Resources **2014**, *3*, 340-361; doi:10.3390/resources3020340

OPEN ACCESS

resources

ISSN 2079-9276

www.mdpi.com/journal/resources

Article

The Status of Industrial Ecology in Australia: Barriers and Enablers

Glen D. Corder [1,*], Artem Golev [2], Julian Fyfe [3] and Sarah King [4]

[1] Centre for Social Responsibility in Mining, Sustainable Minerals Institute, University of Queensland, St Lucia, Queensland 4072, Australia

[2] Centre for Social Responsibility in Mining, Sustainable Minerals Institute, University of Queensland, St Lucia, Queensland 4072, Australia; E-Mail: a.golev@uq.edu.au

[3] Institute for Sustainable Futures, University of Technology Sydney, Sydney NSW 2007, Australia; E-Mail: julian.fyfe@uts.edu.au

[4] Commonwealth Scientific and Industrial Research Organisation, Future Manufacturing Flagship, Geelong, Victoria 3216, Australia; E-Mail: sarah.king@csiro.au

* Author to whom correspondence should be addressed; E-Mail: g.corder@smi.uq.edu.au; Tel.: +61-7-3346-4136; Fax: +61-7-3346-4145.

Received: 9 December 2013, in revised form: 12 February 2014 / Accepted: 12 March 2014 / Published: 25 March 2014

Abstract: Drawing on current international industrial ecology thinking and experiences with Australian initiatives, this article critically overviews the current status of industrial ecology in Australia and examines the barriers and potential strategies to realise greater uptake and application of the concept. The analysis is conducted across three categories: heavy industrial areas (including Kwinana and Gladstone), mixed industrial parks (Wagga Wagga and Port Melbourne), and waste exchange networks, and identifies the past and future significance of seven different types of barriers—regulation, information, community, economic, technical, cooperation and trust, commitment to sustainable development—for each of the three categories. The outcomes from this analysis highlight that regulation, information, and economic barriers for heavy industrial area and mixed industrial parks, and economic and technical barriers for waste exchange networks are the current and future focus for industrial ecology applications in Australia. These findings appear to be consistent with recently published frameworks and learnings. The authors propose key questions that could enhance greater adoption of industrial ecology applications in Australia and acknowledge that international research and experiences,

while partly providing answers to these questions, need to be adapted and refined for the Australian context.

Keywords: industrial ecology; industrial symbiosis; recycling; waste exchange; industrial parks; by-products; barriers

1. Introduction

While industrial ecology is still a relatively new term, commonly accredited to Frosch and Gallopoulos in 1989 [1], the concept has arguably been in existence for much longer. Using nature as a metaphor, and aiming to optimize the total material cycle from virgin material to product and to ultimate disposal, industrial ecology closely examines the opportunities to reuse and recycle different waste streams arising in industrial and consumer activities, as well as reorganizing the industrial systems to ensure resource efficiency and resilience. In a wider sense it can be even seen as "the means by which humanity can deliberately and rationally approach a desirable carrying capacity, given continued economic, cultural, and technological evolution" [2]. It also supports sustainable development through the efficient use of resources, minimizing environmental impact while supporting economic success.

Focusing on the exchanges between different actors and their roles in the industrial system, the concept of industrial ecology can be implemented at various levels of economic aggregation. Environmental and economic benefits of its application have already been demonstrated at numerous eco-industrial parks, heavy industrial areas and regional/national networks [3–12]. These examples show that the presence of different groups of industries (chemical, metallurgical, construction, cement, *etc.*) in the region is beneficial for potential synergies and some industries will be dominantly by-product/waste generators (e.g., oil refinery) while others are dominantly waste receivers (e.g., construction materials industries). In several cases, it has been not easy to find useful applications for many bulk waste materials, effluents streams and waste energy due to technological, economic, regulation and other barriers [13–16]. Nevertheless, industrial intensive regions can present significant opportunities for deriving benefits from the application of industrial ecology, and the degree of success and level of cooperation for regional resource synergies can vary significantly depending on the industry structure in the area, companies' awareness, national legislation, presence of facilitating structures, *etc.* [14]. While industrial ecology can take on a product-based systems perspective or a geographically defined local–regional industrial ecosystem approach [17], the focus of this article is on the latter approach. It briefly reviews the current thinking internationally on industrial ecology and then critically overviews the current status of industrial ecology in Australia, and finally investigates potential strategies to enhance its application in an Australian context.

2. Overview of the International Application of Industrial Ecology

There are numerous applications of industrial ecology, particularly in heavy industrial areas, around the world, such as Kalundborg (Denmark), Forth Valley (Scotland, UK), Kawasaki (Japan), Rotterdam (The Netherlands), Map Ta Phut (Thailand), and North Texas (TX, USA) [15]. In fact, there are more

than 50 regions in the world that showed regional synergy development with physical exchanges of materials, energy, and water for competitive and environmental benefit [18,19]. Many of the existing projects gradually evolved in brown-field areas with different combinations of industries in each case [14]. The actual number of regions may well be much higher than 50, and it is highly likely numerous other examples exist which have not had any formal recognition but have evolved and are now considered part of usual business practice [20].

Recent research outcomes in industrial ecology and the related sub-field of industrial symbiosis emphasise the development and progression of the thinking in this field and the impact this has had on the successful implementation of initiatives. For instance, China has developed since the early part of this century the largest national Eco-industrial Park (EIP) network, involving 15 national demonstration EIPs and 45 national trial EIPs. The China National Demonstration Eco-industrial Park Program has a number of distinct characteristics—such as the expansion from a single regulator to joint leadership across government departments and the cultivation of hundreds of researchers and professionals working in the field of EIP planning and consultancy—which have contributed to the success of the Program [21]. In Europe, the Resource Efficiency Flagship Initiative and the subsequent Roadmap for a Resource Efficient Europe have recommended that opportunities to exploit resource efficiency gains through industrial symbiosis should be a priority for members in the European Union [22]. In addition, the UK's National Industrial Symbiosis Programme (NISP) has been cited as a best practice exemplar of "concrete action" and ought to be replicated across European Union member states [22]. Thinking has now moved to the stage of developing a theory towards industrial symbiosis [23] as well as an evolution in the definition of industrial symbiosis focusing on eco-innovation and establishing sustaining cultural change [24]. This is supported by the extensive review of industrial symbiosis literature which illustrates over a 15 year period from 1997 that the topic has evolved from practice oriented, based on the experience and observation to a more systematic and diverse set of topics in theory building and worldwide practical implementation [25].

While Australian research and experiences have informed current thinking to some degree, outcomes from the broader international knowledge and learnings can enlighten the progression of industrial symbiosis and industrial ecology within an Australian context.

3. Industrial Ecology Initiatives in Australia

Australia's unique geographic location as a continent, with long distances between major cities and industrial centres in regional areas, presents challenges from an industrial ecology perspective. On the other hand, however, these challenges can present particular opportunities to adopt innovative approaches to deliver successful outcomes. Application of industrial ecology in Australia has been demonstrated with a few heavy industrial regions studies, several mixed industrial parks and waste exchange initiatives, as well as with investigations of reuse options for specific waste flows. The level of success, significance of achievements, and detailed reporting greatly varies between different cases. The most well documented and cited examples relate to the regional resource synergies studies, or industrial symbiosis, in such heavy industrial areas as Kwinana in Western Australia, and Gladstone in Queensland. Both are highly developed heavy industrial areas (including alumina, nickel, oil, iron,

cement, and pigment industries) and further details on both these regions as well as Geelong, which is another heavy industrial area, are given in the next section.

The history of applying the concept of industrial ecology in Australia is closely related to cleaner production techniques, eco-efficiency and waste management practices. The combined efforts of the state and federal government, industry associations, academic institutions and environmental organizations in mid-1990s resulted in the successful demonstration of these approaches to minimize environmental impacts arising from industrial activities within different sectors, and in recommending the development of national guidelines for companies based on this experience [26–28].

Further application and promotion of industrial ecology approaches has been attributed to several initiatives supported by the Australian government, such as Green Stamp Program [29], Centre for Sustainable Resource Processing [4], and others. Some of this work resulted in the development of new frameworks that could be used elsewhere, and help to replicate and to enhance successful applications of industrial ecology [3,7]. More recently, the 2013 New South Wales (NSW) Government Waste and Resource Recovery Initiative has recognised the potential of industrial ecology by prioritising the establishment of four industrial ecology networks as part of its Business Recycling Program [30]. This industrial ecology initiative is driven from the success of the NSW Sustainability Advantage program, which supports businesses to reduce risk and cost by reducing their environmental impact. This includes identifying and implementing industrial symbiosis opportunities. The program has resulted in 530 businesses reducing costs by $75 million a year due to reductions of energy, water, waste and raw materials [30]. The support of industrial ecology or symbiosis within government marks a strategic turning point in waste management, recognizing waste as a potential resource. It supports both environmental goals to reduce waste to landfill and industry goals to improve resource efficiency and competitiveness.

In addition, the Waste Management Association of Australia (WMAA), the peak waste industry body established in 1991, actively promotes waste reuse and recycling practices within small and medium enterprises (SMEs). WMAA also supports the Australasian Industrial Ecology Network (AIEN). The AIEN has active industry networks in New South Wales and Victoria and led the organisation of the Australasian Industrial Ecology conferences over the last five years. In June 2013, the AIEN and Enterprise Connect were involved in organising a meeting of industrial ecology stakeholders. This included government representatives from NSW, Victoria and South Australia sharing their experiences in implementing industrial ecology and symbiosis in their respective regions and discussing opportunities for Australia. This was the first meeting of its kind in Australia and representative agencies, while interested to understand the potential benefits of industrial ecology with a view to supporting its uptake, lacked a common approach to implementing programs or strategies to increase the adoption of industrial ecology, in all its forms, for Australia [31].

4. Applications of Industrial Ecology in Australia

4.1. Industrial Ecology Categories

This section examines examples of industrial ecology applications in an Australia context in three categories: heavy industrial areas, mixed industrial parks, and waste exchange networks. The authors

have chosen this categorisation as it covers both large industrial developments and small developments as well as waste re-use opportunities not constrained by geographical locations. The authors used the following criteria to select in which category an industrial ecology initiatives would reside:

- Heavy industrial areas, or industrial complexes, represent geographically concentrated industrial activities, usually with tight couplings of a relatively small number of materials and energy intensive production processes, and often resulting in high volume waste streams [32];
- Mixed industrial parks are situated in dedicated areas, and mainly represented by SMEs of a very diverse nature with no or little coupling of production processes; however there are usually opportunities to share different common services [32]. Often they are cited as eco-industrial parks, especially when established as a result of a government driven initiative [33];
- Waste exchange networks represent a systems form of industrial ecology transactions, are not bound by geographical locations, and are distinct from the industrial symbiosis type arrangements described above in that they tend to be one-way, end-of-life material transfers initiated through database searches at local, regional, national or even global scales [34].

This categorisation was considered valuable for investigating the main areas of application of industrial ecology in Australia.

4.2. Heavy Industrial Areas

4.2.1. Kwinana

The Kwinana Industrial Area covers an area of 8 km from north to south and 2 km east to west. It is located on the shores of the Cockburn Sound, a deep-water port, about 30 km south of the capital city of Western Australia, Perth, making it in a strategic position for export markets to Asia. It was established in the 1950s through a special Act of Parliament to secure an area of about 120 square km for the development of major resource processing industries in Western Australia [6].

Heavy process industries dominate the Kwinana Industrial Area and include Alcoa Alumina refinery, BHP Billiton Kwinana nickel refinery, BP oil refinery, Cockburn Cement lime and cement kilns, Coogee Chemicals, CSBP chemical and fertilisers operation, and Tronox titanium dioxide pigment plant. In addition to these industries there are small to medium enterprises as well as the Verve Energy power station and Water Corporation water and wastewater treatment plants.

In Kwinana, most known synergies are straightforward, occurring between two companies and involve minimum or no processing before by-products/waste reuse. Typically, they substitute a fraction of the raw materials for the current industrial processes. This could indicate the lack of understanding or lack of incentives to implement more complex synergies [12].

The Kwinana Industries Council (KIC) was established in 1991 at the instigation of the core industries. The main aim of the KIC was to collectively organise the necessary air and water monitoring for the industries in the area, in response to government and community pressure to manage the air and watersheds, and protect the sensitive marine environment in the adjacent Cockburn Sound. The number of connections in Kwinana makes it one of the most intense industrial synergy regions in the world and comprises a range of by-product and utility exchanges [12].

A broad range of research investigations has been undertaken in Kwinana over 2000–2010 to enhance the material efficiency and environmental performance of the existing industries through waste reuse and infrastructure sharing, led by the Centre of Excellence in Cleaner Production at Curtin University in close collaboration with the Kwinana Industries Council (KIC) [35,36]. There have been no recent public updates on the research and development of new initiatives in the Kwinana region, however there is an established platform to support new initiatives through regular meetings of KIC members [37].

4.2.2. Gladstone

Gladstone is the largest industrial area in Queensland, Australia. It includes a coal power station, two alumina refineries, an aluminium smelter, cement producer, and ammonia nitrate producer. It is located about 550 km north of Brisbane, and 100 km south-east of Rockhampton.

Similar to Kwinana, most known synergies are straightforward, occurring between two companies with minimum or no processing and typically substitute a fraction of the raw materials for the current industrial processes, although there is potential to implement more complex synergies [12].

The first regional resource synergies study in Gladstone was implemented in 2004–2007 as a special research project funded by the Cooperative Research Centre for Sustainable Resource Processing (CSRP) and the Gladstone Area Industry Network (GAIN) industries [38]. The main outcomes from this project included the detailed analysis of waste material/energy/water flows in the area [11], the investigation of new possible initiatives for the large and smaller waste streams [39], and the comparison of the synergies in Gladstone with Kwinana [12]. In the last report of this research, there was also an attempt to analyse the reasons for the lack of new synergies uptake during the life of the project. These factors included the lack of a funded secretariat in Gladstone at that time (although now the Gladstone Industry Leadership Group [40] exists), the wide range of non-technical issues (regulatory constraints, liability and general lack of trust between companies operating in different industry sector) and the balancing of financial considerations against sustainability benefits of synergies [38]. In relation to the last factor, the research postulated that the difficult area was when synergy initiatives have moderate or low financial benefits but have high or possibly moderate sustainability benefits.

A recent Ph.D. study at the University of Queensland has provided an update on the status of resource synergies in Gladstone, and some insights into the non-technical barriers for higher uptake of the existing waste reuse opportunities [8,41]. The key findings from this analysis were:

- The need for more detailed environmental reporting for public interest, including regular summary reports for the whole area to address the lack of information sharing between different industries;
- That industries should recognise their contribution to community capacities as one of the most important outcomes of their activities in the area and allow local communities greater determination in regard to future industrial development in the region;
- Legislation should be prepared to encourage well known but also potential waste reuse options to overcome limited incentives and guidance for the best environmental outcomes.

4.2.3. Geelong

Geelong is situated 75 km south west of Melbourne in Victoria on the western edge of Port Phillip. The Geelong area has a long history of being one of Australia's major manufacturing and industrial regions. Heavy industries in the region include Alcoa's Point Henry smelter, Shell Australia's oil refinery, Ford Motor Company's manufacturing plant, Boral's Cement Plant. A 1999 study on identifying opportunities for waste re-use was conducted for the Geelong Manufacturing Council (GMC), a not-for-profit organization that represents industries in the Geelong region, and focused on preparing a preliminary assessment and scoping of feasibility studies as well as identification of opportunities for waste reduction and reuse by Geelong manufacturers [10]. Some of the high rating opportunities included a bioremediation trial at Shell, foundry sand re-use, non-prescribed waste exchange facility and an education program to promote waste reduction and exchange. The report recommended a working group should be established with the GMC to promote the report initiatives but it is unclear if this eventuated.

Through the CSRP, a later study was conducted to identify potential for waste and by-product re-use and exchanges. This study found that there were possible re-use options for several wastes such as water, oils, heat, dust, sand and refractory waste. The study recommended further analysis to prioritize the most attractive options which could then be implemented through a typical engineering project process [42].

In 2013, Shell Australia announced its Geelong site is for sale and aims to conclude negotiations by the end of 2014 [43]. Boral and Ford have also announced their intent to close down. This indicates Geelong will undergo significant industrial and economic structural change as traditional heavy industry departs the region. In 2013 the Future Proofing Geelong network, a partnership program involving City of Greater Geelong, EPA Victoria, Barwon Water, Deakin University, Committee for Geelong, Geelong Manufacturing Council and the Geelong Chamber of Commerce, launched Cleantech Innovations Geelong. This is an alliance between business and industry and aims to transition Geelong towards a "Centre of Excellence for cleantech in Australia" [44]. Funding from the Victorian Government Manufacturing Productivity Network Program supported this project. While it does not explicitly focus on industrial ecology, symbiosis or waste exchange, these concepts are included as part of the alliance's search and support for cleantech opportunities.

4.3. Mixed Industrial Parks

4.3.1. Wagga Wagga

Wagga Wagga is a regional city of nearly 60,000 [45] situated in New South Wales on the Murrumbidgee River between Sydney and Melbourne. Being virtually at the midpoint of the two largest cities in Australia (slightly over 450 km in each directions) has enabled Wagga Wagga to establish itself as a regional industrial centre. Industries in the Wagga Wagga region are of a smaller scale compared with Kwinana, Gladstone and Geelong and have included Cargill Beef (beef abattoir), BOC Limited (specialty industrial gases), Heinz Wattie's Australasia (canned beef products), Murrumbidgee Dairy Products Pty Ltd (dairy products manufacturer), Southern Oil Refineries Pty

Limited (used oil refining), Nufarm (agricultural suppliers, chemical supplies), and Riverina Wool Combing Pty Ltd (wool scouring).

Similar to Geelong, a study was conducted to identify potential for waste and by-product re-use and exchanges through the CSRP. This study used a Preliminary Assessment Tool, which had been developed through CSRP, in conjunction with an industry workshop to analyse the potential opportunities for by-product re-use. Although a range of potential opportunities were identified, the opportunities that had the best potential for implementation focused on water re-use, alternative fuels or industries requiring by-products as their main feedstock (such as plastic or timber recyclers) [42]. In 2008–2009, the local Council and State Government initiated the development of Wagga Wagga's Bowen industrial park, focusing on the creation of strategic transport hub and investing in industrial infrastructure, and aiming to widely apply industrial ecology principles to minimize the overall environmental impacts [46].

4.3.2. Port Melbourne

This project was initiated and funded through the Smart Water Fund in Victoria in 2007–2009, and mainly focused on the water reuse opportunities [47]. The Fisherman's Bend site in Port Melbourne, an industrial zone located less than 3 km from the centre of Melbourne, was selected as a case study due to the presence of large manufacturing industries with significant water consumption levels, as well as due to the existing commitments from the companies to explore further industrial ecology opportunities. The companies located at the Fisherman's Bend site in Port Melbourne that participated in the study were: Kraft (food production); Boral (plasterboard production); General Motors Holden (automotive manufacturing); Boeing (metal component manufacture/carbon fibre manufacture); Symex (commercial fats and proteins production); Herald and Weekly Times (HWT) (newspaper printing); Crema Group (precast concrete manufacture); Independent Cement (manufacturer of bulk and bagged cements and blended cement products) [48].

The Port Melbourne project resulted not only in identifying several water reuse options using membrane bioreactor and reverse osmosis technologies between various operations, but also in the formation of a Port Melbourne Industrial Ecology Working Group, bringing together industries, water suppliers, and regulating agencies to negotiate and develop further the discovered opportunities [48]. As funding support ended in 2009, this working group has had difficulty in continuing to actively operate.

4.3.3. Eco-Industrial Parks—Synergy Park (Qld) and Tonsley Park (SA)

Apart from the examples described above, there were several government driven projects to establish eco-industrial parks around Australia [9]. Some of these initiatives have succeeded, while others failed to prove their viability. Roberts [9] stated that there was a need by government and researchers to analyse in more detail the factors that lead to the successful implementation of eco-industrial parks. Two examples of the eco-industrial parks initiatives are given below.

Synergy Park was a proposed eco-industrial park located at Carole Park in southeast Queensland and was originally identified as a suitable site for food and beverage sector development. The State Government decision to pursue the development of the park in 1998 was based on sound planning principles, such as availability of transport, proximity to fertile cropping areas, access to utilities and

employment opportunities and access. The philosophy of Synergy Park was to build economies of scale through shared resources. This was to be achieved through:

(1). Shared warehouse and logistics—minimising waste space through wholly owned warehouses;
(2). Sophisticated logistics management system—unaffordable on an individual firm basis;
(3). Co-generation—minimising the need for individual firms to install a boiler;
(4). Effluent treatment—treatment and reuse in the co-generation plant reducing water consumption.

Critical success factors were the development of a trust, to develop the concept and bring together government and industry to secure ongoing support for the project. In addition, the engagement of planning authorities was also important in supporting co-location of industry and identifying synergies between them [9].

The proposed Synergy Park had strong industry and government support for the project. However in around 2002 a small, vocal community group raised objections to mixed industrial use and co-generation infrastructure. This resulted in delays to project approvals by government officials and ultimately a loss of business confidence in the project. By 2004, the original project and goals to build one of Australia's first designed eco-industrial parks had been dropped. The lack of success in this project highlights a critical barrier—a lack of community awareness and understanding of industrial ecology and modern sustainable development practices. The failure of the original design for Synergy Park illustrates the need to engage with the community early in the project planning cycle. Synergy Park still exists, but as a traditional industrial development site [49].

In South Australia, Tonsley Park, the site of the former Mitsubishi manufacturing plant has been identified for redevelopment. The government has a vision to "*create a centre of cleantech, sustainable technologies and environmental industries, advanced manufacturing and research and development*" [50]. The area aims to be an environment where business, industry and science clusters co-exist, collaborate and innovate for mutual benefit [50]. Given the planning for this site is still within the early planning stages, there is an opportunity for the South Australian Government to avoid the challenges that were faced by Queensland's Synergy Park initiative in developing Tonsley Park.

4.4. Waste Exchange Networks

Waste exchange systems are essentially live databases designed to link organisations looking to dispose of materials with organisations seeking to reuse or recycle the same materials. Most commonly they take the form of a web application that aids users in sharing or procuring waste materials. The Internet has dramatically expanded the reach and viability of waste exchanges that once relied on newsletters, trade magazines and the like to advertise available and wanted waste materials. Moreover, dynamic web-based exchanges help to overcome logistical issues that inhibit reuse and recycling such as the need to stockpile of waste materials [51,52], although some exchanges do specialise in warehousing materials [53]. Current leading international examples of waste exchanges include NYC Waste Match [54], Resource Exchange for Eliminating Waste [55] and California Materials Exchange [56] from the US, the UK Eastex National Materials Exchange [57] and Recipro Online Builders' Surplus Recycling and Exchange [58], The Waste Exchange from New Zealand [59] and the Global Recycling

Network (GRN) [60]. A comprehensive descriptive list of US and international waste exchanges is provided by US EPA [61].

Waste exchange systems may be classified according to the approach taken to matching waste generators with potential users [62]. Most web-based exchanges would be categorized either as passive systems acting simply as clearinghouse of information regarding the availability of waste materials, or as active exchanges that provide help with initiating exchanges by suggesting potential matches between waste generators or users and often some form of post-exchange follow-up. Pro-active and brokered exchanges lend themselves more to industrial symbiosis outcomes (as opposed to waste exchange transactions), with the former offering consultancy on cost-effective waste management and recycling, and the latter acting as an agent or consultant for a waste generator or recycler assuming control of a waste product prior to its resale and receiving a fee or commission for wastes that are successfully sold.

Geographical coverage, target audience, administration and funding/business models and mode of user interaction are other features that characterize waste exchanges. Most exchanges are developed to service a geographical reach of local government scale, although more successful exchanges such as Eastex and RENEW tend to expand to adjacent regions. The GRN is a globally-oriented site that "operates as a part of a network of worldwide recycling websites, portals and exchanges". Exchanges designed to facilitate recovery of waste materials and products (as opposed to directly reusable items) are largely targeted at the broad non-residential sector, encompassing industrial, commercial, government and non-government organisations, although some exchanges target specific sectors, particularly the construction and demolition sector, while others such as Materials for the Arts [63] explicitly seek to help arts and craft communities source materials. Most sites attempt to offer a free service, with funding provided by government or through commercial sponsorship or advertising (GRN). Web development has allowed waste exchanges to become largely user-driven in terms of registering available or wanted wastes, although there remain some examples of administrator-driven sites (e.g., City of West Torrens—see Table 1).

Table 1 summarises known waste exchange systems that have been developed within Australia. The difficulty in reviewing waste exchanges is that most sites are designed primarily with users in mind and provide little information on their development, implementation, adoption, administration or use, successful or otherwise. In addition, many sites become outdated and eventually disappear, most likely due to a lack of awareness and use. Indeed this has been the fate of at least two prominent Australian waste exchange sites. The Victorian WastePro Waste eXchange database was live as recently as April 2013, but has gone offline since that time. The site had very few entries, possibly likely due to insufficient promotion and awareness, but also because some companies can be reluctant to post information about their waste streams as they perceive this to undermine commercial advantage by revealing their level of manufacturing productivity and output. The database was also passive, in the sense that it relied upon users to log into the tool in order to see if there were resources of use to them. It is unclear what role these factors played in the recent cessation of the database. Similarly the now absent Construction Connect website that facilitated exchange of excess and used construction materials was last live in 2009. If nothing more, this demonstrates that this form of industrial ecology has yet to gain traction in Australia, for reasons that, to date, remain largely unexplored but are canvassed in Section 5.3.

Table 1. Known waste exchange systems developed in Australia.

Name	Administrating organization	Year established	Geographic coverage	Reference	Activity
Streamline WasteNot Resource Exchange	Parramatta City Council (NSW)	2010	Not limited by the tool, but originally targeted at Western Sydney	[64,65]	Low since 2011
City of West Torrens Waste exchange register	City of West Torrens (South Australia)	2005	City of West Torrens LGA	[66]	No listings in past 2 years
WastePro Waste exchange database	WastePro Developed by the Victorian Waste Management Association (VWMA) with support from EPA Victoria	Unknown	Victoria	–	Website no longer accessible
Construction Connect	Construction Connect Australia	Unknown	Australia-wide	–	Website no longer accessible
Demolition Materials Management System	NA—research demonstration project	2007	Australia	[52]	Website no longer accessible
Waste Exchange	Anon.	2004	Australia-wide	[67]	Inactive—last updated in August 2006
The Waste Exchange Web Page	Anon.	2003	Australia-wide	[68]	Inactive (no listings to be viewed)
Sydney Waste Exchange	Concrete Recyclers (Group) Pty Ltd	2002	Sydney	[69]	Standard of web design suggests low, if any, activity

5. Barriers and Enablers for Industrial Ecology in the Australia Context

A range of barriers and enablers to industrial ecology development have been addressed in literature, including the role of government environmental policies, planning policy, management practices within the industries, and a lack of specific tools to organize and stimulate the inter-industry collaboration [3,9,13,70–74]. Some studies also identified the triggers that are specific events to help overcome barriers or activate enablers for the realization of synergy projects. For example, the motivational barriers can be targeted by the setting of a stimulator/initiator for the project, establishment of a coordinating institution, or by the regional industry champion who takes the responsibility for industrial ecology development. Information sharing and trust between industries can be improved with the presence of a regional "information office" on existing wastes and their reuse opportunities, and special workshops involving representatives of different regional companies [3,13,38].

5.1. Heavy Industrial Areas

An overview of some barriers and enablers to industrial ecology application in Australia, based on Kwinana and Gladstone case studies, have been done by van Beers *et al.* [3]. In this study, the authors examined barriers and enablers across six categories—economics, information availability, corporate citizenship and business strategy, region-specific issues, regulation, and technical issues—and concluded that these are influenced by diverse sets of stakeholders (e.g., companies, regulators, community). In addition the authors conclude that trigger events play an important role in synergy developments, such as water scarcity that led to the water reclamation plant in Kwinana and the investment in a pipeline to use secondary treated effluent for bauxite residue washing in Gladstone. While synergy connections have to provide a sound business case [6], most industries also agree that financial benefits are not the only driver, and such aspects as supply risks, access to vital resources, environmental regulation, and community relations are also important for proceeding with the waste reuse project [3].

In addition, as mentioned earlier, balancing financial objectives against sustainability benefits of industrial ecology applications presents a challenge when proposed initiatives have moderate or low financial benefits but have high or possibly moderate sustainability benefits [38].

Another recent study on regional synergies in Gladstone, has developed a special tool—industrial symbiosis maturity grid—for the analysis and tracking of the most significant industrial ecology barriers [15]. The findings from this research, mainly based on interviewing industry representatives, indicated that "cooperation and trust" among industries and other stakeholders is the strongest characteristic of industrial symbiosis development in Gladstone, while the lack of information sharing is the characteristic for greatest improvement [16].

5.2. Barriers and Enablers Specific to SMEs

Constituting the bulk of businesses operating in Australia, SMEs make significant contributions to the broader commercial and industrial (C&I) waste stream. A disposal-based survey of C&I waste in Sydney, Australia conducted in 2008 found that SMEs produced 45% of the total C&I waste load, a larger fraction than the next six largest sectors combined, including manufacturing [75]. Statewide SME waste generation rates reported for Victoria, Western Australia and South Australia are lower, but still significant at 19%, 37% and 19%, respectively. Despite the large aggregate waste quantities SMEs produce, they have difficulty engaging recycling collection as their individual recyclate (raw material sent to, and processed in, a waste recycling plant) loads are too small to make the provision of a service viable [76].

Clearly there are gains to be made through engaging SMEs in industrial ecology; however a fundamental issue faced by SMEs, particularly amongst smaller businesses, is the often unavoidable need to de-prioritise waste management (unless costs become very high) and sustainability-related activities in the face of time, resource and know-how constraints, and financial and competitive risks [77,78]. Thus even when SME management have an interest in sustainability, they require encouragement and assistance to undertake initiatives beyond their day-to-day activities and embrace opportunities presented by industrial ecology, because to many, the business case for undertaking sustainability measures, including industrial ecology activities, has yet to be made.

Korhonen [79] sees SMEs playing a specific role of filling gaps in the resource cascade of products, citing the example of a specialised business that uses waste egg packaging board to manufacture degradable seedling protectors. In employing a business model centred around industrial ecology, such a role overcomes the barriers alluded to above; however, it does not offer a means of helping the broader SME population participate in industrial ecology. Peters and Turner [80] documented a "collective innovation" approach to overcoming this "well-recognised SME failure to engage with environmental improvement initiatives". Facilitated workshops were held with SMEs recruited from industrial estates in the East Anglia region of the UK to provide stimulation and guidance in identifying individual and collective sustainability initiatives. Reporting several tangible and realized waste management outcomes from the exercise, including at least one waste exchange arrangement, Peters and Turner [80] noted that once involved, participants sought to make the most of the opportunity to engage with other businesses, leaving initiating participation as the major challenge to broader programs of this nature. As is the case with most forms of industrial ecology, it is the experience of the authors that it often requires the involvement of a committed staff champion for an SME to engage with such programs.

In Australia, the development of the WasteNot Resource Exchange, described by Fyfe *et al.* [64], involved close engagement with over 40 local SMEs through workshops staged to inform the design of the web application and the identification of industrial symbiosis opportunities. As with the Peters and Turner [80] experience, waste exchange opportunities were readily identified in what were essentially facilitated networking opportunities. The key enablers for SME participation in this form of industrial ecology identified by the businesses included its potential to reduce cost of engaging waste contractors and provide cost-effective environmental inputs into processes, and the general perception of it being good for the environment. Importantly, the fact that the proposed exchange was locally oriented and historically grounded (the Duck River Catchment within which the waste exchange program was based has a long history as a unique industrial precinct in the region) was viewed as an important driver to participation in the initiative [81]. Peters and Turner [80] also noted the importance of geographical context, with businesses located within village areas more inclined to improve welfare and amenity of the local community, in contrast to businesses in dedicated industrial parks that were more interested in cost savings and efficiency gains.

Another critical barrier for SMEs is the lack of physical space to stockpile outgoing or incoming waste materials. A face-to-face survey of 12% of SMES in the city of Hobart, Australia by Parsons and Kriwoken [82] found "inadequate storage space" to be a primary barrier to participation in conventional recycling. Space constraints were also a common issue for SMEs participating in the development of WasteNot, especially amongst SMEs having to maintain stringent hygiene standards for food production [83].

5.3. Waste Exchange Networks

With very few examples waste exchanges maintaining long-term success, there is almost no information on successful models. A key issue, however, is initiating and sustaining a minimum level of activity and maintaining an appearance of being "live". Cursory browsing of waste exchange web sites quickly reveals that many are not in active use and therefore would offer little, if any benefit to

new users, presenting a significant barrier to uptake. As such, newer sites go to considerable lengths to build interest and usage by incorporating current news stories and updates. Other strategies include placing expiry dates on listings and generating email notifications of new and expiring listings. Beyond keeping up appearances, however, it is critical that an exchange is actively promoted via other (non-internet) avenues to generate awareness and interest. Experience from the development of the WasteNot exchange showed that linking with industry peak bodies and associations is an excellent means of promoting waste exchanges, building a network of businesses and generating "buy-in" amongst those businesses [81]. Behind the scenes, waste exchanges require system maintenance, some form of moderation and administration, all of which must be factored into the business model of a waste exchange from the outset.

Governance of waste exchanges is not only functionally important, but also influences user perceptions. Exchanges have been set up by various bodies including government agencies, local governments, non-government organisations, and recycling and other businesses, each employing different governance and business models to sustain the ongoing upkeep of the site. However, consultation with businesses to inform the development of the WasteNot exchange indicated that the possibility or even misguided perception that an exchange may be managed or accessed by waste regulators could put businesses off using the tool and that it would best be administered by an independent body. Indeed many of the waste exchanges that have experienced longevity have been run by non-government, non-profit organisations with funding support provided by government. Other barriers to participation in the waste exchange identified by businessses included a lack of local manufacturers to utilise recovered waste, perceptions of conflicting local and state government waste codes and regulations, and conservative business attitudes to waste management (a reflection of the difficulty to engage SMEs noted in the following section) [81].

Waste exchanges may operate on a range of scales from local to national or global, and often tend to grow beyond their initial geographical reach with time. While this might suggest that successful waste exchange systems could draw in users from a large geographical region, the considerable distances between urban centres in Australia may also be the reason why waste exchanges have yet to take hold here. When considering the Australian geographical context, complexities associated with differing landfill (and sewer) classifications and costs and waste regulations between local and State government jurisdictions must also be recognised. For example, the higher landfill levy in metropolitan NSW makes industrial symbiosis transactions more economically feasible than in regional areas of NSW and adjoining states [84]. On the other hand, differentials in landfill classifications and costs have resulted in the perverse outcome of interstate waste dumping [85]. Similarly, regulations related to waste recovery and reuse can differ between states, which could also limit interstate industrial symbiosis [84].

There is a clear need for further research into the factors that determine the success of waste exchange systems to enable growth in waste exchange type industrial ecology within Australia. In particular there is a need for a critical evaluation of effective networks, scales and governance structures to inform development of novel approaches that can be trialled, demonstrated and evaluated at local or regional scales, with a view to incorporating scalability across Australia.

5.4. Comparison of Barriers and Enablers

The analysis of barriers to industrial ecology at different levels of its application, presented in the previous section, has shown that most barriers are similar between all the levels, however they have different significance in facilitating and promoting synergy connections. The authors, having been involved in several industrial ecology projects in Australia, assess that:

- For heavy industrial areas and mixed industrial parks—economic, technical, and cooperation barriers were the most significant in the past, while regulation, information, and community barriers and enablers are in the main focus currently and in the future. Mixed industrial parks, however, still may require more assistance to overcome economic and regulatory barriers;
- For the waste exchange networks, which are fully focused on providing online information support in the past, the current and future success lies in overcoming the limited financial and resource capacity, along with lack of appropriate technical expertise and knowledge.

Table 2 summarises the significance of barriers across the three levels. In addition, having resources available to conduct an independent assessment of the value of implemented industrial ecology initiatives is extremely helpful as these can be used as evidence to promote future initiatives.

Table 2. Barriers to industrial ecology application in an Australian context.

Type of barrier	Heavy industrial areas	Mixed industrial parks	Waste exchange networks
Regulation			
• past focus	medium	medium	low
• current/future focus	medium/significant	significant	low/medium
Information			
• past focus	medium	medium	significant
• current/future focus	significant	medium/significant	low
Community			
• past focus	low/medium	low/medium	low
• current/future focus	significant	medium/significant	low
Economic			
• past focus	significant	significant	low
• current/future focus	medium	medium/significant	medium/significant
Technical			
• past focus	significant	significant	low
• current/future focus	medium	medium	medium/significant
Cooperation and trust			
• past focus	significant	significant	low
• current/future focus	medium	medium	Low/Medium
Commitment to sustainable development			
• past focus	low/medium	low/medium	low
• current/future focus	medium	medium	medium

While all the barriers for increasing uptake of resource synergies in heavy industrial areas and mixed industrial parks ranged from medium to high significance, the development of waste exchange networks usually meets a few key hurdles due to the nature of the exchanges, the generally low

volumes of waste materials, and the typical need of temporary one-off agreements. Waste exchanges need stronger business models to sustain themselves beyond initial development and start-up funding. Subscription fees, however, are likely to be unpalatable to many smaller businesses, although the UK National Industrial Symbiosis Program (NISP) today operates on a subscription basis, which pays for a brokering service rather than only access to a website [86].

The analysis presented in Table 2 agrees with a recently developed framework by Yu *et al.* [87] for identifying the events of key activities for developing eco-industrial parks:

- Institutional activity;
- Technical facilitation;
- Economic and financial enabler;
- Informational activity;
- Company activity.

The key current/future focus for barriers in heavy industrial regions and mixed industrial parks identified in Table 2 of regulation, information, and economic aligns with the institutional activity, information activity, and economic and financial enabler activities in the abovementioned framework. Only the community barrier, which has significant current/future focus in Table 2, does not map directly to this framework but does link in to one of the key indicators as reported by Yu *et al.* [87] in the information activity, namely workshops, conferences, seminars and forums for networking, and another key indicator in the institutional activity, namely planning, voluntary agreement and evaluation for eco-industrial parks.

The evolution of industrial symbiosis is capsulated by the work of Lombardi and Laybourn [24] who proposed an updated definition for industrial symbiosis that emphasizes the need to "engage diverse organizations in a network to foster eco-innovation and long-term culture change" and yield "mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes." Similar to the comparison with the framework above, the analysis presented here echoes these characteristics of industrial ecology development and highlights the complex nature and drivers for realizing success initiatives. Other workers in this area have developed informative frameworks and utilised analysis to understand and explain the complex nature of industrial symbiosis systems [23,88,89]. Again the outcomes from their research support the findings and analysis in the article.

In summary, the analysis presented in this section is attempting to better understand the trends for industrial ecology applications in the three above mentioned categories—heavy industrial areas, mixed industrial parks, and waste exchange networks. By gaining a better appreciation for the drivers of industrial ecology, it will be possible to develop feasible strategies to progress Australia towards a circular economy and in doing so minimise the environmental footprint of the industrial sector.

6. Conclusions

Although the Australian experience provides a case study of detailed analysis of the existing waste streams and multiple opportunities for waste reuse in the respective regions, it also shows that significant barriers still remain for higher uptake and further investigation of waste reuse options.

Over the last 15 years, the concept of industrial ecology has been applied in Australia at different levels—from SME-focused waste exchange networks to heavy industrial areas—with varying degree of success. Undoubtedly, it is now a well-recognised approach to increase resource efficiency and minimise environmental impacts associated with industrial and consumer activities. The country's unique geographic location as a continent, with long distances between major cities and industrial centres in regional areas, being the major challenge, also defines the opportunities to enhance the application of industrial ecology.

Most of the examples described in the article were implemented with the local and state government support (in different forms), while there are very few projects that have been developed and have succeeded solely on the basis of industry interest and funding. With a focus on technical feasibility and establishing inter-industry collaboration in the existing cases, there are still other barriers preventing waste and by-product exchanges from happening. The economic driver usually predetermines the investigation for waste reuse options, with environmental regulation being another important factor to stimulate or prevent any interest in establishing synergy connections.

Answers to the following questions could greatly help enhancing industrial ecology applications in Australia:

- How would better information availability, including detailed reporting on economic and environmental achievements from implementing synergy projects assist uptake of industrial ecology applications?
- Would recognition and active promotion of national champions in industrial ecology, for advertising and sharing best practices and experience increase uptake?
- What further improvements in the environmental regulation could contribute and encourage the adoption of best-known technologies and waste reuse projects?
- Would defining of long term targets for waste reuse and recycling, supported by the development of specific projects drive better industrial ecology outcomes?
- Could sharing of common failures and successful factors between local and State government efforts across Australia expand the collective knowledge base and increase support and acceptance of industrial ecology applications?

While recent reported international research and experiences referenced in this article go some way to addressing the above questions, these findings and learnings need to be adapted and refined for the contextual setting in Australia. As current research thinking in industrial ecology highlights, there are many local variables, parameters and actors involved in the successful application and implementation of the concepts of industrial ecology beyond technical re-use solutions. Without any significant, ongoing and successful examples of industrial ecology, such as those referred to in Section 2, Australia continues to lag behind international efforts. While this could be viewed negatively, it is the authors' view that despite challenges and barriers, Australia remains fertile ground to pursue the efficient use of resources through the implementation of industrial ecology.

Acknowledgments

The authors would like to acknowledge the support of the CSIRO cluster program.

Author Contributions

Glen Corder led the writing of the article apart from the sections referring to Waste Exchange Networks, SMEs (small and medium enterprises) and eco-industrial parks and received significant input and assistance from Artem Golev, particularly in Section 5.4 and Section 6. Julian Fyfe led the writing on the sections referring to Waste Exchange Networks and SMEs (small and medium enterprises) and Sarah King led the writing on the sections referring to eco-industrial parks and both authors assisted with reviewing and revising the other sections of the article.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Frosch, R.A.; Gallopoulos, N.E. Strategies for manufacturing. *Sci. Am.* **1989**, *261*, 144–152.
2. Graedel, T.E.; Allenby, B.R. *Industrial Ecology*; Prentice-Hall: Englewood Cliffs, NJ, USA, 1995.
3. Van Beers, D.; Corder, G.; Bossilkov, A.; van Berkel, R. Industrial symbiosis in the Australian minerals industry—The cases of Kwinana and Gladstone. *J. Ind. Ecol.* **2007**, *11*, 55–72.
4. Van Beers, D.; Corder, G.D.; Bossilkov, A.; van Berkel, R. Regional synergies in the Australian minerals industry: Case-studies and enabling tools. *Miner. Eng.* **2007**, *20*, 830–841.
5. Van Beers, D.; Bossilkov, A.; Lund, C. Development of large scale reuses of inorganic by-products in Australia: The case study of Kwinana, Western Australia. *Resour. Conserv. Recycl.* **2009**, *53*, 365–378.
6. Corder, G.D.; van Beers, D.; Lay, J.; van Berkel, R. Benefits and Success Factors in Regional Resource Synergies in Gladstone and Kwinana. In *Proceedings of the Green Processing 2006: International Conference on the Sustainable Processing of Minerals*, Newcastle, Australia, 5–6 June 2006; Australasian Institute of Mining and Metallurgy: Carlton, Australia, 2006; pp. 83–92.
7. Golev, A.; Corder, G.D. Developing a classification system for regional resource synergies. *Miner. Eng.* **2012**, *29*, 58–64.
8. Golev, A.; Corder, G.D.; Giurco, D.P. Industrial symbiosis in Gladstone: A decade of progress and future development. *J. Clean. Prod.* **2013**, *2013*, doi:10.1016/j.jclepro.2013.06.054.
9. Roberts, B.H. The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: An Australian case study. *J. Clean. Prod.* **2004**, *12*, 997–1010.
10. Ellwood, D.; Grant, B. *Industrial Waste Identification and Opportunity Analysis for Geelong Manufacturers—Main Report*; Meinhardt Pty Ltd: Melbourne, Australia, 1999.
11. Corder, G.D. *Potential Synergy Opportunities in the Gladstone Industrial Region*; Centre for Sustainable Resource Processing: Perth, Australia, 2005.
12. Bossilkov, A.; van Berkel, R.; Corder, G. *Regional Synergies for Sustainable Resource Processing: A Status Report*; Centre for Sustainable Resource Processing: Perth, Australia, 2005.
13. Brand, E.; de Bruijn, T. Shared responsibility at the regional level: The building of sustainable industrial estates. *Eur. Environ.* **1999**, *9*, 221–231.
14. Van Berkel, R. *Regional Resource Synergies for Sustainable Development in Heavy Industrial Areas: An Overview of Opportunities and Experiences*; Curtin University of Technology: Perth, Australia, 2006.

15. Golev, A. Application of Industrial Ecology Principles for Enhanced Resource Efficiency in Heavy Industrial Areas. Ph.D. Thesis, The University of Queensland, Brisbane, Australia, 2013.
16. Golev, A.; Corder, G.; Giurco, D. Barriers to industrial symbiosis: Insights from the use of a maturity grid. *J. Ind. Ecol.* **2014**, in press.
17. Korhonen, J. Two paths to industrial ecology: Applying the product-based and geographical approaches. *J. Environ. Plan. Manag.* **2002**, *45*, 39–57.
18. Van Berkel, R. Comparability of industrial symbioses. *J. Ind. Ecol.* **2009**, *13*, 483–486.
19. Gibbs, D.; Deutz, P. Reflections on implementing industrial ecology through eco-industrial park development. *J. Clean. Prod.* **2007**, *15*, 1683–1695.
20. Chertow, M.R. "Uncovering" industrial symbiosis. *J. Ind. Ecol.* **2007**, *11*, 11–30.
21. Shi, H.; Tian, J.; Chen, L. China's quest for eco-industrial parks, part I. *J. Ind. Ecol.* **2012**, *16*, 8–10.
22. Laybourn, P.; Lombardi, D.R. Industrial symbiosis in european policy. *J. Ind. Ecol.* **2012**, *16*, 11–12.
23. Chertow, M.; Ehrenfeld, J. Organizing self-organizing systems. *J. Ind. Ecol.* **2012**, *16*, 13–27.
24. Lombardi, D.R.; Laybourn, P. Redefining industrial symbiosis. *J. Ind. Ecol.* **2012**, *16*, 28–37.
25. Yu, C.; Davis, C.; Dijkema, G.P.J. Understanding the evolution of industrial symbiosis research. *J. Ind. Ecol.* **2013**, *2013*, doi:10.1111/jiec.12073.
26. Dames & Moore Environment Australia. *Cleaner Production Manual: Environment & Business Profiting from Cleaner Production*; Environment Australia: Canberra, Australia, 1997.
27. Dempster, P.; Jubb, C.; Nagy, L.; Stacey, N.; Versteegen, A.; Lawrence, D. *A Benchmark of Current Cleaner Production Practices*; Environment Australia: Aquatech, Australia, 1997.
28. Australian and New Zealand Environment and Conservation Council (ANZECC). *Towards Sustainability: Achieving Cleaner Production in Australia: Report*. Environment Australia: Hobart, Australia, 1999. Available online: http://www.environment.gov.au/archive/settlements/industry/corporate/eecp/publications/nscp.html (accessed on 14 March 2014).
29. Van Berkel, R. Cleaner production and eco-efficiency initiatives in western Australia 1996–2004. *J. Clean. Prod.* **2007**, *15*, 741–755.
30. NSW Government. Waste Less, Recycle More—A Five-Year $465.7 Million Waste and Resource Recovery Initiative. Available online: http://www.environment.nsw.gov.au/resources/waste/130050WLRM.pdf (accessed on 19 November 2013).
31. Ferrari, D. Project Lead Built Environment and Energy Team, Sustainability Victoria, Melbourne, Australia. Personal Communication, 17 March 2013.
32. Lambert, A.J.D.; Boons, F.A. Eco-industrial parks: Stimulating sustainable development in mixed industrial parks. *Technovation* **2002**, *22*, 471–484.
33. Gibbs, D. Eco-industrial parks and industrial ecology strategic niche or mainstream development. In *The Social Embeddedness of Industrial Ecology*; Boons, F., Howard-Grenville, J.A., Eds.; Edward Elgar: Cheltenham, UK, 2009.
34. Chertow, M.R. Industrial symbiosis: Literature and taxonomy. *Annu. Rev. Energy Environ.* **2000**, *25*, 313–337.
35. Van Beers, D. *Capturing Regional Synergies in the Kwinana Industrial Area*; Status Report; Centre for Sustainable Resource Processing: Perth, Australia, 2008.
36. Bossilkov, A. *Capturing Regional Synergies in the Kwinana Industrial Area 2010*; Centre for Sustainable Resource Processing: Perth, Australia, 2010.

37. Kwinana Industries Council. Available at: http://www.kic.org.au (accessed on 14 March 2014).
38. Corder, G.D. *Developing Local Synergies in the Gladstone Industrial Area*; Project 3c1; Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland: Queensland, Australia, 2008.
39. Corder, G.D. *Interim Report on Long-Term Initiatives for Large Waste Streams in the Gladstone Region*; Project 3c1; Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland: Queensland, Australia, 2006.
40. GILG. Gladstone Industry Leadership Group. Available online: http://gilg.com.au (accessed on 19 November 2013).
41. Golev, A. *A Review of the Regional Synergy Development in Gladstone: Research Report*; Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland: Brisbane, Queensland, Australia, 2012.
42. Bossilkov, A.; Corder, G. *Enabling Tools and Technologies for Capturing Regional Synergies*; Project 3a1; Centre for Social Responsibility in Mining, Sustainable Minerals Institute, The University of Queensland: Queensland, Australia, 2008.
43. Australian Government. Product Stewardship. Available online: http://www.environment.gov.au/topics/environment-protection/national-waste-policy/product-stewardship (accessed on 7 November 2013).
44. Cleantech Innovations Geelong. Cleantech Innovations Geelong—Launch and Forum. Available online: http://www.geelongaustralia.com.au/gbc/event.aspx?id=8d0267bb38d736c (accessed on 10 February 2014).
45. ABS. 2011 Census Quickstats—Wagga Wagga. Available online: http://www.censusdata.abs.gov.au/census_services/getproduct/census/2011/quickstat/LGA17750 (accessed on 4 November 2013)
46. Wagga Wagga City Council (WWCC). *Bomen Strategic Master Plan 2009*; Wagga Wagga City Council: Wagga Wagga, Australia, 2009.
47. Kazaglis, A.; Giurco, D.; van Beers, D.; Bossilkov, A.; Reuter, M.; Fagan, J.; Grant, T.; Moore, T. *Industrial Ecology Opportunities in Melbourne: Literature Review*; Smart Water Fund: Melbourne, Australia, 2007.
48. Giurco, D.; Bossilkov, A.; Patterson, J.; Kazaglis, A. Developing industrial water reuse synergies in port melbourne: Cost effectiveness, barriers and opportunities. *J. Clean. Prod.* **2011**, *19*, 867–876.
49. Roberts, B.H. Applications of Industrial Ecology in Australia. Presented at the CSIRO Intelligent Processing Symposium and Workshops Melbourne, Australia, 29 May 2013.
50. SA Government Tonsley. Available online: http://www.tonsley.com (accessed on 19 November 2013).
51. Chen, Z.; Li, H.; Wong, C.T.C. Webfill before landfill: An e-commerce model for waste exchange in Hong Kong. *Construct. Innov.* **2003**, *3*, 27–43.
52. Pun, S.K.; Liu, C.; Langston, C.; Treloar, G. Electronic waste exchange for just-in-time building demolition. *Int. J. Construct. Manag.* **2007**, *7*, 65–77.
53. US EPA. Community Warehouse Recycle City. Available online: http://www.epa.gov/recyclecity/warehouse.htm (accessed on 19 November 2013).
54. Match, N.W. NYC WasteMatch. Available online: http://www.wastematch.org (accessed on 19 November 2013).

55. RENEW. Resource Exchange for Eliminating Waste (Renew). Available online: http://www.zerowastenetwork.org (accessed on 19 November 2013).
56. CalRecycle Home Page. Available online: http://www.calrecycle.ca.gov (accessed on 19 November 2013).
57. UK Eastex National Materials Exchange. Available at: http://www.eastex.org.uk (accessed on 14 March 2014).
58. Recipro Online Builders' Surplus Recycling and Exchange. Available at: http://www.recipro-uk.com (accessed on 14 March 2014).
59. The Waste Exchange from New Zealand. Available at:http://www.nothrow.co.nz (accessed on 14 March 2014).
60. Global Recycling Network (GRN). Available at: http://www.grn.com (accessed on 14 March 2014).
61. US EPA. Wastes—Resource Conservation—Conservation Tools. Available online: http://www.epa.gov/osw/conserve/tools/exchange.htm (accessed on 19 November 2013).
62. CCREM. Review of Waste Exchange Programs. Available online: http://www.ccme.ca/assets/pdf/pn_1244_e.pdf (accessed on 14 March 2014).
63. Materials for the Arts. Available at: http://www.nyc.gov/html/dcla/mfta/html/home/home.shtml (accessed on 14 March 2014).
64. Fyfe, J.; Blackburn, N.; Mason, L.; Giurco, D.; Read, W. Supporting Industrial Ecology in Smes: The Streamline Waste Exchange. In Proceedings of the 7th Australian Conference on Life Cycle Assessment, Melbourne, Australia, 2011; pp. 1–10.
65. WasteNot Streamline Resoource Exchange. Available at: http://wastenot.net.au (accessed on 14 March 2014).
66. Waste Exchange Register. Available at: http://www.westtorrens.sa.gov.au/Environment_waste/Waste_recycling/Recycling/Waste_exchange_register (accessed on 14 March 2014).
67. Waste Exchange. Available at: http://www.wasteexchange.com.au (accessed on 14 March 2014).
68. The Waste Exchange Web Page. Available at: http://pricom.com.au/waste/waste.html (accessed on 14 March 2014).
69. Sydney Wsste Exchnage Website. Available at: http://www.sydneywaste.com.au/ (accessed on 14 March 2014).
70. Business Council for Sustainable Development—Gulf of Mexico (BCSD-GM). *By-Product Synergy: A Strategy for Sustainable Development, a Primer*; Business Council for Sustainable Development—Gulf of Mexico (BCSD-GM): Austin, TX, USA, 1997.
71. Heeres, R.R.; Vermeulen, W.J.V.; de Walle, F.B. Eco-industrial park initiatives in the USA and the Netherlands: First lessons. *J. Clean. Prod.* **2004**, *12*, 985–995.
72. Fichtner, W.; Tietze-Stöckinger, I.; Frank, M.; Rentz, O. Barriers of interorganisational environmental management: Two case studies on industrial symbiosis. *Prog. Ind. Ecol.* **2005**, *2*, 73–88.
73. Mangan, A.; Olivetti, E. By-product synergy networks: Driving innovation through waste reduction and carbon mitigation. In *Sustainable Development in the Process Industries: Cases and Impact*; Harmsen, J., Powell, J.B., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2010; pp. 81–108.

74. Harris, S. Drivers and Barriers to Industrial Ecology in the UK. Ph.D. Thesis, the University of Edinburgh, Edinburgh, UK, 2004.
75. DECCW. *Disposal Based Survey of the Commercial and Industrial Waste Stream in Sydney*; Department of Environment, Climate Change and Water NSW: Sydney, Australia, 2010.
76. Bremner, A.-M.; Allan, P.; O'Farrell, K.; A'Vard, D. *A Study into Commercial & Industrial (C&I) Waste and Recycling in Australia by Industry Division*; Encycle Consulting Pty Ltd: Canberra, Australia, 2013; pp. 1–158.
77. Holt, D.; Anthony, S.; Howard, V. Supporting environmental improvements in small and medium-sized enterprises in the UK. *Greener Manag. Int.* **2000**, *2000*, 29–49.
78. Petts, J.; Herd, A.; Gerrard, S.; Horne, C. The climate and culture of environmental compliance within smes. *Bus. Strategy Environ.* **1999**, *8*, 14–30.
79. Korhonen, J. Completing the industrial ecology cascade chain in the case of a paper industry—SME potential in industrial ecology. *Eco-Manag. Audit.* **2000**, *7*, 11–20.
80. Peters, M.; Turner, R.K. SME environmental attitudes and participation in local-scale voluntary initiatives: Some practical applications. *J. Environ. Plan. Manag.* **2007**, *47*, 449–473.
81. Fyfe, J.; Herriman, J.; Blackburn, N.J.; Asker, S.; Giruco, D. *Designing the Duck River Waste Exchange Program*; University of Technology, Sydney: Sydney, Australia, 2009.
82. Parsons, S.; Kriwoken, L.K. Report: Maximizing recycling participation to reduce waste to landfill: A study of small to medium-sized enterprises in Hobart, Tasmania, Australia. *Waste Manag. Res.* **2010**, *28*, 472–477.
83. Fyfe, J.; Mason, L.; Boyle, T.; Giurco, D. *Wastenot: The Streamline Resource Exchange. Background, Development and Case Studies*; University of Technology, Sydney: Sydney, Australia, 2010.
84. Branson, R. Bilateral Industrial Symbiosis: An Assessment of Its Potential in New South Wales to Deal Sustainably with Manufacturing Waste. Ph.D. Thesis, The University of Sydney, Sydney, Australia, 2011.
85. EPHC. *National Waste Report*; Environment Protection and Heritage Council and the Department of Environment, Water, Heritage and the Arts: Canberra, Australia, 2010.
86. National Industrial Symbiosis Program. Available at: http://www.nispnetwork.com (accessed on 14 March 2014).
87. Yu, C.; de Jong, M.; Dijkema, G.P.J. Process analysis of eco-industrial park development—The case of Tianjin, China. *J. Clean. Prod.* **2014**, *64*, 464–477.
88. Ashton, W.S. The structure, function, and evolution of a regional industrial ecosystem. *J. Ind. Ecol.* **2009**, *13*, 228–246.
89. Boons, F.; Spekkink, W.; Mouzakitis, Y. The dynamics of industrial symbiosis: A proposal for a conceptual framework based upon a comprehensive literature review. *J. Clean. Prod.* **2011**, *19*, 905–911.