Industrial Ecology for developing an extended network of industrial ecosystems

- an exploration of the solar cell technology industry

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Abstract

The ultimate goal of IE is to develop high levels of closed-loop material exchanges to enhance environmental sustainability through transforming linear transformations of industrial processes to closed-loop industrial ecosystems. There is no exception for the solar cell industry. There will be a problem to deal with a significant amount of after-use solar cell products in a near future. This study considers the applications of IE to the solar cell industry to emphasise the importance of the after use options at the product and process design stage through design for environment (DfE) to close material loops leading to the reduced negative impact on the environment.

Keywords: Industrial Ecology, extended networks, solar cell industry

Introduction

Industrial Ecology (IE) aims to develop industrial ecosystems by mimicking key features of biological ecosystems (Frosch and Gallopoulos, 1989). One of the key features of biological ecosystems for industrial systems to mimic is (nearly) closed-loop material exchanges (Frosch and Gallopoulos, 1989; Korhonen, 2001). Industrial ecosystems with high levels of closed-loop material exchanges dramatically reduce the negative impact on the environment. Developing industrial ecosystems is challenging as it requires cross-industrial collaboration, innovative ideas and an extended system perspective (Dunn and Steinemann, 1998).

IE has been considered in environmental sciences/management and material engineering for decades. However, IE is relatively new and is far from achieving full integration within Operations Management (OM). An extended system perspective from IE supporting closed-loop material exchanges across industries needs to be embedded in all OM areas to fulfil its critical role in improving environmental sustainability.

This study aims to explore how IE can be applied to develop an extended network of industrial ecosystems for manufacturing companies to dramatically reduce negative impact on the environment. The solar cell (photovoltaic – PV) industry has been selected for this exploration. The solar cell industry has been viewed as one of renewable energy industries and contributes to environmental sustainability from the sustainable energy perspective. However, the importance of closed-loop material exchanges and development of industrial ecosystems for this industry has yet to be fully recognised. Most life cycle analysis (LCA) studies for solar cell technologies have focused on energy conversion efficiency, energy payback time (EPBT), and other emission related factors along the product life cycle without the inclusion of the 'after-use' or 'end-of-life' phase (Gerbinet et al, 2014; Giancarlo et al, 2013). The evaluation results on environmental sustainability could be very different if the end-of life phase has been considered in these evaluations (Gerbinet et al, 2014).

The literature has been reviewed for IE and its study areas as well as the criteria used for performing the LCA for different solar cell technologies. Besides, the studies which have mentioned or explored the end-of-life phase of solar cell products have been particularly reviewed. A comparison of these individual phenomena has been made to the key principle of IE and its associated areas to identify potential areas for IE applications in this industry. The areas for this industry to improve its environmental sustainability through IE are revealed.

A visit to a solar cell manufacturing company in Tianjin, China allowed the observation of the solar cell manufacturing process and discussions of the current situation of the industry and the future consideration of end-of-life options for solar cell products. Information regarding solar cell development, material extraction, production, product usage, and product after-use for this industry are also considered in analysis. The average lifetime of the solar cell products is about 25-30 years and the first significant volumes of solar cell installations began in the early 1990s in some developed countries (Giacchetta et al, 2013) and a several years later in some developing countries. By 2020 to 2030, the world will have to deal with a great quantity of end-of-life solar cell products and it could be sooner if new, cheaper and more efficient solar cell technologies are available sooner for mass productions to replace the existing ones in the market. It becomes absolutely necessary for this industry to consider the establishment of a take-back and recycling system for end-of-life solar cell products. There must also be significant intervention by policy makers in order to develop and establish relevant policies to ensure that the end-of-life of solar cell products are recycled and/or remanufactured, instead of passed to landfill. According to IE, the consideration of after-use or end-of-life products should be at product and process design stage. A particular consideration needs to be given to key materials used for different types of solar cell products and improved management of end-life products regarding different options to lead higher level of closed-loop material exchanges.

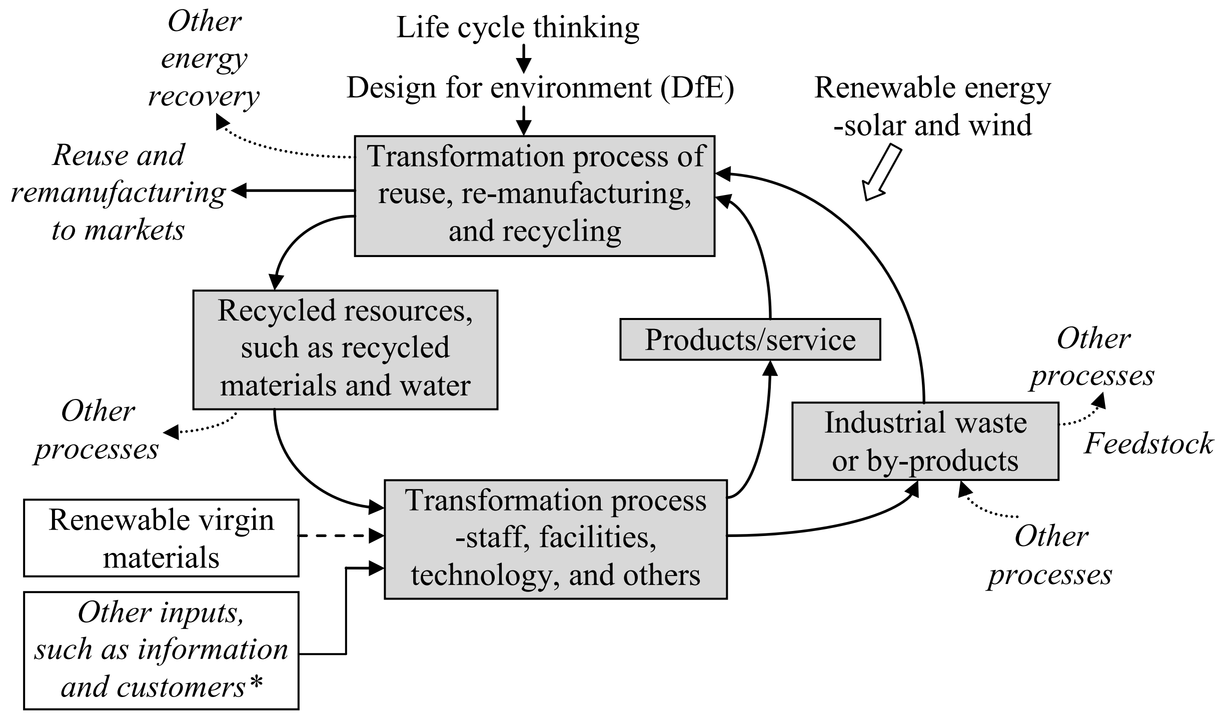
This research explores different IE approaches across its study areas to support the development of industrial ecosystems which have high levels of closed-loop material exchanges for the solar cell industry. It also emphasises the importance of integration and collaboration among companies, waste processers, research institutions, and product users for developing high levels of extended industrial ecosystems.

Literature review of the extended network concept within Industrial Ecology

This literature review is structured in three sections. The first section introduces IE and its four study areas. The second section reviews studies regarding the LCA of solar cell technologies to identify criteria currently used for evaluating the solar cell technologies. The third section focuses on some examples in this industry published in the literature which share the principle of IE. However, it also reveals some gaps which bring potentials for applying IE in the solar cell industry to enhance environmental sustainability for this industry in the longer term.

Industrial Ecology and its four areas

IE is rooted in the principle of developing (nearly) closed-loop material exchanges of industrial ecosystems and their interlocks among different industrial ecosystems at different levels as well as with the mother ecosystem of the Earth (Tibbs, 1992). The end-of-life options must be considered at product and process design phase by applying design for environment (DfE) to avoid end-of-life products going to landfill. DfE considers reuse, remanufacturing and recycling options at the product and process design phase (Jackson et al, 2016). DfE considers different approaches and strategies from eco-design for material selection, eco-design for manufacturing process, eco-design for distribution and delivery, eco-design for use, and eco-design for after-use (Li, 2018, page 97). The eco-design for after-use consists of design for recycling, design for reuse at the product level, and design for remanufacturing to achieve a new upgraded product status, which are totally different reconditioning and repairing used products. The closed-loop material exchange thinking (see Figure 1) needs to be considered for all the industries (Li, 2018, page 4).



* For service industry only.

Figure 1 *Closed-loop thinking of material exchanges*

Figure 1 emphasises the three key elements of a closed-loop thinking compared to the traditional linear transformation for analysing processes in the OM. The three key elements are:

1. At the material selection stage, recycled materials should be considered first, before virgin materials, and for virgin materials, renewable materials should be considered after recycled materials.
2. Industrial waste and by-products need to find their way as feedstock to other processes either in the same industry or different industries.
3. A transformation process is also needed for after-use products and facilities to create opportunities for reuse, remanufacturing and recycling. Remanufacturing products, which have upgraded functions, can enter to the market again and recycled materials as raw materials into material circulations.

Precious metals have been considered in recovery and recycling for centuries. However, it is moving from a linear to a closed-loop system in all realms of human production and consumptions (Lowe and Evans, 1995), which is matter ultimately to achieving the environmental sustainability of our world. This is the central goal of IE

(Lowe and Evans, 1995). As a study field, IE contains four study areas: industrial ecosystems, industrial symbiosis (IS), industrial metabolism (IM), and legislation and regulations for IE applications (Malcolm and Clift, 2002; Tibbs, 1992). In each of these study areas, different approaches and frameworks have been developed to support industrial ecosystem development.

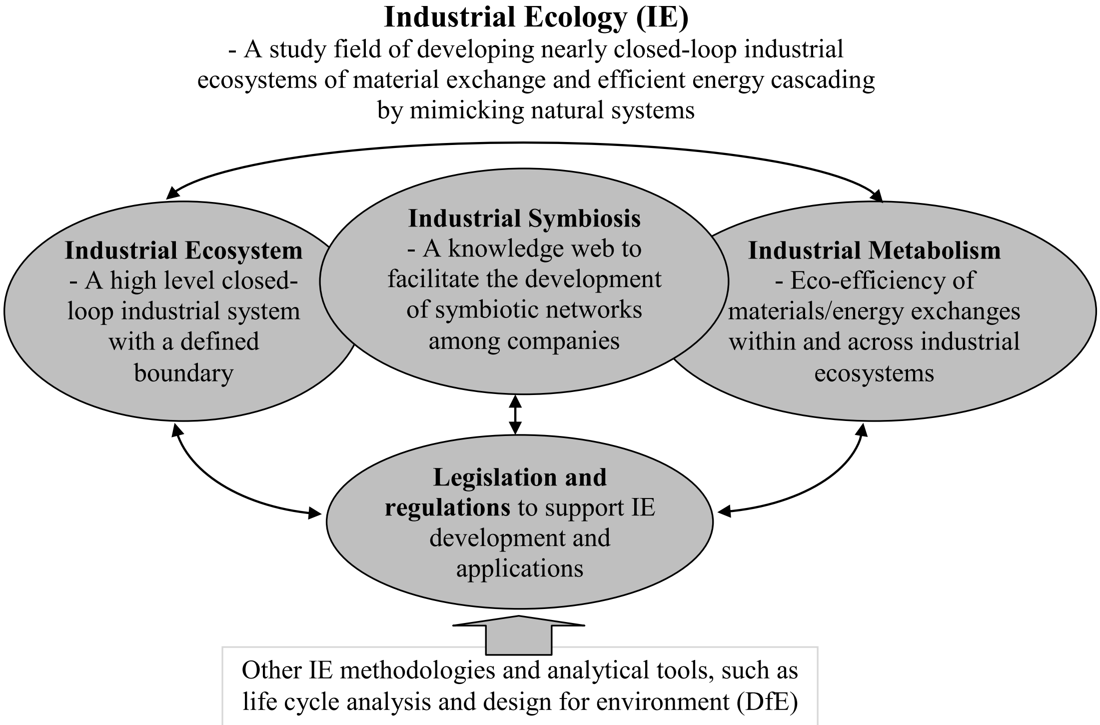


Figure 2 Industrial Ecology and its interrelated four study areas (Li, 2018, page 32)

Figure 2 provides a summary of the four study areas of IE. The area of industrial ecosystems considers determining boundaries of industrial ecosystem and an extended system perspective to create interlocks among industrial ecosystems and the mother ecosystem of the Earth. An industrial ecosystem can be either determined by geographic location or areas or by product or material flows. IS focuses on the development of innovative material exchanges among companies and industries through establishing information and knowledge networks. Potential collaborations among companies, product design and research institutes, as well recycling companies can support innovative ideas for material exchanges among industries to avoid the landfill. IM considers the evaluation of an industry ecosystem regarding the rate of material exchanges within or across system boundaries to determine the level of nearly closed-loop material exchanges. The area of legislation and regulations considers the development of policies and business laws to support applications of IE approaches. These four areas have specified approaches and further details referring to Li (2018).

Solar cell technologies and criteria used for life cycle analysis

The solar cell technologies have been evolved from various silicon (Si) solar cells to cadmium telluride (CdTe) solar cells and further organic solar cells (OPV) (Gerbinet et al, 2014; Giancarlo et al, 2013). The solar cell manufacturing technologies include polymer solar cell technology, dye-sensitised solar cell technology, thin film solar cell technology and quantum dot (QD) solar cell technology (Li, et al., 2015; Espinosa and Krebs, 2014). Other classifications for solar cell modules can be wafer or ingot, single junction or multiple-junction. The solar cell technologies have been innovated consistently, in terms of raw materials used, forms of module, as well as manufacturing processes.

The solar cell field research has focused on the improved efficiency of this renewable energy and the LCA of solar cells technologies. The criteria used to evaluate solar cell technologies in these studies include one or more of the following: energy-conversion efficiency, product energy payback time (EPBT), material and production cost, product lifetime, and emissions (Azzopardi and Mutale, 2010; Li et al, 2015; Espinosa et al, 2011). The LCAs in the literature for the solar cell technologies have offered some insight from product development life cycle from the product development for mass production to markets. However, the product life cycle from material extraction to product after-use options needs to be performed to give a more accurate overall picture of impact the solar cell production on the environment (Gerbinet et al, 2014), not just from energy perspective alone. The current solar technologies accept 10 per cent energy conversion rate commercially and lifetime up to 30 years (Azzopardi and Mutale, 2010). The current world record of energy conversion rate is at 46% percent for a 4-junction solar cell module, (Kobe University, 2017). But this technology innovation is not yet ready for mass production. A few studies on solar cell technologies have mentioned its end-of-life management, which has been largely neglected in most LCAs of solar cell technologies, which are discussed in the next sub-section along with potential applications of IE to this industry.

Recycling technology for end-of-life solar cell products and application of IE

Overall, product after-use options have not been considered by LCAs for solar cell technologies in general. IE has not been applied in the solar cell industry. However, a couple of studies have emphasised the benefits of using recycled wafers to reduce costs and energy for production to reduce EPBT and environmental impact (Azzopardi and Mutale, 2010; Perez, et al, 2012). Using recycled materials for wafer-based solar modules reduced the EPBT in half (Azzopardi and Mutale, 2010). Using waste-stream mono-crystalline silicon (mono-Si) for a facade integrated photovoltaic (PV) system installed in New York has dramatically reduced its environmental impact (Perez, et al, 2012).

A technology has been discussed for treating end-of-life solar cell products of the thin film PV modules (Giacchetta et al., 2013). The study has emphasised the importance of treating end-of-life solar cell products to avoid a large amount of landfill. The study evaluates the environmental benefits of developing and using a high value mechanical process to end-of-life solar cell products of thin film CdTe modules. The process contains shredding, crashing, applying wet mechanical treatments to separate different elements to recover raw materials of CdTe, CdS and glass to more than 90 percent of the original input materials (Giacchetta et al., 2013). The process illustrates the possibility of recycling of end-of-life solar cell products. There are other technologies available to deal with silane recycling in amorphous silicon-based solar cell manufacturing (Kreiger et al., 2013). However, technologies are not available to deal with all existing types of solar cells as the DfE was not integrated when the products or technologies were developed several decades ago.

Considering the use of recycled materials and options of recycling of end-of-life products are consistent with the principle of IE, even though they are only partially in principle. These studies have not been associated with IE and a full application of IE is still yet considered.

It is clear that a systematic approach to the application of IE is needed for the solar cell industry, which is currently lacking. Developing a closed loop material exchanges needs to consider different approaches to determine industrial ecosystem boundaries for the solar cell industry. It needs to develop collaborations among different companies, waste processers, research institutions, and product and process development and design institutions for facilitating innovative ideas for material exchanges. The metabolism of the industrial ecosystems is also needed to be evaluated besides applying LCAs to solar cell technologies and products. Last but not least, the legislation and regulations for developing solar cell technologies should not just consider from renewable energy perspective of the solar cell technology but also from the product life cycle perspective to close material exchange loops.

Research Methodology
Figure 1 presents the key elements which this research contains in order to achieve the research aim.

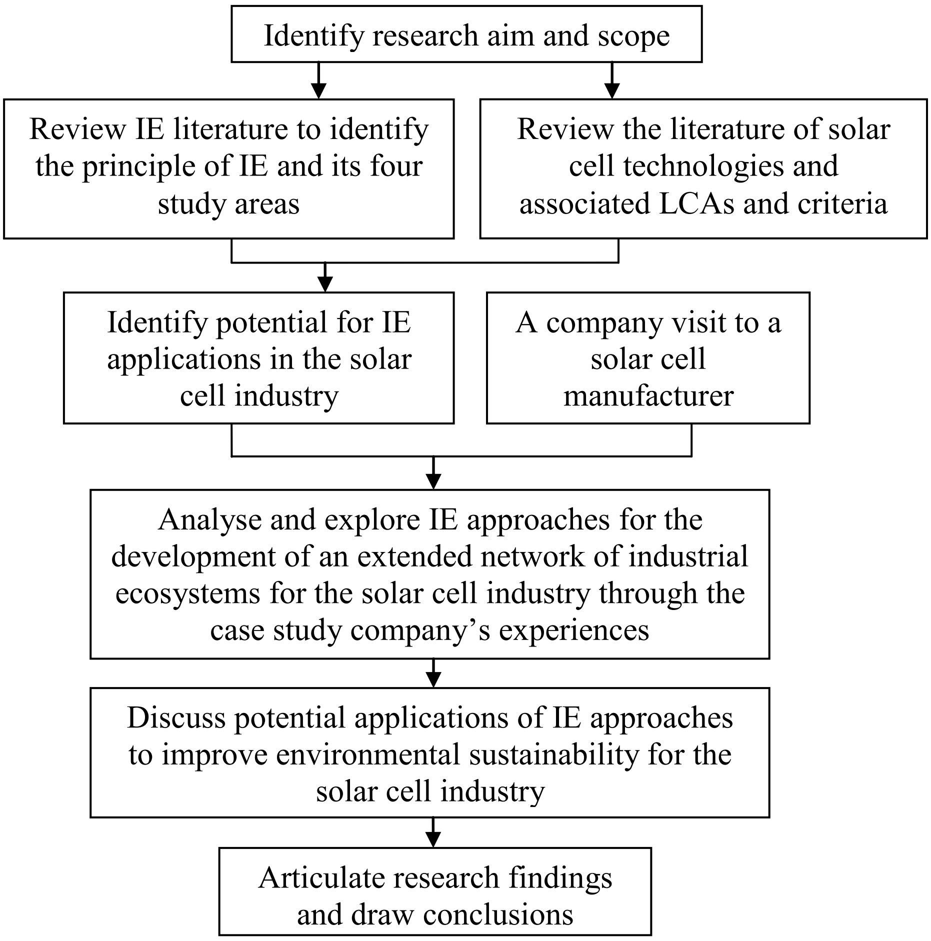


Figure 3 Research design key elements

Data for this research have been collected from the literature, the company visit and various sources of documentation. An initial literature review assists the establishment of research aim and scope. Further literature review focuses on approaches within four IE study areas. A company visit has been made to a manufacturing company which produces solar cell related products in Tianjin, China. The production process has been illustrated and different inputs and outputs have been identified along this production process. A life cycle of solar cell products in this industry both from published works and documentation of the industry has been produced and used in analyses. Analyses investigate the applicability of some key IE approaches across its four study areas in developing an extended network of industrial ecosystems. Discussions of these approaches with the case study company have been made to evaluate practical implications of this extended network of industrial ecosystems to improve environmental sustainability. Research findings are generated both for academic researchers and practitioners.

Case study company background

A large silicon solar cell manufacturer in Tianjin, China provides the case study materials, regarding the production process of producing solar cell panels mainly and some solar cell related products. The company belongs to a national group which have a number of manufacturing companies across the country. The company has been well established over nearly two decades. The company works with a local institute for the new product development and currently stays in the traditional silicon-based solar cell productions and the efficiency of the current production for energy conversion is about 17 per cent. The manufacturing process requires a set of 'printing' machines for printing silicon onto the panels. The main products are solar panels for the roof installation. The company have installed their own solar cell products on the roof of their large manufacturing workshops. However, the electricity generated by these solar panels are just for the office use, not for the manufacturing processes to operate because the level of stability of electricity generation is issufficient to ensure the quality of the production required.

When visiting the manufacturing facilities, the solar panel expert from the local institute was also present for answering questionsl. The cleanness requirement of the manufacturing plant is extremely strict and a set of wind tunnels are separated and ensure the dust free environment along the corridors besides the each compartment of the large workshop. The glass separation between the corridors and workshop compartments further ensures the air-tight cleanness to guarantee the quality of the products, while allows the observation by visitors. A technical manager was present from the factory facility as well as the solar cell expert from the local institute. They had emphasised heavily on the importance of the energy conversion efficiency rate improvement to the business. However, they also stated they had invested in new machineries to support the updated technology change in productions. The old facilities were discarded. The company constantly monitors the energy conversion efficiency rates based on samples of the production.

When the question was asked about whether they were concerned with the end-of-life solar panels, they answered there were no agreement to take back end-of-life solar panels, as there were almost none at the moment to consider. For the competition purpose of this industry, they focused on energy efficiency conversion rate and production costs, because raw materials used were not expensive comparatively to the production costs. The solar cell expert mentioned they were currently considering using a different raw material which would give much higher in energy conversion rate but much more expensive. Therefore, its mass production is unlikely in near future. The solar cell expert totally rejected the possibility of considering recycling of end-of-life solar cell panels and associated solar cell products at the current economy.

Analysis and findings

The analysis considers the four study areas of IE and the potential applications to the solar cell industry, referring to the case study companies. The technology development for recycling solar cell modules and using recycled materials for solar cell production reported in the literature are also considered in the analysis and discussions (Giacchetta et al, 2013). It is to demonstrate the directions of the development of this industry in order to take on the IE principle to develop higher level of industrial ecosystems with closed-loop material exchanges to improve the environmental sustainability for the industry. The research findings are summarised mainly from the IE four study areas with the consideration of the current situation in the industry.

Table 1 – The analysis of the four IE study areas in relation to the case study company

IE areas	The current situation of the case study company	Potential IE application
Industry ecosystems	Developing industrial ecosystem has not been considered purposefully. No end-of-life consideration at the product design stage.	Production facility could have been considered as an industrial ecosystem. However, without the consideration of end-of-life solar cell products, the closed-loop industrial ecosystem is far from complete. Implementation of DfE at the product and production facility design stage. Product-based industries ecosystems for beyond the factory location.
Industrial Symbiosis	Collaboration with a local institute, but not with other companies.	Knowledge and information on potential collaborations among industries need to be explored.
Industrial Metabolism	The industrial ecosystem concept needs to be established first.	With the established different levels of industrial ecosystems, the evaluation of their metabolism can be used to further development.
IE legislation and regulations	Legislation and regulation focus on the development of this industry but not on the end-of-life products recycling, particularly integrated in the design stage	Legislation and regulations in both developing and developed countries support the solar cell technology development as a renewable energy source. However, the legislation and regulations needs to consider the IE principle to support product and process design phase integration to end-of-life product recycling and remanufacturing.

Technology development for remanufacturing and recycling end-of-life solar cell related products is essential as it is one of the first few steps moving towards the development of nearly closed-loop material exchanges in this industry. The use of recycled or waste stream is also another way to close the material loops with involvement of other industries or recycling companies. However, the development of these technologies is at their infant stages and far from mature. Reuse at the product level for solar cell products might not be an effective option, as the industry is at its rapid development and using upgraded products are essential to the industry's further development and also for a solar cell manufacturer to be competitive in the market. Remanufacturing which uses old but durable components with upgrading possibilities to bring the products to a superior performance level with much lower cost and reduced environmental impact. If at the design stage, the design for disassembly has been considered, some components could be reused for remanufacturing together with other new critical components to upgrade products both at lower cost and higher level of closed-loop material exchanges. Beside, recycling of materials, for example cadmium telluride and copper indium selenide which can be toxic to the environment, ensures these materials staying in the circulation without negative impact on the environment.

The analysis generates the following findings:

1. Product-based approach instead of geographic-based approach is more appropriate to determine industrial ecosystem boundaries for this industry (Korhonen, 2002).
2. Design for environment (DfE) provides a strategy to develop preventative-based approaches and technologies along the product life cycle for developing an extended network of industrial ecosystems (Jackson et al. 2016).
3. A knowledge web of information and data for collaborations across companies, industries, institutions and final users supports the development of an extended network of industrial ecosystems (Lombardi and Laybourn, 2012).
4. Improving the metabolism by creating innovative material and energy pathways (Lu et al., 2015).
5. Development of legislation and regulations in line with IE applications, with a particular consideration of after-use product management is critical for the future development of this industry with potentially closing the material loops for improved environmental sustainability (Malcolm and Clift, 2002).

Conclusion

The significant contribution of this research is to integrate IE for improving environmental sustainability for manufacturing industries, particularly for solar cell manufacturing industry. This research is interdisciplinary, but focuses on environmental sustainability theory building, with extended system thinking from IE.

Potential consideration and applications of IE across its four study areas to the development of an extended network of industrial ecosystems are not limited in this industry. The exploration and discussion based on the solar cell industry demonstrates the possibility and development of IE to the contribution to environmental sustainability through closing material loops. Along the four IE study areas, the particular attention is given to the DfE approach in IE to integrate end-of-life options at the product and process design phase. DfE explores the full potential of product after use options at the design phase and therefore a higher level of closed-loop material exchanges is more likely to achieve.

Developing an extended network demonstrates the possibility of industrial ecosystem development through stimulating innovative ideas across industrial boundaries. This also presents challenges in managing the complexity of collaboration and information sharing. The industry needs to focus not only on the improvement of efficiency of generating electricity of solar cell technologies, but also on pursuing closing material loops in the long run in order to contribute to environmental sustainability profoundly.

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