13 Eco-efficiency analysis of the plastic recovery systems in Hyogo eco-town project

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Abstract

Japan started the promotion and development of eco-towns in 1997, with the aim of reducing the environmental pressure through a symbiosis of industries and cities. Hyogo prefecture (located in the west of Japan) has been promoting a recycling-oriented society with the cooperation of industries, citizens and businesses.

This study analysed the possibilities of implementing a reverse logistics network for plastics recovery and its coupling with existing industries and technologies. Since many industries are operating in Hyogo, the use of their facilities and/or equipment for plastics recovery has been proposed, specially the steel and chemical industries. Reverse logistics was used to analyse the supply of input plastics in terms of quantity and quality. This means clustering small neighbouring cities for synchronised sorted collection (there is a difference between small cities, which already use sorted collection, and big cities, where no sorted collection for plastics exists), and coordinating activities between larger cities.

This study was part of a research project aimed at closing the loop in the Japanese plastics industry by introducing an integral approach with improvements to the upstream and downstream sides of the plastic supply chain life cycle.

This paper presents the results of the first part of the study, which included the use of domestic plastic packaging as plastic sources and material, feedstock and energy recovery as recovery technologies. The results

G. Huppes and M. Ishikawa (eds.), Quantified Eco-Efficiency, 307–327.

of this study indicate that the application of reverse logistics, combined with the appropriate recovery technologies in Hyogo eco-town, is both environmentally and economically beneficial. However, it requires close collaboration between local governments and the industrial sector.

13.1 Introduction

Fostering sustainable development requires changing linear economies towards a system where production and consumption cycles are closed as much as possible. Strategies for this goal of closing the loops include the re-use and re-integration of products and components, recycling of materials and energy recovery (Indigo Development 2004). Further strategies towards more sustainable production include increasing yields by new or optimised production technologies and using less material to manufacture the same product. All of these options aim to reduce the materials input into a given system (Moriguchi 1999). The reduction of materials requirements, both absolute and relative, is also referred to as dematerialisation.

This paper is part of a research project which aims at closing the loop in the Japanese plastics manufacturing sector. The research project introduces improvement strategies to both the upstream and downstream sides of the sector's supply chain (Morioka et al. 2003).

In this paper, we focus on an eco-efficiency analysis of the plastics end-of-life improvement strategies based on streamlining plastic waste materials and energy recovery. Since the main impediment to improving recycling levels are the collection, sorting and transport costs (Yabar and Morioka 2002), we propose the introduction of reverse logistics as a method to reduce these costs, in order to make plastics recycling an economically attractive option. Coupling the reverse logistics system with an adequate recycling technology, using existing industrial facilities should make it possible to construct a plastic recovery system covering a wide area. The scenarios were driven by the Japanese environmental policy, which set targets to increase recycling levels and reduce final waste disposal. As for the methodology, the environmental and cost impacts of four scenarios were evaluated, using life cycle assessment and life cycle costs, respectively. Both evaluations were normalised and an eco-efficiency analysis was used to identify the best scenario.

Hyogo eco-town

The concept of eco-towns was introduced in Japan in 1997, as a way to promote the symbiosis of industries and cities. Since then, more than 20 eco-towns have been implemented in cities and regions across the country, Kitakyushu being the best known.

Hyogo prefecture has been promoting a recycling-oriented society as part of the restoration efforts after the devastating earthquake of 1994, and has received from many areas and sources. This experience served as a basis to construct a wide area sustainable closed loop system for recycling, involving partnerships of industry, government and citizens. The basic plan of Hyogo eco-town includes (Hyogo Eco Town Promotion Conference 2003a):

- Recycling promotion based on industry cooperation: the steel and the chemical industries (primary industry) are located in the western part of the Hyogo area, while the main consumption area (process assembly type industries) is in the eastern part. The know-how and technologies available at the advanced industries can be used to provide a recycling base for the existing factories.
- Construction of a recycling system covering a wide area in cooperation with other cities and prefectures: the industrial infrastructure and physical distribution facilities available at Hyogo can be used to meet the needs of other areas, in order to promote a recycling system covering a wide area.
- Promotion of citizen cooperation: citizen groups such as the ‘environmentally conscious purchasing’ group and the ‘take your bag for shopping’ group have been active in Hyogo for almost a decade. Starting from this basis, the Hyogo eco-town plan also aims at active participation by citizens in the promotion of recycling.

Basic plan of the eco-town and plastics recovery facilities

The main object of Hyogo eco-town is to construct a closed loop recycling system using existing facilities (Hyogo Eco Town Promotion Conference 2003b). This means taking advantage of some key industries that are already operating in the area, such as the steel industry, chemical industry, energy supply industry, etc. However, the focus should not only be on recovery technologies, but also on the logistics of an adequate supply of the input plastics, in terms of both quantity and quality (Yoshinaga et al. 2002). This requires clustering small neighbouring cities for synchronised sorted collection and coordination among larger cities. It is also necessary to determine the best option for the locations and characteristics of Materials Recovery Facilities (MRF) and/or pre-treatment facilities. Finally, the most adequate transport system must be established.

13.2 Reverse logistics approach to plastic recovery

Reverse logistics entails collection, handling and transport facilities to return recyclables to an established recycling centre or a recovery facility (Fleischmann 2001). In order to achieve an efficient reverse logistics network, the following factors should be addressed (De Brito and Dekker 2004):

- Mismatches in demand and supply in terms of timing, amounts and quality of the product.
- Economies of scale must be sufficient to make reverse logistics environmentally and economically viable.
- On the operational side, a cost–benefit analysis must be made of collection, transport, freight, MRF, etc.

Reverse logistics and recovery technologies analysis

In order to establish an efficient reverse logistics network for plastics recovery and then couple it with the existing technologies, the current situation must first be analysed. This means analysing the cities that are already applying sorted collection for plastics, the industries that usually discharge plastic wastes in their processes, the existing technologies for plastics recycling in the area, etc. Subsequently, the main factors affecting the collection system should be determined. These factors include collection areas and frequencies, collection efficiency, transport modes as well as the Materials Recovery Facilities (MRF), which are usually the first destination of the collected waste plastics. The next step is an analysis of the recovery technologies. As mentioned above, there are many industries in Hyogo whose technologies and facilities can be used for the recovery of plastics. The present study focused on the steel and chemical industries. In the case of the steel industry, plastic wastes can replace virgin resources such as coal and coke in the steel-making process. As for the chemical industry, plastics can be transformed back to basic chemical compounds through gasification. After the analysis of all these factors has been completed, possible scenarios for the reverse logistics network and the best plastics recovery technologies can be established. Figure 13.1 shows the reverse logistics flow analysis.

Plastics recovery technologies in Japan

As a result of many years of research and technological development, as well as policy support, Japan now has available many methods and

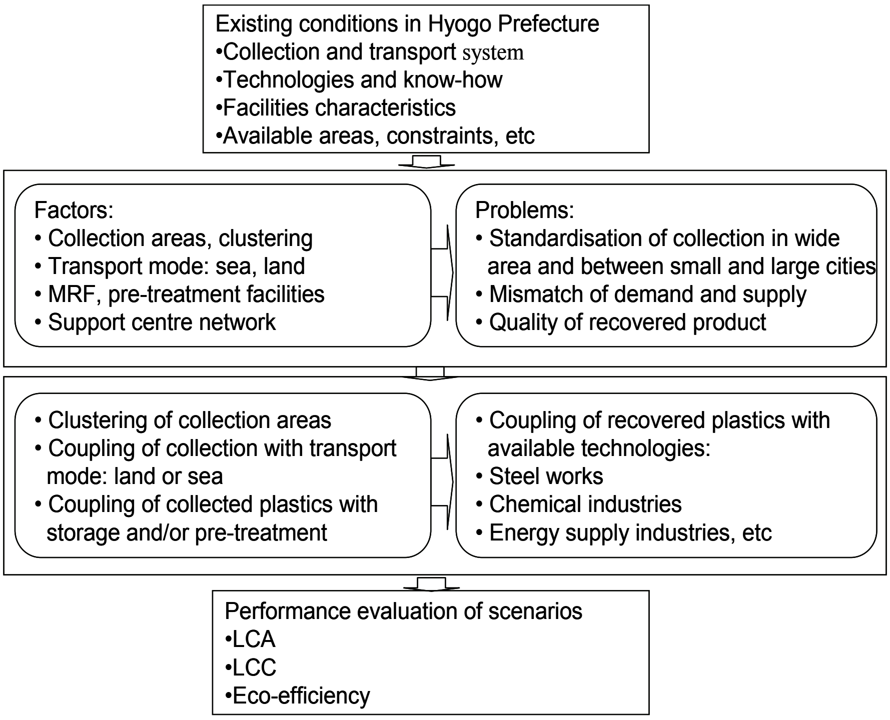

Figure 13.1 Reverse logistics approach to plastic wastes recovery

technologies for plastic waste recycling. These recycling methods, insofar as they are currently recognised under the Japanese plastics containers and packaging recycling legislation (PWMI 2004) include material, chemical and thermal recycling (see Table 13.1). Material recovery technologies include the transformation of waste plastics into flakes for further product making (open loop) and the chemical transformation of polymers into their original monomers (closed loop). In the case of chemical recycling, which is also known as feedstock recycling in Europe (Lundquist et al. 2000); it includes using plastics as a feedstock in blast furnaces, liquefaction, transformation into coke and gasification. Thermal recovery options being considered include incineration with energy recovery, use as fuel in cement industries and transformation into refuse-derived fuel (RDF) pellets. In general, all plastics recovery technologies need some form of sorting and pre-treatment in order to obtain a good quality recovered product (PWMI

Table 13.1 Plastic wastes recycling methods

<table>
<tr><th>CATEGORY</th><th colspan="2">RECYCLING METHOD</th><th>TERM USED IN JAPAN</th></tr>
<tr><td>Mechanical recycling</td><td colspan="2">Plastic raw materials
Plastic products</td><td>Material recycling</td></tr>
<tr><td rowspan="4">Feedstock recycling</td><td colspan="2">Monomerization</td><td rowspan="4">Chemical recycling</td></tr>
<tr><td colspan="2">Blast furnace reducing agent</td></tr>
<tr><td colspan="2">Coke oven chemical feedstock recycling</td></tr>
<tr><td rowspan="2">Gasification
Liquefaction</td><td>Chemical feedstock</td></tr>
<tr><td rowspan="2">Energy recovery</td><td>Fuel</td><td rowspan="2">Thermal recycling</td></tr>
<tr><td colspan="2">Cement kiln
Waste power generation
Refuse-derived fuel (RDF)</td></tr>
</table>

2002). The government is promoting the chemical recycling of plastics, because of the large treatment capacity available in the steel industry, which already has the know-how and installed facilities, such as coke ovens and blast furnaces.

Recovery technologies evaluation: basket-of-goods method

The basket-of-goods approach (Heyde and Kremer 1999) allows a fair comparison of recovery technologies. In this method, each scenario contains one recovery process and a number of conventional processes (complementary processes) that manufacture the products of recycling and recovery processes included in other scenarios. This way, each scenario produces the full complement of products of all recovery processes in given proportions (basket of goods). This approach allows scenarios to be directly compared in terms of a given indicator, because their waste input and product output are the same (Patel et al. 1999).

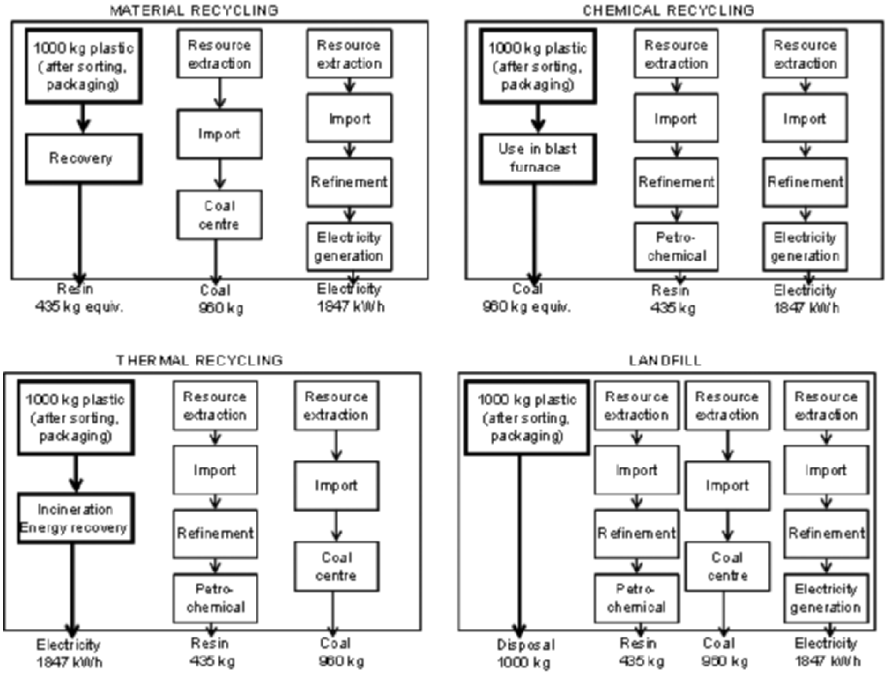

Figure 13.2 Scenarios for plastic recovery technologies

As recovery technologies, our study considered material recycling, chemical (feedstock) recycling and incineration with energy recovery. Figure 13.2 shows the details of the scenarios we analysed. Scenario 1 includes a materials recovery system in which the recyclate substitutes different products made of primary plastics (open loop). It also contains two complementary processes that produce electricity and coal through conventional methods. The same principle applies to the other two scenarios, involving chemical recovery and thermal recovery, respectively. In the case of chemical recovery, we assumed that the plastic wastes would be used as a substitute for coal in a blast furnace, and the thermal recovery scenario assumes energy recovery from a regular municipal solid waste incinerator. Finally, landfill was assumed as a base scenario. The functional unit we used was one ton of plastics (collected, compressed and packed) transported to the recovery facility.

Plastics recovery technologies: environmental impacts and costs analysis

The evaluation of the recovery technologies considered both environmental and economic performance. Indicators used for the environmental performance of the scenarios were virgin resources and energy use, global warming potential and final disposal waste potential (Figure 13.3). The selection of indicators was mainly driven by Japanese environmental law, which sets targets to increase materials recycling by 40% and reduce final waste disposal by 50% by the year 2010 (Yabar and Morioka 2003). Since Japan has committed itself to reducing greenhouse gas emissions by 7% over the period 2008–2012 period, we also included energy use and global warming potential as indicators. The economic evaluation included the costs of recovery technology as well as those of the complementary processes (Figure 13.4). In the case of the materials recovery scenario, 44% recovery efficiency was assumed.

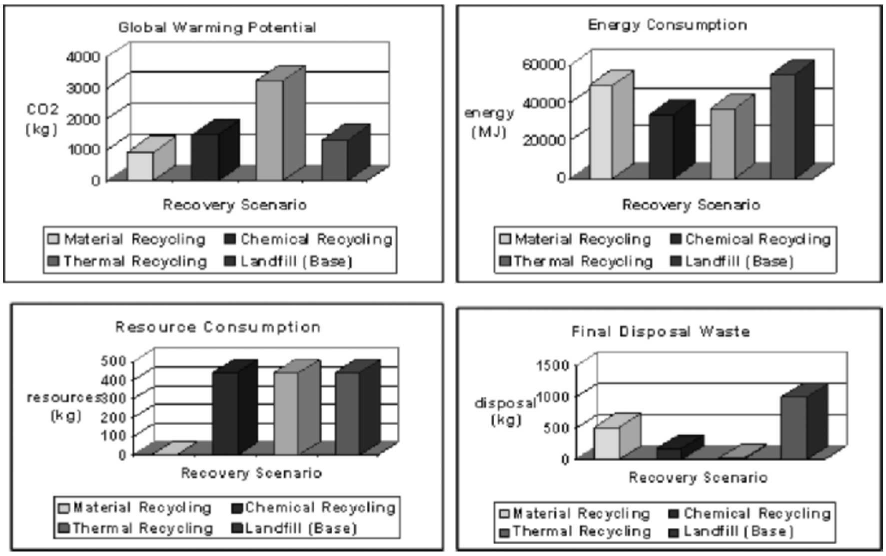

Figure 13.3 Environmental impact analysis of the scenarios

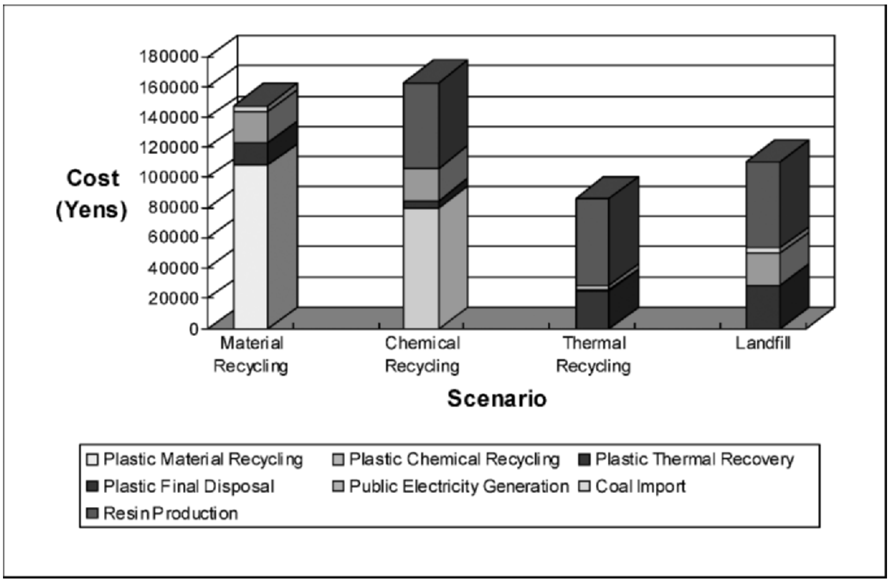

Figure 13.4 Economic analysis of the scenarios

Evaluation of plastics recovery technologies

Although the landfill scenario had the worst environmental performance for three of the four indicators, it is very difficult to estimate from the environmental analysis which scenarios deliver the best and worst environmental performance overall. The economic analysis showed that the material recycling scenario and the chemical recycling scenario are the most expensive ones. One possible reason for the high costs of the material recycling scenario is that we only assumed 44% materials recovery efficiency. Increasing this factor significantly improves the scenario's economic performance. The thermal recovery scenario has the best economic performance, and its environmental impact is comparatively low.

This analysis of the environmental and costs impacts of various recovery technologies provides only a partial view of the plastic waste management problem. In order to propose viable alternative scenarios, it is necessary to analyse the plastic waste management system from a cradle-to-grave perspective, i.e. from the time plastic wastes are collected until they are reclaimed and/or disposed.

13.3 Plastic recovery systems: reverse supply chain analysis

Reverse supply chain analysis takes into account all the steps in the waste plastics flow: from the time the plastic wastes are discarded until their final recovery or disposal. The present analysis focused on the waste collection, sorting and transport phase and its linkage with the most appropriate recovery technologies in order to construct an effective plastics recovery system for Hyogo.

Collection analysis: grid city model

Most collection analyses are based on assumptions of transport distances without considering important factors such as population densities, different collection systems for urban and rural areas, collection types, collection frequencies, truck capacities, distance to transfer stations, etc. The grid city model was conceived to allow a reliable and relatively easy calculation of the environmental and economic impacts of collection (Ishikawa 1996). The basic characteristics of this model are as follows:

Calculation Model

For the purpose of the study, it is assumed that the urban area has a regular grid type configuration. A collection truck starts its journey from the Materials Recovery Facility (which in Japan is called a recycling centre) to its collection area. In the collection area, the truck starts collecting waste from the stations, usually located at every block, until it is loaded to capacity. The collection truck then returns to the transfer station, unloads the wastes and goes back to the collection area to repeat the operation. This means that the collection trip can be expressed in terms of the distance travelled inside the collection area and the round trip to the transfer station. The calculation of the distance travelled by one truck during a round trip is showed in Figure 13.5.

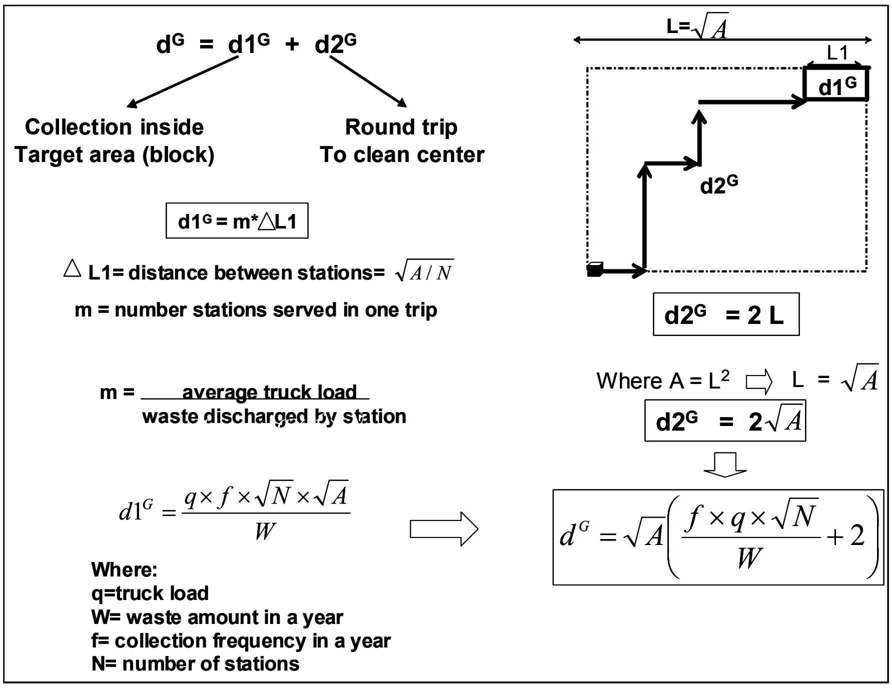

Figure 13.5 Collection analysis: grid city model

The formula shown in Figure 13.5 allows us to calculate the average transport distance of a collection trip (d^G). This means the round trip to the recycling centre or MRF and the distance travelled inside the collection area. Since the total number of collection trips in a year is given by:

$$\#\text{ of collection trips/year} = \frac{W}{q} \tag{13.1}$$

It is possible to calculate the total driving distance per year:

$$D\mathrm{G} = \sqrt{A}\left(f \times \sqrt{N} + \frac{2 \times W}{q} \right) \tag{13.2}$$

The actual driving distance differs from the calculated value because the actual roads configuration is not a perfect square, so a tortuosity factor is introduced. This factor is given by:

$$\xi = \frac{D^{\circ}}{\mathrm{DG}} \tag{13.3}$$

In this equation, D^0 denotes the actual observed value in cities for which data on waste transport distances are available. The tortuosity factor is obtained from a correlation graph of the real and calculated distance values for cities with different population sizes. This factor allows a more reliable estimate of the total driving distance per year.

Collection system boundary

The Hyogo eco-town target area includes 4 large cities (80% of total population), 3 medium-size cities, 8 small cities and 42 towns. Our model for big cities assumes a collection model with a Material Recovery Facility (MRF) inside each city. For the rest, we proposed clusters of small and medium-size cities and towns, assuming that the MRF is inside a medium-size city. Details of the Hyogo eco-town area statistics are shown in Table 13.2.

Table 13.2 Hyogo eco-town statistics

Item	Detail
Area	8,391 km^2
Population	5,540,308 people
Domestic waste generation	2,700,000 tons/year
Per capita waste generation	1.33 kg/person.day
Plastic packages waste generation	156,000 tons/year
Per capita plastic waste generation	77 g/person.day
# of cities over 1 million people	1
# of cities over 400,000 people	3
# of cities over 200,000 people	3
# of cities over 50,000 people	8
# of towns with less than 50,000 people	42

Integral plastics recovery in Hyogo eco-town

The objective of applying reverse logistics to plastics recovery in the Hyogo eco-town area is to reduce the collection, pre-treatment and transport costs to make the plastic recycling an economically attractive option. By coupling the reverse logistics system with an adequate recycling technology, using existing industrial facilities, it is possible to construct a wide area plastics recovery system. In order to determine the most adequate recovery technology according to the type of collected waste, it was therefore necessary to analyse the industries that are operating in the eco-town area and possess the technology and know-how that could be used for plastics recovery. The details of the plastics recovery system in Hyogo eco-town are shown in Figure 13.6.

As mentioned above, there is one plastic recovery related technology in Hyogo: the use of plastic wastes in the blast furnace at Kobe Steel Corporation (Kobelco). This furnace uses plastic wastes as a reducing agent for the transformation of iron ore into pig iron. Plastic wastes can also be used in the steel industry as raw materials along with coal in coke ovens. This allows the recovery of coke gas for use as fuel, coke for use in blast furnaces and oil for use in the chemical industry. Besides the possibility of using plastic wastes in the steel industry, the chemical industry and the energy supply industry also possess technologies and know-how that could be used for plastic waste recovery. Gasification is an attractive alternative because the high quality synthetic gas obtained from this process can be used in the chemical industry. Even though all these recovery technologies are already being applied in Japan, this paper only considers the use of plastic wastes as feedstock in blast furnaces as a chemical recycling option besides material and thermal recycling.

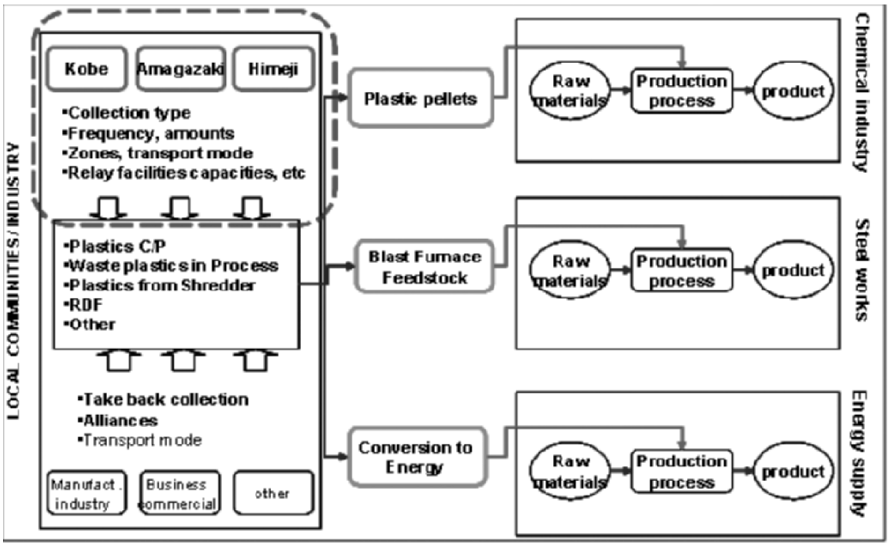

Figure 13.6 System boundaries for plastic wastes recovery

13.4 Eco-efficiency for recycling systems

The concept of eco-efficiency was developed by the World Business Council on Sustainable Development (WBSD) as a way to maximise the economic output or service while at the same time minimising the environmental impacts of human activities. However, the WBSD approach is mostly intended to evaluate the performance of production processes of products and services, and does not include the final recycling and recovery phase (Eik and Brattebo 2001). Since there are many types of recovery systems, it is particularly important to design the eco-efficiency indicators in such a way that they are applicable to the actual system being analysed. Eik and Brattebo (2001) proposed a set of indicators to be developed and applied when analysing an existing or possible future recovery scenario (see Table 13.3). The generally applicable indicators are to be developed for the analysis of all recovery systems. Additionally, if more information is needed, system-specific indicators for the actual system being analysed should be developed and applied. The application of these two types of indicators assesses the eco-efficiency of existing and future recovery scenarios.

Table 13.3 Eco-efficiency indicators for recovery systems

	System analyzed	Decision makers/users	Criteria for the indicators	Indicators
Generally applicable indicators (GAI)	- Entire recovery system - Indicators calculated per functional unit	- National authorities - Local authorities - Recycling companies - Firms	- Valid for all recovery systems - Reflect global environmental concern - Relevant and scientifically valid	- Amount recycled - Resources saving - Energy consumption - CO_2 emissions - Total net costs
System specific indicators (SSI)	- Entire recovery system - Indicators calculated per functional unit	- National authorities - Local authorities - Recycling companies - Firms	- Developed for the actual system - Reflect concern in the system - Relevant and scientifically valid	- Landfill pressure - SO_x - NO_x - etc

Scenario setting

The most important factor in setting our scenarios, along with the Japanese environmental legislation, was the diversion of plastic wastes from landfill, rather than the choice of a specific recovery option. Previous studies had shown that material recycling over 15% has no major benefit in terms of eco-efficiency (Eggels et al. 2001). In Japan, only 7% (PWMI 2004) of plastic wastes currently goes to open-loop material recycling. In the case of Hyogo, this recycling rate is actually zero, mainly due to the imbalance between collectable plastic wastes and potential end markets. Therefore, a maximum of 10% material recycling was assumed. Another important factor was the policy on plastic wastes in Japan, as the Japanese government has set a target of 40% for material and/or chemical recycling of plastic wastes by 2010. Finally, we also considered the recovery technology capacities available in the Hyogo eco-town area in our scenario setting. The resulting scenarios are shown in Figure 13.7.

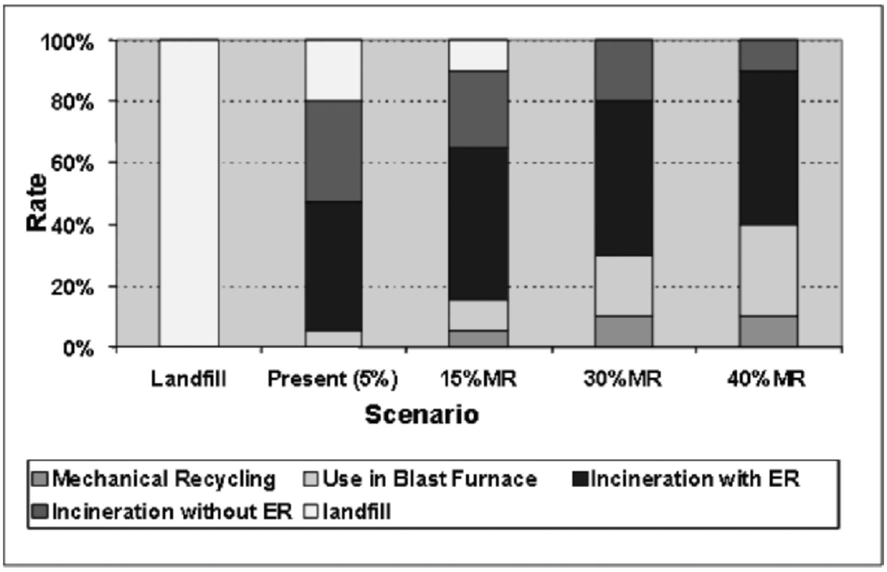

Figure 13.7 Scenarios for plastic wastes recovery

Environmental and cost analysis of the scenarios

The environmental evaluation used the same indicators used for the recycling technologies analysis: global warming potential, resource depletion, energy depletion and landfill use. The economic impact analysis included the costs along the reverse supply chain. The last three scenarios were evaluated with and without reverse logistics.

The normalisation of the environmental impacts was based on the annual emissions in Japan. The values were weighted using the social coefficient developed by the Fraunhofer Institute and the Association of Plastics Manufacturers in Europe (APME 2001). According to this method, the social coefficient for greenhouse gases is 35%, the social coefficient for energy depletion and that for resource depletion are both 25% and the social coefficient for landfill use is 15%. Figure 13.8 summarises the environmental evaluation approach.

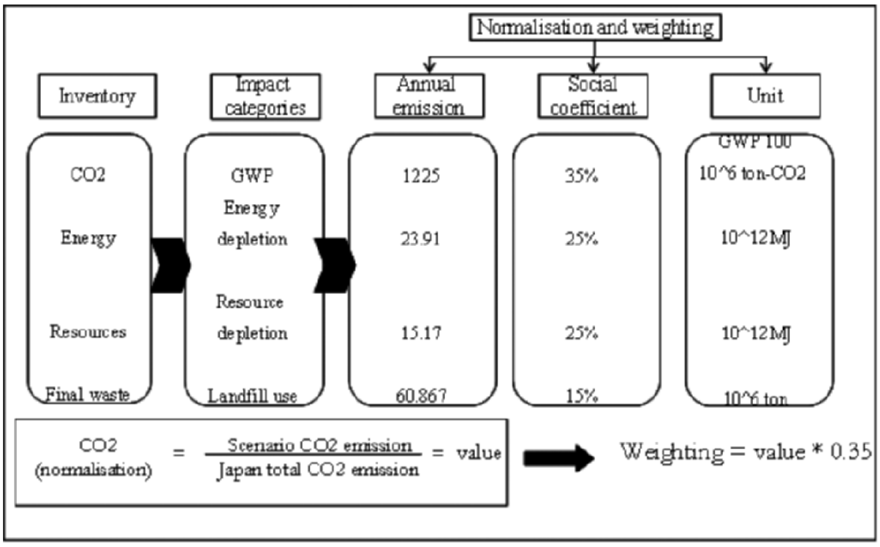

Figure 13.8 Normalisation and weighting of environmental impacts

Eco-efficiency evaluation of the scenarios

The environmental and economic impacts of the scenarios considered for the evaluation of the Hyogo eco-town plastics recovery system were normalised in an eco-efficiency graph (Saling et al. 2002), which is shown in Figure 13.9. The environmental impacts are shown on the vertical axis and the economic impacts on the horizontal axis. The introduction of reverse logistics reduces the collection costs by around 10% in the proposed scenarios (as indicated by the black arrows).

The results of the eco-efficiency analysis allow the following conclusions:

- While 100% landfill is the cheapest option, it has the greatest environmental impact.

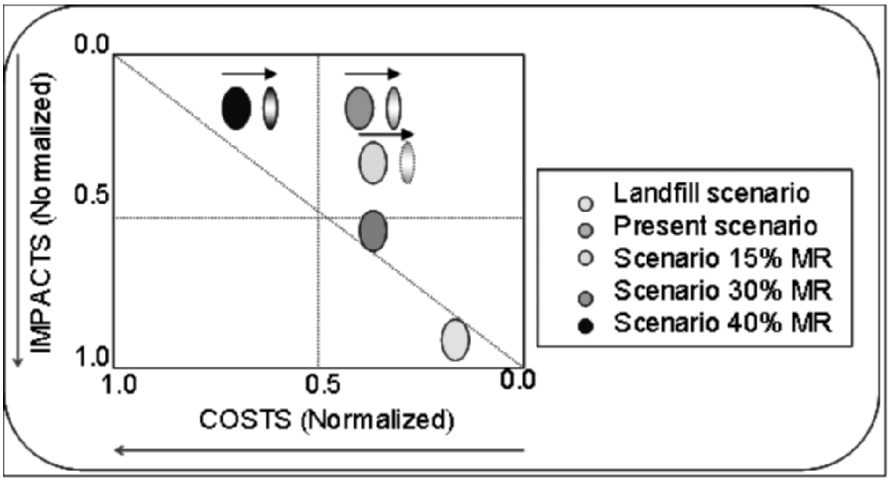

Figure 13.9. Eco-efficiency evaluation of the scenarios

- The scenario with 40% materials recovery has the best environmental performance but it is at the same time the most expensive option.
- The scenario that combines 30% materials recovery (10% material recycling and 20% chemical recycling) with a high level of energy recovery (50%) is slightly more expensive than the current situation but offers the best environmental performance. Applying reverse logistics improves the benefit in both respects.
- The scenario that combines 15% materials recovery (5% mechanical recycling and 10% chemical recycling) with a high level of energy recovery (50%) also offers a better option in terms of both environmental and cost impact than the current situation. Applying reverse logistics greatly improves the benefit.

13.5 Conclusion

This study analysed the possibilities of implementing a reverse logistics system for plastics recovery in the Hyogo eco-town project and its coupling with technologies and know-how available in the area. Applying the reverse logistics concept in the eco-town can produce both environmental and economic benefits by increasing recycling rates and reducing environmental impacts without incurring excessive costs. Our study focused on the environmental and economic performance of the main recovery technologies as well as a detailed evaluation of the plastic waste flow by analysing alternative scenarios to improve plastic waste management in the eco-town. The results allow the following conclusions:

- By using the existing industries and facilities for plastics recovery in Hyogo eco-town and coupling those with an efficient reverse logistics network for plastic collection and treatment it is possible to construct a wide area plastic recycling system.
- It is possible to reduce the overall costs impact by around 10% by introducing a reverse logistics system for plastics collection in the eco-town area.
- Combining increased material recycling levels with efficient reverse logistics allows both environmental and economic gains. However, material recycling levels over 30% seem to produce minimum environmental gain compared with the current approach, while greatly increasing costs: it is necessary to focus on diversion from landfill and simple burning rather than on a specific recovery option.
- Further research should include other sources of plastic wastes, i.e. industrial and commercial sources. The emphasis should also be on other types of recovery technology, especially gasification and pyrolysis (coke ovens).

Note.
Ishikawa has also developed a model to calculate the total number of trucks needed per recycling centre. This formula is important to estimate the economic impacts of the collection model. For more details on this model, see Ishikawa (1996).

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