economic instruments), regulatory and informational (e.g. IS networks).**

3. **Be supportive in the removal of barriers, and in particular support capital investment and the development of appropriate technology.** This could be done for example by making economic instruments cost neutral to companies by feeding revenue back to companies to support IS practice. This would be similar to the UK’s Landfill Tax and Climate Change Levy (Harris, 2007; Varma, 2003). Policy also needs to remove ‘soft’ barriers, such as the requirement of additional licenses for handling ‘wastes’ that are to be reused rather than disposed of.

4. **Be supportive in the building of trust and collaboration across industry; and promote knowledge and information dissemination.** This could be supported by IS networks but methods to encourage companies to work together (particularly on energy issues) could for example include a requirement to report emissions on a regional basis. The Kyoto has already placed national targets on countries for GHG reductions. Could similar regional agreements that prompt, regional reporting, be designed to encourage closer industrial integration? Instead of single company reporting, industrial regions may come under scrutiny as entities themselves.

5 **Concluding Comments**

Although the available data was patchy and incomplete the paper shows that IS exchanges have achieved significant savings in GHG reduction. In addition, research suggests that further integration and savings are possible in many regions. IS can aid the reduction of GHG through both direct savings, e.g. CHP, and indirect savings such as reduction of transport and raw material processing. IS networks can help foster collaboration between industries to form IS exchanges and also provide a platform for stakeholder learning towards sustainable development (and associated GHG reductions). Although potentially small compared to other savings, studies have generally ignored transport savings. A closer look at these would reinforce the industrial symbiosis view of the advantages of close proximity for diverse industries.

To encourage further IS a mix of policy instruments is likely to be most effective, for example economic instruments supported by informational devices, such as IS networks. To lower the risk and create a haven for environmental innovation, regulation needs to be based on a clear and predictable vision, but be flexible in its application.

As carbon taxes and carbon trading begin to take hold, and the successor to Kyoto Protocol emerges, the future of IS could be central to industries bid to greatly increase production efficiencies and cut its GHG emissions. The carbon issue could therefore be a prominent driver in encouraging companies to cooperate on GHG reductions; this in turn is likely to foster further cooperation, industrial symbiosis and spin-off innovations. Finally, there is a particular need for an in-depth life cycle analysis of the case study regions that looks at the full CO2 savings of the regional IS activities, including for example the life cycle CO2 savings from material IS exchanges (e.g. reduced material processing and transport).
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